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DE L'INFLUENCE DES CRUES SUR LES SERVICES ÉCOSYSTÉMIQUES DES PRAIRIES INONDABLES

Application à la production fourragère dans le delta du fleuve Tana, au Kenya

ON THE INFLUENCE OF FLOODS ON ECOSYSTEM SERVICES OF FLOODPLAIN GRASSLANDS

An application to fodder production in the Tana River Delta, Kenya

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Crystèle Léauthaud-Harnett: *On the influence of floods on the ecosystem services of floodplain grasslands:* An application to fodder production in the Tana River Delta, Kenya. Doctoral dissertation, February 2013 ©

Ohana means family.
Family means nobody gets left behind, or forgotten.

— Lilo & Stitch

To my father, and his love of science

To my mother, and the imaginative power of the rainbow serpent

To my sisters, love, unity... and a little bit of chaos

To my grand-parents, those here and those gone

PREFACE

Global challenges have become part of our daily lives. We hear about them in the media, feel them in the rainy summers and sunny winters and pay for them with human lives. They have become a major concern, and yet, despite the whole progress and awareness that has emerged in the last two to three decades, ecosystem degradation and climate change have been increasing.

2012 has witnessed the worst drought in the USA, and November was the 333^{rd} consecutive month during which the mean world temperature was higher than the XX^{th} century's average. The killings that are happening right now in Tana Delta are just another tragic illustration of land and resource conflicts. Even though they are going quite unobserved in the world, they are the worst killings in Kenya since the post-electoral violence of 2008. Ironically, it justifies, in a very sad manner, the present work. The equation is quite simple: *in fine*, it is a matter of life and death.

Concepts and new institutions have emerged to face global challenges (GAEC, CBD, MA). By filling in ours gaps of knowledge, and seeking novel solutions, they defend a certain vision of the future. The work presented here is a humble contribution to this goal. In this year where exiting discoveries have been made (Higgs boson, etc.), it is a small step for humanity and a big step for me. Just one small step, but that I hope exciting.

21^{st} December 2012.

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This whole story began in 2009 when I discovered the Tana Delta[1]. This whole story is for those I met over there. Special thoughts go to those who died in the recent conflicts, and to the dead that will undoubtedly come unless proper management strategies of the wetland are fixed.

Many research centers and teams contributed to this research. The National Museums of Kenya. Many thanks to W. Musila for accepting to take care of the biomass measurements. Thanks to M. Obunga and C. Chesire for the 2033, and probably more, plant samples dried. To Kenweb and the whole team led by W. Nyingi. Special thanks to Q. Luke, his acolyte N. Mwadime and O. Hamerlynck for the botanical survey. WRMA and the Maji House provided discharge data and support; KMD and TDIP provided

1 I did my Master's study (AgroParisTech, supervision H. Cochet and S. Duvail) there, which was already hosted by the "Eaux et Territoires" project.

rainfall data. The PEL (ILRI), especially J. De Leeuw and M. Said, encouraged me and broadened my thoughts. I also received help from ICRAF. IRD as my Research Institution is behind this whole project. The LISAH laboratory welcomed me in France. Many thanks to the current and former management teams, the informatics team, especially D. Crevoisier and M. Rabotin, the secretarial team, C. Fontana, Azziza and Laura, and the fellow students. Supagro for such a lovely campus. The IRD representation in Eastern Kenya gave technical support. The PALOC team offered me an office space in Nairobi and provided scientific and logistical support in the field. IFRA also hosted me in their premises, and helped me in getting a research permit. The MTD, with N. Bagdhadi, and G-Eau with C. Dejean who designed the irrigation scheme. I received a grant from the SIBAGHE doctoral school. Fieldwork was funded by the French Ministry of Environment in the framework of the program "Eaux et Territoires", by the Research Institute for Development (IRD), by the LISAH laboratory (INRA/IRD/Supagro) and by the PALOC laboratory (IRD/MNHN) .

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PUBLICATIONS AND CONTRIBUTIONS

PEER-REVIEWED PUBLICATIONS:

C. Leauthaud, S. Duvail, O. Hamerlynck, J-L Paul, H. Cochet, J. Nyunja, J. Albergel, and O. Grünberger, 2013. Floods and livelihoods: The impact of changing water resources on wetland agro-ecological production systems in the Tana River Delta, Kenya. *Global Environmental Change*, 23, 252–263.

O. Hamerlynk, Q. Luke, T.M. Nyange, S. Duvail, and C. Leauthaud, 2012. Range extension, imminent threats and conservation options for two endangered primates: The Tana River red colobus *Procolobus rufomitratus rufomitratus* (Peters, 1879) and the Tana River mangabey *Cercocebus galeritus* (Peters, 1879) in the lower Tana floodplain and Delta, Kenya. *African Primates*, 7(2):211–217.

C. Leauthaud, S. Duvail, G. Belaud, R. Moussa, O. Grünberger, and J. Albergel, 2012. Floods and wetlands: combining a water-balance model and remote-sensing techniques to characterize hydrological processes of ecological importance in the Tana River Delta (Kenya). *Hydrol. Earth Syst. Sci. Discuss.*, 9, 11267-11318, 2012.

C. Leauthaud, P. Hiernaux, W. Musila, S. Duvail, L. Kergoat, M. Grippa, M. Obunga, K. Otoi. Growth patterns of *Echinochloa stagnina* (Retz) P Beauv. under different management scenarios. in prep. *Journal of Applied Ecology.*

C. Leauthaud, L. Kergoat, P. Hiernaux, M. Grippa, S. Duvail, W. Musila, M. Obunga, K. Otoi. A plant growth model for floodplain grasslands. in prep. *Ecological modelling*.

Impact of changing hydrological regimes on the fodder production of the floodplain grasslands of the Tana River Delta, in Kenya. in prep.

ORAL COMMUNICATIONS AT INTERNATIONAL CONFERENCES

C. Leauthaud, S. Duvail, G. Belaud, J. Albergel, R. Moussa, O. Grunberger. Drought and water scarcity for a pastoralist in coastal Kenya: the role of wetlands (and their floods) in a semi-arid region, oral presentation. EGU General Assembly 2012, April 22 – April 27, Vienna, Austria.

poster presentations at international conferences

C. Leauthaud, S. Duvail, G. Belaud, J. Albergel, R. Moussa, O. Grunberger. Contribution of MODIS satellite imagery in modelling the flooding patterns of the coastal wetlands of the Tana River, Kenya, poster presentation. EGU General Assembly 2012, April 22 – April 27, Vienna, Austria. Prix du "Outstanding Student Poster Award".

Leauthaud C., Duvail S., Hamerlynck O., Paul J-L., Cochet H., Nyunja J., Albergel J., The Tana river delta, Kenya: The impact of changing hydrological regimes of rivers on agro-ecological services for downstream users, poster presentation. Hydrology Conference 2010 The Changing Physical and Social Environment: Hydrologic Impacts and Feedbacks, October 11 - 13, 2010, San Diego, CA, USA.

Acreman M., Albergel J., Cormier-Salem M. C., Duvail S., Fattal P., Hamerlynck O., Leauthaud-Harnett C., Lebrun D., Lolivier K., Paul J.L., Mwakalinga A. , Mwansasu S., Nyingi D., Nyunja J., Omengo F., Robin M., Valimba P., Yanda P., Water and land in East-African coastal wetlands: a prospective analysis of change in the Lower Rufiji and Tana Basins, poster presentation. 6th Western Indian Ocean Marine Science Association International Scientific Congress, August 24-29, 2009, Saint Denis, Réunion Island, France

other

Stéphanie Duvail, Crystele Leauthaud, Daniel Gathima, Henry Njuguna, Peter Ngubu, Dorothy Wanja Nyingi, Olivier Hamerlynck, Jean Albergel. Assessment of flood flow restoration conditions in the Tana River Delta, oral presentation. Hydrological Workshop at the Kenya Wildlife Service Training Institute, November 29 – December 2 2011, Naivasha, Kenya.

C. Leauthaud, W. Musila, S. Duvail, Quantifying the effects of floods on ecosystem services of wetlands: application on fodder production in the floodplain grasslands of the Tana River Delta, Kenya, oral presentation. 3rd Scientific Conference of the National Museums of Kenya, November 7-9, 2011, Nairobi, Kenya.

C. Leauthaud, 2009. Diagnostic agraire dans le delta du Tana, au Kenya. Master's thesis, AgroParisTech, France.

RÉSUMÉ ÉTENDU EN FRANÇAIS/EXTENDED SUMMARY IN FRENCH

Les zones humides, telles que définies par la convention de Ramsar (Ramsar 1971), forment d'importants écosystèmes qui s'étendent sur plus de 1200 million de hectares (MEA, 2005a). Elles fournissent de nombreux services à l'homme, dont des services production agricole, de régulation du climat, d'atténuation des inondations en aval des zones humides et de recharge des nappes phréatiques (Table 1). Pourtant, ces zones sont fortement dégradées, et on estime que plus de 50 % des zones humides ont déjà été détruites au cours du 20*ème* siècle (MEA, 2005b). La croissance de la population et le développement économique sont principalement mis en cause : ils engendrent, entre autres, la construction d'infrastructures, la conversion des terres inondées en périmètres irriguées, et la surexploitation des ressources naturelles.

Au sein des zones humides, les prairies inondables forment un écosystème particulier, caractérisé par la prépondérance des graminées et l'absence d'espèces ligneuses. Elles se distinguent aussi par la présence de nombreux herbivores, et, contrairement aux autres types de prairies, par une inondation régulière. Leur localisation et caractéristiques (en particulier leur étendue, composition spécifique et productivité) dépendent essentiellement du régime d'inondation (Taylor and Dunlop 1985; Zeilhofer and Schessl 2000; Pinder and Rosso 1998; Goslee et al. 1997; Robertson et al. 1984), et dans une moindre mesure des caractéristiques pédologiques du sol. Tout comme les autres écosystèmes des zones humides, les prairies inondables sont menacées par des changements d'origine anthropique. En particulier, la construction de barrages hydroélectriques peut modifier la durée, hauteur, et périodes d'inondation de ces prairies. Pourtant, ces dernières fournissent de nombreux services, tels que la production fourragère, la production de poisson, la recharge des nappes et l'atténuation des inondations en aval des zones humides.

Les prairies inondables sont particulièrement importantes pour les pastoralistes en Afrique Sub-Saharienne car elles fournissent deux ressources clefs pour le bétail : l'eau et le pâturage. Outre leur très forte productivité, (jusqu'à 200-250 kg de matière sèche par hectare et par jour), ces prairies ont pour avantage un calendrier de production décalé par rapport aux prairies semi-arides environnantes. Elles sont donc des prairies de contre-saison, et aident à la survie du bétail en périodes d'étiage fourrager. Dans le contexte de construction de barrages hydro-électriques, il est essentiel d'évaluer l'impact de l'infrastructure hydro-électrique sur les dynamiques d'inondations en aval des barrages, et leur impact sur la production fourragère des prairies inondables en Afrique Sub-Saharienne.

Le concept des services écosystémiques permet d'apporter des éléments de réponse à cette problématique. Ce dernier, qui stipule que les écosystèmes fournissent des bénéfices à l'homme (Daily 1997, MEA 2005a), est né à la fin du siècle dernier en réponse au constat de dégradation de l'environnement. Les êtres humains utilisent de plus en plus leur environnement, et de ce fait changent les propriétés et fonctionnement de ces écosystèmes. En conséquence, le flux de services est modifié, ce qui à son tour peut avoir un impact sur le bien-être humain. La caractérisation et quantification des liens entre moteurs de changements, propriétés et services des écosystèmes et bien-être humain est essentielle pour une meilleure gestion de nos ressources naturelles (Figure 2). Ce concept permet aussi de traduire des notions scientifiques complexes en des notions plus facilement utilisables par les gestionnaires de ressources naturelles. Il propose par ailleurs une vue intégrative pour la gestion des ressources naturelles, inspirée des sphères de l'écologie, l'économie, des sciences géophysiques et des sciences sociales.

Le delta du Tana, avec ses prairies inondables à *Echinochloa stagnina*, constitue un site d'étude pertinent pour étudier l'impact des changements du régime hydrologique sur la production fourragère, tant au niveau des questions scientifiques que de l'intérêt sociétal de cette recherche. Ces prairies constituent d'importantes zones de pâturage pour les pastoralistes Orma, Wardei et Somali. Ces derniers les utilisaient en tant que zone de pâturage de saison sèche, et avait mis en place un système de transhumance entre les prairies semi-arides des alentours et les prairies deltaïques. Or la construction de cinq barrages hydro-électriques des années 1960 à 1990 en amont du delta a fortement perturbé le régime hydrologique du fleuve (Maingi and Marsh 2002), et par conséquent l'utilisation des prairies inondables (Leauthaud et al. 2013a, **Annexe A**).

Cette thèse aborde par conséquent la problématique suivante, en se focalisant sur la quantification de la production fourragère des prairies inondables du delta du Tana, au Kenya :

COMMENT LE RÉGIME HYDROLOGIQUE D'UN FLEUVE, ET SES CHANGEMENTS, INFLUENCENT LES SERVICES ÉCOSYSTÉMIQUES QUE LES COMMUNAUTÉS LOCALES OBTIENNENT DES ZONES HUMIDES ?

Trois axes importants, qui ont permis de définir les objectifs spécifiques de la thèse, y sont développés :

1. QUELLES SONT LES CARACTÉRISTIQUES DE CROISSANCE DE LA PRAIRIE INONDABLE À *ECHINOCHLOA STAGNINA* ? Cet axe vise les objectifs suivants:

a) caractériser la productivité des prairies inondables pour différents traitements hydrologiques et de gestion de ces prairies

b) construire un modèle de croissance adapté aux prairies inondables

2. QUELLES SONT LES CARACTÉRISTIQUES D'INONDATION DANS LE DELTA DU FLEUVE TANA ? Les objectifs liés à cette question étaient de :

a) construire un modèle hydrologique du fleuve Tana

b) caractériser la durée d'inondation, l'étendue, l'époque et la fréquence d'inondation

3. COMMENT DIFFÉRENTS RÉGIMES D'INONDATIONS PEUVENT-ILS IMPACTER LE SERVICE DE PRODUCTION FOURRAGÈRE DE CES PRAIRIES INONDABLES ? Dans ce dernier cas, les objectifs visés étaient de :

a) définir des scénarios hypothétiques d'inondations, représentatifs des situations passées, présentes et futures

b) simuler la production fourragère pour ces scénarios et évaluer de façon quantitative trois indicateurs de services écosystémiques : la quantité, la qualité et la disponibilité du fourrage.

La méthodologie d'étude (Figure 8) a été choisie en fonction des objectifs et des données disponibles. Elle combine de l'expérimentation sur le terrain, de la collecte de données et de la modélisation. Le manuscrit de thèse est découpé en six parties : **I** introduction générale et définition des objectifs, **II** caractérisation et modélisation de la croissance prairiale, **III** caractérisation du régime d'inondation dans le delta du Tana, **IV** construction des scénarios de production fourragère, **V** synthèse, discussion des résultats et perspectives de recherche, **VI** appendices. Les approches et les principaux résultats des **parties II, III** et **IV** sont résumés ci-dessous.

Les prairies inondables centrales occupent une zone très plate, sur un sol profond et fertile de type vertisol. Elles s'étendent sur 200 km^2 entre les bras Matomba et Oda du fleuve Tana (Figure 11). Aux alentours de cette zone centrale, la prairie inondable se mélange avec d'autres formations végétales. La prairie inondable est essentiellement formée de trois espèces : *Echinochloa stagnina* (Retz) P. Beauv., *Paspalidium obtusifolium* (Delile) N.D. Simpson and *Vossia cuspidata* (Roxb.) Griff. *Echinochloa stagnina* (Retz). P. Beauv. est l'espèce dominante. Les différents stades de croissance sont semblables à ceux décrits par François et al (1989) pour la prairie à *Echinochloa* *stagnina* du delta intérieur du Niger. La croissance de la prairie commence à l'arrivée des pluies, avec un tallage important. Ensuite, à l'arrivée de la crue, les tiges s'allongent, permettant aux feuilles de rester au-dessus de la lame d'eau et à la photosynthèse de continuer. A l'issue de cette phase, les tiges peuvent atteindre plusieurs mètres de longueur (Morton and Obot 1984). A la décrue, les plantes tombent au sol encore saturé en eau et produisent des racines caulinaires (au niveau des nœuds) qui permettent une croissance végétative de la plante. L'arrivée du bétail dans la parcelle à ce moment favorise l'enracinement de la plante par piétinement. La croissance continue jusqu'à épuisement de la réserve utile en eau. Pour caractériser la productivité de la prairie, une parcelle expérimentale clôturée (13.6 m x 17.6 m), semblable à ceux de Hiernaux and Diarra (1986) a été mise en place près du village d'Onkolde (2°19'1.18" S - 40°11'19.74" E, Figure 11 et Figure 13) du 4 décembre 2010 au 1er mars 2012. Trois blocs ont été délimités et soumis à des traitements d'irrigation différents (0, 2.5 et 7.5 mm.jour^{-1}). Chacun de ces blocs a été subdivisé en trois sous-blocs, constitué de quatre quadrats de 1m^2 chacun. La biomasse aérienne de chaque quadrat a été prélevée régulièrement à 3 intervalles de temps différents : 16, 32 et 64 jours. La parcelle a aussi été inondée en novembre et décembre 2011. La productivité annuelle (cumul de la matière sèche récolté par an) et la croissance journalière (incrément de matière sèche produite par jour) ont été calculées. L'analyse statistique des données met en évidence les résultats suivants :

- La croissance de la prairie était saisonnière, et maximale après les inondations (Figure 14).
- La productivité de la prairie était élevée, avec des biomasses cumulées annuelles mesurées dans la parcelle expérimentale allant de 10.79 T.ha^{-1} à 32.44 T.ha^{-1}.
- L'inondation influençait la croissance journalière de la prairie (modèle linéaire généralisé avec une distribution gamma : ΔAICc=68 sans cet effet), et expliquait une partie de cette croissance (R^2=12% pour ce même modèle). Les croissances mesurées avant, pendant, et après l'inondation (moyennées sur les traitements irrigation et coupe) étaient respectivement comprise entre 0.07-17.91 g·m^{-2} · jour^{-1} ; de 4.76-22.5 g·m^{-2}·jour^{-1} ; et de 3.6-14.03 g·m^{-2}·jour^{-1}.
- En période non-inondée, les facteurs suivants ont été retenus comme pouvant expliquer la croissance journalière : irrigation et fréquence de coupe, certaines variables climatiques (rayonnement journalier moyen, précipitation moyenne), la date de coupe et position pré ou post inondation (facteur qualitatif). Le modèle linéaire ainsi testé retenu expliquait 77 % de la croissance journalière (Figure 18).

Les résultats concernant les mesures d'azote foliaire et caulinaire ainsi que la détermination de la répartition de la biomasse aérienne entre tiges et feuilles sont discutées dans le manuscrit.

La prise en compte de l'effet des variables climatiques sur la croissance journalière, et donc sur la productivité de prairies, est pratique courante dans des modèles de croissance (Parton et al. 1983; Rambal and Cornet 1982; Mougin et al. 1995; LoSeen et al. 1997; Nouvellon et al. 2000). Cependant, les modèles actuellement disponibles ne simulent pas les périodes d'inondations. Une analyse bibliographique, et les résultats de la parcelle expérimentale, ont montré que les prairies inondables présentent trois caractéristiques à prendre en compte dans un modèle de croissance prairial :

- des efficiences de conversion élevées durant la période inondée (Piedade et al. 1991), pouvant engendrer des croissances très supérieures à celles simulées pour une prairie classique ;
- une allocation des produits issus de la photosynthèse entre les tiges et les feuilles différente entre la période inondée et la période non-inondée (Piedade et al. 1991), avec une allocation préférentielle vers les tiges en période inondée ;
- la sénescence et la production de litière plus rapides en période inondée par rapport à la période non-inondée.

En prenant en compte ces trois aspects, nous avons donc construit un modèle de croissance, couplé à un modèle hydrique du sol, et adapté aux prairies inondées (Figure 21). Une analyse de sensibilité a permis de déterminer les paramètres les plus sensibles du modèle. Ces derniers ont ensuite été calibrés par la méthodologie GLUE (Beven and Binley 1992Beven and Binley 1992) puis le modèle a été validé, en utilisant les données de biomasse aérienne issues de la parcelle expérimentale (Figure 27 et 29).

La **partie III** de cette thèse concerne la caractérisation des inondations du fleuve Tana dans son delta. Un modèle global (Tana Inundation Model, TIM, figures 36 and 37) a été construit à partir des données hydrologiques et climatiques disponibles. Il est constitué de deux parties :

1. un modèle de propagation non-linéaire qui calcule le débit à l'entrée du delta à partir de débits mesurés 250 km en amont du delta
2. un bilan d'eau au sein du delta. Ce dernier prend en compte le débit à l'entrée, le ruissellement de surface, la pluie, l'évaporation réelle, l'infiltration et le débit à l'exutoire.

Le bilan d'eau a été calibré en comparant les surfaces inondées simulées avec des surfaces inondées mesurées à partir d'images satellitaires

(MYD09A1). En l'absence de données topographiques précises, la relation entre la hauteur de la lame d'eau et la surface inondée a été simulée par une équation de type logistique. Enfin, une carte des fréquences empiriques d'inondation dans le delta a été générée à partir de l'analyse complémentaire des images satellitaires (Figure 40). Pour 2002-2011, la surface inondée maximale a dépassé 340 km^2. Des inondations de plus de 200 km^2 se sont produits en moyenne une fois par an, et ont duré en moyenne moins de 25 jours. Le débit à l'entrée du delta comptait pour plus de 95 % des flux entrants dans le delta. Cette étude a permis une première quantification, de façon spatiale et temporelle, des inondations dans le delta du fleuve Tana pour 2002-2011. Les résultats sont primordiaux pour la gestion des ressources naturelles dans la zone, et en particulier pour la prairie à *Echinochloa stagnina*. La méthodologie, une combinaison de modélisation hydrologique et d'analyse d'images satellitaires, est applicable à d'autres zones humides semblables où les données sont éparses et où un couvert nuageux important limite l'utilisation de produits issus de la télédétection. Enfin cette étude contribue à élargir nos connaissances et méthodes d'études des bassins non-jaugés.

La **partie IV** de cette thèse présente une étude préliminaire sur la quantification du service de production fourragère pour différents scénarios d'inondations représentatifs de situations passées, présentes et futures. Huit scénarios annuels avec des durées et étendues d'inondations représentatifs des inondations possibles dans le delta, et un scénario annuel alternatif avec une irrigation partielle de la prairie ont été retenus (Table 21). La croissance journalière de la prairie centrale à *Echinochloa stagnina* a ensuite pu être simulée pour ces différents scénarios en utilisant le modèle de plante décrit ci-dessus. Enfin le service de production fourragère a été quantifié en utilisant trois indicateurs : la quantité de fourrage produit (biomasse cumulée pâturée), la qualité de ce fourrage (la quantité d'unités fourragères prélevées) et la disponibilité de ce fourrage pendant les saisons sèches (nombre de jours où la productivité primaire nette n'excédait pas 10 $kgMS \cdot ha^{-1} \cdot day^{-1}$). Ces scénarios ont permis de mettre en évidence que les trois indicateurs de service présentent une forte variabilité en fonction des différents scénarios d'inondation et d'irrigation (Figures 48, 49 et 50). En revanche, pour un scénario donné, les différents indicateurs peuvent évoluer en sens inverse. Ceci souligne la nécessité de prendre en compte les différents aspects du service pour déterminer l'effet bénéfique ou néfaste des changements. Enfin, cette étude préliminaire a permis une première quantification de l'effet du changement du régime d'inondation sur le service de production fourragère de la prairie centrale à *Echinochloa stagnina* dans le delta du Tana. Bien que ces scénarios ne soient que des représentations simplifiées de la réalité, ils permettent de comprendre les tendances majeures de cette évolution.

Sur le plan scientifique, cette thèse s'inspire et utilise des approches et techniques issues de différentes disciplines, allant de l'agronomie, à l'écologie en passant par l'hydrologie et la télédétection. L'utilisation à la fois d'images satellites et d'un modèle de bilan d'eau a permis de déterminer des caractéristiques temporelles et spatiales des inondations dans le delta du Tana, zone faiblement jaugée. Une première quantification de la productivité des prairies inondables à *Echinochloa stagnina* a été réalisée. Ce type de données est rare en Afrique Sub-Saharienne. Un modèle de croissance adapté à des Graminées en C4, tropicales et pérennes, de prairies inondables a été développé. Il constitue, à notre connaissance, le premier modèle écophysiologique adapté à ce type de prairies. Sur le plan écosystémique, cette thèse a permis de quantifier un des services majeurs des prairies inondables en Afrique Sub-Saharienne pour différents scénarios pertinents. Cette thèse souligne l'importance de caractériser de façon plus précise les inondations dans le delta du fleuve Tana, la croissance de sa prairie inondable et les usages de ces prairies. Une meilleure connaissance pourra être apportée par le développement d'un modèle hydrologique à réservoir multiple et par l'analyse d'images radar. Il est aussi urgent de continuer l'acquisition de données *in situ* et *ex situ*, tant sur l'hydrologie que sur la prairie elle-même. Le lancement prochain de satellites permettant une acquisition journalière ou hebdomadaire de données hydrologiques et végétales à des résolutions spatiales fines est prometteur. Enfin, il serait pertinent d'intégrer cette étude dans un cadre plus large où l'ensemble des services de la prairie inondable seraient quantifiés et comparés, et ce pour différents scénarios définis par une approche participative. Cela permettrait une meilleure évaluation économique et écologique des bénéfices fournis par le fleuve Tana et ses zones humides, et mènerait à une estimation plus précise des conséquences de la construction de barrages hydro-électriques sur ce fleuve.

CONTENTS

Part I

FRAMEWORK, CONTEXT AND OBJECTIVES

In **Chapter 1**, the basic scientific concepts used in this study are explored along with a bibliographical review on wetlands and floodplain grasslands. The Tana River Delta and its socio-economic context are then described in **Chapter 2**. These two sections lead me to define the objectives of the study, which are presented in **Chapter 3**.

Figure 1: A wetland and its people. Orma women fetching water. Photo: Cyril Ledéaut. April 2009

1 LITERATURE REVIEW

1.1 STATE OF THE ART ON THE ECOSYSTEM SERVICE APPROACH

1.1.1 *The Ecosystem Service framework*

The science of ecosystem services appeared some decades back (Holdren and Ehrlich 1974; Westman 1977; Daily 1997; Costanza et al. 1997) to answer our concerns on environmental degradation. It aims at integrating social, ecological and economical perspectives into decision making processes and policies related to environmental management (Seppelt et al. 2011). The idea was that by understanding and valuing our natural assets, better decisions and take better actions to improve land, water and other natural resources management could be made.

The Millennium Ecosystem Assessment (MA) report handed over to the United Nations in 2005 set up the general framework and propelled research in the arena. Ecosystem services were defined as the benefits provided by ecosystems (MA2005a). They were classified into 4 types of services: the provisioning, the regulating, the cultural and the supporting services. Humans are increasingly using the ecosystems of the planet. Through their actions (climate change, land-use change, propagation of invasive species, overexploitation, etc.), they are altering the properties or functions of the ecosystems which in turn modifies the flow of benefits we obtain from them. Changes in the provision of ecosystem services in turn affect human well-being. Figure 2 (Carpenter et al. 2009, modified from MA 2005a) shows how the drivers of change, ecosystem structure and processes, ecosystem services and human well-being are intricately linked to each other and must be studied together.

The Ecosystem Services (ES) concept has received much attention in the past decades and is becoming a paradigm in ecosystem management (Vihervaara et al. 2010; Seppelt et al. 2011). It has been widely acknowledged by the scientific community as well as by internationally recognized institutions (through the MEA, the CBD, the protocol of Kyoto), even though critical views have also emerged (Norgaard 2010; Spangenberg and Settele 2010). Considering Nature as a stock providing a flow of services (see Norgaard 2010) is a simplified representation of reality, but the concept can be easily integrated in the policy making arena to foster a sustainable use of natural resources. In fact, the ES concept has two main advantages (Vihervaara et al. 2010): 1/ the current degradation of the environment calls for

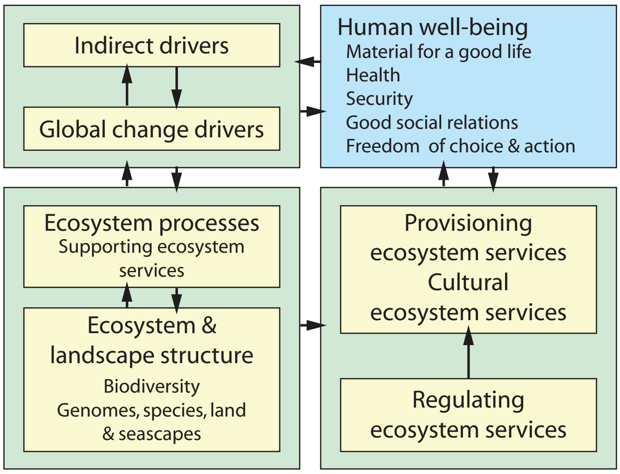


Figure 2: Link between drivers of change, functions and services of ecosystems. This diagram is drawn from Carpenter (2009), modified from its original source (MA 2005).

their sustainable use so that valuation and regulation methods are required; and 2/ the concept translates complex scientific notions into a common notion used in multidisciplinary scientific discussion and in the decision making arena (Norton 2000).

1.1.2 *Ecosystem service science as an integrative science*

ES science is based on pre-existing knowledge that goes back to Plato (Daily et al. 2009). It integrates concepts from ecology, economy, agronomy, geophysical sciences, social sciences and many other disciplines. For example, production functions linking input to output variables have long existed in the agriculture and manufacturing fields and have inspired the ES science progress in quantification and service mapping. It is also closely linked to the resilience framework (Holling 1973; Holling and Gunderson [2002]; Poff and Zimmerman 2010; Folke 2006) in which the robustness to change and adaptive capacities of living systems are studied. Finally, it is also linked to biodiversity (Le Roux et al. 2008, Hooper et al. 2005; Mertz et al. 2007). In fine, ES science proposes an integrated view of environmental management and is necessarily pluridisciplinary.

1.1.3 *Research agenda*

The ES approach is a growing discipline in which the basic concepts have been set but where fully operational methodologies are still being constructed. Its popularity has led to a proliferation of the use of the term ES, as testified by over 2.5 million results on Google and the 1048 scientific papers found on the Web of Knowledge database[1].

The diversity of methodologies has led many researchers to see the field as fragmented (Seppelt et al. 2011) with a need to improve its scientific bases (Ash et al. 2010). Several recommendations have followed, including:

1. implement rigorous measurements, modelling and monitoring of ecosystems functions (Costanza et al. 2011, Seppelt et al. 2011).
2. represent realistic biological processes (Nicholson et al. 2009).
3. involve stakeholders when defining services and implementing the concepts.
4. widen the studies on different services and have a more diverse representation of the ecosystems, and especially in under-represented parts of the globe (Vihervaara et al. 2010).
5. develop an institutional framework (Daily and Matson 2008).
6. integrate the measurement of uncertainty (Nicholson et al. 2009).
7. favour interdisciplinary approaches (Nicholson et al. 2009; Vihervaara et al. 2010), and
8. integrate feedbacks between and within the social and ecological spheres (Nicholson et al. 2009) as well as regime shifts and the notion of resilience of socio-ecosystems.

1.2 WETLANDS AND FLOODED GRASSLANDS

1.2.1 *Wetlands*

1.2.1.1 *Definition, context and services*

The Ramsar Convention on Wetlands (Convention 1971) provided a clear and broadly accepted definition of wetlands. They are: "areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water the depth of which at low tide does not exceed six metres". Wetlands extend over 1200 million hectares, with 120 million hectares located in Africa (MA, 2005, wetland), even though this is an underestimation as national databases lack appropriate censing methods, and global quantification methods do not capture the whole diversity of the wetlands. In particular, small and temporary wetlands are poorly identified. Wetlands are important ecosystems protected under the Ramsar Convention.

1 Term searched: "ecosystem service". There were over 14 000 entries for *ecosystem services* without brackets.

The benefits that wetlands provide have been specified in extensive literature (Convention 1971; Costanza et al. 1997; Millennium Ecosystem Assessment 2005a; Daily 1997; Turpie et al. 2010, and many others), summarized Table 1. It is noteworthy to acknowledge that wetlands can also provide dis-services, like breeding grounds for pests and pathogens (wetlands are famously known for malaria), but these dis-services, most of the time, are largely outbalanced by the services provided. Otherwise appropriate measures can be taken to specifically eradicate or diminish these dis-services. In some cases, wetlands are extremely important for livelihoods. In Africa, they are used extensively for fishing, livestock keeping, farming, or the harvest other natural resources (reeds, sedges, grasses, palm leaves, medicinal plants, wild food plants, seafood, salt, poles). These are not only used for home consumption (food, poles and clay for house building) but also to manufacture a whole range of goods (milk, dry fish, rice, sleeping mats, baskets, ropes, brooms, fishing equipment, etc.) that then provide an income through trade.

1.2.1.2 *A "natural" resource under threat*

Currently, 2049 sites have been designated as wetlands of international importance, covering over 193 million hectares (http://www.ramsar.org, consulted 24/08/2012). Even though, many are still being degraded, lost or converted. It is estimated that over 50 % of specific types of wetlands have been converted in the 20th century (MA,2005ba). But once again, it is difficult to estimate their loss as information on the extent of different wetland types are not available worldwide. The degradation of wetlands in the past 50 years seems to be more rapid than that of many other ecosystems (Millennium Ecosystem Assessment 2005a). The primary causes of wetland disappearance include population growth and economic development, with infrastructure development, land conversion, water withdrawal, pollution, over-harvesting and over-exploitation, and the introduction of invasive alien species (MA,2005ba). Wetlands are also particularly vulnerable to climate change (Kundzewicz et al. 2007). A main challenge in protecting wetlands systems is that the people most concerned by the loss are disconnected from the political decision making arena (MA,2005ba). Furthermore, mis-information or lack of information at the political level are such that decision makers do not weigh all the costs and benefits generated by wetlands (MA,2005ba). Finally, the non-marketed aspect of many of the services of wetlands and its public good character decreases incentives from individuals to protect wetlands (MA,2005ba).

Ecosystem	Ecosystem functions/properties	Ecosystem services
cultivated landscapes : rice paddies, tree farming, intercropped maize	primary production	food production (cereals, fruits, vegetables, etc.)
	primary production	income
	organic matter decomposition & mineralization	soil fertility
	carbon sequestration/ greenhouse gas absorption	microclimate regulation
floodplain grasslands	primary production/biodiversity	animal productions (meat, milk, leather, etc.)
	primary production/biodiversity	invasive species protection
	flood duration/resource availability	fisheries
	flood duration/ decomposition processes	water purification
	C, methane & nitrous oxide sequestration	microclimate regulation
	species composition	diversity conservation
mangrove	resource availability/water residence time	fish nursery
	primary production	wood & raw materials
	storm mitigation	coastal protection
	species composition	aesthetic
	species composition	ecotourism, recreation
lakes, swamps, open water	water and nutrient flow	fish
	flood duration & extent/resource availability/ species composition	diversity conservation
	flood duration and extent	freshwater provision

Table 1: General ecosystem services of the Tana River Delta wetlands, differentiated by the major ecosystems encountered. Cultural services are not specified. Complied by the author, but inspired by Le Roux et al. 2008.

1.2.1.3 *Valuation of wetlands and requirements*

Valuation of wetlands, by explicitly giving a value to their services, leads to a more balanced decision-making process, facilitates optimal decision making and, in fine, optimizes human well-being (Turpie et al. 2010). Valuation is used in water resource planning, to build local and political support, to achieve conservation goals, to evaluate the effects of alternative development options, and in many other ways. Many valuation exercises of wetlands have already been undertaken in Africa (Barbier et al. 1991;Barbier [1993]). However, wetland values are often underestimated because they do not take into account the whole range of services provided (often because of the public good characteristic of wetlands (Brander et al. 2006) or because of market or government failures (Turpie et al. 2010).

A substantial literature now exists on wetland valuation and many valuation methods exist (see Brander 2006 for a short list). In particular, rural appraisal methods build local capacity, promote discussion and reinforce capacity building and local management. The development of models and scenario building through a participative approach is a complementary method. They can be used to assess the current value of wetlands but also of alternative situations (historical ones, future development schemes, those preferred by the different stakeholders). Obviously and ideally, all valuation methods should be used concurrently to get a broader opinion and assessment and better converge to a consensus.

These valuations have not been applied to all the ES and are geographically more focused on temperate zones like the US and Europe. In order to value wetlands for use and conservancy issues, more quantitative studies need to be performed. Data availability and the lack of biophysical data on wetland functioning are some of the biggest obstacles (Turpie et al. 2010). Especially, there is a need to estimate the variability of ecosystem productivities and the availability of resources under changing wetland characteristics and functioning. This is even more urgent in Sub-Sahara where issues of sustainability, livelihood security are ever more a priority.

1.2.2 *Floodplain grasslands*

1.2.2.1 *Grasslands and their services*

DEFINITION AND SERVICES

Grasslands can be defined as “a plant community in which the Gramineae are dominant and trees absent” (Milner et al. 1968 in Gibson 2009). Other than the prevalence of grasses, they are often characterized by a low abundance of woody vegetation, deep fertile soils, an arid climate and important herds of grazing animals (Gibson 2009). Grasslands form some of the most extensive ecosystems on the planet and are the potential natural vegetation of approximately 25 % of the total land area ($36 \cdot 10^6$ km^2) (Sala and Paruelo 1997). They constitute the largest biome on Earth, largely in front of forests and agricultural land (White et al. 2000). They are important for humankind, with over 800 million people living in these areas (White et al. 2000). Grasslands are most extensive in sub-Saharan Africa (over $14 \cdot 10^6$ km^2) where 266 million people depend on them (White et al. 2000). Despite their significance for humankind, this biome has undergone rapid changes, mainly due to agriculture, fragmentation, invasive non-native species, lack of fire, desertification, human settlement and (the lack or too intensive use by) domestic livestock (Gibson 2009). It is estimated that 45.8 % of temperate grasslands, savannas and shrublands, 23.6 % of tropical/subtropical grasslands, savannas and shrublands, 26.6 % of flooded grasslands and savannas and 12.7 % of montane grasslands and shrublands have already been converted (Hoekstra et al. 2004).

This massive degradation takes place despite the important services we obtain from grasslands. These are food, forage and livestock, biodiversity, carbon storage, tourism and recreation, but also the provision of drinking and irrigated water, the maintenance of genetic resources, weather control, the maintenance of watershed functions, nutrient recycling, habitat for humans and wildlife, the removal of air pollutants, oxygen emission, employment, soil generation and aesthetic beauty (Sala and Paruelo 1997; White et al. 2000).

SPECIFIC CHARACTERISTICS OF FLOODPLAIN GRASSLANDS

Flooded grasslands form a specific grassland type characterized by frequent floods. They are found within the floodplains of rivers on most continents, such as the Llanos of the Orinoco floodplain, the campos of the Pantanal of Matto Grosso floodplain and within the Amazon floodplain in South America, the Everglades in North America, in Australia's tropical floodplains (Finlayson 2005), the Inner Delta of the Niger River, the Okavango delta and the Waza Logone floodplains in Africa. They are also under threat, mostly due to changes in the hydrologic regime of the adjacent rivers, but also by land conversion into cropland. For example, the Sudd-Sahelian flooded grasslands and savannas have been identified as a critically endangered grassland ecoregion (Conservation Science Program-WWF-US Global 200 in Gibson 2009). As grasslands, floodplain grasslands provide important functions and ecosystem services (see list above). An additional benefit compared to dry grasslands is that during the flooded seasons, they are feeding zones and nurseries for fish and enhance the fish production of the adjacent river. Figure 3 depicts the main services of the Tana River grasslands and their links to the functions of the ecosystem and the main drivers of change.

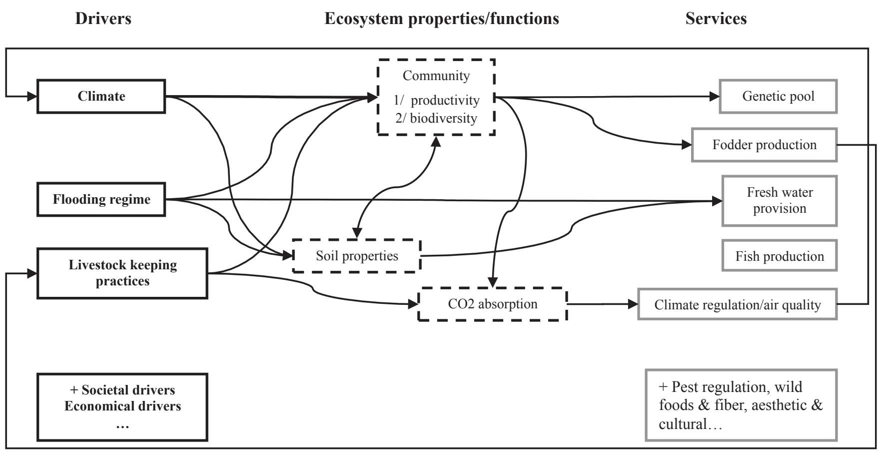


Figure 3: Simplified representation of the drivers of change, properties and services of the grasslands of the Tana River Delta

1.2.2.2 *Characterization of floodplain grassland formations*

INFLUENCING FACTORS

Determining the characteristics of grassland plant formations and the environmental variables that determine their distribution is important for their management. However, plant growth, primary production and plant adaptations to floodplain environments have been poorly investigated. Up to now, very little is known about the extent and variability of palustrine wetland habitats in the world (Pinder 1998) and the relative importance of the factors depend on the location, climate and management of the wetland grasslands.

The main influencing factors seem to be:

- The water regime (Taylor and Dunlop 1985; Taylor and Dunlop 1985; Zeilhofer and Schessl 2000; Pinder and Rosso 1998; Goslee et al. 1997; Robertson et al. 1984). In particular the duration and depth of inundation influence species distribution (Finlayson et al. 1989). Scholte (2007) found that flood depth characterizes above-ground biomass in seasonally flooded African grasslands for shallow depths. Pinder (1998) also states that the distribution of the plant formations in their study site in the Pantanal resulted from the hydroperiod, and probably the availability of moisture in the soil during the dry season.

- The soil type (Zeilhofer and Schessl 2000) and fertility (Pinder and Rosso 1998)

- Other management and environmental factors. Grazing, pugging and wallowing determine the domination or establishment of a species (Skeat et al. 1996). pH, saline intrusion (Finlayson 2005), the invasion of exotic species (flora and fauna) (Finlayson 2005) and the fire regime (Finlayson 2005) can also play a role.

These factors are all important factors in determining the type of flooded grasslands, their distribution, their properties and functions and the resulting services.

ADAPTATION OF PLANTS TO FLOODED CONDITIONS

The plants that thrive in flooded situations have adapted their morphology, physiology and reproduction strategies to this specific environment. Finlayson (2005) lists some of the major adaptations for herbaceous species:

- the development of aerenchyma and cavities, especially in floating leaves and emergent species .
- the development of adventitious roots on submerged nodes.
- the use of dispersal mechanisms involving water: dispersal by floating plants (entire or broken parts) or buoyancy in the seeds and/or fruit for transport.
- reproduction mostly by vegetative means.

1.3 FROM A PASTORALIST'S PERSPECTIVE IN AFRICA

1.3.1 *Pastoralist societies in Africa*

Sub-Saharan Africa counted 800 million people in 2006 (United Nations Population Division 2007) and the UN predicts a regional population of nearly 1.95 billion in 2050 (United Nations Population Division 2007). The type of livelihoods encountered are extremely various, and I do not intend to describe them here. Very broadly speaking, and maybe a bit simply, many areas are faced by regional scarcity, like in the Sahelian zone, and generally weak institutional frames. Many areas also face significant challenges, including water and food scarcity, a growing population, poverty and conflicts, all of which are interconnected in some way.

Pastoralist societies are mainly defined by their association with domestic grazing animals (Homewood 2008). This definition includes nomads, semi-nomads, agro-pastoralists, stockowners, livestock traders and many other categories, and even people with few or no animals. Hudgson (2001) indeed defined a pastoralist as one for whom pastoralism is an ideal, if not a reality. This broad definition makes it difficult to estimate the number of African pastoralists. Sandford (1983) suggest that around 30 million people were primarily dependent on livestock, and similar figures are still used today (Fratkin 2001).

Even though pastoralists form an extremely diverse group, some common factors underlie this diversity, like land-use, livestock management, pastoralist economies and subsistence and some demographical characteristics (Homewood 2008). In particular, according to this same author, "many pastoralist groups are centered on arid and semi-arid lands over which they move to find water and forage for their herds".

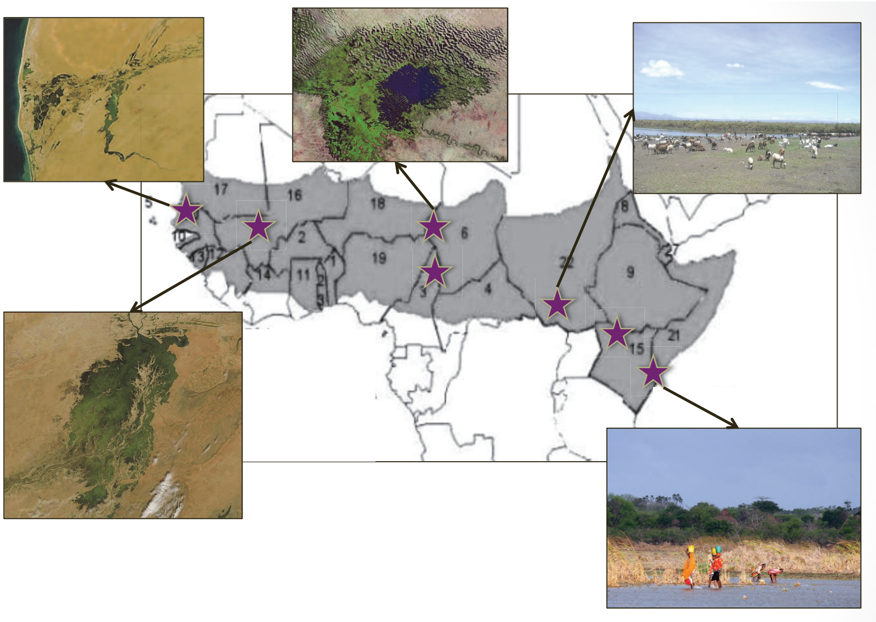
1.3.2 *Water and grazing resources*

Water is a limited and strategic resource that needs to be managed and divided between different users. This can be illustrated by the long standing negotiations on the Nile River water resources. Freshwater resources are used in many ways, from basic consumption, to food and electricity production. They support livelihoods but are under pressure from increasing demands and competing uses. Furthermore, climate change can exacerbate spatial and temporal variability of water resources making their management an even more important question. It is also recognized that water needs to be left for the environment.

These are particularly true for the arid and semi-arid zones where pastoralists live. Water constitutes a key resource and pastoralists depend on wetlands for dry season grazing (Homewood 2008). Numerous wetlands, going from vast zones like the Interior Delta of the Niger Delta (64 000 km^2) to small and temporary marshes spread out under these climates. Some of these wetlands are illustrated in Figure 4. They constitute key resources for people throughout the seasons and are essential in drought times when people and livestock concentrate there for water, food and grazing.

In particular, floodplain grasslands are important as they provide counter-seasonal grazing zones. For example, a central floodplain grassland area of 1500 km^2 in the Interior Delta of the Niger River can sustain 400-500 000 cattle for 3 to 4 months (Homewood 2008). Stocking rates can reach extremely high levels, in this case a maximal value close to 330 cattle per square kilometre. This is partly due to their high productivity, as water stress is limited during and just after the floods and large amounts of fertile soil deposits by the floods probably limit nutrient stress. *Echinochloa stagnina* (Retz) P. Beauv. grasslands are highly productive, with measured daily productivities of 200-250 kg $DM.ha^{-1}$ compared to the rainfed pastures (800-2500 $kgDM.ha^{-1}.yr^{-1}$) (Penning De Vries and Djitèye 1982). They form excellent dry-season grazing zones under the sahelian climate (Francois et al. 1989). Indeed, their peak of productivity and grazing period are delayed in time compared to the other semi-arid surrounding grasslands as the floods usually occur in the rainy season. Their disappearance, partly due to the spread of rice cultivation, other land conversion or a decrease in the flooding regime undermines the traditional pastoral systems (Homewood 2008).

Figure 4: Location of some important wetlands for pastoralists in Sub-Saharan Africa. The stars represent, from left to right: the Senegal delta, the Interior Delta of the Niger River, Chad lake (upper star), the Waza Logone floodplains, the Sudd marshes, lake Turkana and the Tana River Delta.



1.4 floods: a main driver of change of wetland ecosystems

1.4.1 *Floods and dams*

The hydrological processes of the rivers (Mitsch and Gosselink 2000), in particular, flood extent, timing, frequency, duration, flood peaks and water height, largely determine the physical, chemical and biological properties of wetlands. Floods are therefore the primary drivers of wetland health. Indeed, floods are essential for the riparian forests, floodplains, mangroves and the estuarine fish population, which in turn all provide food supplies and other assets to the local communities. Emerton (2003) estimated that over one million people in the Tana River basin, Kenya, relied on the flooding regime for their livelihoods, including 800 000 nomadic or semi-nomadic pastoralists with over 2.5 million livestock.

A major concern therefore for wetlands and their residents is the construction of dams that modify the flood pulse of river systems (Junk et al. 1989). In the past century, more than 45 000 dams over 15 m high (Avakyan and Iakovleva 1998 , WCD 2000) storing about 15 % of the total annual river runoff (Gornitz 2000) have been built worldwide. In Africa alone, 114 dams were under construction or planned (McCartney 2007). Africa is the continent with the least amount of water stored in a dam per capita, with 400 times less compared to North America (IIASTD 2009). It is therefore likely that large dam construction projects will develop even more in Africa in the near future to provide an answer to the energy crisis and food security issues.

This infrastructure has contributed to economic development through hydropower generation, food production and urban water supply and has improved livelihoods by bringing water and electricity, irrigated agriculture, flood control and improved navigation (WCD 2000). However, there is a growing recognition that dams have also had many negative effects, through ecological and social impacts (WCD 2000, Millennium Ecosystem Assessment 2005a among others). Dams alter key hydrological factors such as timing, flood extent and frequency, sediment flow, water quality, water temperature and chemistry (Olden and Naiman 2010) and the morphology of river channels and their associated floodplains (Petts and Gurnell 2005). The disruption of these patterns and of the river continuum, in turn, affect the integrity of the adjacent ecosystems like riparian forests (Hughes 1984; Hughes 1990; Shafroth et al. 2010), floodplains, cultivated systems like rice fields and the mangrove and coral systems (MA 2005a). The people who are impacted are not only those located where the dam is constructed, but also the whole downstream community. Worldwide, over 472 million river-dependent people live downstream of rivers impacted by dams (Richter et al. 2010). The poor communities who depend on the river for their livelihoods are those most likely to be impacted by river development (WCD 2000), igniting debates on social justice and equity. The consequences of changes in the hydrological regime of rivers on downstream ecosystems has been abundantly documented with numerous reports (WCD 2000) and case studies (such as, but not exclusively the Huaihe river, China, Hu et al. 2008, the Bill Williams river, Arizona, Shafroth et al. 2010, the Waza Logone in Cameroon, Loth 2004, the Okavango delta in Botswana, Murray-Hudson et al. 2006, the Kafue Flat floodplains in Zambia, Mumba and Thompson 2005 and in Tunisia, Zahar et al. 2008).

1.4.2 *The environmental flow framework*

The total costs and human and environmental implications of hydroelectric infrastructure development need to be evaluated and integrated into the decision making process. In such an effort, water directives have been voted for and implemented in different parts of the world (for example, the Water Directive in the European Union or South Africa's Water Act). They usually follow the environmental flow concept, which defines the required 'quantity, timing and quality of water flows" in a river necessary "to sustain freshwater and estuarine ecosystems and the human livelihood and well-being that depend on these ecosystems' (Brisbane Declaration http://www.eflownet.org/download_documents/brisbane-declaration-english.pdf). By taking into account the economy, resource uses, cultural, health, societal and ecological issues involved with river water management, it seeks a trade-off between development and resource protection, for each specific context (basin and society). It does so by pulling together the stakeholders, often with different and competing uses of the water resource, to come to a consensus on the best possible development scenario.

To achieve such a goal, knowledge on how increased water-resource development can impact the ecosystem attributes (wild fisheries, water quality, floodplain attributes, cultural and religious values, channel configuration, livestock health, human health, etc) is necessary. Different methods have been developed such as integrated basin flow assessments (King et al. 2010), the Ecological Limits of Hydrologic Alteration (ELOHA, Poff and Zimmerman 2010) and others (Brown and Joubert 2004; Tharme and King 1998; Arthington et al. 2010; King and Brown 2006). These have been implemented in many basins (Lesotho Highlands Water Project, the Zambezi River Basin, the Zambezi river basin (Tanzania), the Mekong River, the Murray-Darling basin in Australia, etc.). Despite their success, challenges still exist. Basic knowledge of the ecosystems and site-specific quantitative relationships between various flow regimes and the ecological response of key ecosystems are required (Poff and Zimmerman 2010; Shafroth et al. 2010). At a higher level, appropriate ecological and socio-economical objectives using a participatory approach need to be set (Acreman 2000). Implementation of such a framework is complex and lengthly, even where political will and technical skills exist (King et al. 2010).

1.5 GENERAL RESEARCH AGENDA DERIVED FROM THE BIBLIOGRAPHICAL REVIEW

In the previous section, I defined general problematics related to floodplain grasslands, approaching them from different angles. We saw that water and fodder are important but scarce resources for pastoralists in Sub-Saharan Africa. As they can be provided by wetlands, the latter constitute a key resource for pastoralists and are essential in drought times when people and livestock concentrate there for water, food and grazing. In particular, floodplain grasslands are important as they provide counter-seasonal grazing zones. Despite this, and the other numerous services they also provide, these ecosystems are being degraded.

Various disciplines call for similar recommendations and mostly for more quantitative studies. In particular, there is a need to estimate the variability of ecosystem productivities and the availability of resources under changing wetland characteristics and functioning.

This would help to translate basic eco-hydrological knowledge into site-specific quantified rules, to examine various scenarios and finally to determine their impact on river ecosystems and livelihoods. However, data availability and the lack of biophysical data on wetland functioning are some of the biggest obstacles in achieving this.

1.5.1 *Ecosystem service science as an integrative science*

ES science integrates concepts from ecology, economy, agronomy, geophysical sciences, social sciences and many other disciplines. In fine, the ES approach proposes an integrated view of environmental management. This is why I chose to set this study within this framework rather than in a specific discipline, as my work englobed different sectors such as hydrology, remote-sensing, ecology and agronomy.

Two research recommendations from Daily (1997) caught my attention: 1/ develop "ecosystem production functions and service mapping" and 2/ "implement [the ES approach] in diverse biophysical and social contexts". Environmental science could be broadly seen as the work of untangling the complexity of the bio-geo-sociosphere. Models are needed that would translate ecosystem structure and functions into the provision of ecosystem services (Mäler et al. 2008). Many of them focus on quantifying the delivery of one service while others attempt to incorporate multiple services and multiple scales into the analysis (like in Nelson et al. 2009). This second approach helps us to weigh our decisions in the light of the total sum of ES provided, and is thus better adapted for decision makers. However, prior to this step, knowledge on each ecosystem service on its own is required. Implementing the ideas and concepts in diverse social contexts is necessary, but challenging. Indeed, we live in a diverse array of ecosystems, both geographically and climatically, and each ecosystem provides multiple services. Furthermore, these services change with time and the linkages between the properties, functions and ecosystem services can be complex.

1.5.2 *Fodder as an intermediate service*

Fodder production can be seen as the link between the water resources of a wetland and the livestock keeping activities of pastoralists. Understanding fodder production and its availability under various scenarios are important when considering the impact of changing hydrological regimes on pastoralists' livelihoods.

Since the definition of services and the framework of the MA, some debates have focused on the definition of the terms and the typology of services. Boyd and Banzhaf (2007) and Wallace (2007) pointed out that the MA mixes the 'ends' and 'means'. This can come from the confusion between the functions of an ecosystem and the services this ecosystem provides (Le Roux et al. 2008). The functions or properties of an ecosystem are the objects generally studied in ecology, agronomy, hydrology, pedology and many other disciplines. The services that these ecosystems provide are defined by societal demand and their provision depends on one or several functions/properties of the ecosystem (Le Roux et al. 2008). The ambiguity resides in the term 'supporting' services. For example, should nutrient cycling be considered as a function or a service? Or should fodder production just be seen as the primary productivity of the grasslands (and hence a property of the ecosystem and not a service) or can it be seen as a benefit provided by the ecosystem?

In this study, I stay close to the original definitions of Daily (1997) and the MA (2005a). Fodder production is considered as a service provided by the grasslands. It is supported by primary production, nutrient recycling and the other supporting services/functions of the ecosystem. It is not a final service from the grassland, which would be meat or milk, but acts rather like an intermediate service. It is a benefit for the pastoralists who use the grasslands as grazing zones, and hence is defined by a societal demand. The hydrological regime is considered as a driver of change which affects the functions and properties of the grasslands therefore impacting primary production, then fodder production and finally the livestock keeping activities of the pastoralists.

In the next section, I present the Tana River Delta (TRD), through a brief view of its recent history, its geographical context, its people and the main problems encountered in the zone to finally show why it is a good (but not perfect!) field site to study the previous questions.

2

GEOGRAPHICAL AND HUMAN CONTEXT: THE TANA RIVER DELTA AND ITS PEOPLE

2.1 CONTEXT

The Tana River Delta (TRD, Figure 5) is located in Kenya. It is an area of approximately 1 300 km^2 and roughly extends between the main towns of Garsen, Malindi and Lamu in the Coast Province. It has recently been designated as a wetland of international importance by the Ramsar Convention (1971) to protect its high level of biodiversity. It is home to over 100 000 inhabitants (Kenya Population Census 2010), essentially from the Pokomo, Orma, Somali, Wardei and Wata communities. The Pokomo culturally define themselves as farmers and fishermen; the Orma, Wardei and Somali groups as pastoralists and the Wata are former hunter-gatherers. They have occupied the delta for centuries (Fitzgerald 1898; Miller 1981). The delta provides a whole range of natural resources for the local communities who mainly rely on agricultural production, fishing and livestock keeping (Leauthaud 2009; Duvail et al. 2012; Leauthaud et al. 2013a) for subsistence. The delta is also used by the Orma and fellow pastoralist communities from the surrounding region as a pastureland. Figure 6 shows that a large concentration of cattle from the Tana River district can be concentrated within the delta. In severe drought years, tens of thousands of livestock converge to the delta all the way from the Somali border, Garissa and Tsavo East National Park. As such, it is not only the local community that relies on the river but the whole regional economy and society

The region is among the poorest in Kenya and its 2009 indicators of human well-being (United Nations Development Program, 2010) are extremely low. The Human Development Index (HDI) was of only 0.389 compared to the already low national average of 0.561, while the Gender-related (GDI) and the Human Poverty Development Indices (HPI) were ranked in the ten worst nationwide. Human illiteracy was beyond 68 % and life expectancy was under 54 years - lower than the national average by nearly three years.

As a highly productive zone, the TRD has in the last decades received much attention from public and private investors. In the 1980s, the Tana Delta Irrigation Project (TDIP) leased 16 800 ha of prime agricultural and grazing land for rice production, but failed due to mismanagement (Lebrun et al. 2010). Recently, 160 000 ha have been appropriated within and surrounding the TRD for the production of biofuels (*Jatropha curcas*). Another 40 000 ha of prime grazing land

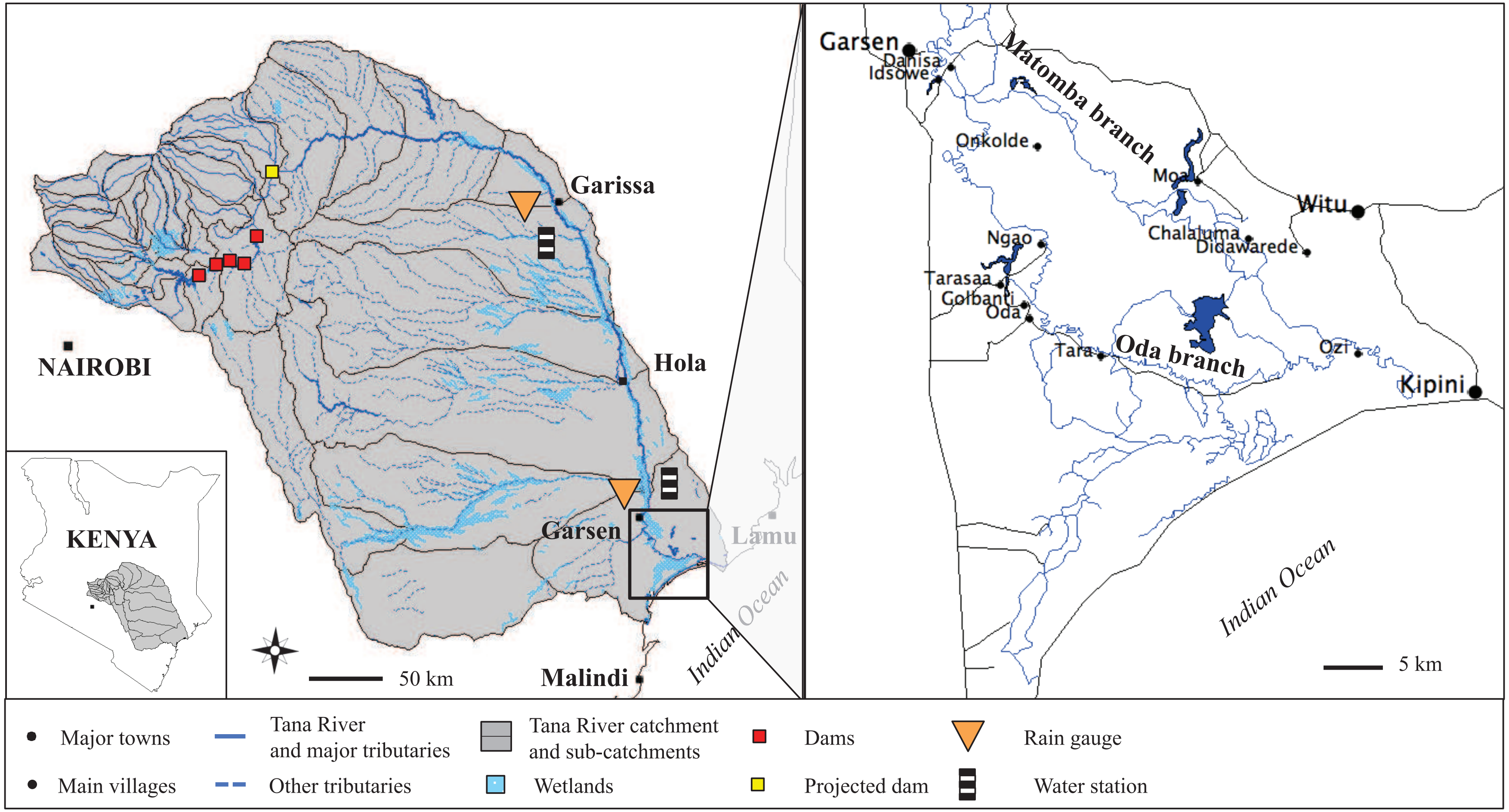


Figure 5: Left: The Tana River catchment, with the Tana River and its main tributaries, and the location of the hydroelectric infrastructure. Right: zoom on the Tana River Delta, with the main river channels and lakes. The major towns and villages as well as the roads are specified.

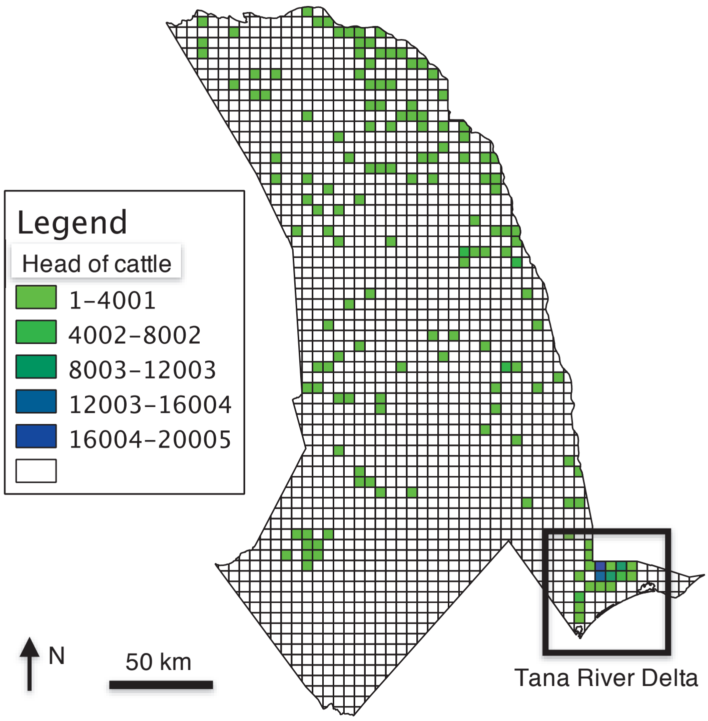


Figure 6: Location of heads of livestock in the Tana River District in June 2010. A large number of cattle are concentrated within the delta.

is also scheduled to be converted for the production of sugar cane. These large-scale projects, backed up by the political institutions, do not take into account or acknowledge the former informal land rights and current use of the lands and will enter directly in conflict with the current uses of the land and water (Duvail et al. 2012).

Despite the productive potential of the TRD, poverty and the scarcity of natural resources have generated or at least sparked up conflicts between the different communities. The latter had informal access rights to the water and natural resources, but major changes in land and water allocations (upstream versus downstream water uses, subsistence versus large-scale irrigated projects, grazing versus cropping) have unbalanced the fragile equilibrium. In 2001, over 180 people died in clashes following land (and hence access to water) reallocation projects (Duvail et al. 2012). In 2012, over 100 new victims were reported and at least two villages burnt. These are the worst killings perpetrated in Kenya since the post electoral violence of 2008. Conflicts have been reported between the two groups since at least the 19th century (Fitzgerald 1898). However, one can legitimately ask whether the hydrological changes that have taken place in the past 50 years have not played at least a role in the generation or continuation of these conflicts. And whether alternative development scenarios (environmental flows) to the current ones (large scale irrigation schemes, biofuels) would not help to solve these conflicts, to alleviate poverty and more generally to improve the well-being of the local communities.

2.2 THE TANA RIVER AS A KEY WATER RESOURCE

The Tana is the largest river in Kenya, and flows over nearly 1 000 km from Mount Kenya and the Aberdare Mountains to the Indian Ocean. Its flowing pattern is bi-modal, with peak flows during the long and short rainy seasons. With a catchment area covering over a sixth of the country, the river carries between 2.7 and 10.2 billion cubic metres yearly (Hamerlynck et al. 2010).

The Tana River is the main water resource of the catchment and is used for a whole variety of projects. In the upper catchment, the Tana River is used for hydroelectric production. Five major reservoirs, with an installed capacity of just over 500 MW, were constructed between 1968 and 1981 to provide electricity to urban centers and to develop irrigation schemes further downstream. Maingi and Marsh (2002) found that the peak May flows of the Tana River decreased by 20 % following the construction of the Masinga dam in 1981. Currently, a sixth dam is planned to bring another 700 MW to the national grid. In the mid catchment, large irrigation projects were initiated in the 1980s for cotton production, but they were economic failures (Ledec 1987; Adams 1990 in Duvail et al. 2012). The large-scale irrigation and biofuel projects underway in and around the Tana River Delta will also require large amounts of water from the main river. Downstream of the dams, the Tana River provides essential water resources for over one million farmers, fishers and livestock keepers (Emerton 2003). Within the TRD, the Tana River is the main water resource for the inhabitants (Emerton 2003; Terer et al. 2004; Leauthaud et al. 2012) as it supplies abundant water and nutrients to the natural and cultivated ecosystems. They, in turn, provide food, grazing zones, building materials and other vital resources. Fishing is also practiced in the lakes, channels and floodplains throughout the year. The Tana River water resources are also primordial for the maintenance of the riverine forests (Hughes 1990) and other adjacent ecosystems. The course of the river within the delta is highly dynamic and shifts after important flood events or is redirected by human intervention. The Tana River used to pass on the western side of the delta through the Oda branch which, like the other old river channels, has well-formed sandy levees. In the last decade, and despite costly efforts to keep the river in its former main course, the flow in the Matomba branch, located rather on the Eastern part of the delta, has increased and the Matomba branch has now become the main course. Finally, the Tana River supplies water to the mangrove system at the river mouth and feeds an important fish industry in Ungwana bay.

To satisfy the current use of the water resources of the Tana River and the intended developments, a sound knowledge of the available water resources is necessary. In particular, knowing the quantity of water available at the different sites, its quality and its availability throughout the year is the base for a sound management of the water resources.

2.3 ECOSYSTEMS ENCOUNTERED AND THEIR USE BY THE COMMUNITIES

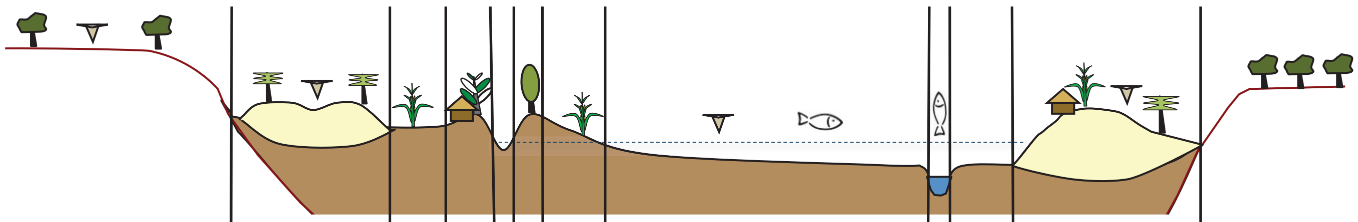
The TRD landscape is a complex intertwinement of forests, wooded bush land, bush land, grasslands and lakes (Kenya 1984a; Kenya 1984b). The landscape pattern derives from soil and water conditions controlled by the Tana River.

The inhabitants use them in a variety of ways, as shown in Figure 7. Floodplains close to villages are used as cropland and banana and mango plantations located on the levees of old riverbeds. Dry grasslands cover the upper floodplains and are used as grazing zones. The lower floodplains, periodically under water, form grasslands composed of *Echinochloa stagnina* (Retz) P. Beauv, *Vossia cuspidata* (Roxb.) Griff., *Paspalidium obtusifolium* (Delile) N.D. Simpson and various species of sedges that offer good pasture land when not flooded and fishing grounds when flooded. Other low-lying areas form permanent or temporary lakes, swamps or marshes where fishing is practiced. Hughes (1990) distinguished five main forest vegetation types in the Tana River floodplains, depending on their location in relation with the river and their soil type (not depicted in Figure 7). These forests provide fuel wood, building materials, and medicinal plants. The delta itself is surrounded on both the eastern and western sides by ancient alluvial plain terraces covered by degraded woods or wooded bush that periodically serve as pastureland. Lastly, at the interface with the Indian Ocean, high coastal dunes give way to an extensive mangrove system at the river's mouth.

The pastoralists carve the TRD and surrounding area into three distinct ecotypes, depending on their livestock keeping practices. The *kofira* is the wetland zone where cows preferentially graze. The *balo* is the surrounding bushland where the cattle occasionally graze when waiting to leave or enter the wetlands. Finally, the *omara* is the dry western hinterland that is used as the rainy season grazing land (Figure 7).

2.4 IMPACT OF CHANGING WATER RESOURCES ON THE LOCAL COMMUNITIES

Previous to and during my PhD, I undertook social interviews in the TRD pertaining to the use of the natural resources and how they had



Geomorphology	Eastern terrace	Ancient sand dunes	UFP	B	R	B	MFP	LFP	R	LFP	Ancient sand dunes	Western terrace
Flooding frequency												
Soil type	Ancient sands and clays	Arenosols	f&v	a		a	f&v	Fluvisols and Vertisols		f&v	Arenosols	Ancient sands and clays
Vegetation	Wooded bushland	Bushland	*g*	*f*		*f*		Grasslands		*g*	Bushland	Degraded forest
Land-use	Pastureland	Pasturelands	Maize/ P	A		A	Maize/ Rice	Pastureland/ Fishing	F	P	Maize/ Pasturelands	Pastureland
Orma ecotypes	*Omara*	*Balo*						*Kofira*			*Balo*	

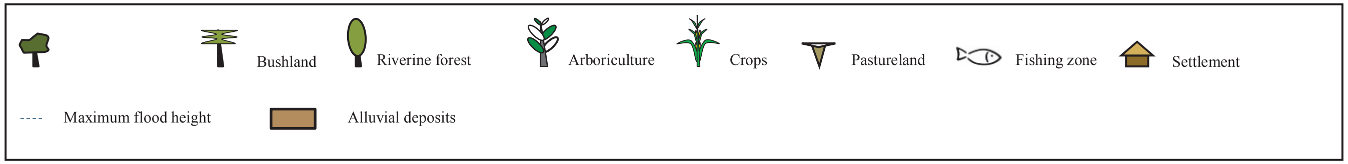


Figure 7: Schematic transect of the delta. The flooding frequency , soil and vegetation characteristics along with the land-use by the communities are specified. B: banks, LFP: lower floodplain, MFP: mid floodplain, R: river, UFP: upper floodplain, a: arenosols, f&v: fluvisols and arenosols, f: riparian forest, g: grassland, A: arboriculture, F: fishing, P: pastureland.

evolved in the past 50 years. The general framework was to understand the different types of agricultural production systems encountered within the TRD. I give some of the results here as it puts the whole PhD work in perspective with the other agricultural uses of the wetlands and justifies why it is important to study the floodplain grasslands of the Tana River Delta. The whole paper is presented in **Appendix A**.

Through qualitative interviews, we showed that the traditional agro-ecological production systems were adapted to the dynamic flooding patterns of the river. The Pokomo combined rice cultivation (flood recession farming) and fishing within the river, lakes and floodplains while the Orma rather focused on livestock keeping and would only do farming in emergency situations. These farming, fishing and livestock keeping components were dynamic and their relative importance would change through the seasons and years depending on the inundation characteristics.

As flooding characteristics changed, the local population diversified, abandoned or adopted various farming, fishing and rearing techniques. The main consequences of the changes in the hydrological characteristics were:

- the switch from biannual rice crops to maize crops planted only during the long rainy season.
- the translocation of the fields in the mid-floodplain formerly inundated part of the year and used as dry-season grazing zones.
- a change in the transhumance patterns of the Orma, linked to the disruption of the seasonal floods.
- a decrease in the fishing activities.

In general, the loss of water resources led to a drop in productivity of both the farming and livestock systems. Other socio-economic components, such as population growth, globalization, the lack of national incentives to alleviate poverty, also shaped the current situation. However, water depletion was a major factor that negatively impacted local human well-being, through the loss of food security and the associated monetary income.

2.5 THE TANA RIVER DELTA AS A RESEARCH FIELD SITE

2.5.1 *A case-study site*

The TRD concentrates a variety of questions relative to wetland, water resource and ES research, which makes it an interesting location to undertake research. The TRD is representative of poorly-gauged catchments where new, or a combination of existing methodologies need to be used to conceive and validate models. Its ecosystems have been poorly studied and hence knowledge on their spatial organization, diversity, productivity and link to the adjacent river is still lacking. In the ES arena, it constitutes an ideal ground to study novel production functions, to evaluate the benefits of wetlands for local communities and to draw future development scenarios.

Finally, the TRD can be seen as a productive and fragile ecosystem where land and water issues are pending. The contrasting interests for the land and water and the resulting conflicts in the zone give the research undertaken in this area all of its social relevance. Research can lead to practical applications and innovative solutions that could drastically change the lives of many people.

2.5.2 *Field work challenges*

During my field work, several challenges arose linked to the specificity of remote, poor and dangerous zones. These determined, in one way or another, the objectives that I fixed for this PhD, the methodology used and the final results. I therefore decided to list them here to give a better idea of how the field work actually took place.

- remote and difficult access. The TRD research site was 14 hours from our main research centers in Nairobi. Access to villages was mainly by motorbike, and many roads were impracticable during rainy events. Access to the floodplains was exclusively by boat or canoe. As there were no laboratory facilities in the TRD, all samples to analyze were sent to Nairobi, mainly by public transportation.

- work in a poverty-stricken zone. Obtaining daily necessities (food, water) were the main concerns for the inhabitants. Research takes place during a much longer time-period and does not necessarily address day-to-day requirements. There was therefore a need to repeatedly explain why a long-term vision was necessary and how research was a long-term response to the main concerns of the zone. The poor level of education was such that it was difficult to find the necessary technical skills in the field.

- danger. Hippopotamus, *Hippopotamus amphibius*, buffaloes, *Syncerus caffer,* and crocodiles, *Crocodylus niloticus* (Laurenti, 1768), thrive in the TRD, causing frequent and often deadly accidents.

3 OBJECTIVES AND IMPLEMENTATION OF THE PHD

3.1 FRAMEWORK OF THE PHD STUDY : THE WATER AND TERRITORY AND KENWEB RESEARCH PROJECTS

This PhD field work was undertaken within the framework of three projects implemented by French and Kenyan scientists based at the French Institute of Research for Development (IRD), the National Museums of Kenya (NMK), the University of Nairobi and the Kenya Wildlife Service (KWS).

- GEOPAR (2008-2012) is a program funded by the French Ministry of Ecology, Sustainable Development, Transport and Housing (MEDDTL). This project on 'water management scenarios and natural resource use in the lower valleys of East-African rivers' aims at understanding the hydrology of the Tana River Delta and undertaking an evaluation of the water requirements of the various ecosystems and users.
- PACTER (2011-2013, MEDDTL) targets the socio-economic and environmental impacts of biofuel development, including access to land. "The impacts on the functioning of the ecosystems, of water circulation and on land use will be analyzed."[1].
- KENWEB, specifically addresses biodiversity and local knowledge issues. The project's objectives include: "1/ to establish a methodology for a better description [...] of the various ecosystem services provided by tropical wetlands ; and 2/ to undertake simple hydrologic modelling of the studied wetlands allowing us to prospect several scenarios of flooding for the future" [2]

The research team's vision of the research is field-based, participatory, multidisciplinary and integrates capacity-building.

Within these projects, my PhD aimed at getting a better understanding of the hydrology of the TRD and looking at the impact of floods on the livestock keeping activities of the zone.

1 from Réponse à l'APR Programme EAUX & TERRITOIRES Projets d'Agro-Carburants et transformations TERritoriales PACTER
2 from the KENWEB application form to be a young researcher's team (JEAI) associated to the IRD.

3.2 PROBLEMATIC AND OBJECTIVES

Getting a comprehensive understanding of the services provided by tropical wetland requires a proper quantification of the main drivers of change and their impact on the services. I focus my study on *one driver of change*, *one ecosystem* and *one service*. It is restrictive but this work is part of a larger research scheme that will combine different sub-models to understand the multi-functionality of East African coastal wetlands.

In the previous section, I presented a bibliographical review on (what I see as) important aspects of ecosystem services and on floodplain grasslands. The research undertaken in this study is at their interface. Basically, the work aims at providing some answers to the following question:

HOW DOES THE HYDROLOGICAL REGIME OF A RIVER, AND ITS CHANGES, IMPACT THE BENEFITS LOCAL STAKEHOLDERS OBTAIN FROM WETLAND ECOSYSTEMS?

More specifically, my work aims at understanding how the hydrological regime of a river can impact the provision of fodder, as an ecosystem service, from a floodplain grassland, in the TRD. During this PhD, I worked on three aspects relative to this question, at different conceptual levels and various temporal and spatial scales. Three main research questions defined my work, from which I drew the objectives of this research:

1. WHAT ARE THE GROWTH CHARACTERISTICS OF THE FLOODPLAIN GRASSLANDS OF *ECHINOCHLOA STAGNINA* (RETZ) P. BEAUV.?
    a) characterize the productivity of the grasslands under different hydrologic and management scenarios.
    b) construct a grass growth model adapted to floodplain grasslands to understand the underlying physiological processes.
2. WHAT ARE THE FLOODING CHARACTERISTICS IN THE POORLY GAUGED TANA RIVER DELTA?
    a) construct a hydrological model of the Tana River using the available hydrological data in combination with moderate-scale remote-sensing data.
    b) characterize current hydrological processes of ecological importance: flood timing, extent, duration and frequency.
3. HOW DO DIFFERENT FLOODING PATTERNS IMPACT THE ECOSYSTEM SERVICE OF FODDER PRODUCTION IN A FLOODPLAIN GRASSLAND?

a) define hypothetic, representative flooding regimes of historical, past and possible future scenarios.

b) simulate fodder production for these scenarios through the quantification of three ecosystem service indicators: the quantity, quality and seasonal availability of fodder.

3.3 GENERAL METHODOLOGY

The choice on the approach, scale and methodology resulted from the objectives and the data available. As such, it is difficult to define one general methodology. Rather, I explored each question from various angles and chose the most appropriate discipline and methodology (Figure 8). I worked on each question in parallel and explored different spatial and temporal scales. Traveling back and forth from the field site to the laboratory in France allowed to collect data and conceptualize the models in parallel. The methodology relevant to each section is described within each chapter.

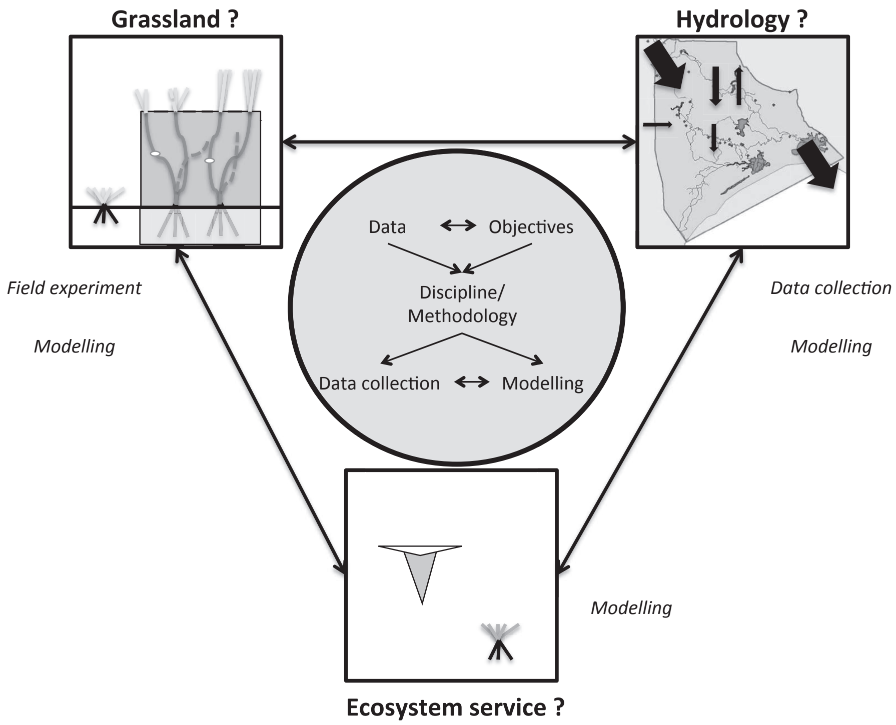


Figure 8: The general approach used in this study to answer the objectives.

3.4 MANUSCRIPT LAYOUT

This manuscript is organized into six parts (Figure 9).

Part I forms the introduction.

Chapter 1 overviewed the general problematics linked to ecosystem services of floodplain grasslands.

Chapter 2 described the study site: the Tana River Delta in Kenya.

Chapter 3 presented the objectives of the PhD.

Part II is focused on characterizing the growth processes of the floodplain grasslands of *Echinochloa stagnina* (Retz) P. Beauv..

Chapter 4 presents the field work undertaken on the floodplain grasslands. In a first section, the vegetation formation and its use as pastureland are described. In a second section, the aboveground biomass production of the grassland under various flooding, cutting and irrigation scenarios is quantified.

Chapter 5 presents the modelling work undertaken concerning the floodplain grasslands. A grass growth model is developed, in which novel functions adapted to flooded conditions are specified. A section is dedicated to the sensitivity analysis of the main parameters. The model is finally calibrated and validated using field data.

Part III is focused on characterizing the hydrology of the Tana River and developing a water-balance model.

Chapter 6 is a paper submitted to Hydrology and Earth System Sciences (HESS). MODIS satellite imagery are used to obtain a time series of inundation extent measurements in the Tana River Delta. The methodology and the index used are described. The Tana Inundation Model (TIM) is then described along with the calibration and validation procedure using the Generalized Likelihood Uncertainty Estimation (Beven et al., 1991). In the last section, the hydrological processes of ecological importance are computed for 2001-2011, using the hydrological model, then described.

Part IV is focused on scenario building.

A small introduction summarizes how the studies in the two previous parts can be used to study the impact of changing hydrological regimes on the ES of fodder production.

Chapter 7 is a preliminary analysis on scenario building. Nine scenarios with various flooding regimes and management strategies are defined and the quantity, quality and availability of fodder are calculated. Two scenarios focus on alternative possibilities to flooding. In a discussion section, the fodder production is compared to two other services of the grasslands .

Part V englobes a synthesis of the study, the research perspectives and some concluding remarks.

Chapter 8 first synthesizes the results and discusses their limits and perspectives. After integrating the results into a larger framework, I end with some personal reflexions on modelling, the necessity to know the field site and to use an experimental approach, and finally on the notion of complexity.

Chapter 9 forms the conclusion.

Part VI contains the appendices.

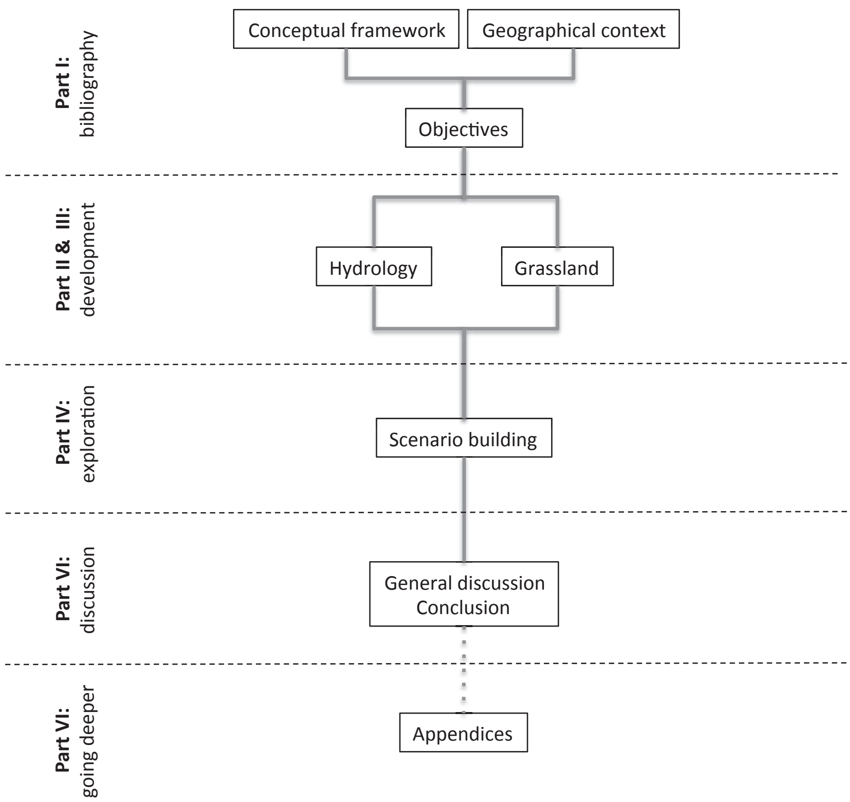


Figure 9: Synoptic diagram of this manuscript.

Appendix A is a paper accepted in Global Environment Change: Human and Policy dimensions, that details the context in which this PhD was undertaken.

Appendices B and C contain supplementary data.

Appendix D presents some photos of the Tana River Delta grasslands and of the experimental site.

The result chapters in **Part II**, **Part III** and **Part IV** are presented under an article format. Each chapter can thus be read independently. The drawback is that they can be slightly redundant as each chapter includes an introduction followed by a description of the field site. The results are discussed within each chapter so that the final discussion of the PhD focuses more on integrating the ensemble.

Part II

FOCUS 1: THE GRASSLANDS

In this second part, research is focused on the floodplain grasslands and on their growth processes. I present two papers which are in the process of being submitted. Contributing authors are: C. Leauthaud, L. Kergoat, W. Musila, P. Hiernaux, S. Duvail, M. Grippa, M. Obunga, K. Otoi. The first one, forming **Chapter 4**, describes the *Echinochloa stagnina* grasslands of the Tana River Delta and presents an experiment undertaken during the PhD field work to quantify biomass production under different flooding and management scenarios. The second paper, forming **Chapter 5**, uses these experimental results to construct a grass growth model adapted to floodplain grasslands.

Figure 10: Cows grazing in the flooded grasslands. May 2010.

4 CHARACTERIZATION OF THE FLOODPLAIN GRASSLANDS OF *ECHINOCHLOA STAGNINA*

4.1 INTRODUCTION

4.1.1 *Context and objectives*

Flooded grasslands form a specific grassland type characterized by frequent immersion. They are found within the floodplains on most continents. Floodplains are highly productive ecosystems as seasonal floods deposit nutrient-rich sediments and replenish the soil's water supply, which together boost primary productivity. Some of the highest primary productivties have been recorded for floodplain grasslands (Piedade et al. 1991).

Floodplain grasslands provide important ecosystem services. In sub-Saharan Africa, they are important for livestock keepers as counter-seasonal grazing zones. Other benefits include flood control, ground water recharge, fish production, carbon stoking and pollution control. Floodplains are fragile ecosystems that have undergone drastic changes in the past 50 years. It is estimated that 26.6 % of flooded grasslands and savannas have been destroyed (Gibson 2009)

Echinochloa stagnina (Retz) P. Beauv. is a C_4 perennial semi-aquatic grass. In Africa, it is found in the floodplains of the Niger River (Hiernaux and Diarra 1986; Seguin 1986; Francois et al. 1989), the Senegal River (Seguin 1986), the Nile River (Seguin 1986), Chari River (Seguin 1986), the Oubanyi rivers (Seguin 1986), in Lake Chad (IUCN Conservation Monitoring Centre and IUCN Commission on National Parks and Protected Areas 1987), in the Manovo-Gounda-St Floris National Park (IUCN Conservation Monitoring Centre and IUCN Commission on National Parks and Protected Areas 1987), in the Kafue floodplains in Zambia (IUCN Conservation Monitoring Centre and IUCN Commission on National Parks and Protected Areas 1987), in the Tana River Delta (Leauthaud et al. 2013a) and possibly in many other sites, including at least eight other potential sites where other species from the Echinochloa genus have been reported (IUCN Conservation Monitoring Centre and IUCN Commission on National Parks and Protected Areas 1987; Homewood 2008). *Echinochloa stagnina* grasslands form excellent dry-season grazing zones under the sahelian climate (Francois et al. 1989). For example, 4-500 000 cattle can graze for 3 to 4 months in a zone of 1500 km^2 in the Interior Delta of the Niger River (Homewood 2008). Indeed, *Echinochloa stagnina* grasslands are highly productive, with measured daily productivities of 200-250 kg

DM.ha^{-1} (Dry Matter) (Francois et al. 1989) compared to the nearby rainfed pasturelands (800-2500 kgDM.ha^{-1}.yr^{-1}) (Penning De Vries and Djitèye 1982). *Echinochloa stagnina* constitutes a key resource for pastoralists. The disappearance of the grasslands, partly due to the spread of rice cultivation, other land conversion or changes in the flooding regime undermines the traditional pastoral systems (Homewood 2008).

Plant formation characteristics and the environmental variables that determine their distribution need to be known to improve the management of flooded grasslands. Many factors determine their distribution, properties and functions. The hydroperiod is the main factor influencing plant formations and their distribution in wetlands (Williams 2006; Taylor and Dunlop 1985; Finlayson et al. 1989; Zeilhofer and Schessl 2000; Pinder and Rosso 1998; Goslee et al. 1997; Robertson et al. 1984). In particular, duration and height of inundation influence species distribution (Finlayson et al. [1989]). Scholte [2007] found that flood height characterized above-ground biomass in seasonally flooded African grasslands for shallow floods. Pinder and Rosso (1998) stated that the distribution of plant formations resulted from the hydroperiod, and the soil moisture during the dry season. Soil type (Zeilhofer and Schessl 2000) and fertility (Pinder and Rosso 1998) also influence species distribution. Grazing, pugging and wallowing also determine the domination or establishment of a species (Skeat et al. 1996). Finally, other environmental factors such as pH, saline intrusion (Finlayson 2005), the invasion of exotic species (Finlayson 2005) and the fire regime (Finlayson 2005) influence species distribution and primary production.

Many floodplain grasslands are undergoing drastic changes due to hydroelectric infrastructure development, or are rapidly disappearing. In the Tana River catchment, Kenya, dams have already modified the flooding regime, with an estimated 20 % reduction in peak flows during the long rainy season of April to June (Maingi and Marsh 2002). As a consequence, the *Echinochloa stagnina* floodplain grasslands of the Tana River Delta may have been affected. To assess the effect of changing hydrological regimes on fodder production of these grasslands, and hence on livestock keeping activities, their productivity and growth characteristics need to be known. The objectives of this study are triple: 1/ describe the growth patterns of these grasslands and quantify the possible range of annual aboveground dry biomass produced and their net primary production, 2/ determine the effect of floods, irrigation, cutting frequency and climate on their daily growth rates in flooded and non-flooded conditions, and 3/ determine the effect of floods on leaf nitrogen concentration and on the allocation of aboveground biomass to leaves. Objectives 1/ and 2/ contribute to determining the quantity of fodder produced that can be produced under contrasted management options, and 3/ contributes to determining the quality of this fodder.

4.1.2 *The TRD grasslands: description*

4.1.2.1 *Ecology*

The Tana River Delta (TRD) forms a biodiversity hotspot with numerous ecosystems and species (Hamerlynk et al. 2012). A wide variety of grassland types exist and are located according to the hydrological gradient, soil type and management.

The central grasslands (Figure 11) extend over 200 km^2 within the flat and nearly treeless floodplains of the Tana River, in between the Oda and Matomba branches of the Tana River. The grasslands are located on deep, dark brown and cracking vertisols (Kenya 1984a; Kenya 1984b). On the central grasslands' outskirts, the grass formations intertwine with patchy formations of trees and shrubs, including *Borassus aethiopium*, *Terminalia brevipes*, *Combretum constrictum* (Benth.) Laws. and *Clerodendrum acerbianum* (Vis.) Benth. & Hook.f..

The central grasslands are mainly composed of *Echinochloa stagnina* (Retz) P. Beauv., *Paspalidium obtusifolium* (Delile) N.D. Simpson and *Vossia cuspidata (Roxb.) Griff.*. *Echinochloa stagnina* (Retz) P. Beauv. is the most dominant species, even though here and there *Paspalidium obtusifolium* (Delile) N.D.Simpson can be dominant. Species distribution is determined by slight variations in the topography of the grasslands and by the proximity of villages. In the rather low areas, where the soil is saturated for long periods of time, marshes with a high density (approximately over 60% of the cover) of sedges (like *Cyperus exaltatus* Retz.) and an under-cover of emergents (*Ludwigia stolonifera* (Guill. & Perr.) P.H.Raven, *Echinochloa stagnina* (Retz) P. Beauv., *Paspalidium obtusifolium* (Delile) N.D.Simpson, and *Vossia cuspidata (Roxb.) Griff.*) are established. In poorly drained areas where water stagnates after the floods, shallowly flooded vegetation, represented mostly by *Ludwigia stolonifera* (Guill. & Perr.) P.H.Raven and *Neptunia oleracea* Lour., accompagny the three dominant species. On each side of the river channels, vegetation represented by *Vossia cuspidata* (Roxb.) Griff. and *Persicaria senegalensis* (Meisn.) Sojak invade the water. A scarce canopy, mainly represented by *Nymphaea lotus* L. and *Pistia stratiote*s L., and more occasionally *Azolla nilotica* Mett. and *Utricularia inflexa* Forssk. var inflexa, forms in open water during flood events.

At the beginning of the rainy season, species of low nutritive value and more representative of the surrounding dry grasslands (*Corchorus trilocularis* L. L., *Heliotropium indicum* L., *Abutilon guineense* (Schumach.) Baker f. & Exell, *Amaranthus spinosus* L., *Ocimum americanum* L., *Gomphrena celoscoides* Mart., *Physalis angulata* L., *Coldenia procumbens* L. and Digitaria species) can establish. The latter rapidly die

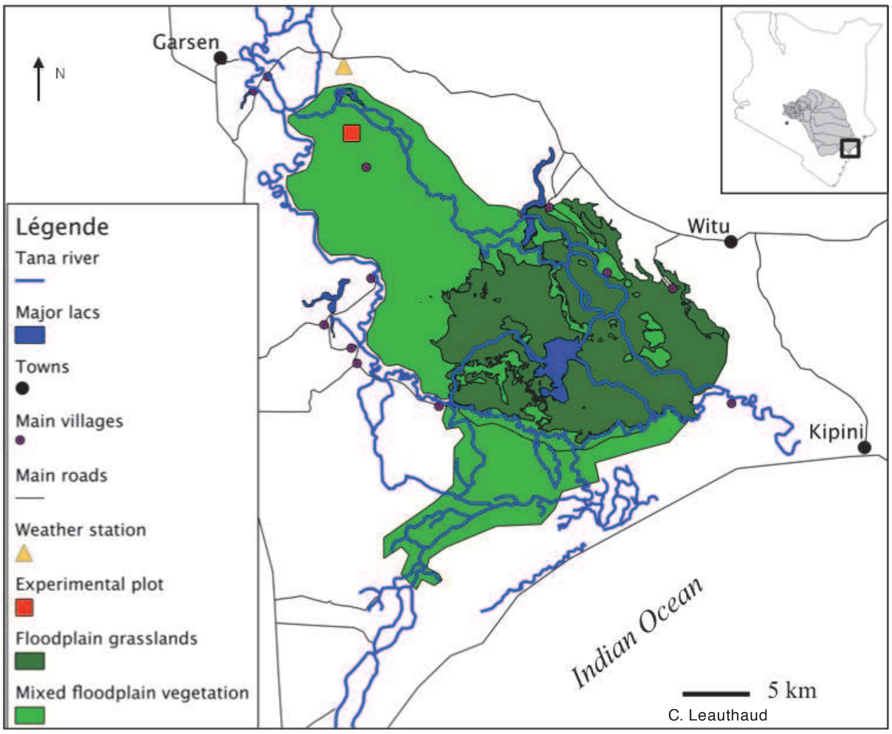


Figure 11: Location of the floodplain grasslands within the Tana River Delta. The central floodplain grasslands, composed mainly of *Echinochloa stagnina,* are distinguished from the grass formations mixed with bushy and woody vegetation. The location of the experimental plot and of the weather station are specified. The central floodplain grasslands were visually delimited using a SPOT image (2008) and verified in the field.

if submerged by the floods. On the contrary, they can cover large portions of the grasslands in the absence of floods.

4.1.2.2 *Physiology*

Growth initiation of *Echinochloa stagnina* starts at the beginning of the rainy season (Figure 12). As the grassland is continuously grazed by livestock, plants stay short, in a vegetative state, and produce mainly leaves. At the arrival of the floods, the most rigorous stems produce new internods from the apical meristem that can elongate up to 20 cm while the other stems die off (Figure 12). The surviving stems thicken and develop cavities that favour floating. The leaves connected to the submerged part of the plant rapidly die off but leaf growth continues above the water surface with 6 to 7 leaves, with blades that can reach 60 cm, that remain above water (Francois et al. 1989). Leaf turnover is probably rapid, similar to that found for *Echinochloa polystachya* in flooded conditions (Piedade et al. 1991). When undisturbed, the leaf canopy thickens in two to three weeks, until it completely covers the water surface. The underground system develops, although

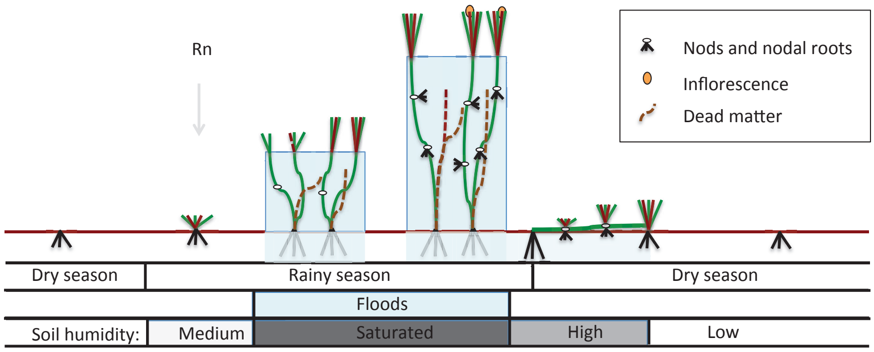


Figure 12: Phenological cycle of *Echinochloa stagnina* (Retz) P. Beauv. for one dry and one rainy season where a flood occurs. Adapted from François et al. (1989) The phenological cycle is also described and related to flood levels in Hiernaux and Diarra 1986 and Hiernaux 1982.

not extensively. Instead, roots develop on the submerged nods of the stems (Figure 12). Growth and stem elongation continue until the end of the floods. *Echinochloa stagnina* can support 4 to 5 cm of daily water increases (Francois et al. 1989) by investing most of its photosynthates into stems. Stems in flooded conditions can reach 2-5 m, with a maximum recorded length of 9.5 m (Morton and Obot 1984). According to François et al (1989), flowering and seed formation takes place at the end or just after the floods, then the plant enters a senescent phase. Flowering was observed at a very low level during the field work in the TRD, but because of the short flooded period, followed by heavy grazing just after the floods, the plants did not enter a senescent phase.

With the decrease of the floods, stems and leaves fall on the ground and nodal roots develop. There is probably an important translocation of the reserves allocated in the stems to the developing roots and leaves. At this stage, livestock enter the floodplains to graze and favour plant rooting by stamping the plants and pushing the stems and roots into the muddy ground. The action of the cattle is critical in the maintenance of the grasslands (Hiernaux and Diarra 1986) as the propagation of *Echinochloa stagnina* is mainly by vegetative means. Throughout this second growth phase, rooting is important (Francois et al. 1989) and prepares the plant to resist the following dry season by accumulating reserves underground. The second vegetative growth phase lasts until the soil dries up and the aerial part of the plants senescence. This cycle is repeated for each flood event. The latter can occur during the rainy seasons of April to June and November to December in the TRD.

4.1.2.3 *Use*

These grasslands are intensively used by the Orma communities and other subsistence pastoralists as grazing grounds. Traditionally, livestock were brought to the floodplains during the dry seasons, when the surrounding rainfed semi-arid grasslands no longer provided fodder, and were taken out before the arrival of the floods. With the decrease of floods, this transhumant pattern changed, and the livestock now spend most of their time within the floodplains and only move out when the floods arrive. Livestock include *Bos indicus*, *Capra hircus* and *Ovis aries*. Wild herbivores also graze, mostly *Syncerus caffer* and *Hippopotamus amphibius*. *Echinochloa stagnina* is highly valued by the Orma pastoralists who distinguish its non-flooded ('Oba lesa') and flood forms ('Oba kawisa').

4.2 MATERIAL AND METHODS

4.2.1 *Experimental setup*

An experimental plot was set up to monitor grass growth in flooded and non flooded conditions, and for different irrigation and cutting treatments. Clipping and irrigation were used as a surrogate to grazing and extra rainfall. The plot was located next to the village of Onkolde in the TRD (2°19'1.18" S - 40°11'19.74" E, Figure 11). This site was chosen because of its vegetation cover, identical to the grasslands found in the central floodplains, its easy access and its location close to a weather station (approximately 5 km away). The vegetation was homogeneous within and surrounding the plot throughout the experiment. Monitoring started on the 4^{th} of December 2010 and ended on the 1^{st} of March 2012 and captured non-flooded, flooded and post-flood conditions.

The experimental plot consisted of a 13.6 m by 17.6 m exclosure that excluded domestic and wild grazers for the whole duration of the experiment (Figure 13). In the exclosure, two 3.2 m by 11.6 m blocs were irrigated homogeneously every eight days at 20 mm and 60 mm. Irrigation was done by sprinkling (Rain Bird U10F U series nozzle) at a height of 1 m from the soil, using river water which was the only available water. Irrigation was controlled using automatic metering valves. A third 3.2 m by 11.6 m bloc was not irrigated. Within each bloc, three sub-blocs consisting of four 1 m^2 pseudo-replicates with an adjacent 40 cm border were clipped at different frequencies. Clipping consisted in cutting all biomass above 1 cm within the quadrate every 16 days, 32 days or 64 days. Clippings were first pre-dried in the sun on site, then sent to Nairobi and dried in a drying chamber at 60°C until constant weight. All samples weighing over 200 g were subsampled for 200 g before being sent to Nairobi. Semi-dry weight

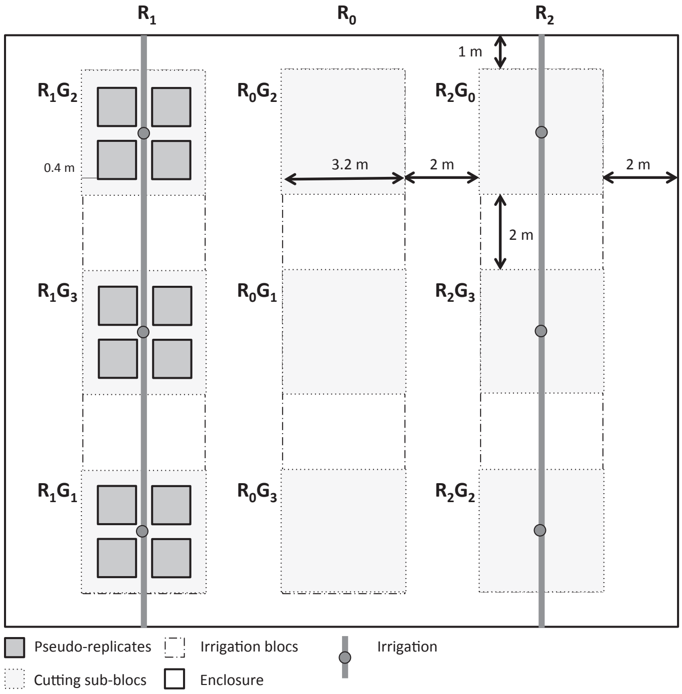


Figure 13: Schematic diagram of the experimental plot. The pseudo-replicates found in each cutting sub-bloc have not been represented in the R0 and R2 blocs for an easier viewing.

at the field site was noted for all the collected samples and used to calculate the total aboveground dry biomass (AGDB) for each sample. AGDB was calculated as the average cut biomass from the four pseudo-replicates for each irrigation and cutting treatment at each sampling date. By crossing the three cutting frequency and three irrigation treatments, nine different situations were investigated, going from natural rainfall conditions to an irrigated supplement of 60 mm every eight days and from low to high cutting rates (Table 2). In total, 510 samples were collected from the experimental plot.

The experimental site was naturally flooded during the short rainy season of 2011 for two periods (5-6/11/2011, for 2 days, and 21/11/2011-27/12/2011, for 37 days) during which daily water height measurements were taken. The first flooded period concerned only the R1 bloc and R0G2, with a mean water height of 5 cm. The second flood covered the experimental plot homogeneously, with a mean and maximum height of water 27 cm and 51 cm, respectively. As complete submersion of the plant causes its death (Francois et al. 1989), clippings were done just after the floods (28/12/2011), after respectively 37, 41, and 69 days for the G1, G2 and G3 modalities. During the floods, a layer of mud of approximately 10 cm thick was deposited. It was visually estimated that about 10 % of the stems were stuck in the mud and could not be sampled just after the floods.

It was hypothesized that the exclosure itself and that cutting as a surrogate to grazing could have affected the sampled biomass. Indeed, the exclusion of cattle could limit soil fertility on the long term or change the vegetation characteristics as it is no longer trampled. Cutting could also have an effect compared to grazing by an animal. To test these effects, point measurements of biomass were also taken outside of the experimental plot, in its nearby vicinity using a mobile cage (CI, Table 2) that could temporarily exclude grazers. The protocol used was similar to that of Hiernaux and Diarra (1986). The mobile cage was moved every 16 days, at the same dates as the G1 cuttings within the exclosure, and four 1 m^2 quadrates were sampled inside the mobile cage. Cut biomass was compared to the non-irrigated and frequently cut samples (R0G1) at different dates, in both flooded and non flooded situations. We assume that excluding grazers for a limited period of 16 days does not modify the soil or the vegetation characteristics.

Point measurements of biomass were also taken in the central floodplains (2°28′7 S - 40°18′59 E) to compare growth rates within the experimental plot with those in the central floodplains. 12 cages (1.5 m by 1.5 m) were positioned along a transect perpendicular to the main channel at slightly different elevations (less than 1 m difference in elevation) so that different flooding or soil humidity conditions could be captured. Non-flooded (T) and flooded (Tf) biomass were measured (Table 2). We were unable to obtain regular biomass measurements within the remote central floodplain as the cages were systematically destroyed by the cattle or the herdsmen. Indeed the context of high competition over natural resources (Duvail et al. 2012, Leauthaud et al. 2013a) in the area and the possible conversion of the floodplains into large-scale irrigated farmland made the herdsmen suspicious about grassland monitoring. Furthermore, as highly mobile groups, it was impossible to explain the research interests regularly enough so that arriving herdsmen were aware of the work. Lastly, due to the remoteness of the area, the cages could not be protected. As data was scarce, statistical analysis was not undertaken on the inner floodplain measurements and were included for comparison only.

To answer Objective 3/, the clippings were separated into, respectively, the blade and the sheath/culm material, at different dates representing the variability on vegetation cover and the flooded and non flooded situations. Similarly, leaf and stem nitrogen concentration were measured by the calorimetric method.

Rainfall was measured daily and manually at the experimental site with a rain gauge. Incoming radiation and rainfall were measured at a neighboring automatic weather station (Campbell Scientific Ltd., SBS500 rain gauge and CS300 APOGEE PYR-P pyranometer). Mean

Location		Experimental plot			Central floodplain
	Irrigation (mm.day^{-1})				
Duration between cuttings (days)*		16	32	64	16
Exclosure	0	R0G1	R0G2	R0G3	
	2.5	R1G1	R1G2	R1G3	
	7.5	R2G1	R2G2	R2G3	
Mobile cage	0	CI			T, Tf

Table 2: Summary of the cutting treatments and their abbreviation in the text. * cutting was done after 37, 41 and 69 days after the flooded period of 37 days. R stand for Rain (i.e. for which irrigation is used as a surrogate) and G for Grazing (i.e. cutting)

daily rainfall and mean daily radiation between two clippings were calculated.

4.2.2 *Data analysis for each Objective*

4.2.2.1 *Objective 1*

The collected samples were first used to describe the general growth patterns of the grasslands in the experimental plot and determine their similarity with non-enclosed vegetation next to the plot and within the central floodplains. To do so, Fisher's Least Significant Difference (LSD) tests were performed on Aboveground Dry Biomass (AGDB) obtained at R0G1, CI, T and Tf on the same dates.

Total AGDB was calculated as the sum of all clippings per quadrate. The effects of cutting frequency, C, and irrigation, W, on Total AGDB were tested using a linear model (LM) and the significance of each factor tested through a Fisher's Least Significant Difference test with a 5 % significant threshold level.

Annual net primary production, NPP, was calculated assuming that some phytomass detached from the plant to form litter and was thus not collected. It was assumed that most of the senescent matter between two successive cuttings was lost, so NPP was calculated as:

$$NPP = \delta \cdot (s_{NF} \cdot \sum AGDB_{NF} + s_F \cdot \sum AGDB_F) \qquad (1)$$

where δ (0.80) is the ratio of the number of days in a year over duration of the experiment, and $AGDB_{NF}$ and $AGDB_F$ are AGDBs in non-flooded and flooded situations. Variable senescent rates based on literature were used as this factor was not measured (5 % loss of biomass in non-flooded conditions, s_{NF}, and a 10 %, 25 % (Junk and Piedade 1993) or 40 % (Engle et al. 2008) loss, s_F, in flooded conditions). Annual AGDB was calculated prorata to the duration of the experiment and are included in this section for comparison to literature.

4.2.2.2 *Objective 2*

The effect of floods on daily growth rates (GR; $g \cdot m^{-2} \cdot day^{-1}$), and the effect of cutting, irrigation and other climatic variables on daily growth rates during the non-flooded periods were tested. Daily growth rates were calculated from the clippings as:

$$GR = \frac{AGDB}{dt} \tag{2}$$

where dt is duration between two cuttings. Doing so, the 1 cm of remaining biomass after removing the clippings is neglected.

Firstly, the effect of the floods (three levels: non-flooded, NF, flooded, F, and after flood AF) on GR was tested using the whole data set (n = 510) from the enclosed plot. GR analysis was performed using a generalized linear model (GLM) with a Gamma distribution. All data collected after the flood until the 1st of March 2012 were considered as AF as the soil residual humidity was still high at this date. As the floods occurred naturally, they did not coincide with the cutting dates. All samples that were flooded for at least one day were given the status F. G2 and G3 cuttings were flooded 37 days out of 41 and 69 days respectively.

In a second step, we hypothesized that the number of days from the cutting just prior to the floods and the arrival of the floods, NFd (non-flooded duration) and irrigation,W (0, 2.55, 7.64 $mm \cdot day^{-1}$), applied during this period had an effect on GR as the latter was averaged over the flooded and non-flooded periods. Nfd, W, and their interactions were tested on the flooded data (n = 40) using a linear model (LM). The best predictive model according to the corrected Akaike Information Criterion (AICc; Akaike 1973, Hurvich and Tsai 1989, Hurvich and Tsai 1995) was selected.

Thirdly, an analysis on the non-flooded dataset (n = 470) was performed to examine the variables influencing GR during this phase. Explanatory factors tested were cutting frequency, C, (G1, G2, G3) and a two-level variable, A, specifying if the sample was taken before or after the floods. Tested covariates were irrigation, W, (0, 2.55, 7.64 $mm \cdot day^{-1}$), mean daily rainfall, Rn, ($mm \cdot day^{-1}$), mean daily radiation, Rd, ($MJ \cdot day^{-1}$), and time from the beginning of the experiment to sampling date, T (1 to 454 days). All interactions up to the sixth order between the variables, excluding T, and all the interactions between T, W and C were tested. Models including the neperian logarithm of irrigation, $log(W)$, and the square of irrigation, W^2, were also tested. Inclusion of the flood status as a covariable (number of days between the end of the flood and the cutting) or of C as a co-variable (inverse of the time between two cuts) were tested. Model selection was again based on AICc.

4.2.2.3 *Objective 3*

The effects of floods on the distribution of biomass between leaves and stems, and finally on leaf nitrogen concentration were tested.

We hypothesized that allocation of AGDB to leaf (and hence stem) compartments can be different in non-flooded and flooded conditions: leaf biomass, B_L, would not only depend on AGDB but also on flood status (F, AF and NF). As a high leaf turnover has been reported in flooded situations (Piedade et al. 1991) compared to non-flooded conditions, a corrected leaf biomass ($B_{L,cor}$, flood status: F_{cor}) was calculated to check that the differences were not due to higher senescence rates. To do so, we considered that stem senescent rates were similar in both the flooded and non-flood situations, that leaf senescence in non-flooded conditions was negligible compared to that in flooded conditions, and that daily leaf senescent rate was 5 % in flooded conditions (Junk and Howard-Williams 1984). Therefore, $B_{L,cor}$ was calculated by adding 5 % to B_L when flooded. Models with and without each effect or their interaction were fitted and compared to each other using F-tests.

Lastly, the effect of flooding status, leaf biomass B_L, and their interactions on leaf nitrogen concentration were tested through a GLM (Gamma distribution, n = 155). Leaf biomass was estimated using the ANOVA model from the previous paragraph. When total biomass was lower than 46 g.m2 (see result section, leaf-biomass relationships), AGDB was considered constituted of only leaf tissue. Model selection was again based on AICc.

For all tests previously described hypothesizing a Gaussian distribution, deviation from normality and homoscedasticity were checked with a Shapiro-Walk and a Levene's test, with a 5 % significant threshold level. All analyses were performed using the R software and packages (version 2.1.12, R Development Core Team2008).

4.2.3 *Missing data*

Manual rainfall measurements at the experimental site were unavailable from December 2010 to March 2011 and from January 2012 to March 2012. This missing data was completed using the nearby automatic weather station when data was available. Due to the spatial heterogeneity in rainfall distribution, the daily rainfall data from the experimental site and the automatic weather station were poorly correlated (cor = 0.37), however, the daily floating averages over 30 days were well correlated (cor = 0.82). A linear regression was therefore fitted between the two datasets (p value <2e-16, R^2 = 0.68) and used to

Flood status	Irrigation treatment (W) every 8 days (mm)	Cutting frequency (C) (days) 16	32	64
		Mean AGDB (±SD) ($g \cdot m^{-2}$)		
Non Flooded	0	29 ± 37	72 ± 54	119 ± 124
Non Flooded	20	80 ± 29	202 ± 49	431 ± 206
Non Flooded	60	100 ± 37	185 ± 85	487 ± 251
After Flood	0	104 ± 40	279 ± 93	671 ± 124
After Flood	20	108 ± 20	302 ± 66	695 ± 130
After Flood	60	93 ± 8	272 ± 52	544 ± 121
Flooded	0	461 ± 49	775 ± 315	793 ± 106
Flooded	20	538 ± 91	834 ± 117	748 ± 110
Flooded	60	722 ± 134	681 ± 272	537 ± 145

Table 3: Mean AGDB (±SD) between successive samples differentiated according to cutting, irrigation and flood modalities.

complete the missing data. Missing data occurring during part of the dry season, for which rainfall data at the automatic weather station were missing (12/01/2011-14/02/2011), was set to zero.

To calculate Total AGDB, missing data needed to be filled and was therefore interpolated from the previous and next clippings or taken to be similar to the clipping of the same quadrate in a similar growing season. Missing data for the GR analysis were excluded from the statistical tests.

4.3 RESULTS

4.3.1 *Growth patterns and productivity of the floodplain grasslands*

4.3.1.1 *Description of growth patterns for selected treatments*

Aboveground dry biomass (AGDB) was maximal after the flooded period with a mean per treatment between 461±49 $g \cdot m^{-2}$ and 834±117 $g \cdot m^{-2}$ (Table 3). In flooded conditions, AGDB was higher for R1G2 compared to R1G3 and for the shorter growth durations in the R2 treatment, even though growth duration was inversely longer. In non-flooded conditions, NF and AF, AGDB was higher for longer growth durations (G3, Table 3) and for irrigated treatments. AGDB was also higher, except for R2G1, in AF than NF conditions. As growth duration is differs according to cutting frequency, it is easier to interpret these results looking at their daily growth rates (GR).

Figure 14 shows, as an illustration of the growth patterns throughout the experiment, AGDB for the three G1 irrigation treatments. AGDB was at minimum three times higher in the flooded condi-

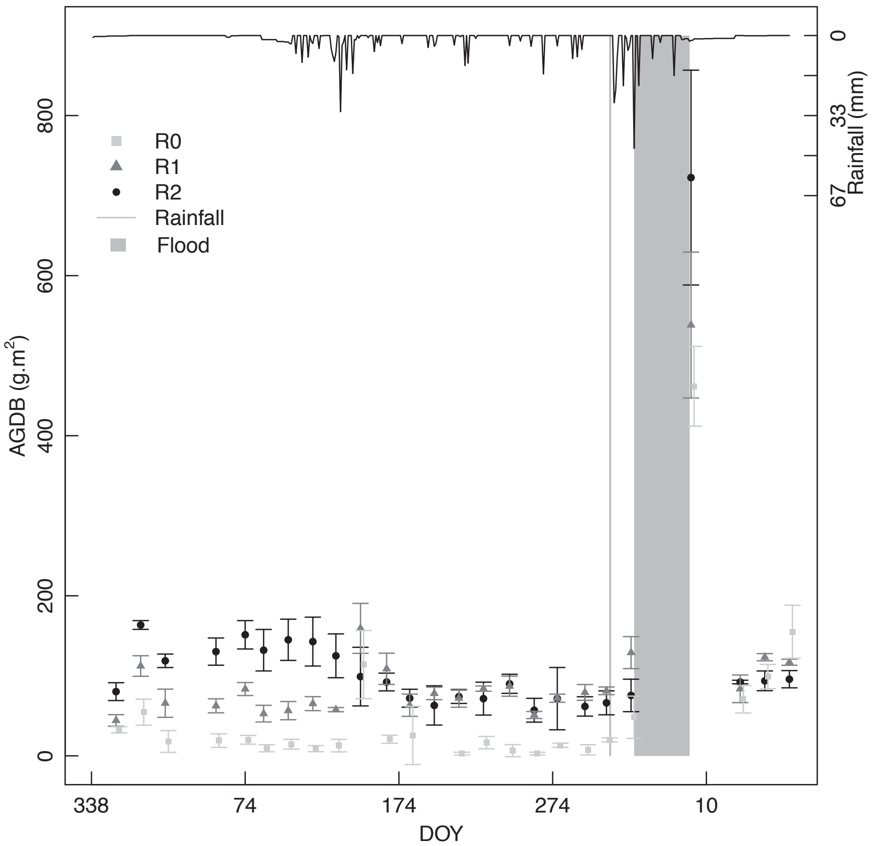


Figure 14: Aboveground dry biomass (AGDB) for different irrigation treatments, but identical cutting frequencies (R0G1, R1G1 and R2G1).

tions compared to all the other cuttings. In non-flooded conditions, NF, AGDB was relatively low when not irrigated (maximum of 186 $g \cdot m^{-2}$) and stable. AGDB for R1 increased during the rainy period whereas AGDB for R2 increased at the beginning of the first rainy season then declined to levels similar to R1. After the floods, AGDB tended to be similar for all G1 treatments.

4.3.1.2 *Effect of the exclosure on aboveground dry biomass*

For 9 out of the 13 AGDB available conjointly for R0G1 and CI, AGDB was not significantly different between CI and R0G1 (LSD test, p-value > 5 %) as shown in Figure 15. Biomass within CI was slightly higher at three dates during the rainy season, possibly due to a difference in initial biomass as R0G1 was systematically cut to 1 cm high whereas CI was left as had been grazed by the cattle. The non-flooded data at the inner floodplain site was in the same biomass range as at the experimental site. The flooded biomass at the inner floodplain site was higher compared to the non-flooded biomass at the same site.

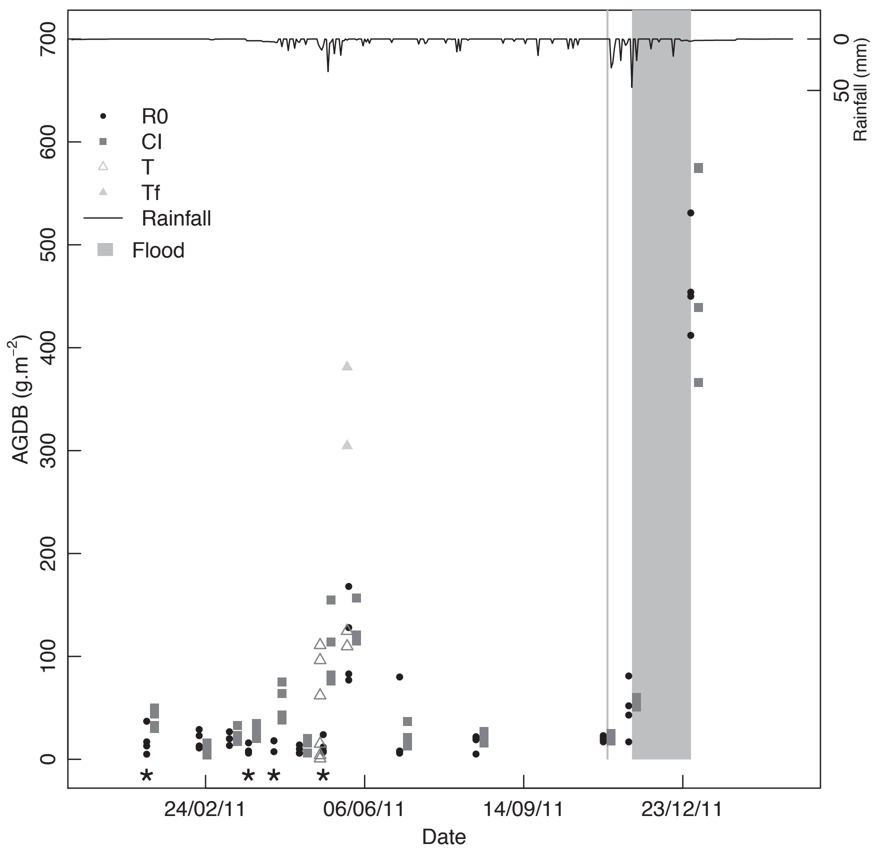


Figure 15: Comparison between the Aboveground Dry Biomass (AGDB) for the R0G1 and CI treatments at the experimental site and that of the T (non-flooded) and Tf (flooded) treatments within the central floodplains. *: dates at which R0G1 and CI were significantly different.

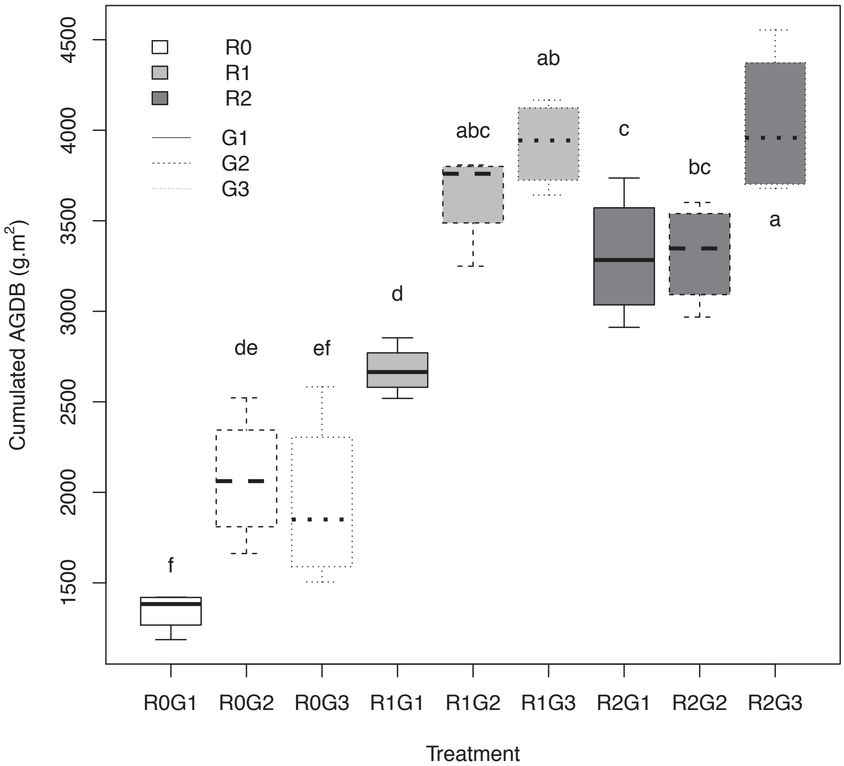


Figure 16: Total cumulated aboveground dry biomass (AGDB) at the end of the experiment for each treatment within the experimental plot. Different letters between boxes show that Total AGDBs were significantly different (LSD test with a Bonferroni adjustment: p-value < 5 %). Boxes represent the 1^{st} to 3^{rd} quartiles.

This data shows that:

- growth patterns within the experimental site and in the central floodplains were similar and the results from the experimental site could be extrapolated to the central floodplains.

- growth patterns within and next to the experimental site were similar. This comforts our hypothesis that 1/ the exclusion of cattle from the experimental plot did not affect vegetation growth, and 2/ the experimental site and its vicinity are homogeneous in nature (soil type, and vegetation characteristics).

4.3.1.3 *Effect of irrigation and cutting on Total AGDB*

Total AGDB ranged from 11.9 $T \cdot ha^{-1}$ to 45.5 $T \cdot ha^{-1}$ (Figure 16). Irrigation and cutting were significant explanatory variables (LSD test with a Bonferroni correction for multiple testing, p-value < 5 %). Total AGDB was highest for high to moderate irrigation and moderate cutting rates (R1G2, R1G3, R2G3). Irrigation increased Total AGDB but its effect seemed to saturate at high doses (R1 and R2). Total AGDB was lowest for the heavily cut and non-irrigated treatment (ROG1). For low to moderate irrigation, frequent cuttings (G1) significantly decreased Total AGDB.

Three groups, all significantly different from each other, appeared:

- moderate to high irrigation (R1 and R2) and low to moderate cutting rates (G1 and G2) induced high biomass production (30-40 $T \cdot ha^{-1}$).

- moderate irrigation (R1) combined with frequent (G1) cuttings and a low to moderate cutting rate for non irrigated vegetation led to moderate biomass production (15-30 $T \cdot ha^{-1}$).

- the absence of irrigation (R0) for regularly cut vegetation (G1) led to low biomass production (< 15 $T \cdot ha^{-1}$).

4.3.1.4 *Annual net primary production*

Annual AGDB ranged between 10.79 $T \cdot ha^{-1}$ and 32.44 $T \cdot ha^{-1}$ for all treatments (Table 4). Considering a 10 to 40 % loss during the 30-day (annual) flooded period, and a 5 % loss for the remaining time, calculated annual net primary production of the grasslands attained a maximum of 35.01 $T \cdot ha^{-1} \cdot year^{-1}$ (Table 4).

4.3.2 *Effect of floods, practices, and climatic variables on daily growth rates*

4.3.2.1 *Effect of floods and pre-flood conditions on GR*

Measured growth rates over the different cutting and irrigation treatments ranged from 0.07 $g \cdot m^{-2} \cdot day^{-1}$ to 17.91 $g \cdot m^{-2} \cdot day^{-1}$ during the pre-flood period, from 3.6 $g \cdot m^{-2} \cdot day^{-1}$ to 14.03 $g \cdot m^{-2} \cdot day^{-1}$ after the floods and from 4.76 $g \cdot m^{-2} \cdot day^{-1}$ to 22.5 $g \cdot m^{-2} \cdot day^{-1}$ during the flooded period.

The effect of floods on GR was well supported (ΔAIC_c=68 without this effect, **Appendix B**, Table 29). Indeed, GR was more than twice as fast during the flooded periods (Figure 17) compared to the pre-flood period. Interestingly, GR was 50 % faster after the floods compared to the pre-flood period. (Figure 17). Modelled GR were respectively 5.21 $g \cdot m^{-2} \cdot day^{-1}$, 8.16 $g \cdot m^{-2} \cdot day^{-1}$ and 12.05 $g \cdot m^{-2} \cdot day^{-1}$ (Figure 17). Overall, the flood factor explained a large part of GR (R^2=12.2 %, **Appendix B**, Table 29).

GR calculated for the flood modality F was mostly determined by the Number of non-flooded days, NfD (ΔAIC_c=15.94 without this effect, Table 30, **Appendix B**), and also by irrigation, W (ΔAIC_c=3.94 without this effect, Table 30, **Appendix B**). Interaction between NfD and W was included in the best selective model (ΔAIC_c=4.97 without the interaction, Table 30, **Appendix B**) showing that the effect of NfD differed across irrigation treatments. GR increased with decreasing NfD and increasing W. Maximal growth rates (19.0±3.5 $g \cdot$

	AAGDB			Productivity (+10 %)			Productivity (+20 %)			Productivity (+ 40 %)		
	G1	G2	G3	G1	G2	G3	G1	G2	G3	G1	G2	G3
R0	10.79	16.62	15.64	11.41	17.64	16.54	11.54	17.85	16.73	11.68	18.05	16.92
R1	21.50	29.28	31.53	22.72	30.95	33.33	22.99	31.31	33.71	23.25	31.67	34.11
R2	26.55	26.64	32.44	28.06	28.16	34.29	28.39	28.49	34.69	28.71	28.82	35.09

Table 4: Annual Aboveground Dry Biomass, AAGDB, ($T \cdot ha^{-1}$) and productivity ($T \cdot ha^{-1} \cdot year^{-1}$) considering a 10 %, 25 % and 40 % loss during the floods.

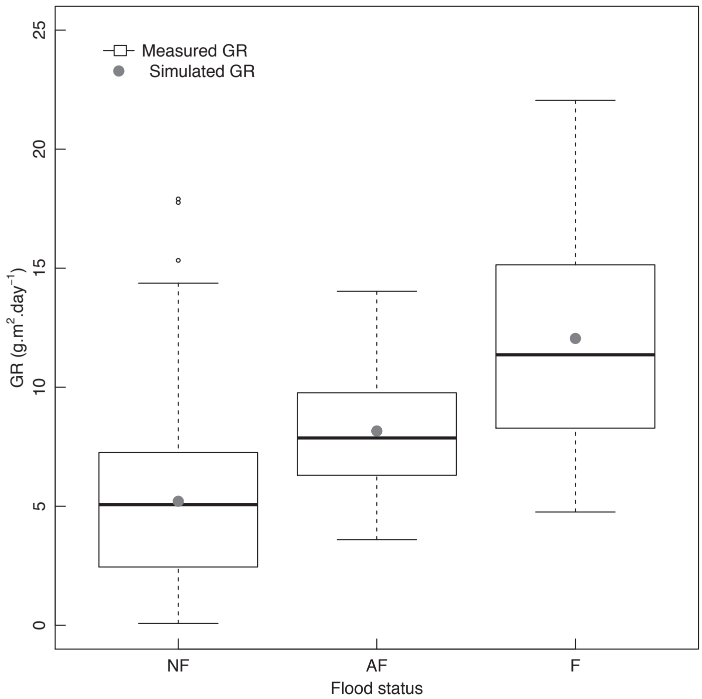


Figure 17: Effect of floods on daily growth rates, GR. Modelled points were calculated using model F1 (Table 29, **Appendix B**). Experimental data include all experimental points (n=510). Boxes represent the 1^{st} to 3^{rd} quartiles and small points are outside values.

$m^{-2} \cdot day^{-1}$) were recorded for the highly irrigated vegetation (R2) under an intense cutting regime (G1). Interestingly, these results indicate that 1/ intense cutting regimes for a well-irrigated vegetation was not detrimental for GR during the flood event, and 2/ irrigation prior to floods improved overall GR calculated for the flood event.

4.3.2.2 *Effect of practices and climate on GR in non-flooded conditions*

Irrigation, cutting frequency, mean radiation, mean rainfall, the post-flood qualitative effect and date of measurement were retained in the best tested model (model g11, ΔAIC_c=10.78, with second best model, Table 33, **Appendix B**), indicating that all these variables determined GR when the grassland was not flooded. However, specific effects for each variable were difficult to determine as interactions up to the third order were also retained (ΔAIC_c g11,g14=171.40, Table 33, **Appendix B**). The best predictive model correctly simulated GR (R^2=77 %, Table 33, **Appendix B** and Figure 18), with a root mean square error (RMSE) between the fitted and experimental data of 2.22 $g \cdot m^{-2} \cdot day^{-1}$, and an absolute error (maximal difference between observed and fitted values) of 5.89 $g \cdot m^{-2} \cdot day^{-1}$. This suggests that the most important variables determining GR in these conditions have been taken into account. However, there was a slight heteroscedas-

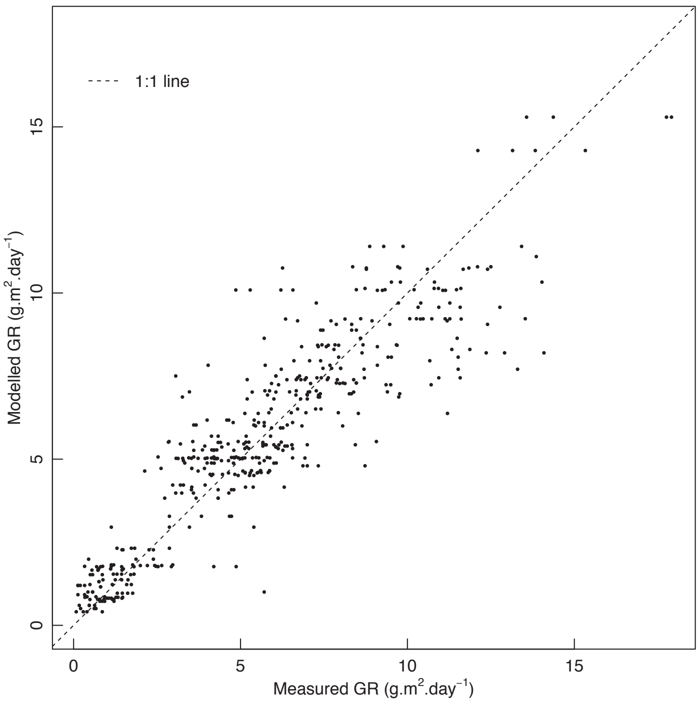


Figure 18: Modelled versus measured daily growth rates (GR) for the retained GLM model (g11).

ticity for the residuals in the absence of irrigation (R0) and for high cutting frequencies (C1), for which other explanatory variables may come into account. No tendencies in the model residuals against rain and radiation were noted. No autocorrelation through time of the residuals was noted.

Irrigation increased GR. The inclusion of $Log(W)$ improved the model (ΔAIC_c g10,g13=393.9, Table 33, **Appendix B**), indicating that GR saturates at high irrigation levels. The interaction between LW and the cutting treatments was significant, showing that the increase of GR with irrigation differed across cutting treatments. Interactions between W or LW and other explanatory variables were significant (Table 33, **Appendix B**), indicating that the effect of irrigation also differed following climatic conditions.

Time between the beginning of the experiment and the clipping date, T, was a significant variable (p-value<5 %) and was retained in the best predictive model (ΔAIC_c g14,g15=7.41, Table 33, **Appendix B**). Its effect depended on its interaction with W (p value < 1%), LW (p-value < 1%) and cutting frequency. However, the magnitude of the effect of T was low as shown by the quasi-nill parameter estimators relative to T and its interactions (Table 61, Appendix B). These results indicate that GR slightly decreased throughout the non-flooded period of the experiment, but was not the main variable determining GR.

Both Rn and Rd were retained in the best predictive model. The interactions between Rn and W, LW and flooded status were significant, showing that the positive effect of Rn on GR, for irrigated grasslands or during a flooded period, was attenuated. Interestingly, an increase of 1 mm of rain water increased GR more than the same increase in irrigated water, showing that water use efficiency was better for rainwater than for water provided through irrigation. Finally, radiation tended to decrease GR but its effect was complex and depended on rainfall and the other treatments.

4.3.3 *Effect of floods on physiological traits*

4.3.3.1 *Effect of floods on the allocation of aboveground dry biomass to leaves*

Leaf biomass, B_L, increased with aboveground dry biomass, AGDB (F-test, p-value<$2 \cdot 10^{-16}$, Table 31 , **Appendix B**), and the magnitude of this increase depended on flood status (F-test, p-value=0.021, Table 31 , **Appendix B**). AGDB and flood status explained a large portion of B_L (R^2=84 %, Figure 19). However, the retained model intercepts the Y-axis at 42 $g \cdot m^{-2}$, indicating that this model is not valid for low AGDB.

Leaf biomass increased with AGDB (Figure 19), but the slope of the regression line was <0.5, showing that a higher proportion of AGDB was invested in stem tissue. Indeed, at a total AGDB of 400 $g \cdot m^{-2}$, leaf tissue represented 44 % (46 %), 52 % and 64 % in respectively the flooded (corrected for senescence), post-flood and pre-flood conditions. This percentage decreased to 38 %, (40 %) 50 % and 58 % for 800 $g \cdot m^{-2}$ of AGDB. This preferential allocation to stems seems to be higher in flooded conditions than in non-flooded conditions (Figure 19), even when corrected for high leaf loss rates in flooded conditions. Similarly, the grassland seemed to produce more stems following a flood than in the pre-flood situation (Figure 19). This is interesting because, in comparison to pre-flood conditions, the plant produces less leaves, even though more water is available.

4.3.3.2 *Effect of floods on leaf nitrogen concentration*

Percent N leaf concentration varied from 0.42 % to 3.6 %, for a mean value of 1.7 % in all the irrigation and cutting frequency treatments.

Flood status was retained in the final model (ΔAIC_c= 234 without this effect, Table 32, **Appendix B**), indicating that floods had a strong effect on N leaf concentration, with the latter decreasing in the flooded situation compared to pre-flood conditions. Leaf biomass B_L was also retained (ΔAIC_c= 60 without this effect, Table 32, **Appendix B**) as well as its interaction with flood status (ΔAIC_c= 14 without this effect, Table 32, **Appendix B**), so that leaf biomass not only increased

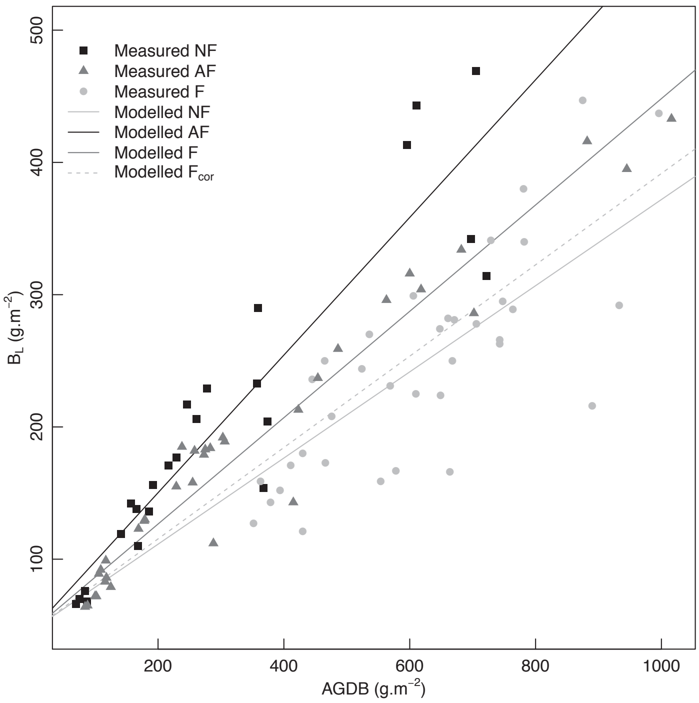


Figure 19: Dry leaf mass, B_L, as a function of Aboveground Dry Biomass (AGDB), for the different flood status'.

leaf N concentration but also modulated the magnitude of the effect of floods. Overall, leaf biomass and floods explained a large portion of leaf N concentration (R^2= 79 %, Table 32, **Appendix B**).

Interestingly, over 85 % of measured percent N leaf concentration were above 1 %. The former increased to 88 % and to 94 % for post-flood and pre-flooded conditions respectively. These concentrations show that the plants were most likely not under stressed conditions throughout the experiment. Correlation between percent N leaf concentration and T for pre-flood conditions was low (cor = -0.09). Furthermore, there was no effect of T on percent N leaf concentration (Fisher's test, p-value = 0.24). These results suggest that N was available for the plant throughout the experiment.

4.4 DISCUSSION

4.4.1 *Floods: a productivity enhancer for floodplain grasslands*

The floodplain grasslands composed mainly of *Echinochloa stagnina* show high productivities, comparable to well irrigated and well fertilized fields in a temperate climate (Duvick and Cassman 1999). A comparison of daily productivities of flooded grasslands recorded in various geographic areas by various authors and the corresponding flood characteristics are provided in Table 5. Maximum recorded daily productivity found in this study is similar to those of François et al. (1989) for the same species in Mali. However, maximum standing biomass was lower (11 $T \cdot ha^{-1}$, compared to the 30-32 $T \cdot ha^{-1}$, Francois et al. 1989), possibly because: 1/ flood height and duration were lower in the Tana River Delta (51 cm and 37 days in this study) compared to the Inner Delta of the Niger River (up to 4 m and six months), and 2/ biomass during the floods was underestimated as part of the stems were in the mud and it was not possible to sample them. Annual productivities calculated in this study reached 34-35 $T \cdot ha^{-1}$. The latter are not as high as productivities recorded for floodplain grasslands (99 $T \cdot ha^{-1}$ for *Echinochloa polystachya* (H.B.K.) Hitchcock, Piedade et al. 1991), but remain remarkable, especially when considering the short flooded period.

This study shows that floods have a very strong positive effect on grassland productivity, during and after the floods. The highest measured growth rates occurred during the floods, and high growth rates were maintained after the floods probably due to the absence of water stress as the soil water stock was recharged. Scholte (2007) also showed that the height of the floods influenced biomass production in shallowly flooded grasslands. As only one flood was recorded during the experiment, this study does not tackle the underlying complexities of the effect of flood characteristics on biomass production. Submersion characteristics such as maximal height, duration, the rising speed of water, and the flood's starting and ending dates in relation with rainfall can influence the floristic composition of the grasslands (Hiernaux 1982; Hiernaux and Diarra 1986), and hence their productivity.

High growth rates measured in this study could be explained by high radiation use efficiencies linked to high LAI values. Piedade et al. (1994) and Morison et al. (2000) reported high annual interception efficiencies (mostly in flooded conditions) for *Echinochloa polystachya*, with an average of 0.946 (Piedade et al. 1994), resulting from high LAI values. Growth rates could also be explained by high photosynthesis rates. Indeed, Piedade et al. (1994) reported mean photosynthetic rates of 30 $\mu mol \cdot m^{-2} \cdot s^{-1}$ and maximal values of 40 $\mu mol \cdot m^{-2} \cdot s^{-1}$ for *Echinochloa polystachya* in flooded conditions.

Our analyses evidenced that *Echinochloa stagnina* showed adaptations to flooded conditions. One of such adaptations is the allocation of a large part of the photosynthates to the stem compartment so that the plant can withstand partial immersion. Stem tissue represented 64 % to 58 % of total aboveground biomass in the flooded situation. These values are lower than the 89 % reported during immersion by François et al. (1989) probably due to the smaller height of floods and shorter flood duration. They are of the same order as Pompeo (2001) (63.1 %) for *Echinochloa polystachya*.

Floods slightly decreased leaf nitrogen concentration of the leaves, possibly through a dilution effect as biomass production was high. This is interesting because high growth rates were maintained despite a lower allocation to leaves and a lower leaf nitrogen concentration, both of which affect photosynthesis. Lastly, measured nitrogen concentrations in this study are similar to those of Hiernaux & Diarra (1986) for the same species: a nitrogen concentration of 1.18 % during the dry season. Generally, plants exhibit a wide range of tissue nitrogen concentration, ranging between 1 % to 5.3 % for temperate grasslands (Taiz & Zeyer 2000 in Gibson 2008). C_4 plant requirements for N are lower. Considering the nitrogen concentration in the leaves during the non-flooded conditions and the high growth rates during the flooded period, it is most likely that the grasslands were not under nitrogen stress throughout most of the experiment.

4.4.2 *Climate and management of the floodplains*

This study shows that general climatic variables such as rainfall and solar radiation, but also management options of the grasslands such as irrigation and cutting rates all influenced daily growth rates of the *Echinochloa stagnina* (Retz) P. Beauv. grassland and hence their productivity.

Frequent cuttings in the absence of irrigation had a very negative effect on annual productivity, despite high growth rates during the flooded period. It is hypothesized that this is linked to an excessive mobilization of the root reserves during the pre-flood conditions and resulted in a slow but steady death of the vegetation. Despite the depreciating effect of high cutting frequencies in non-flooded conditions, the same quadrates had high growth rates during the flooded period. This result suggests that these grasslands could withstand high rates of stocking or cutting at certain periods of the year and still exhibit high growth rates during and after the flooded period. The maintenance of these heavily grazed grasslands could be achieved with regular floods.

Irrigation had a positive effect on annual productivity of the grasslands. Growth rates increased with irrigation, but the latter's effect saturated at high irrigation rates. This result suggests that plants receiving on average 7 $mm \cdot day^{-1}$ of extra water were not under water stress. Water use efficiency of irrigated water was lower than that of rainfall, possibly due to higher evaporation rates as irrigation often occurred on sunny days when daily temperatures and radiation were high. Irrigation may have had another effect that would need to be tested: enhance root growth. Indeed, maximum growth rates were recorded for plants cut just before the floods, that had been irrigated during the pre-flood period. Irrigation during the non-flooded period could have favoured the development of the root system which could

Species	Site	Maximum AGDBM ($T \cdot ha^{-1}$)	Maximum water height (m)	Maximum recorded daily productivity ($kg \cdot ha^{-1} \cdot day^{-1}$)	Flood duration	References
Echinochloa stagnina	Mali	30-32	4	200-250 [(3)]	6 months	Francois et al. 1989
Echinochloa polystachya	Brazil	80	8	259 [(4)]	10 months	Piedade et al. 1991
Echinochloa polystachya	Brazil	19-27	2[(2)]	53 [(5)]	permanent	Pompeo et al. 2001
Echinochloa polystachya dominated community	Brazil	61[(1)]	-	-	permanent	Silva et al. 2009
Echinochloa stagnina [(6)]	**Kenya**	**11.6**	**0.51**	**190 ± 35**[(3)]	**37 days**	**present study**
Echinochloa stagnina	Mali	30	-	-	-	Hiernaux and Diarra 1986

Table 5: Measured maximum standing aboveground dry biomass in various aquatic macrophytes, and flooding characteristics. [(1)] monthly average [(2)] variation, [(3)] from standing biomass, [(4)] Net Primary Production, [(5)] annual average, [(6)] and *Vossia cuspidata*. Silva et al. 2009 list more references for *Echinochloa polystachya*

have then be remobilized during the floods. Finally, irrigation during the dry seasons maintained high growth rates. As fodder is rare during the dry-seasons, irrigation of the grasslands could improve the livestock keeping activities of the zone, even though its practical implementation would need to be assessed.

A simple relationship between growth rates, floods, irrigation and cutting frequency was not found in this study and interactions between the tested variables were numerous. This study shows that climate and flooding conditions, along with the management of the grasslands, all had an effect on growth rates, and must therefore be taken into account to calculate the annual production of the grasslands for different climate, flood and management scenarios. This could be achieved by building a physiological plant growth model, taking into account the main results of this study (Figure 37). In non-flooded conditions, aboveground dry biomass, AGDB, depended on rainfall, incoming radiation and management options of the grasslands. In a non-irrigated situation, growth rates followed the seasonal trends in rainfall and AGDB tended to be low during the dry seasons and slightly higher during the rainy seasons. High growth rates occur during the floods, which led to high AGDBs during the flooded period. High levels of AGDB were also maintained after the floods, probably because soil water humidity was high. Management of the grasslands through irrigation and cutting modulated AGDB. In particular, irrigation and frequent cuttings led to higher growth rates during the flooded period, and irrigation increased growth rates during the non-flooded periods. Finally, floods also changed the physiological characteristics of the grassland. More stem mass was produced comparatively to leaf mass on flooded and post-flood conditions. Leaf nitrogen concentration of the plants depended on flooding status, with leaf N concentration higher for non-flooded conditions. However, the plants were not under nitrogen stress.

4.4.3 *The floodplain grasslands as grazing grounds*

The comparison of aboveground dry biomass, AGDB, between the experimental plot and its surroundings and with the central floodplain grasslands suggested that these results can be extrapolated to the central grazing zone. Under this assumption, we roughly calculated fodder production within the floodplain grasslands of the Tana River Delta. The high productivities calculated in this study already suggest that the floodplain grasslands of *Echinochloa stagnina* (Retz) P. Beauv. of the TRD are good pasturelands. 'Natural' conditions found in the TRD (no additional irrigation and a moderate to intense grazing) are similar to treatments R0G1 and R0G2. Using the study's cumulated annual AGDB for these two treatments, and considering a 20 % loss during the flooded period, the total yearly production of

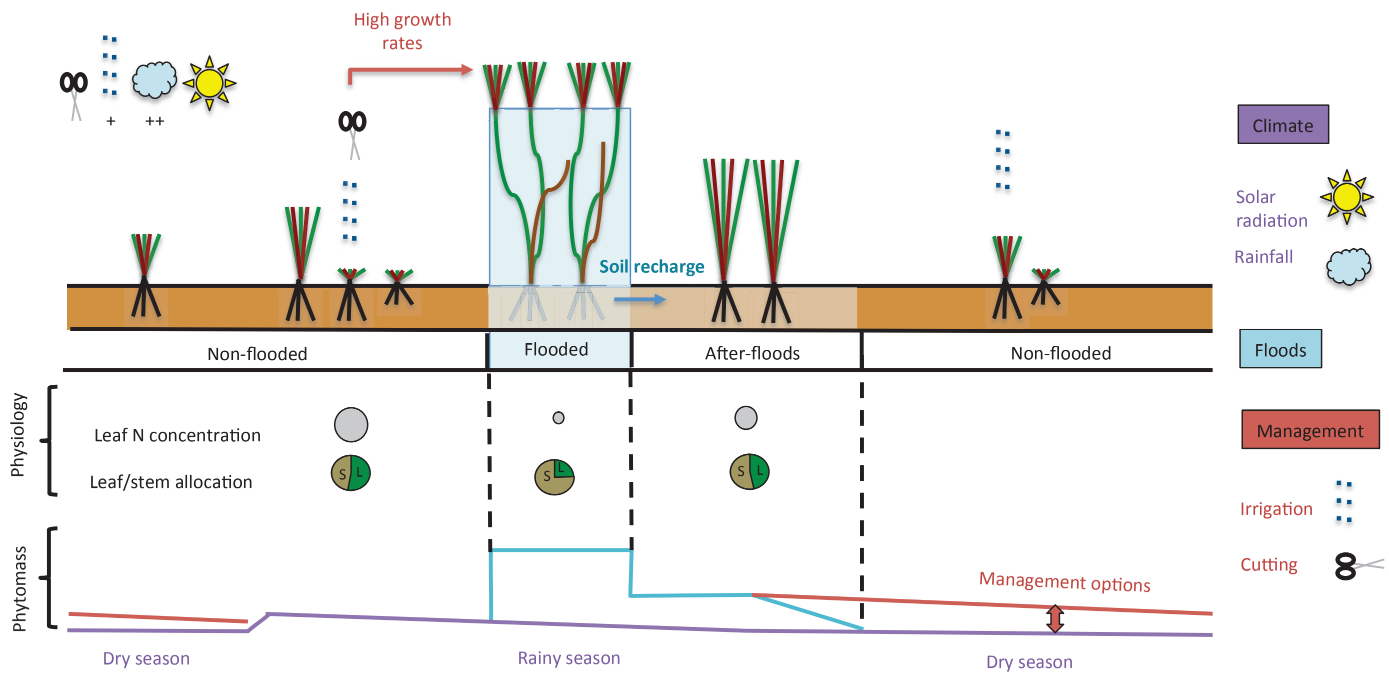


Figure 20: Schematic diagram of the effect of floods, management and climate on the phenological cycle, on N leaf concentration and leaf/stem allometry and on aboveground biomass of the grasslands.

the 200 km^2 central floodplains is estimated at $230 \cdot 10^3$ T to $360 \cdot 10^3$ T. By taking into account the surrounding floodplain grasslands with mixed vegetation that occupy about the same surface as the central floodplains, this yearly production would double, attaining $460 \cdot 10^3$ T to $720 \cdot 10^3$ T. This would be the approximate production for a year like 2011 where one only short flood occurred. In a year with two floods, this production could again double. The total production of the floodplains would therefore attain $1.4 \cdot 10^6$ - $1.5 \cdot 10^6$ T in a good year. Irrigation would further increase this production, but its implementation at a large scale seems limited because of the public nature of the grasslands, the limited monetary income of most of the pastoralists and the current socio-economic context within the Tana River Delta. These figures provide an estimation of the potential and actual stocking rate for the Tana River Delta, even though a large part of the production is lost. Besides the quantity of fodder produced, its availability throughout the seasons and its quality are important determinants of fodder production and further studies focused on these two factors need to be undertaken.

4.5 CONCLUSION

The central floodplain grasslands of the Tana River Delta are very productive. The daily growth rates depend on flooding conditions, climate and management practices, all of which interact in a complex manner. Floods increase biomass production and also extend the growth period of the grasslands. This leads us to suggest that they are primordial to maintain these grasslands as high quality grazing zones for the pastoralists. The possible development of new hydroelectric infrastructure on the Tana River can modify the flooding characteristics within the Tana River Delta: the most likely detrimental impact of hydroelectric infrastructure on fodder production will need to be evaluated.

5 A PLANT GROWTH MODEL FOR FLOODPLAIN GRASSLANDS

5.1 INTRODUCTION

Grasslands form some of the most extensive ecosystems on the planet and are the potential natural vegetation of approximately 25 % of the total land area ($36 \cdot 10^6$ km^2) (Sala and Paruelo 1997). They are mostly characterized by a low abundance of woody vegetation, deep fertile soils, important herds of grazing animals and a harsh climate (Gibson 2009). In sub-Saharan Africa alone, over 266 million people rely on them for their livelihoods (White et al. 2000). Floodplain grasslands form a specific type of grasslands characterized by frequent floods. They render important ecosystem services, such as downstream flood regulation, ground water recharge, climate regulation through carbon sequestration and important productive services (farming, grazing and fishing) (Daily 1997; Millennium Ecosystem Assessment (MA), 2005a). In particular, grasslands of *Echinochloa stagnina* (Retz) P. Beauv. form important grazing zones for the nomadic to sedentary pastoralists in the Sahel (Hiernaux and Diarra 1986; François et al.,1989). Despite these numerous services, it is estimated that 53 % of flooded grasslands and savannas worldwide were lost before the 1990s and a further decrease by 11 % is expected before 2050 (MA, 2005a).

Models are important tools for the management of natural ecosystems. They provide information on ecosystems, including energy and nutrient cycling and provide quantitative assessments (effect of species type and species richness, of precipitation or temperature, productivity, etc.). The development of crop models flourished in the 1960s and 1970s at Wageningen University (van Ittersum et al. 2003) and initiated growth models for natural vegetation. Specific models have since been developed for semi-arid climates where water-stress is the main limiting factor (Parton et al. 1983;Rambal and Cornet 1982; Mougin et al. 1995; LoSeen et al. 1997; Nouvellon et al. 2000). They take into account factors such as water stress, nutrients and temperature to calculate the productivity of the vegetation. It has been previously shown that numerous ecophysiological responses occur in floodplain grasslands in response to floods. In particular, they have a high energy conversion efficiency (Piedade et al. 1991), and hence high growth rates (**Chapter 4**) and productivity (Junk et al. 1989). They also modify the allocation of photosynthates (Piedade et al. 1991), plant nutrient status (Piedade et al. 1994, and **Chapter 4**), develop aerenchyma (Voesenek et al. 2006) and enhance shoot elongation (Kende et al. 1998; Voesenek et al. 2006). As such, current grassland models are inadequate to simulate flooded grasslands.

Our objective was therefore to construct a plant model adapted to tropical floodplain grasslands and more specifically to perennial grasslands composed mainly of *Echinochloa stagnina* (Retz) P. Beauv.. The model simulates leaf, stem and root growth, at a daily time-step. It is process-based and photosynthesis, evapotranspiration, water fluxes within the soil, senescence and litter production are modelled. Grazing is also modelled as these grasslands form important pasturelands when not under water. The model has the same structure as previously developed ones (Mougin et al. 1995; Cayrol et al. 2000; Nouvellon et al. 2000) but also incorporates the effect of floods on photosynthesis, photosynthetate allocation, senescence and litter production. Vegetation growth depends on the presence or absence of floods and on soil moisture during the non-flooded seasons. It is a rather simplified representation of the vegetation but still simulates the main mechanisms so that a realistic description of the processes is possible.

5.2 MODEL DESCRIPTION

5.2.1 *Overview of the model*

Vegetation is represented by its biomass and attached dead matter, and is separated into four compartments: live leaf biomass B_l, live stem biomass B_s, the root biomass B_r, and total aboveground dead mass B_{ad} (Figure 21). All biomasses are expressed as dry matter per square meter ($gDM \cdot m^{-2}$). The root compartment is important to represent inter-seasonal variations in biomass for perennial grasses.

Total vegetation biomass can be described by the following equation:

$$B_{tot} = B_{aer} + B_r \tag{3}$$

and the standing above-ground biomass, B_{aer}, by:

$$B_{aer} = B_l + B_s + B_{ad} \tag{4}$$

Photosynthesis provides the biomass input into the system. Photosynthates are first produced within the leaves, partly respired, and then allocated to the different compartments. Biomass can then be further respired by the plant, senesce or be lost to the plant system through grazing (or clippings). Aboveground senescent matter, attached to the live mass, is lost by decomposition or through litter formation. Root senescent matter is not represented for simplicity and is directly lost to the system. Within the plant, translocation of reserves from roots to leaves is also represented. These processes vary within each compartment.

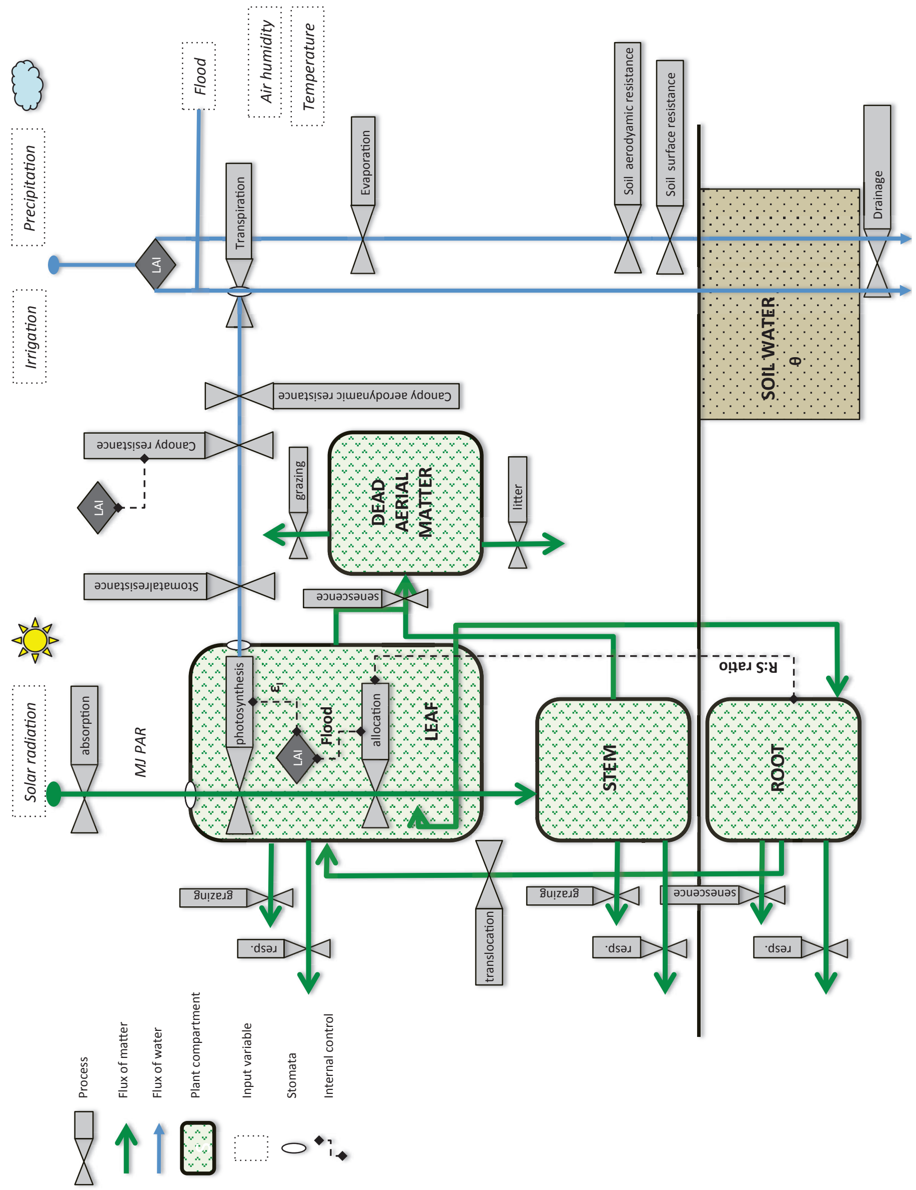


Figure 21: Diagram showing compartments, flows and processes of the model.

The daily variation of biomass in the different compartments can be expressed as the biomass arriving at each time step within the compartment minus the biomass lost to the compartment during the same period:

$$\frac{dB_l}{dt} = a_l \cdot P_{net} + T_{r:l} - S_l - G_l \quad (5)$$

$$\frac{dB_s}{dt} = a_s \cdot P_{net} - S_s - G_s \quad (6)$$

$$\frac{dB_r}{dt} = a_r \cdot P_{net} - T_{r:l} - S_r \quad (7)$$

$$\frac{dB_{ad}}{dt} = S_l + S_s - G_{ad} - L_{sl} \quad (8)$$

where P_{net} is the net photosynthesis ($gDM \cdot m^{-2} \cdot day^{-1}$), $a_{l,s,r}$ the allocation of photosynthates between leaves, stem and root compartments ($gDM \cdot gDM^{-1}$), $T_{r:l}$ the translocation of reserves from roots to leaves ($gDM \cdot m^{-2} \cdot day^{-1}$), G_{l}, G_{s} and G_{ad} the grazing (or cutting) of leaves, stems and aboveground dead material ($gDM \cdot m^{-2} \cdot day^{-1}$) by herbivores, S_{l}, S_{s} and S_{r} the senescence rate of the leaves, stems and roots ($gDM \cdot m^{-2} \cdot day^{-1}$) and L_{sl} the litter formation rate ($gDM \cdot m^{-2} \cdot day^{-1}$).

The plant model is coupled to a soil water module (Figure 21) as water stress influences many growth processes. Both models are run on a daily basis. Input variables are: mean 24 h incoming solar radiation ($MJ \cdot m^{-2} \cdot day^{-1}$), cumulated 24 h precipitation and irrigation ($mm \cdot m^{-2} \cdot day^{-1}$), mean 24 h air humidity (%), maximal and minimal 24 h air temperature (°C), the occurrence or not of floods (as a binary operator) and monthly values of extraterrestrial radiation ($MJ \cdot m^{-2} \cdot month^{-1}$). Each process occurring in the model, and the resulting equations are described in the following section.

The model was coded under R (R Development Core Team 2008) and is publicly available. The parameters used and their range of values are reported in **Appendix C**.

5.2.2 *Carbon balance*

5.2.2.1 *Photosynthesis*

Photosynthesis is the assimilation of atmospheric CO_2 by plants and its conversion into organic matter. It has been modelled in numerous ways, with the Ball-Berry model (Ball et al. 1987) being one of the most commonly used. The latter couples biochemistry relationships with an empirical stomatal model. As it requires a number of parameters that were not measured, we preferred to use a simpler approach based on the Monteith efficiency concept.

In a non-limiting situation, photosynthesis depends on the solar radiation reaching the plant and the latter's ability to capture this solar energy. Therefore, maximal photosynthesis P_G can be expressed as:

$$P_G = I \cdot \varepsilon_c \cdot \varepsilon_I \cdot \varepsilon_E \tag{9}$$

where I is the incoming solar radiation ($MJ \cdot m^{-2} \cdot day^{-1}$), ε_c (-) the climatic efficiency coefficient linked to the fact that plants use only part of the incoming radiation (within the Photosynthetically Active Radiation region, PAR, spanning from 400 nm to 700 nm of the light spectrum), ε_I (-) the interception efficiency coefficient, and ε_E the conversion efficiency coefficient ($gDM \cdot MJ^{-1}$) denoting the ability of the plant to convert energy into biomass.

The incoming solar radiation, I, is obtained from climatic data. ε_c is fixed at 0.47 (Szeicz 1974) and ε_I depends on leaf biomass and geometry. It was expressed as a function of Leaf Area Index (LAI, $m^2_{leaves} \cdot m^{-2}_{ground}$):

$$\varepsilon_I = (1 - \exp(-k_1 \cdot LAI)) \tag{10}$$

with k_1 expressed from field data. High interception efficiencies have been recorded for flooded grasslands of *Echinochloa polystachya* (H.B.K.) Hitchcock (Piedade et al. 1994; Morison et al. 2000) associated with elevated LAI values.

LAI is related to aboveground dry biomass. It is computed from leaf biomass according to a relationship that takes into account the increase of stem tissue at high biomass levels:

$$LAI = SLA \cdot BM_l \tag{11}$$

where SLA is the Specific Leaf Area ($m^{-2}_{leaves} \cdot gDM^{-1}_{leaves}$).

5.2.2.2 *Respiration*

Through respiration, a large portion of photosynthates are transformed back to CO_2. Respiration to gross photosynthesis ratios range from 0.35 to 0.8 (Amthor 2000), indicating that respiration is not negligible and needs to be modelled. Two respiration processes are usually distinguished (McCree 1970): growth respiration which occurs as new biomass is formed and maintenance respiration which includes processes that maintain cellular structures or allow phenotypic adjustments to environmental conditions (Penning de Vries 1975).

Net photosynthesis rate is the quantity of dry matter produced by the plant through photosynthesis, after the deduction of respiration processes. Net photosynthesis can therefore be expressed, following Thornley (1970), as:

$$P_{net} = Y_G \cdot (P_G - R_M) \tag{12}$$

where Y_G (-) is the yield of growth processes (i.e. the amount of photosynthesized matter used after respiration has occurred), P_G

($gDM \cdot m^{-2} \cdot day^{-1}$) is gross photosynthesis and R_M is maintenance respiration. In a steady state, the previous equation can be decomposed into:

$$P_{net} = Y_G \cdot P_G - Y_G \cdot m_R \cdot B_{tot} \tag{13}$$

where m_R is the maintenance respiration coefficient. To comply with theory (Amthor 2000), respiration due to changes in reserve material are neglected. Y_G is temperature independent (Amthor 2000) and varies from 0.7 to 0.89 across organs (Penning de Vries et al. 1983), while m_R responds to temperature and plant N content (de Wit et al. 1970) and ranges from $4.84 \cdot 10^{-3}$ to $202.4 \cdot 10^{-3}$ $g \cdot g^{-1} \cdot day^{-1}$ (Amthor 1989). Maintenance rates can be higher in roots compared to shoots and leaves (Amthor 1989). Leaf respiratory rates were found to be identical in flooded and non-flooded conditions for *Echinochloa polystachya* (H.B.K.) Hitchcock (Piedade et al. 1994). Because of scarce values in the literature, m_R and Y_G were fixed although they could also be considered as internal variables.

5.2.2.3 *Conversion efficiency coefficient*

Photosynthesis and hence biomass production depends on total CO_2 intake and on the ability of the plant to use solar radiation to produce organic matter from CO_2. This is expressed through the conversion efficiency coefficient, ε_E.

Factors like water, nutrient and temperature influence the rate of CO_2 intake of the plant. When soil water content is low, photosynthesis can be limited by stomatal closure. On the contrary, floods, for some plants adapted to flooded conditions, induce high photosynthesis rates and high primary productivity (Piedade et al. 1991). High temperatures can also induce stomatal closure. Due to the specific C_4 pathway to assimilate atmospheric CO_2 , temperature stress is limited for *Echinochloa stagnina* (Retz) P. Beauv., especially in the range of climate conditions considered here, and therefore is not included. The nitrogen status of the plant also affects photosynthesis rates, but as seen in **Chapter 4**, leaf nitrogen concentration is high enough to assume the plant is not stressed. Finally, under flooded conditions, daily growth rates are high enough to hypothesize that other limitations are not occurring (as in Piedade et al. 1991). Temperature and nitrogen stress were therefore not included in this study. A higher conversion efficiency under flooded conditions is possible and a couple of hypothesis have been put forward. Piedade et al. (1991) suggest that CO_2 diffusion from the water to the stem could occur. Similarly, translocation of plant reserves to the stems could boost plant growth. These mechanisms are not made explicit here.

The conversion coefficient efficiency depends in this model only on the soil water content (Figure 22). ε_E is maximal, ε_{Emax}, when the grassland is flooded. It then decreases linearly until the soil water

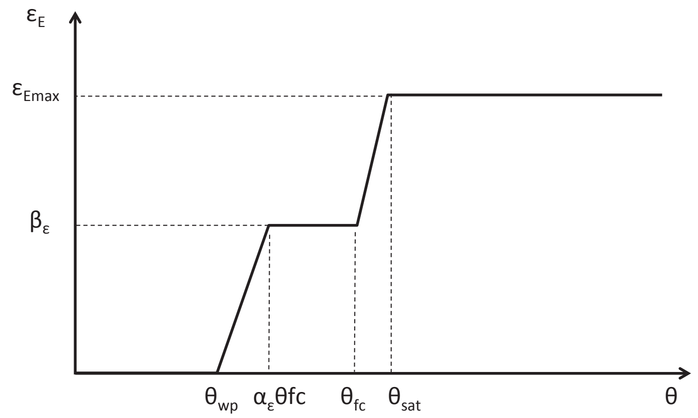


Figure 22: The energy conversion coefficient as a function of soil water content.

content reaches its field capacity, θ_{fc}. At this point and until $\theta = \alpha \cdot \theta_{fc}$, there is no longer an effect of the flood and the soil has enough water so that the plant is not in a stressed state: ε_E stays constant. At lower soil water contents, ε_E decreases linearly, reaching zero at the wilting point, θ_{wp}.

The conversion efficiency has therefore been expressed here as:

$$\begin{cases} \theta \leq \theta_{wp}, & \varepsilon_E = 0 \\ \theta_{wp} < \theta \leq \alpha \cdot \theta_{fc}, & \varepsilon_E = \frac{\beta}{\alpha \cdot \theta_{fc} - \theta_{wp}} \cdot (\theta - \theta_{wp}) \\ \alpha \cdot \theta_{fc} < \theta \leq \theta_{fc}, & \varepsilon_E = \beta \\ \theta_{fc} < \theta \leq \theta_{sat}, & \varepsilon_E = \frac{\varepsilon_{Emax} - \beta}{\theta_{sat} - \theta_{fc}} \cdot (\theta - \theta_{fc}) + \beta \end{cases} \tag{14}$$

ε_E is the weighted average of its value for each soil horizon.

5.2.2.4 *Allocation of photosynthates*

Photosynthates are allocated within the plant between the leaves, stems and roots.

Root biomass is important for water and nutrient uptake. In perennial grasses, it also enables regrowth at the beginning of the rainy season or after severe grazing events. The proportion of biomass allocated to the root system depends on species and environmental conditions. In non-flooded vegetation, root to shoot ratios range from 0.7:1 to 4:1, and mostly between 0.8:1 and 1.5:1 (Gould and Shaw 1983), but could be lower for *Echinochloa stagnina* (Retz) P. Beauv. which doesn't have a very developed root system. For the dry season, we considered that if the root to shoot ratio is higher than the root to shoot ratio for typical C4 grasslands, $r_{r:s}$ (-), then no allocation occurs (on the contrary, translocation from root to shoots can occur). Otherwise, allocation to the roots occurs so that the the total root biomass after allocation can support the aboveground biomass of the day:

$$\frac{B_r \cdot (1 + a_R)}{B_l \cdot (1 + a_L) + B_s \cdot (1 + a_S)} = r_{r:s} \tag{15}$$

The remaining biomass is then allocated to the leaf and stem compartment according to the allometric relationship found in the **Chapter 4** ($B_L = a_{l,NF} \cdot B_{aer}$, with $a_{l,NF}$ the fraction of leaf to aboveground biomass).

In a flooded situation, the plant has two requirements: 1/ keep enough leaf biomass above water to photosynthesize, and 2/ develop or elongate stem biomass to keep up with the rising water. Roots could be less necessary as adventitious roots can uptake nutrients in the nutrient-rich water. For flooded vegetation, Piedade et al. (1991) estimated on average that 30.7 % and 5.5 % of photosynthates were allocated to the leaves and roots, the rest going to stem growth.

Root allocation was set to a constant value during the floods. Of the remaining photosynthates, we considered that they were prioritarily allocated to the leaf compartment to favour photosynthesis (Figure 23). In this case, stem allocation is set at a minimal level that still allows the plant to stay above water. When leaf biomass reaches an amount where all the light is intercepted, B_{LAImax}, (so when LAI is maximal), photosynthates are progressively allocated to the stem compartment until reaching a maximal stem allocation value (corresponding to a fraction, γ_a , of B_{LAImax}):

$$\begin{cases} B_L < B_{LAImax}, & a_L = a_{Lmax} \\ B_{LAImax} < B_L < \gamma_a \cdot B_{LAImax}, & a_L = \Psi \cdot (B_L - \gamma_a \cdot B_{LAImax}) + a_{Lmin} \\ \gamma_a \cdot B_{LAImax} < B_L, & a_L = a_{Lmin} \end{cases} \tag{16}$$

where

$$\Psi = \frac{a_{Lmax} - a_{Lmin}}{B_{LAImax} - \gamma_a \cdot B_{LAImax}} \tag{17}$$

5.2.2.5 *Translocation from roots to aboveground biomass*

Translocation from the roots to the above ground biomass occurs mainly at the end of the dry season when growth reinitiates or when a critical amount of biomass has been removed (by grazing, cutting etc.). Environmental conditions also need to be favorable for growth, e.g. enough water in the ground.

When there is a critical amount of root biomass to sustain the aboveground biomass $\frac{B_r}{B_s+B_l} \geq r_{r:s}$ and enough water in the soil, $\theta_1 > \alpha \cdot \theta_{1,fc}$, the translocation rate, t_R, is such that:

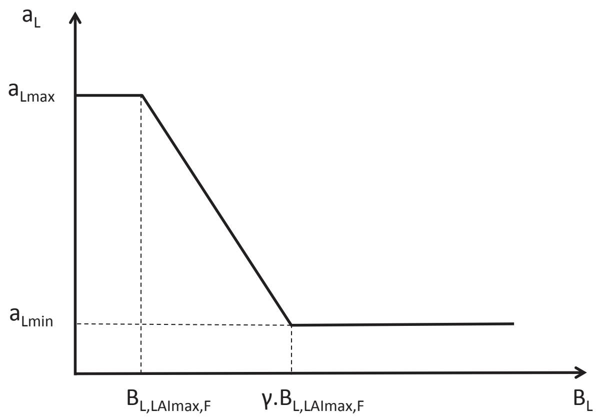


Figure 23: Leaf allocation as a function of leaf biomass in a flooded situation

$$\frac{B_r}{B_l \cdot (1 + t_R) + B_s} = r_{r:s} \tag{18}$$

We assume that root reserves are only translocated to the leaves so that the plant can photosynthesize immediately. Maximum translocation rate is set to 0.01 so that root reserves are gradually restituted to the aerial part.

5.2.2.6 *Senescence*

Senescence occurs within each compartment and is related to plant age and environmental conditions. Senescence processes were separated according to the flood status, as the mechanisms of senescence differ.

In non-flooded conditions, senescence depends on soil water availability. Here, we consider a constant senescent coefficient, s_i ($gDM \cdot gDM^{-1} \cdot day^{-1}$) for the leaf and stem compartment, and a water stress effect, $f_s(\theta)$:

$$S_i = s_i \cdot f_{s(\theta)} \cdot B_i \tag{19}$$

$f_{s(\theta)}$ is the weighted average of the water stress effect within each layer, considering root distribution within each horizon, j (ϑ, $m^3_{roots} \cdot m^{-3}_{soil}$):

$$f_{s(\theta)} = \frac{\sum f_{s(\theta),j} \cdot \vartheta_j}{\sum \vartheta_j} \tag{20}$$

with:

$$\begin{cases} \theta_j > \alpha \cdot \theta_{j,fc}, & f_{s(\theta),j} = 1 \\ \theta_j < \alpha \cdot \theta_{j,fc}, & f_{s(\theta),j} = (1 + (1 - \frac{\theta - \theta_{wp}}{\alpha \cdot \theta_{fc} - \theta_{wp}})) \end{cases} \tag{21}$$

In flooded situations, high leaf turnover has been reported Piedade et al. (1991) as the leaf, attached to the stem, sinks with rising water. Average monthly loss rates in *Echinochloa polystachya* (H.B.K.) Hitchcock (Junk and Howard-Williams 1984) were estimated at 5 %, but they can go up to 40 % for other species (*Ludwigia densiflora*, Junk and Piedade 1993). A constant senescent rate was calculated considering the turnover rate of 34 days (Piedade et al. 1991), after which only 1 % of the initial biomass remained. s is therefore the solution of the differential equation $\frac{dB_L}{dt} = s_L \cdot B_L$ and equals 13.5 %. The daily senescent of the stems was taken as 5 % of this value.

5.2.2.7 *Litter production and decomposition of the senescent matter*

Litter is produced when the senescent parts of the plant fall to the ground. Dead material can also decompose as it is still attached to the plant. Many phenomena come into account to explain litter formation and decomposition rates. They depend primarily on the structure of senescent matter (lignin content, carbon to nitrogen ratio and lignin to nitrogen ratio) (Silver and Miya 2001; de Neiff et al. 2006; Bontti et al. 2009), but also on the microbial environment (Singhal et al. 1992; Gamage and Asaeda 2005), and on physical processes (temperature, rainfall, water current, wind, grazing events) (Singhal et al. 1992).

Decomposition rates are highly variable and can differ for flooded and non-flooded conditions. Junk and Furch 1991 found that loss of dry weight was lower in terrestrial conditions compared to aquatic conditions, with a 30 % and 75 % respective decrease of dry weight for *Sphenoclea zeylanica* in two weeks.

Considering the main difference in flooded and terrestrial conditions, removal of dead mass from the plant system was differentiated for these two phases, and was written as:

$$L_{lit} = l_k \cdot B_{ad} \tag{22}$$

where l_k is the litter and decomposition coefficient during the flooded, l_F , or non flooded, l_{NF} , phases. In flooded conditions, 92 % - 98 % of the dry mass of the water hyacinth *Eichhornia crassipes* (Mart.) Solms. was removed in 61 days (Gamage and Asaeda 2005). For *Echinochloa polystachya* (H.B.K.) Hitchcock, 20 % of the initial dry biomass was removed after one week under water, with the loss reaching 50 % after six weeks (Furch and Junk 1992). A first estimation of l_F was calculated considering the decomposition rate of 20 % of *Echinochloa polystachya* (H.B.K.) Hitchcock during the initial flooded phase, in the same way as for the senescence coefficient ($l_F = 0.02$). l_{NF} was taken as 10 % of this value, as decomposition rates have been found to be higher for leaves compared to stems under flooded conditions (Esteves and Barbieri 1983).

5.2.2.8 *Removal of dry matter through grazing or clipping events*

Grasslands are used by wild or domestic herbivores to graze. Through this action, part of the aerial biomass is removed from the plant system. In some cases, the nutrient stocks are partly restituted to the grassland through the excrements. Grazers, by trampling, can also alter growth processes. Growth can also be modified by humans who cut the aboveground biomass to produce hay and sometimes by researchers through clipping events which are commonly used as a surrogate to grazing.

These actions, leading to a decrease of aboveground biomass, are modelled through the following equation:

$$G_k = \frac{B_{k,r}}{d} \tag{23}$$

where $B_{k,r}$ ($gDM \cdot m^{-2}$) is the biomass removed from each compartment during a specified period, d (day). For the clippings undertaken in this study, all aboveground biomass over 1 cm high was removed. It is assumed that at each cutting event, the above-ground biomass is reduced to $B_{l,min}$, $B_{s,min}$ and $B_{ad,min}$, leading to (d=1):

$$G_k = B_k - B_{k,min} \tag{24}$$

$B_{k,min}$ is important as it determines the LAI after each sampling.

5.2.3 *Soil water balance*

5.2.3.1 *Tipping bucket model*

As seen in many of the previous equations, the quantity of water available in the soil for the plant is a crucial factor influencing many plant processes. To take this into account, a daily soil water budget, in which the effect of floods, irrigation, rainfall and evapotranspiration are modelled, was coupled to the plant model.

The soil was defined by it's number of layers (two), and each horizon is characterized by it's water content θ ($m^3.m^{-3}$). When the grassland was flooded, the soil water content of each horizon was set to saturation, $\theta_{j,sat}$. It was considered that the soil was saturated in water for 10 days following a flood event. In a non-flooded situation, water penetrates the first layer at rain or irrigation events, then consecutively fills each layer to its field capacity. No rise of the water table into the root zone is considered here, considering the depth of the water table in the studied zone. When field capacity for one layer is reached, the remaining water percolates to the next layer. Water can also be lost through evaporation or be transpired from the plant.

The daily variation in soil water content in the different horizons can be expressed as:

$$\frac{d\theta_1}{dt} = \frac{R_1 + Ir_1 - E_1 - T_1 - D_1}{z_1} \tag{25}$$

for the first layer, or as:

$$\frac{d\theta_j}{dt} = \frac{D_{j-1} - D_j - Tj}{z_j - z_{j-1}} \tag{26}$$

for the other layers, where R, Ir, E, D are respectively daily rainfall, irrigation, evapotranspiration and drainage per unit area at a daily time step ($mm \cdot day^{-1}$) and z is the thickness of the horizon (mm).

5.2.3.2 *Inputs*

Daily rainfall and irrigation are input variables.

5.2.3.3 *Outputs*

Drainage occurs as water percolates from one horizon to the next and mainly depends on soil texture. Drainage occurs when the soil water content is above the soil's field capacity. It increases linearly with the soil water content to reach a maximal rate when the soil is at saturation:

$$\begin{cases} \theta_j \leq \theta_{fc,j}, & D_j = 0 \\ \theta_{fc,j} < \theta_j \leq \theta_{sat,j}, & D_j = D_{max,j} \cdot \frac{\theta - \theta_{fc}}{\theta_{sat} - \theta_{fc}} \\ \theta_{sat,j} < \theta_j, & D_j = D_{max,j} \end{cases} \tag{27}$$

where $D_{max,j}$ is the maximal drainage rate. It can be considered as the soil hydraulic conductivity at saturation. Casenave and Valentin (1989) give hydraulic conductivity values between 0 $m \cdot s^{-1}$ et $0.556 \cdot 10^{-6} m \cdot s^{-1}$. Clapp and Hornberger (1978) give a value of $1.28 \cdot 10^{-4}$ $cm \cdot s^{-1}$ for clay soils.

Water can be lost to the soil system as water evaporates from the soils surface or is transpired by the plant. Canopy evapotranspiration, E_c, and soil evaporation, E_s, can be calculated using the Penman-Monteith equation (Monteith 1965):

$$T = f_{vg} \cdot \frac{sA + \rho c_p VPD / r_{ac}}{\lambda[s + \gamma(1 + r_{sc}/r_{ac})]} \tag{28}$$

$$E = f_s \cdot \frac{sA + \rho c_p VPD / r_{as}}{\lambda[s + \gamma(1 + r_{ss}/r_{as})]} \tag{29}$$

where f_{vg} and f_s are respectively the cover fraction of green vegetation and bare soil such that $f_{vg} + f_d = 1$, A is the available energy

$(MJ \cdot m^{-2} \cdot day^{-1})$, VPD is the vapor pressure deficit of the air at a reference height above the surface (kPa), s is the slope of the saturated vapour pressure curve at the temperature of the air $(kPa \cdot °C^{-1})$, c_p is the specific heat of air at constant pressure, ρ is the air density , γ is the psychometric constant $(kPa \cdot °C^{-1})$, λ is the latent heat of vaporization $(MJ \cdot kg^{-1})$, r_{sc}, r_{ss}, r_{ac}, r_{as} are respectively the resistances $(m \cdot day^{-1})$ for a full canopy and a bare soil and the corresponding aerodynamic resistances.

The fraction of soil covered by vegetation, f_{vg} , can be calculated as:

$$f_{vg,t} = (1 - \exp(-k_1 \cdot LAI) \tag{30}$$

where k_1 is a coefficient (-).

Transpiration is distributed within each soil horizon depending on the root distribution, and on the soil water content in each horizon, according to:

$$T_j = \nu_r \cdot T \cdot \frac{\theta_1}{\theta_2} \tag{31}$$

where ϑ_r is the ratio of root volume found within the the considered layer j to the total root volume. Transpiration from one horizon therefore increases when roots are well distributed within the horizon and when the soil water content of the horizon is higher compared to the other horizons. Relative root distribution is considered constant, even though root biomass varies. If transpiration from one layer was higher than its maximal potential value (i.e. the quantity of water available within the horizon), transpiration was set to this maximal value and the remaining transpiration distributed in the other horizons.

5.2.4 *Climate and resistance models*

5.2.4.1 *Climate variables*

The climate variables necessary to calculate evapotranspiration are summarized here below, and calculated following the FAO recommendations (Allen et al. 1998).

The net radiation is calculated as the difference between the net shortwave radiation and the long-wave radiation.

$$I_n = I_{ns} - I_{nl} \tag{32}$$

The net shortwave radiation is calculated from the incoming solar radiation and the surface albedo:

$$I_{ns} = I_s(1 - \alpha) \tag{33}$$

The net long-wave radiation is calculated as:

$$I_{nl} = (a_c \cdot \frac{I}{I_0} + b_c) \cdot \sigma \cdot (a_e + b_e\sqrt{e}) \cdot \frac{(T_{max} + 273.2)^4 + (T_{min} + 273.2)^4}{2} \tag{34}$$

where I is the incoming solar radiation, I_0 the incoming clear sky radiation , a_e and b_e are regression coefficients, e is the actual vapour pressure, a_c and b_c are the adjustment coefficients for clear skies, σ is the Stephan-Boltzman constant and T_{max} and T_{min}, the maximum and minimum temperatures during the 24-hour period (°C). The clear sky radiation is calculated from monthly values of extraterrestrial radiation, Ia (Allen et al. 1998):

$$I_0 = 0.75 \cdot Ia \tag{35}$$

A is the difference between net radiation, I_n, and soil heat flux, G:

$$A = I_n - G \tag{36}$$

G is neglected on a daily basis as the magnitude of soil heat flux of the day is relatively small. Water vapour deficit, VPD, is calculated as the difference between water vapour pressure at saturation and actual water vapour pressure (kPa). The slope of the saturated vapour curve, s, and the actual vapour pressure are calculated following the FAO standards.

5.2.4.2 *Resistance models*

The canopy resistance to water vapor diffusion, r_{sc} , is calculated from the stomatal resistance, r_s, assuming an inversely proportional relation to LAI.

$$r_{sc} = \frac{r_s}{LAI} \tag{37}$$

r_s is calculated using the Jarvis model (Jarvis 1976) where the resistance increases with a water stress factor:

$$r_s = r_{smin} \cdot f_2(\theta) \tag{38}$$

A stress factor was calculated for each horizon as:

$$f_{2,j}(\theta) = \frac{\theta_{fc} - \theta_{wp}}{\theta - \theta_{wp}} \tag{39}$$

The minimal value of the two layers was taken as the global stress factor for the soil. Stress is null when there is a flood or when at least one horizon has a water content exceeding its field capacity.

r_{as} and r_{ac} are set to constants. The soil surface resistance, r_{ss}, depends on the soil water content of the first layer (Camillo and Gurney 1986):

Irrigation ($mm \cdot day^{-1}$)	Duration between cuttings (days)*		
	16	32	64
0	R_0G_1	R_0G_2	R_0G_3
2.5	R_1G_1	R_1G_2	R_1G_3
7.5	R_2G_1	R_2G_2	R_2G_3

Table 6: Summary of the irrigation and cutting treatments and their abbreviations in the text. * cutting was done after 37 days when the floods occurred.

$$r_{ss} = a_r \cdot (\theta_{sat} - \theta_1) - b_r \tag{40}$$

The minimal soil surface resistance value was set to zero.

5.3 SITE DESCRIPTION

5.3.1 *The Tana River Delta grasslands*

The central floodplains of Tana River Delta (TRD) form a grassland area of over 200 km^2, mainly composed of *Echinochloa stagnina* (Retz) P. Beauv., *Paspalidium obtusifolium* (Delile) N.D. Simpson and *Vossia cuspidata (Roxb.) Griff.*. *Echinochloa stagnina* (Retz) P. Beauv. is the dominant species. The grasslands are located on the deep, dark brown and cracking vertisols of the floodplain (Kenya 1984a; Kenya 1984b). They are intensively used by the Orma and other subsistence pastoralists as grazing grounds (Leauthaud 2009, Leauthaud et al. 2013a). They have been extensively described in **Chapter 4**.

5.3.2 *The experimental site*

The model was validated against data obtained from the TRD from the 4th of December 2010 to the 1st of March 2012 at an experimental field site (2°18'51.08"S, 40°12'39.84"E), located near the village of Onkolde. The experiment consisted in sampling aboveground dry biomass under different irrigation and cutting scenarios (Table 6) and has been previously described (**Chapter 4**). For modelling purposes, additional data were obtained, and are described in this section.

The soil is characterized by a high clay content (63-75 % for the different horizons) (Table 7) and is of the vertisol type. Soil field capacity and permanent wilting point were calculated using the Richard's method on soil aggregates. Soils were slightly acidic, and nitrogen and phosphate (Olsen method) content were around 16-27 mg.kg^{-1} and 8-16 %. Soil organic carbon ranged from 6-11 %. Bulk dry density varied from 0.95 to 1.08. These low values are probably due to the swelling of the clays when the density was measured during the rainy season and possibly a high concentration of dead organic matter in the first horizon. Initial soil water content was determined by sampling soil and drying in an oven at 105°C for 24 hours. Massic soil water content was calculated for the first (n=4) and second soil layer (n=12) and converted to volumetric soil water content.

Because of the similar hydrological characteristics of the second and third horizons, the soil was modelled as a superposition of two horizons: a superficial horizon where evaporation and transpiration take place (0-5 cm in depth) and a second horizon (5-65 cm) where only transpiration takes place. As the rooting system was restricted to the first 65 cm of soil, all water draining through the second horizon at 65 cm was considered lost to the soil-plant-atmosphere system and gained the underground water compartment.

Relationships relating LAI to leaf dry matter and LAI to the fraction of soil covered by vegetation, f_{vg}, were also determined as they were required for the model. Hemispherical photos (n=8 for each determination) were taken for various aboveground dry biomasses and processed in CanEye 6.3 to obtain LAI and f_{vg}. Considering that under 200 g, aboveground dry biomass is mainly constituted of leaves, total biomasses not exceeding 200 g (n=20) and data where biomass had been separated into leaf biomass (n=2) were used to model the LAI-leaf dry biomass relationship. For the LAI-f_{vg} relationship, the exponential relationship in Equation 30 was tested and the corresponding coefficient determined.

Finally, initial root biomass was measured by removing whole plants (n=4) and measuring the root biomass (0.51$\pm$ 0.22 g). Considering a 20 % loss due to the extraction process, and a plant density of 42$\pm$10 (n=43, Leauthaud, unpublished data), leads to an initial root biomass estimated at 25 $g \cdot m^{-2}$.

5.3.3 *Climate*

Daily climate data were measured with a Campbell Scientific Ltd. (CSI) automatic weather station installed at the Tana Delta Irrigation Project (TDIP, 2°316′22.07″S, 40°11′00.55″E) from the 18th of August 2011 onwards (Figure 24). Meteorological data included rainfall (SBS500, CSI), air temperature and relative humidity (HMP155A, CSI), wind speed (WINDSONIC1 GILL ULTRASONIC anenometer, CSI) and radiation (CS300 APOGEE PYR-P pyranometer, CSI). All, except rainfall, were measured at 2 m above ground level. Additional rainfall measurements were conducted on a daily basis at the experimental site.

Climate data were not available for the whole duration of the experiment. As temperature, humidity and wind are relatively homogeneous in the zone from one year to another, missing data were filled in by that of the same Julian date from the available record.

Table 7: Pedological characteristics of the experimental site (measured on 26-31/05/2011). Soil organic carbon was determined by the wet oxidation method (Walkley and Black procedure) and the soil nitrogen by the colorimetric method. EC: electrical conductivity, P: soil phosphorous, N: soil nitrogen, C: soil carbon

Horizon (cm)	clay (%)	silt (%)	Dry bulk density	θ_{fc} (%)	θ_{wp} (%)	pH	EC (H_2O 1:2.5) ($\mu S.cm^{-1}$)	P ($mg.kg^{-1}$)	N (%)	C (%)
0-5	67	19	0.99±0.02	48	38	6.82	923	27.53	12.39	10.91
5-25	63	25	1.08±0.04	46	35	6.81	639	20.25	16.26	6.93
25-65	71	15	0.95±0.12	48	34	6.16	516	16.10	8.22	8.55
65-90	75					5.79	756			

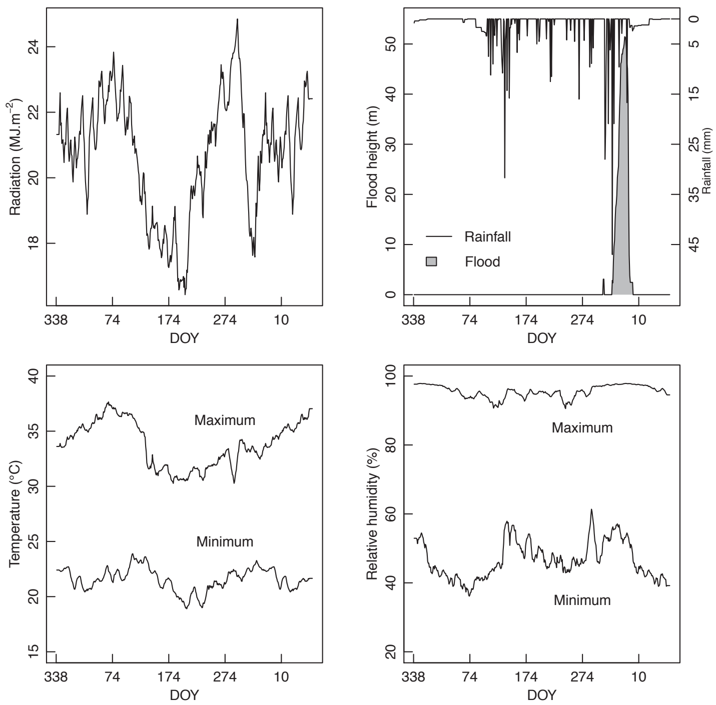


Figure 24: Measured and interpolated daily radiation, rainfall and flood height, minimal and maximal air temperature and minimal and maximal air humidity data from the 4^{th} of December 2010 to the 1^{st} of March 2012 at the experimental field site.

Because heavy rainfalls decrease daily radiation, but respective missing data were not concurrent, a minimum daily radiation was set to 15 $MJ \cdot day^{-1}$ (26 data points concerned), and a 10-day moving average of radiation, temperature and air humidity were calculated to smooth out day-to-day large variations. Rainfall has a high spatial heterogeneity. As daily rainfall between the two sites was not well correlated (cor=0.37) and the daily floating averages over 30 days were well correlated (cor=0.82), the latter, downscaled to daily values, were used to fill in missing rainfall data at the experimental site.

Mean maximal and minimal temperatures, maximal and minimal relative humidity and daily radiation measured during the experiment were respectively 33.8°C, 21.5°C, 95.5 %, 46.6 % and 20.5 MJ. Two rainy seasons, during which floods can occur, can be distinguished, spanning from April to June and from November to December. Total rainfall throughout the experiment (interpolated data) was 554 mm. A flood event occurred at the experimental site during the short rainy season of 2011 for 2 and 37 days (5-6/11/2011 and 21/11/2011-27/12/2011) during which daily water height measurements were taken. Mean and maximum height of water were respectively 27 cm and 51 cm.

5.3.4 *Constraints*

The difficulty to access the experimental site and the frequent disappearance of equipment made it impossible to monitor soil moisture content on a regular basis at the field site. Due to this constraint, we opted for a simplified soil water model. The model was also constructed so that it could be used,with scarce climatic data (see section **Climate variables** where net short-wave, long-wave radiation, and other internal variables are calculated using the FAO recommendations).

5.4 ANALYSIS OF THE MODEL: METHODOLOGY

Vegetation models typically have many parameters (like STICS which has over 200 parameters, Brisson et al. 2003). This is driven by the necessity to incorporate enough complexity within the models to reproduce key biological processes that are thought to occur. Some of the parameters are already known from measurements done throughout the experiment or within the same grassland while others may have been already estimated in other experiments or model runs. Others, on the contrary, may have been newly defined, may depend on the experimental setup (e.g. initial conditions) or may be poorly known.

A correct estimation of parameters is required in order to provide good simulations of the grassland growth cycle. Two approaches exist: a frequentist approach, in which an optimal set of parameters that answers a cost function is sought after, and the Bayesian approach. In the latter, the parameters are random parameters with probability distributions. Prior information is used to define the prior probability distribution and the new observed data is used to update the distribution function (the posterior distribution). An advantage is that it better incorporates the uncertainty linked to parameter estimation.

Both methods can lead to inaccurate estimations and poor model predictions, due in particular, to over-parametrisation (Wallach 2006). Additionally, the algorithms can fail to converge due to the large number of parameters. Finally, it can be impossible to estimate the whole set of parameters as they can be unidentifiable due to the structure of the model equations. Due to these reasons, a common practice is to select a subset of parameters to estimate and set the others to predefined values.

The model presented here is a complex model with 45 internal parameters (see **Appendix C** for more details). Estimation of the most sensitive parameters by a frequentist approach (Ordinary Least Squares and Weighted Least Squares, with a gradient or simplex method) was not conclusive. To estimate the parameters, we first did a sensitivity analysis to select a limited number of parameters to estimate and fixed the others to likely values. Then, we estimated the remaining parameters using the bayesian approach.

5.4.1 *Choice of parameters to estimate*

The goal of this model is to approximate the aboveground dry biomass of floodplain grasslands. Furthermore, the available data is mainly aboveground dry biomass measurements. The subset of parameters to calibrate was therefore chosen on the basis of their importance in providing correct estimates of aboveground dry biomasses. In a first step, a sensitivity analysis was performed to determine which parameters most influenced the output variables. This initial parameter set was then restrained to avoid identifiability problems and decrease computational time. Parameters that have been well studied in previous literature or which have been determined for the experimental site were fixed. Accordingly, we:

1. performed a sensitivity analysis. Many types of sensitivity analysis exist (for a review, see Hamby 1994). As the objective here was to screen for the most influential parameters on output variables among a large number of parameters, the method of Morris (Morris 1991) was chosen. The latter consists in defining the elementary effect of each parameter for a series of scenarios. The resulting distribution of the elementary effects are then characterized by its mean and variance. A high mean indicates the parameter has a strong influence on the model's outputs, while a high variance indicates important interactions with another factor or non-linearity. Morris' method allows the investigation of the whole uncertainty ranges of the input factors (Wallach 2006) while taking into account the possible interactions between parameter values. As the main output of the model are dry biomasses, the influence of different parameter values on simulated dry biomasses were investigated. The range of values to test derived from a literature review. When only one value was found, the range was determined by decreasing or increasing the parameter's value by 20 %. Sensitivity analysis was conducted on the total cumulated biomass for each treatment. However, some parameters can largely influence plant growth during a specific period (e.g. flooded), a specific compartment (e.g. leaf) or a specific treatment (e.g., R_0G_1) and this first analysis does not capture these more precise influences. As we were interesting in correctly estimating biomasses for each period, each compartment and each treatment, the analysis was refined to capture the influence of the parameters that cause variability on the mean cumulated biomass for the three flood status (non flooded, NF, flooded, F and after the flood, AF) and for the stem and leaf compartments (S and L). In total, the influence

of all parameters on 81 output variables (cumulated standing biomass, cumulated standing leaf biomass, cumulated standing stem biomass, and the factorial combination of NF, F, AF by S and L, for each of the nine treatments) were tested by performing the sensitivity analysis on these 81 output variables.

2. restrained the number of parameters to estimate. The number of times each parameter was among the ten most sensitive parameters for each output variable was counted. A high count reflects that the parameter influences most of the output variables of interest. Through a trial and error process, a number of parameters (five) were selected for parameterization. Sets of two and three parameters were tested for parameterization but they yielded RMSE values slightly higher than that of five parameters. Selecting eight parameters did not improve the RMSE value either, so that five parameters seemed like a reasonable number of parameters to calibrate.

3. set the remaining parameters to their most likely values based on literature values. Measurements of LAI and stem and leaf biomass as well as the soil hydraulic properties of the experimental site were used to fix some of the parameters.

5.4.2 *Estimation of the remaining parameters*

The Generalized Likelihood Uncertainty Estimation (GLUE, Beven and Binley 1992) method was used to estimate the set of five parameters. According to the methodology, we:

1. Defined the prior ranges of parameter values and generated random and independent sets of parameters. The parameters to calibrate, their prior distribution and ranges are defined in Table 35. All parameters were given a uniform prior distribution.

2. Defined the likelihood measure used to select the acceptable parameter sets as the Root Mean Squared Error (RMSE), defined as:

$$RMSE = \sqrt{\frac{1}{N} \cdot \sum (BM_{tot}^{OBS} - BM_{tot}^{SIM})^2} \qquad (41)$$

where BM_{tot}^{OBS} and BM_{tot}^{SIM} are the observed and simulated aboveground total dry biomasses and N the number of data points. The threshold of acceptability in retaining a parameter set was defined as $RMSE < 95$.

3. Ran the plant model with each parameter set (20 000 sets). Nine different situations with ranging water availability and cutting frequency were available to test the model. Five diverse situations were used to calibrate (R_0G_1, R_0G_3 , R_1G_2 , R_2G_1 , R_2G_3)

Quality indicators	Abbreviation	Equation
Absolute Mean Error	AME	$max \mid BM_{tot}^{OBS} - BM_{tot}^{SIM} \mid$
Mean Absolute Error	MAE	$\frac{1}{N} \sum \mid BM_{tot}^{OBS} - BM_{tot}^{SIM} \mid$
Efficiency	-	$1 - \frac{\sum(BM_{tot}^{OBS} - BM_{tot}^{SIM})^2}{\sum(BM_{tot}^{OBS} - \bar{BM}_{tot}^{OBS})^2}$
Root Mean Square Error	RMSE	$\sqrt{\frac{1}{N} \cdot \sum(BM_{tot}^{OBS} - BM_{tot}^{SIM})^2}$

Table 8: Definition of the cost functions used to estimate the quality of the final model output. $B\bar{M}$ is the mean observed aboveground dry biomass.

the model and the four remaining situations were used to validate the model. A RMSE for the calibration treatments ($RMSE_c$) and for the validation treatments ($RMSE_v$) were calculated.

4. Calculated the prediction limits of the model (Beven and Binley 1992). The uncertainty range was defined by the 90^{th} and 10^{th} prediction quantiles obtained from the likelihood-weighted model. Indeed, because of the existence of multiple parameter sets, each parameter set gives a percentile for every time-step. In doing so, all the different sets contribute to define the uncertainty range and the ensemble prediction.

5.4.3 *Model validation*

The final output of the model is a range of values, due to the existence of multiple parameter sets. The global quality of the model was assessed by calculating general indicators for which the relative errors take into account the uncertainty range of the model. The relative errors have been defined as the difference between the measured value and the outer envelope boundary for the modelled outputs. When the measured point is within the modelled envelope, the relative error is equal to zero. The cost functions used were the Absolute Maximum Error (AME), the Mean Average Error (MAE), the model efficiency and RMSE, as defined by Dawson (Dawson et al. 2007) (Table 8).

5.5 RESULTS

5.5.1 *Experimental determination of key parameters*

The linear regression between the aboveground dry biomass and the LAI was significant (p-value<1 %, $R^2 = 0.87$, Figure 25), leading to a SLA of 0.0248. Similarly, the coefficient k_1 determining the LAI-f_{gv} relationship (Equation 30) was determined using a linear model (p-value < 1 %, $R^2 = 0.93$, Figure 26), with $k_1 = 0.496$. Soil characteristics are presented in Table 7. The leaf-stem allometry in non-flooded

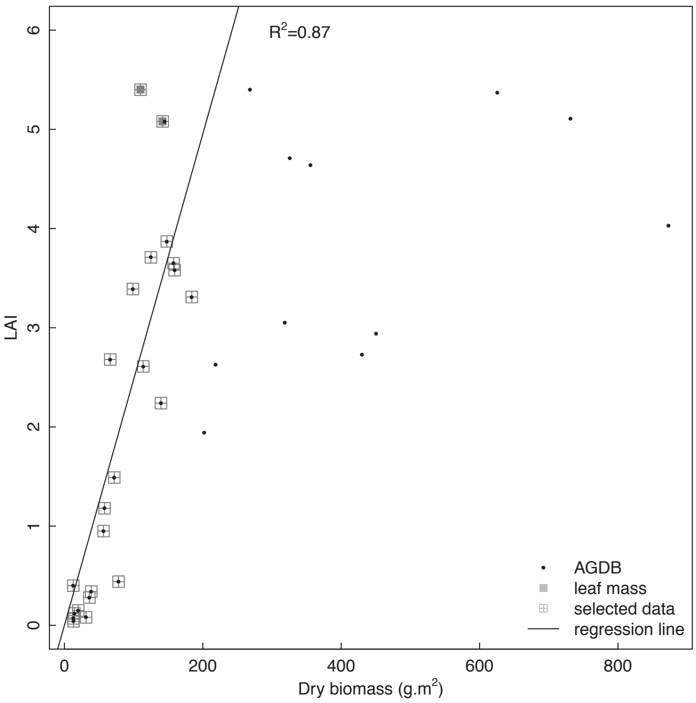


Figure 25: LAI as a function of aboveground dry biomass (AGDB). AGDB not exceeding 200 g and two data points where leaf biomass was available were used to perform the regression analysis ("selected data"). See methodology for more details.

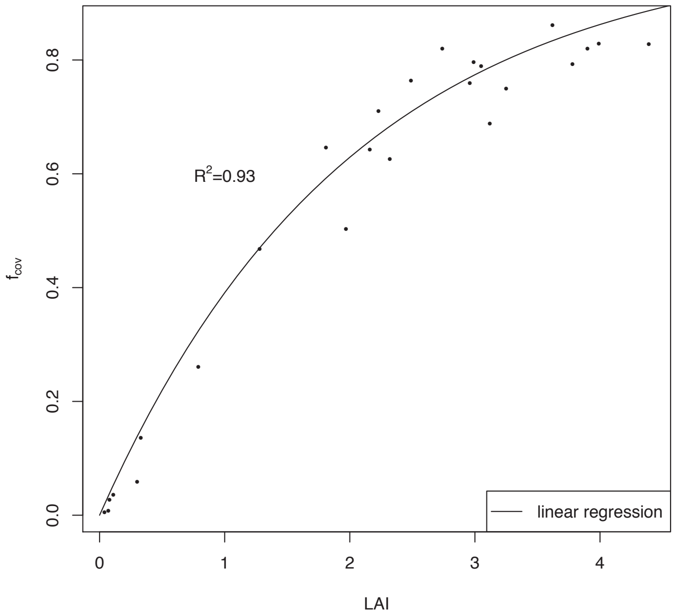
conditions has previously been determined (**Chapter 4**). with 52 % of the above ground dry biomass being leaves.

5.5.2 *Analysis of the model: results*

5.5.2.1 *Sensitivity analysis*

The parameters and the range of values which were tested during the sensitivity analysis are presented in **Appendix C** (Tables 35 and 37). 25 out the the 45 parameters appeared at least once (Table 9) within the ten most influential parameters affecting the output dry biomass variables. Out of them, the first 17 parameters affected several of the output variables. m and $r_{r:s}$ were the most sensitive. E_{max}, a_{Lmax} and s_{IF} appeared lower in the ranking because they only affected the output variables when a flooded event was included. Soil characteristics as well as the remaining biomasses after cutting were sensitive parameters. As expected, parameters affecting water transport (soil and root characteristics) as well as NPP (respiration, parameters for conversion efficiency) also strongly influenced the studied output variables. By setting parameters according the literature and the measured characteristics, five parameters were calibrated (Table 9). The calibrated maximal conversion efficiency coefficient is higher

Figure 26: Vegetation cover as a function of LAI.



than that suggested by Piedade et al. (1991), but does not exceed the maximal theoretical value of 6.6 $gDM \cdot MJ^{-1}$ (Long et al. 2006).

5.5.2.2 *Calibration and validation*

101 sets of parameters had a RMSE < 95. Mean $RMSE_c$ and $RMSE_v$ considering each set of parameters were respectively 93±1 $gDM \cdot m^{-2}$ and 102±1 $gDM \cdot m^{-2}$. The posterior mean value for the calibrated parameters are presented in Table 9.

By integrating the fact that all parameter sets are equifinal, and hence the final model is defined by the 10^{th} and 90^{th} percentile envelope (the model does not make any error for each data point within this envelope), the cost functions improve (Table 10). RMSE for the whole set of parameters was 10.3 $gDM \cdot m^{-2}$, and the MAE was 0.9 $gDM \cdot m^{-2}$. The efficiency of the model was 0.92 while AME is 293 $gDM \cdot m^{-2}$.

5.5.3 *Mechanisms of the model*

5.5.3.1 *Biomasses and carbon budget*

The simulated aboveground dry biomass (AGDB) are plotted against the measured data in Figure 27. Cutting frequency ordinates the biomass ranges, with frequent (inversely not frequent) cuttings resulting in low (high) AGDB. Irrigation and floods also favour high

Parameter	Count	Values	Parameter	Count	Values
m_R	81		ε_{Emax}	19	5.3 (4.9-5.4)
$r_{r:s}$	81	1.4 (0.90-2.25)	$B_{min,l,R2}$	19	
β	76	4.2 (3.49-4.5)	a_{Lmax}	18	0.65 (0.56-0.71)
θ_{fc}	66		slF	18	
α	60		$teta_{pf,2}$	8	
k_1	59		$teta_{cc,2}$	7	
SLA	56		$s_{l,NF}$	7	
Y_G	56		$s_{s,NF}$	6	
θ_{wp}	45		$Dr_{max,2}$	2	
a_l	43		$s_{r,NF}$	2	
ϑ_r	41	0.38 (0.3-0.51)	$Dr_{max,1}$	1	
$B_{min,l,R0}$	19		r_{as}	1	
$B_{min,l,R1}$	19				

Table 9: Key parameters from the sensitivity analysis. Count: number of times the parameter appeared in the 10 most sensitive parameters for each output variable. Values: mean, minimal and maximal (in brackets) value for the parameters that were adjusted during calibration. The values for all the other parameters are given in **Appendix C** (Tables 35 and 37).

AME ($gDM \cdot m^{-2}$)	MAE ($gDM \cdot m^{-2}$)	RMSE ($gDM \cdot m^{-2}$)	Efficiency (-)
293	0.9	10.3	0.92

Table 10: Value of the cost functions for the selected model.

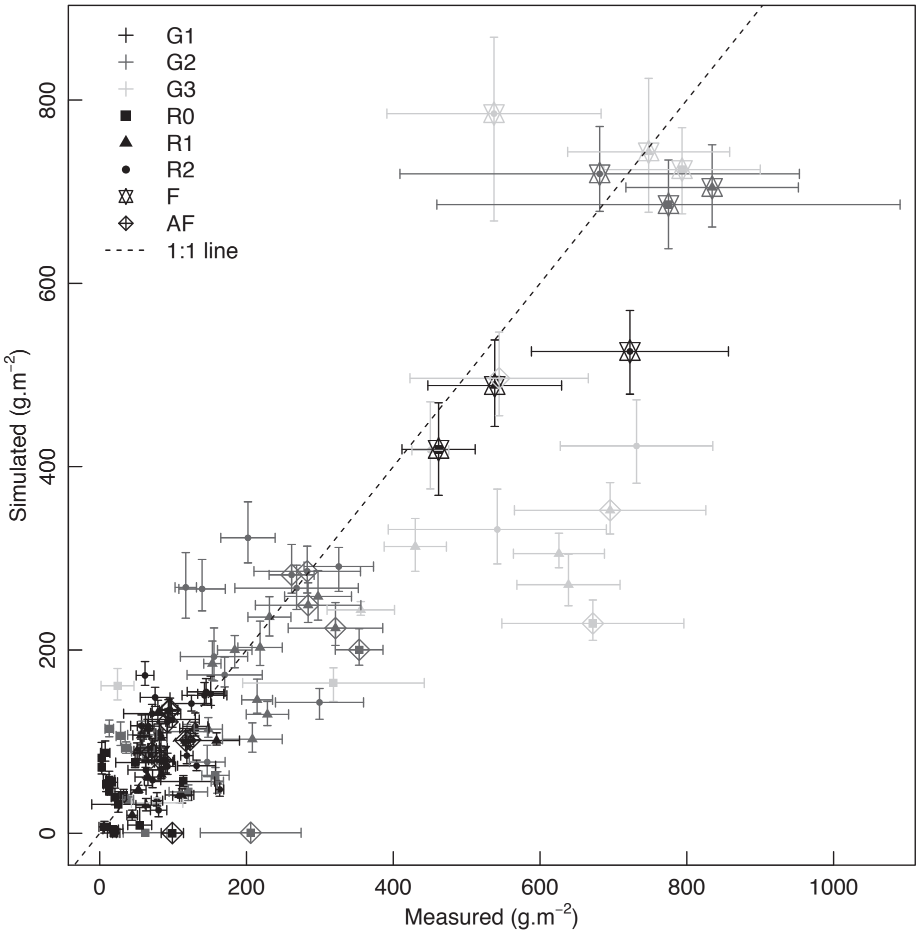


Figure 27: Comparison between simulated and measured aboveground dry biomass (AGDB), differentiated by the irrigation and cutting treatments and by their flood status. The vertical confidence intervals represent the 10^{th} and 90^{th} percentiles and the horizontal confidence intervals are given at ± 1 standard deviation.

AGDBM. Peak standing mean experimental and median simulated biomasses were 834 $gDM \cdot m^{-2}$ and 930 $gDM \cdot m^{-2}$ respectively. The global fit between the simulated and observed values is correct, although there is a slight underestimation for non flooded AGDB at high biomass values. The uncertainty related to both the simulated and the measured values increase with biomass (Figure 27).

A comparison between the simulated LAI and the measured LAI is given in Figure 28. Despite the large variability of the measurements, model prediction for the non-flooded canopy is in relative good agreement with the experimental data. The LAI for the flooded period is under-estimated by the model at high LAI values.

The model reproduces the seasonal growth patterns of the floodplain grasslands (Figure 29) as well as the cumulated biomasses (Figure 30). The fit between the simulated and observed data is better for frequent cuttings (i.e. low biomasses), with lower RMSE values

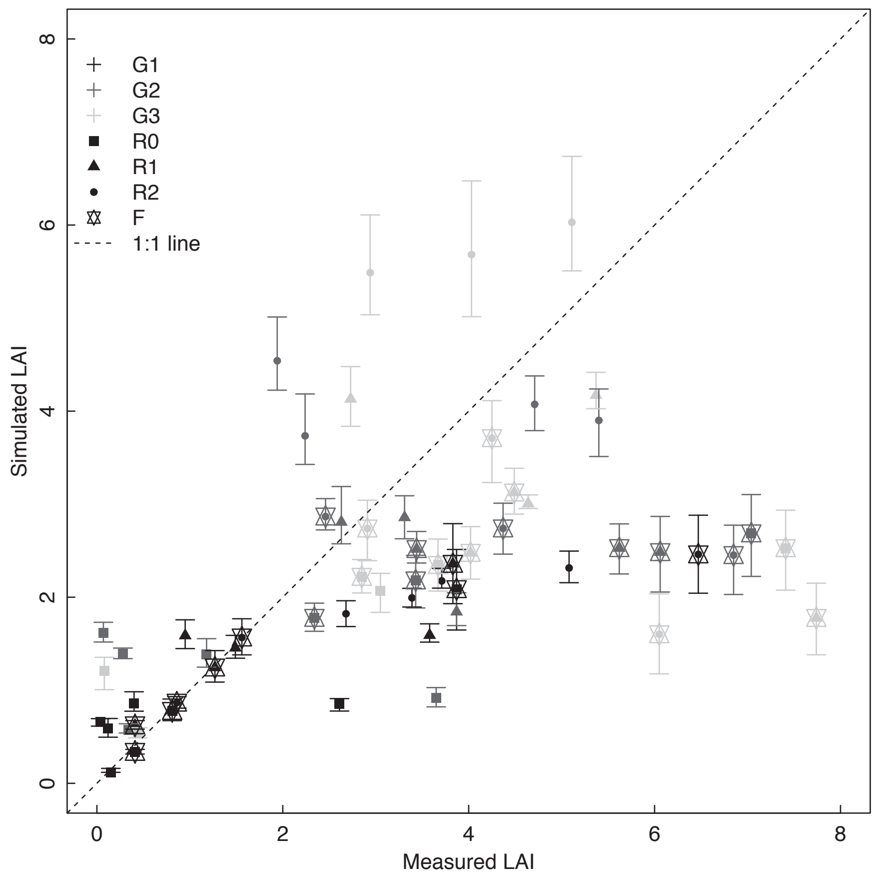


Figure 28: Comparison of simulated and measured LAI, differentiated by the irrigation and cutting treatments and by their flood status.. The vertical confidence intervals represent the 10^{th} and 90^{th} percentiles of the model.

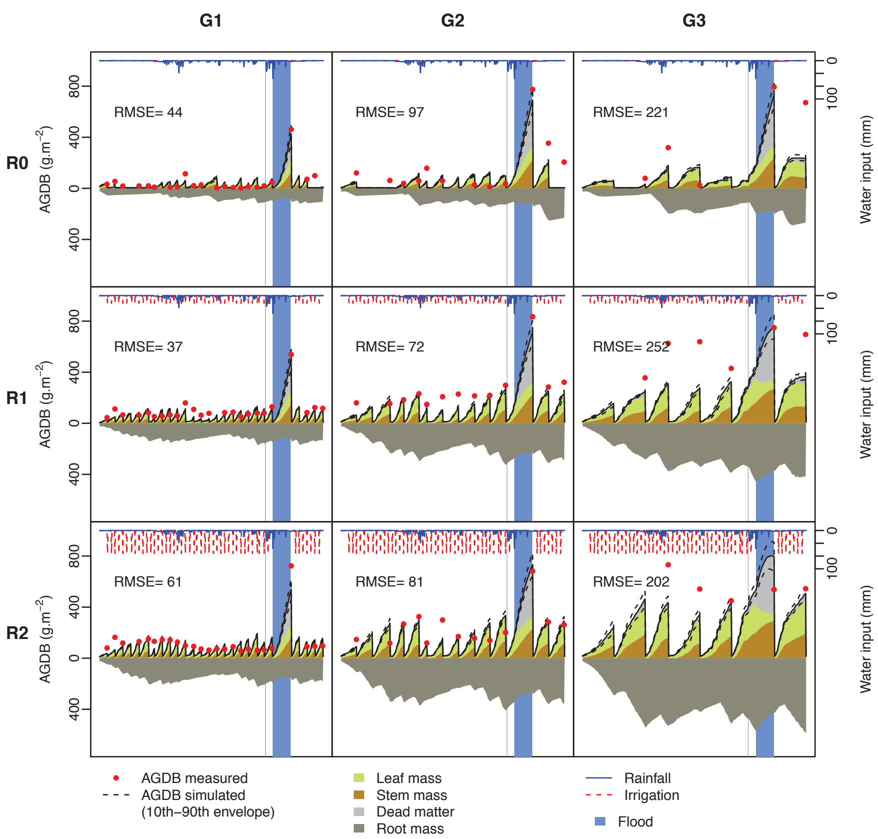
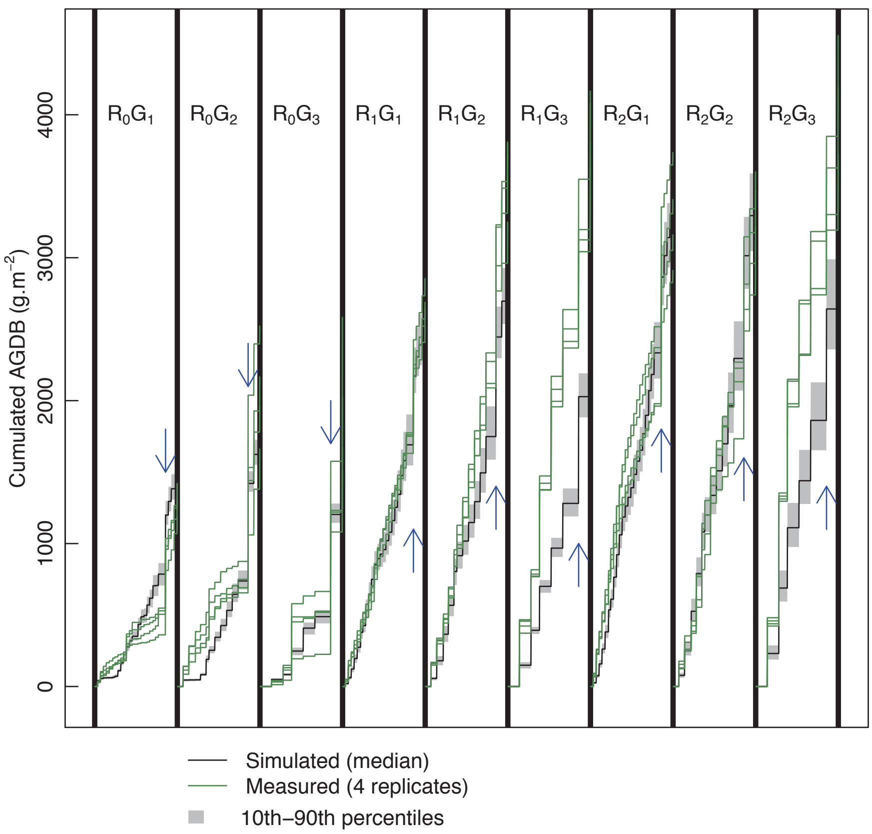


Figure 29: Simulated and observed plant biomass $gDM \cdot m^{-2}$ for each treatment. Rainfall, irrigation and the flooded period are depicted to differentiate the treatments and the dry and rainy seasons. Modelled standing biomass is divided into leaves, stems, root biomass and dead matter. The dotted lines represent the 10^{th} and 90^{th} percentiles values for the total standing biomass of the model. RMSE is calculated here between the experimental data and the median values of the model.

compared to $G2$ and $G3$. The rapid growth phase during the flooded phase is also reproduced. The cumulated biomass simulated is close to the observed values for each treatment. However, compensation between under-estimation and over-estimation can occur, as for R_0G1 and R_0G3 where the model overestimated standing biomass in the first dry season but inversely under-estimated growth rates during the floods.

As an illustration, the average effect of cutting, irrigation and flooded situations are illustrated in Figure 29. Daily growth rates increase with irrigation and slightly increase as cutting frequency decreases. Floods induce high growth rates during and after the floods. Maximum median and 90^{th} percentile modelled daily growth values attained 29 $gDM \cdot m^{-2} \cdot day^{-1}$ and 32 $gDM \cdot m^{-2} \cdot day^{-1}$.

Figure 30: Cumulated simulated and experimental aboveground dry biomass (AGDB) for the different treatments. The arrows indicate the cutting event that occurred just after the floods. For each treatment, four measurements (in red) were available. The grey envelope represents the 10^{th} and 90^{th} percentiles of the model.



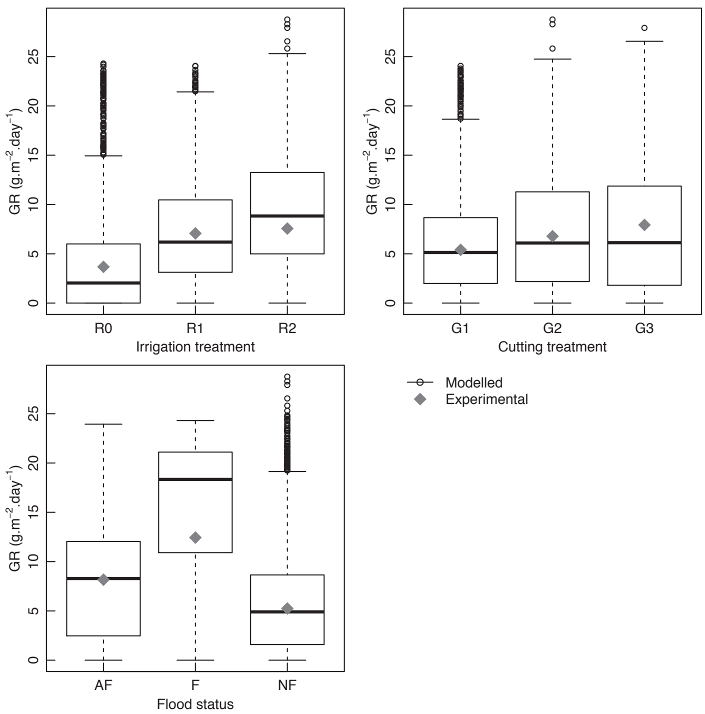


Figure 31: Modelled effect of irrigation, cutting and floods (median value of the model) on daily growth rates (GR). The boxplots represent the 1st to 3rd quartile values of the model. Comparison to the experimental data should be done with caution as the latter includes the senescence processes.

5.5.3.2 *Water budget*

Soil water availability and the components of the water budget for three treatments (R_0G_1, R_1G_1, R_2G_1) are depicted in Figure 32. Although there is no observed data to verify actual soil water content during the experiment, soil water content and the processes inducing its variation follow the generally admitted scheme.

Soil water content varies between its upper and lower ranges (θ_{sat} and θ_{wp}). Irrigation, rainfall events and floods induce an increase in soil water content. For irrigated situations, soil water content gradually increases at the beginning of the experiment as the soil water reservoir fills up. Irrigation successfully fills up the two soil horizons to their maximal value for both irrigation treatments. Irrigation at R_1 and R_2 levels therefore induce the same evaporation and transpiration rates from the soil and canopy, while R_2 causes a higher drainage to the lower horizons. After the floods, soil water content is at its maximal value then gradually declines. Soil evaporation occurs just after rainfall or irrigation events and rapidly stops as the first layer dries up. Maximal soil evaporation is about 6 mm. Evaporation is highly variable due to PET and soil water availability. Transpiration is also high for these events and increases or decreases as the canopy grows or is cut. Transpiration increases with plant development to reach a value of about 6 mm when fully irrigated.

5.6 DISCUSSION

5.6.1 *Model fit*

Despite large variability in simulated and modelled values, the model is able to reproduce the general trends observed in the experimental dataset. Although it is a rather simplified representation of the plant, the model still simulates the main mechanisms involved so that a realistic description of the processes is possible. A quantitative analysis of the growth processes of the current grasslands is available (**Chapter 4**). This model improves our knowledge of these grasslands by making more explicite the possible internal mechanisms that occur.

This model constitutes, to our knowledge, the first attempt to model the beneficial effects of floods on the primary productivity of a floodplain grassland. Compared to previous models for grasslands, the model presented in this study develops three new aspects to incorporate the effect of floods on growth processes. Firstly, allocation of photosynthates to the leaf and stem compartments depends on the flooding status (Figure 23 and Equation 16). Secondly, the increase in senescence during the flooded period is taken into account. Finally, litter decomposition also takes into account the effect of floods.

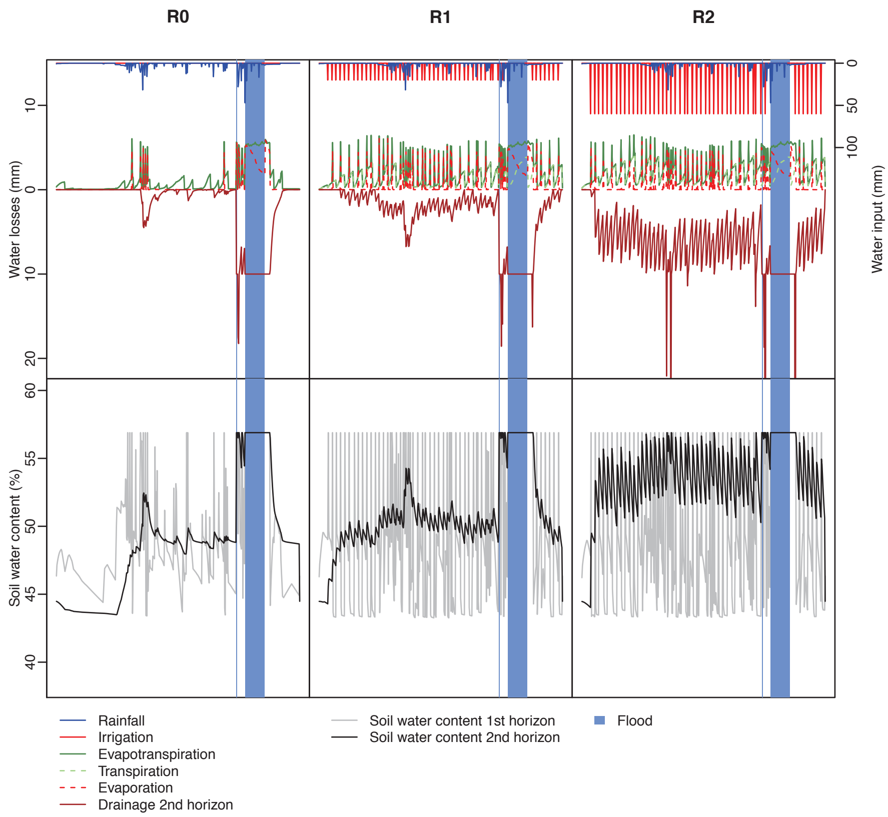


Figure 32: Daily simulated parameters of the water budget for R_0G_1, R_1G_1 and R_2G_1. Upper line: Daily rainfall, irrigation, evaporation, transpiration, evapotranspiration and water losses from the second horizon. Lower line: daily soil water content for each horizon.

5.6.1.1 *Actual limits of the model*

Firstly, we chose to do one general calibration for all treatments and flood status' in order to have a generic model capable of simulating a wide variety of situations. The drawback is that specific periods can be less well represented. It is the case for the post-flood period of the non-irrigated treatment, R_0 (see Figure 29). Indeed, the model under-estimates most data points for this situation, probably due to the soil drying up too quickly in the model. Secondly, no data exist for the root biomass. Simple assumptions were therefore made to represent the processes. Root biomass seems high for R_2G_3, probably due to a slightly over-estimated root to shoot ratio. Finally, the model has limits relative to its representation of the effect of floods. As the experimental data only had one flooded period on which to calibrate and validate the model, the uncertainty of the model is higher for this period. Furthermore, the mean effect of floods and other variables have been determined, but their extreme values have not been studied and can influence grassland structure. Other variables like the speed of water increase could be taken into account. Indeed, if the latter is too rapid (for example, during a dam release) it could lead to the death of large portions of the grassland.

Dams constructed before the 1990's decreased the frequency of the floods in the Lower Tana River Catchment (Maingi and Marsh 2002). The model was therefore calibrated during a period in which the floods were less frequent compared to past situations. In other floodplains, the return of regular floods after their disappearance led to higher productivities as the grasslands regenerated (Loth 2004). If inter-annual and long-term variability depend mainly on root development, then the model may adequately simulate these changes. On the contrary, if this regeneration affects processes not represented, the calibrated model could lead to an under-estimation of the primary productivity for a regularly flooded situation.

Another limit is that the floristic changes due to the variation of the hydrological regime are not taken into account. A change in vegetation composition would probably occur if the floods decrease drastically for long periods of time, with the spread of species that are not tolerant to floods, but more tolerant to drought.

5.6.1.2 *Further developments*

The model and its limitations point out the necessity to obtain more precise knowledge of these grasslands and of the processes inducing their growth.

FORMALISMS AND EXPERIMENTAL DATA

To improve the current model, a better knowledge of the internal processes is required. This can be done by acquiring additional empirical data and by improving the model formalisms.

Future data collection could include sampling of the rooting system and measurements of the soil water content. If physiological studies were undertaken, they could also give precise measurements of the most sensitive parameters.

Model formalisms could also be further developed. In particular, a water budget model better adapted to black cotton soils where large cracks form, and where water movement is probably limited when the soil water content reaches saturation, could be developed or the current model could be coupled with already existing hydrological models. To improve our understanding and modelling of the mechanisms occurring during the floods, a minimal growth rate to withstand the increasing height of floods, a possible transfer of reserves from the stem compartment or the inclusion of high senescence rates just after the floods could be considered.

Finally, the under estimation of non-flooded standing biomass at high biomass values could be caused by the simple formalisms used to represent respiration. Through the maintenance respiration, total respiration is partly proportional to biomass. As photosynthesis saturates at high biomass levels, this generates the highest growth rates at biomasses around 300-400 $gDM \cdot m^{-2}$. The experimental data suggests that optimal biomass values should be higher and are reached for the G_3 cutting frequency. The difference could be explained by lower respiration rates at high biomass values.

Calibration and validation design and parameter estimations

At the time being, the application of the results to larger areas needs to be undertaken with care. Indeed, the experimental data were collected on small quadrates at one experimental site with specific environmental conditions (an exclosure limiting N transfer, regular irrigation and cutting). To confirm the results, further validation on larger portions of land with effective grazing taking place or with the same experimental design in another site or another floodplain should be undertaken. Calibration was also undertaken partly through a trial and error design. The model could be better tuned to fit the data or so that less parameters need to be estimated. Nevertheless, and despite these possible improvements, the model is suitable to give first estimates of primary productivity of these specific grasslands.

Due to the methodology used to take into account the uncertainty linked to parameter estimation, a range of values for each estimated parameter is obtained. Control studies to better estimate these parameters are difficult to find for natural vegetation and even more for flooded grasslands. By using the equifinality concept, we acknowledge the limits of the model, the modelling processes and the calibration procedures. The value of certain parameters is not always known, and in reality, these parameters can even vary.

5.6.2 *Possible use of the model*

The model presented in this study could be used to explore contrasted flood, climate and management scenarios. In the case of the TRD, this could help, in conjunction with socio-economical studies, to answer urgent environmental and societal questions concerning water and pastoral management of the floodplains. Because of the model limitations, climate and flood specifications would need to be in similar ranges as those presented here. For example, it could be used to answer questions such as:

- could counter-seasonal irrigation contribute to improve fodder availability? If so, how much irrigation would be required for the grasslands to attain their maximal growth potential?
- what is the effect of changing hydrological regimes on grass growth and fodder production?

5.7 CONCLUSIONS

This study presents a coupled plant-soil model adapted to seasonally flooded grasslands. It was described and calibrated using data collected in the Tana River Delta, Kenya, during a 14-month experiment, during which different irrigation and cutting treatments and one flood event were recorded. A sensitivity analysis showed that a limited number of parameters strongly affected the output variables of interest. During the calibration process, five parameters were selected for calibration using the GLUE methodology. Overall, the model predictions are in good agreement with the experimental data. Although further improvements are possible, this model can already be used to understand the impact of changing rain, grazing or flooding patterns on the growth processes and primary productivity of Sahelian floodplain grasslands. Scientifically, it also raises further questions and points out the necessity to obtain more precise knowledge of these grasslands and the processes inducing their growth.

Part III

FOCUS 2: THE HYDROLOGY

Now that the importance of the flooding regime for the grasslands has been highlighted, the next question I wanted to answer concerned the hydrology of the floodplains. In **Chapter 6**, the general flooding characteristics of the Tana river in the delta are determined, through a combination of remote sensing techniques and hydrological modelling. This section has been submitted to Hydrology and Earth Systems Science as an article and is currently under revision. Contributing authors to this section are: C. Leauthaud, S. Duvail, G. Belaud, R. Moussa, O. Grünberger, and J. Albergel.

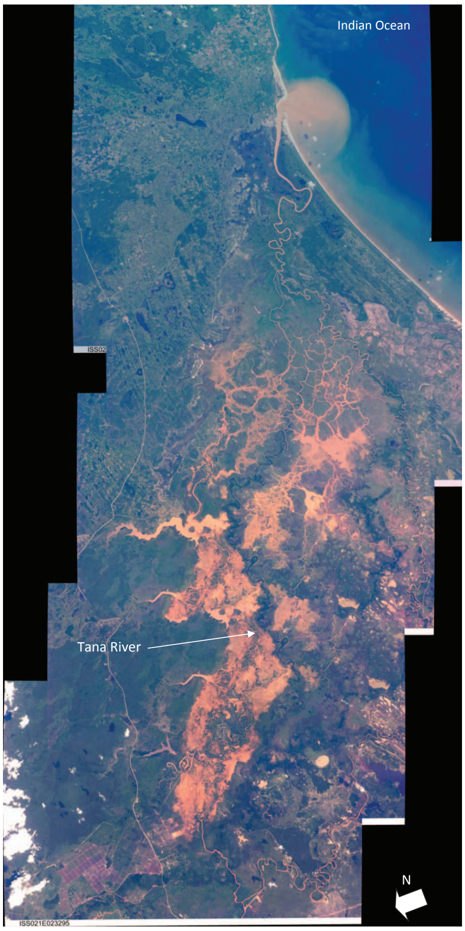


Figure 33: Photo-mosaic of the November-December 2009 floods on the terminal portion of the Tana River, Kenya. Photo courtesy of Justin Wilkinson, Crew Earth Observations, Johnson Space Center, Houston Texas, NASA, taken on 11-11-2009.

6

CHARACTERIZING FLOODS IN THE POORLY GAUGED WETLANDS OF THE TANA RIVER DELTA, KENYA, USING A WATER BALANCE MODEL AND SATELLITE DATA

6.1 ABSTRACT

Wetlands, such as those of the Tana River Delta in Kenya, are vital but threatened ecosystems. The flooding characteristics of wetlands largely determine their physical, chemical and biological properties, so their quantification is crucial for wetland management. This quantification can be achieved through hydrological modelling. In addition, the analysis of satellite imagery provides essential hydrological data to monitor floods in poorly gauged zones.

The objective of this study was to quantify the main water fluxes and flooding characteristics (extent, duration and frequency) in the poorly gauged Tana River Delta in East Africa during 2002-2011. To do so, we constructed a lumped hydrological model (the Tana Inundation Model, TIM) that was calibrated and validated with MODIS data. Further analysis of the MYD09A1 500 m composite product provided a map of the empirical probability of flooded state. In non-extreme years and for the actual configuration of the Tana River, the flood extent exceeded 340 km^2. Floods over 200 km^2 occurred on average once a year, with a mean duration of less than 25 days. River discharge from the upper basin counted for over 95 % of the total water inflow. The results are discussed in the light of possible improvements of the models and wetland management issues.

This study provides the first known quantification of spatial and temporal flooding characteristics in the Tana River Delta. As such, it is essential for the water and natural resource management of the zone. The water balance approach was pertinent to the study of this system, for which information on its internal properties and processes is limited. The methodology, a combination of hydrological modelling and flood mapping using MODIS products, should be applicable to other areas, including those for which data are scarce and cloud cover may be high, and where a medium spatial resolution is required.

6.2 INTRODUCTION

Wetlands are increasingly recognized as ecosystems that are essential to human activities (Mitsch and Gosselink 2000) because they provide a wide range of ecosystem services (Daily 1997; Millennium Ecosystem Assessment [2005a]). However, they are amongst the most threatened ecosystems worldwide (Vitousek et al. 1997). Their extent is rapidly declining, with an estimated decrease in the global average maximum inundated area of 6 % from 1993 to 2007 (Prigent et al. 2012).

Modifications in up-stream land use, hydro-electric infrastructure, and increased water withdrawal, in conjunction with climate change, are considered to be the main factors modifying the flooding characteristics of wetlands. In particular, dam construction has altered many wetlands throughout Africa, such as those of the Senegal River Delta in Mauritania (Duvail and Hamerlynck 2003) and in Senegal (Lamagat et al. 1996; Bader et al. 2003), the Inner Delta of the Niger River in Mali, the Waza Logone in Cameroon (Loth 2004), the Medjerda River in North Africa (Zahar et al. 2008), the Tana River in Kenya (Maingi and Marsh 2002) and the Hadejia-Jama'are floodplains in Nigeria (Barbier and Thompson 1998); while many others are threatened such as the Okavango Delta in Botswana (Milzow et al. 2009) and the Rufiji Delta (Duvail and Hamerlynck 2007).

The flooding characteristics of wetlands, particularly the flood extent, timing, frequency, duration and flood peaks, largely determine the physical, chemical and biological properties of wetlands (Mitsch and Gosselink 2000). Their quantification is therefore crucial for the management of wetlands and can be achieved through hydrological modelling.

Many types of flood models exist, ranging from lumped to distributed models. They mainly differ in their physical basis, complexity and data requirements. Distributed models are generally used when accurate data are available, while conceptual models are better suited to poorly gauged sites where data acquisition is difficult.

In recent years, there has been a rapid development of distributed models due to the proliferation of high-quality quantitative data (e.g., topography, remote-sensing) and increasing computational power (Hunter et al. 2007). However, data, end-user and computational constraints also need to be considered (Beven and Freer 2001). Furthermore, hydro-dynamic modelling of river-floodplain systems must be undertaken with precaution in large and flat floodplains, where small uncertainties in the water level can generate large errors in the prediction of flood extents.

For these reasons, more parsimonious approaches using simplified assumptions, have recently (re-)emerged in the scientific literature. In particular, lumped models combined with remote-sensing data have been used to characterize flood extents in poorly gauged and poorly characterized wetlands, such as the Okavango Delta (Wolski et al. 2006), and the Inner Delta of the Niger River (Mahe et al. 2011).

Remote sensing data can be used to detect water bodies and their characteristics (water extent, level, vegetation cover, sediment load, etc.) for calibration and validation of hydrological models. However, there are no standard methods to do so. Synthetic Aperture Radar imagery is very popular because of its high spatial resolution (e.g., a pixel size of 12.5 m for ERS-1 PRI data) and its capacity to map water under thick vegetation. However, the radar signals are sensitive to wind-induced waves, especially in the C-band, limiting the usefulness of this band for water detection (Alsdorf et al. 2007). L-band data are limited by their low orbital repeat cycles, cost and limited archives. Passive microwave data have been used to detect flood extents (Sippel et al. 1998; Ticehurst et al. 2009) but are also limited by a low spatial resolution. Thermal satellite data have been used to map inundated areas (Leblanc et al. 2011), but to our knowledge, these data have an inadequate monthly time-scale for characterizing rapidly changing flood extents. An alternative solution is the use of passive optical/infrared sensors on board the Landsat, Aqua, Terra or SPOT satellites.

The MODIS instruments on-board the Terra and Aqua satellites have been providing daily data for 36 spectral bands between 0.405 µm and 14.385 µm at a 250 m to 1 km resolution since 2000 and 2002, respectively. They have been used to characterize water levels (Ordoyne and Friedl 2008), the seasonality of lake systems (Feng et al. 2012), the extent of annual flooding (Sakamoto et al. 2007) and to map wetlands and flooding patterns (Ticehurst et al. 2009; Islam et al. 2010). MYD09A1 is a level-3 high-quality composite product, with a 500 m resolution. Each pixel contains the best possible observation during an 8-day period, corrected for atmospheric gases and aerosols, and is hence useful in zones subject to high cloud cover. Furthermore, two bands describe the quality of each pixel regarding aerosols and the presence of clouds or cloud shadow so that masking poor quality pixels is possible. Despite their moderate resolution, the long-term data collection and frequent overpasses make this product a good candidate for monitoring large- to medium-sized wetland complexes.

The objective of this study was to quantify the main water fluxes and flooding characteristics in a poorly gauged East African wetland, the Tana River Delta. To do so, we constructed a lumped hydrological model (the Tana Inundation Model, TIM) that allowed us to determine the role of river fluxes in flooding events and the number of flood events from 2002 to 2011 and to characterize the extent and duration of these floods. Satellite data were used to calibrate and validate the model, and to provide a spatial representation of the flooded zones. The hydrological variables quantified in this study are relevant for the management of the wetlands. After a description of the TRD, focusing in particular on its hydrological characteristics, the MODIS satellite data are analyzed, and the Tana Inundation Model is presented. Finally, the results are described in detail and then discussed in the light of wetland management issues.

6.3 THE TANA RIVER DELTA, KENYA

6.3.1 *Socio-economic and environmental context*

The Tana River Delta (TRD, Fig.34) is located on the Kenyan coast between the towns of Garsen, Lamu and Malindi and extends roughly over 1 300 km^2. The region is among the poorest in Kenya and its indicators of human well-being are extremely low (United Nations Development Programme 2010). The local population (over 100 000 inhabitants) is predominantly from the Pokomo, Orma, Somali, Wardei and Wata communities (Kenya Population Census, 2010), and they mainly rely on farming, fishing and livestock-keeping activities for their subsistence (Leauthaud 2009; Duvail et al. 2012; Leauthaud et al. 2013b). In addition to the economical and human value of the TRD, its complex landscape mosaic has an exceptional biodiversity value (Hamerlynk et al. 2012).

Over the past fifty years, five major reservoirs have been built in the upper basin that have significantly modified the hydrological regime of the river, with a 20 % decrease in the peak flows of May (Maingi and Marsh 2002). Other projects, particularly those of the Grand Falls Dam, could further impact the downstream flooding processes in the near future. In recent years, many biofuel and large irrigation schemes have also been initiated that will deprive the local communities of essential land and water resources (Duvail et al. 2012). It is therefore important to quantify current river water resources within the delta.

6.3.2 *Basin characteristics and data constraints for hydrological modelling*

The Tana is the largest river in Kenya and flows over nearly 1000 km from Mount Kenya and the Aberdare Mountains to the Indian Ocean. Its flowing pattern is bi-modal, with peak flows occurring during the long and short rainy seasons. Long-term discharge data were available at three locations within the Lower Tana Catchment. The closest long-term and active gauging station is at Garissa (0°27′49.19″S, 39°38′11.77″E, 1941-current), which is located 250 km upstream of the TRD. Two other gauging stations were located at Hola (1°30′00.00″S, 40°02′00.17″E, 1949-1991) and Garsen (2°16′09.36″S, 40°07′16.32″E, 1950-1998); however they are no longer monitored, and their data are discontinuous (22.8 and 41.2 % of gaps in record, respectively). Maximum peak discharges in Garissa were 1622 m^3.s^{-1} in 1941 and then 1585 m^3.s^{-1} in 1961.

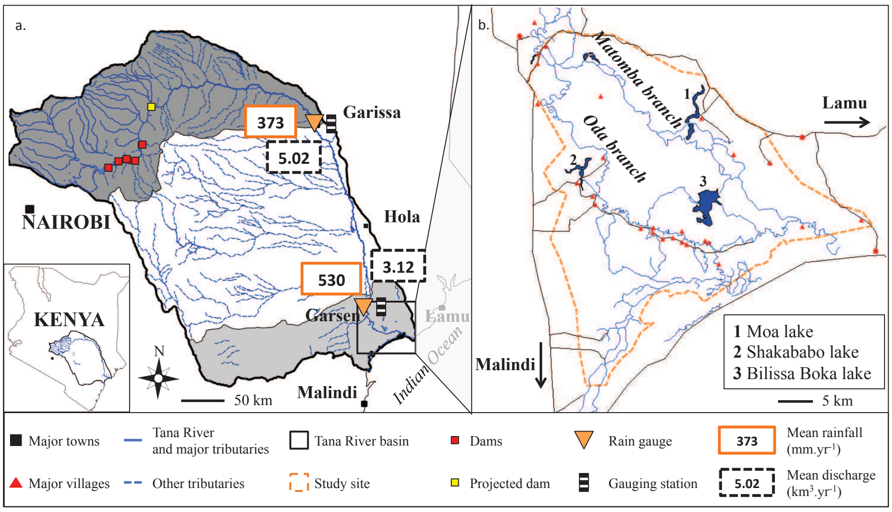


Figure 34: a. The Tana River basin and its main hydrological characteristics. The location of the precipitation and discharge data used for this study are specified. The sub-basins before the Garissa and after the Garsen gauging stations are presented in dark and light grey, respectively. b. The Tana River Delta, its major channels, lakes, villages and roads.

Maingi and Marsh (2002) consider flood propagation and losses due to evaporation to be the major hydrological processes that occur within the semi-arid stretch between Garissa and Garsen. This consideration is supported by three facts:

1. A rapid analysis of river discharges at Garissa and Garsen show that peak discharge rates are largely attenuated and smoothed out between the two stations (Fig.35), with an average decrease in transiting volume of 76 % (Table 11).

2. Only seasonal rivers, such as Laga Tula, the Laga Galole and the Laga Tiva, flow into the Tana River within this stretch.

3. With a hypothetical water requirement of 2 $L.s^{-1}.ha^{-1}$ and a cultivated area of 4000 ha, water abstraction at the Bura and TDIP irrigation schemes would not significantly alter the Tana River discharge during peak flows and hence the flooding characteristics in the TRD.

The precipitation decreases from the coast at Malindi (1098 $\pm$ 306 $mm.yr^{-1}$,1962-2008) to the inlands (530 $\pm$ 202 $mm.yr^{-1}$ in Garsen, 1972-1986, data from the Kenya Meteorological Department, KMD, Kenya. Years with over one month of missing data were excluded). The rainfall pattern is bi-modal, with two rainy seasons extending from April to June and from November to December, both of which correspond to the flooding periods for the Tana River in natural conditions. Recent daily precipitation and minimum and maximum daily

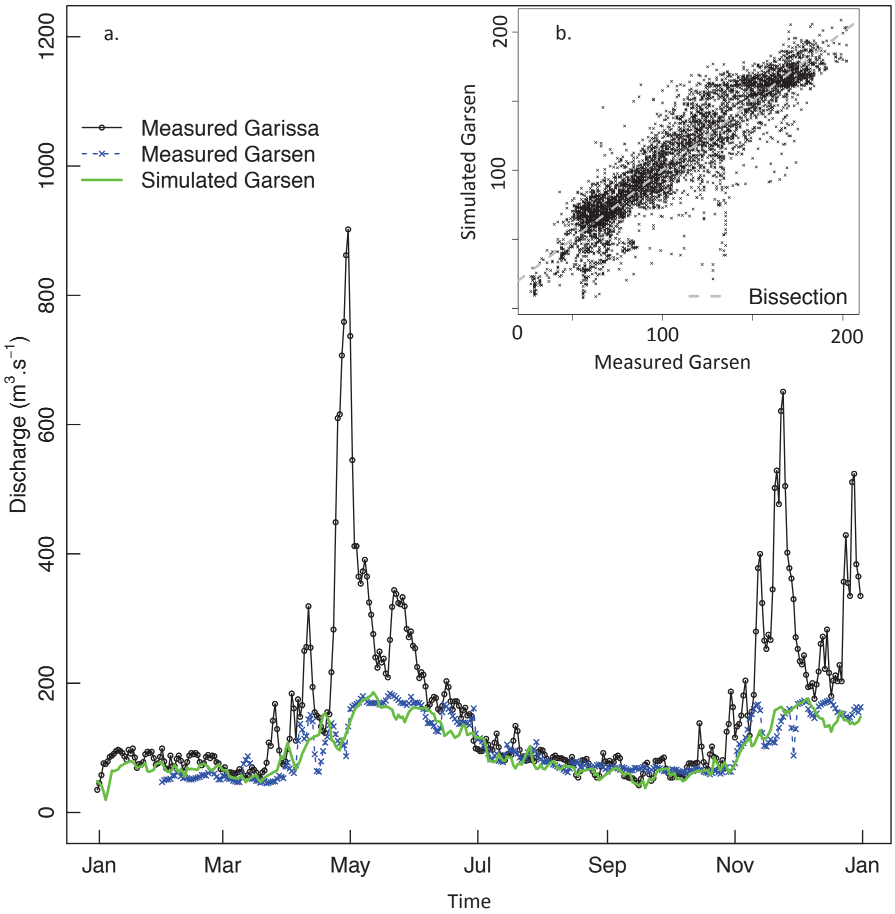


Figure 35: a. Example (1988) of measured discharges at Garissa, Q_1, and Garsen, and simulated discharge at Garsen, Q_2. b. Simulated versus measured discharge at Garsen for the validation periods (1963-1986 and 1991-1998).

Station	Water flow	Nb	Period
Garissa (km3)	2.51 ± 1.34	115	1941-2009
Garsen (km3)	1.56 ± 0.46	23	1951-1992
Volume ratio	0.76 ± 0.28	22	1951-1992

Table 11: Mean water flow per season (and 1 standard deviation) at each station and the resulting water volume ratio between the stations. The number of seasons (Nb) used and the periods considered for each calculation are specified. Each year was divided into two hydrological seasons (1 March - 31 August and 1 September - 29 February) to better use the available data. Seasons with more than 20 % of missing data were excluded (10 seasons for Garissa for 1941-2009; 60 for Garsen for 1951-1998). The remaining missing data, 2.3 % (542 days) and 6.0 % (397 days) for Garissa and Garsen, respectively, were filled in by linear interpolation.

air temperatures for the delta are also provided by the Tana Delta Irrigation Project (TDIP, 2°316′22.07″S, 40°11′00.55″E). Monthly precipitation data (from the KMD) are available from Garissa. Local precipitation most likely does not induce the floods but instead acts as a ″wetting″ event before the arrival of the flood wave. Precipitation is low in the semi-arid zones surrounding the delta. With an annual precipitation similar to that in Garissa (373± 202 mm.yr^{-1}, 1962-2008, KMD) and a low topographical gradient, overland flow and regional groundwater flows to the floodplains are most likely limited, compared to the water brought by the Tana River.

The mean temperature in the delta (1998-2009, TDIP) is 28°, with a mean maximum and minimum of 31° in March and 26° in July, respectively, suggesting high evaporation rates over the flooded areas, in accordance with regional monthly values (150-210 mm.month^{-1}, Woodhead 1968).

Within the delta itself, the main soil types encountered are deep, well drained, dark brown and cracking vertisols and fluvisols (Kenya Soil Survey, 1984a; Kenya Soil Survey, 1984b). The clayey nature of the floodplain soils most likely limits the infiltration of water within the floodplains during flood events. Ground water recharge could occur through infiltration at the sandier locations within the TRD, but quantitative data are unavailable.

Classical digital elevation models (DEM), e.g., ASTER and SRTM, exist for the whole basin. However, the high uncertainties of these models relative to the measurements of the altitude makes them inapproriate for hydrological modelling in the flat floodplains of the TRD (slope gradient from the delta inlet to the estuary c. 0.03 %).

Finally, numerous satellite products (LANDSAT, SPOT, MODIS, radar products) are available at different spatial and temporal scales. However, a high cloud cover limits the use of many of those in the optical spectral range, while the overpass frequency of current radar products is too low to obtain a time-series of flood extents.

The limited availability of hydrological, climate and topographical data makes the quantification of these hydrological variables challenging. The rapid analysis of the discharge data suggests that downstream discharge rates can be reconstructed using those at Garissa but that peak discharge attenuation and delay time, as well as the decrease in the discharge rates, are important and hence need to be modelled. Within the delta itself, many water fluxes are ungauged while the DEMs are not precise enough to be used in hydrological studies. Therefore, a water balance model was used to quantify these fluxes, and the flood extents extracted from the medium temporal and spatial resolution remote-sensing products were used to calibrate the model in the absence of other data.

Data	Time-step	Use
Discharge at Garissa1	daily	Flood propagation
MYD09A1 (76 images)2	8-day composite	Calibration/validation
MYD09A1 (434 images)2	8-day composite	Empirical probabilities
Rainfall at Garissa3	monthly	Surface inflow
Rainfall at Garsen3	daily	Rainfall inflow
Potential evapotranspiration4	monthly	Evaporated outflow

Table 12: Hydrological, climate and remote sensing data used in the Tana Inundation Model (2002-2011). Sources: [1] WRMA; [2] Nasa; [3] KMD; [4] Woodhead 1968.

6.4 APPROACH: SATELLITE DATA ANALYSIS AND HYDROLOGICAL MODEL SPECIFICATION

6.4.1 *Strategy*

To characterize flooded extents in the context of limited data, we constructed a tailor-made hydrological model, the Tana Inundation Model (TIM, Fig.36). It first reconstitutes river discharge at the delta inlet and then performs a water balance within the delta, taking into account the main water fluxes (river discharges, rainfall, surface flow, evaporation and infiltration). In the absence of topographical data, a logistic equation related the water level within the delta with the flood extent. Calibrated parameters and their associated uncertainties were calculated by comparing these flood extents with those measured from the MODIS satellite data. The temporal dynamics of the floods in the TRD throughout the past decade were simulated with an estimation of the flood extent, duration and frequency. A yearly water balance was also calculated. Finally, the MODIS MYD09A1 products also generated a spatial representation of the flooded zones. The data used in this study are listed in Table 12, and each step of the analysis (Fig.37) is further explained below.

6.4.2 *Analysis of MODIS MYD09A1 product*

6.4.2.1 *Acquisition and pre-processing of images*

The MYD09A1 500 m, 8-day composite images (tile H22V09) were downloaded from the NASA website (434 images from 4 July 2002 to 19 December 2011). All pixels with a high aerosol quantity or a MOD35 cloud cover (indices extracted from the surface reflectance state quality layer) in the visual or mid infrared bands (bands 2 and 5) were masked (LDOPE software tool, MODIS Land quality assessment group: Roy et al. 2002). The processed images were then re-

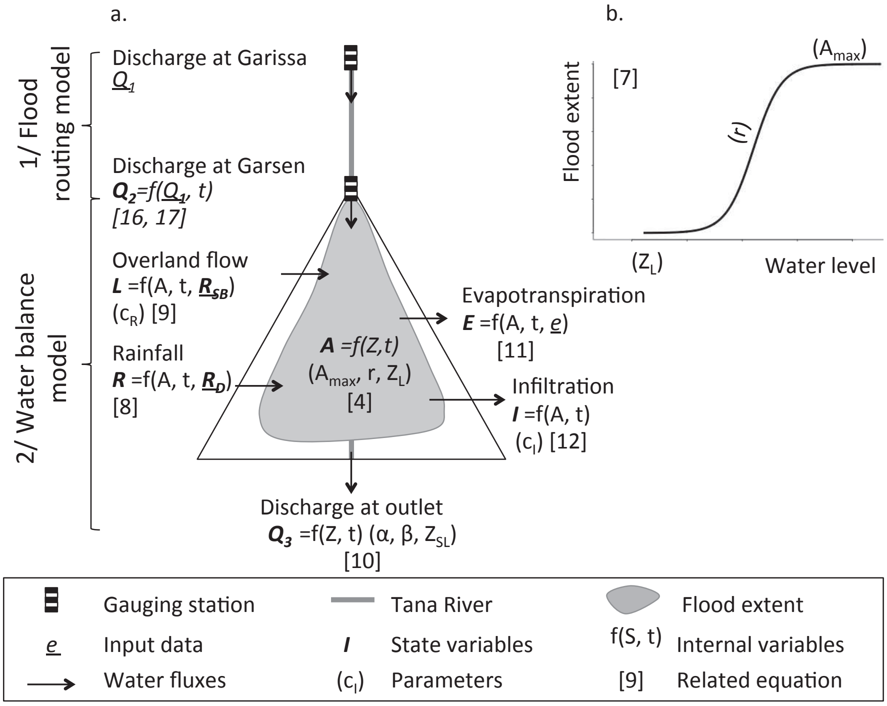


Figure 36: a. Schematic representation of the Tana Inundation Model. b. Logistic equation type relating flood extent A to water level Z in the delta. Q_1, Q_2 and Q_3: discharges at Garissa, Garsen and the delta outlet; t: time; R, R_D and R_{SB}: rainfall over the flooded area, at Garissa and at TDIP; L: overland flow; E: evapotranspiration over the flooded area; e: potential evapotranspiration; I: infiltration from the flooded area; c_R, A_{max}, r, Z_L, c_I, α, β, and Z_{SL} are model parameters defined in Table 14.

projected into geographical coordinates, subset to the studied area (upper left corner: 2°6′0″S, 39°59′56.4″E, lower right corner: 2°6′0″S, 39°59′56.4″E) and transformed into geotiffs (HDF-EOS To GeoTIFF Conversion Tool, HEG v2.11: EOS 2012).

Image analysis was carried out on the deltaic floodplains, excluding the river mouth, mangroves and coastal forests. The geographical mask used was constructed manually through a visual interpretation of the 90 m Shuttle Radar Topography Mission Digital Elevation Model (SRTM DEM). Its contours roughly follow the Menjila-Lamu road to the North, the Eastern and Western terraces and the Southern coastal forest and sand dunes (Fig. 34).

6.4.2.2 *Detection of vegetated flooded pixels*

Differences in the spectral signature of the land and water covers are used to distinguish the water bodies from the other surfaces. Many water indices have been developed using different spectral bands and different satellite data (Gao 1996; McFeeters 1996; Rogers and Kear-

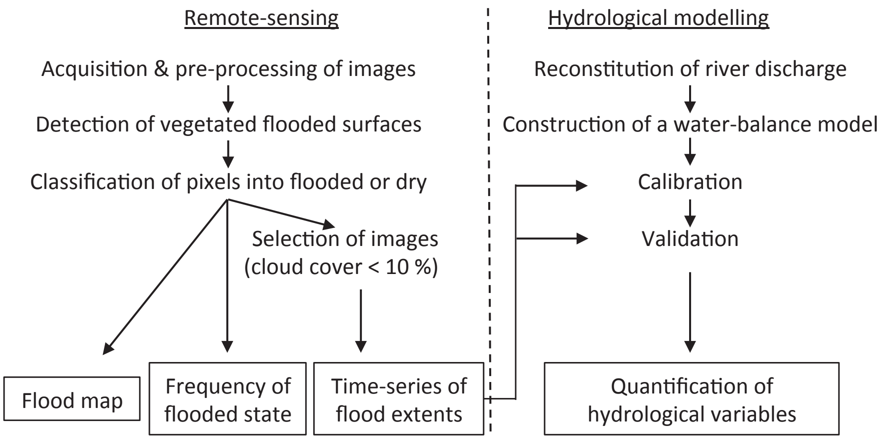


Figure 37: Workflow diagram.

ney 2004; Xu 2006) and are commonly used to differentiate land cover types.

A major characteristic of the TRD is the frequent presence of a dense and low-lying vegetation cove above the water. Water indices do not always distinguish between the flooded and non-flooded vegetation. However, Oliesak (2008) used the Modified Normalized Difference Water Index (2006) to map the open water bodies in the Inner Niger Delta and the Normalized Difference Water Index of Gao ($NDWI_{Gao,M2-5}$) (Gao 1996) to include the vegetated water. Despite large differences in spatial extent between the Inner Niger Delta and the TRD, some main characteristics of the wetlands (flooded vegetation of *Echinochloa stagnina* (Retz) P. Beauv) are identical. We therefore used $NDWI_{Gao,M2-5}$ to map flood extents in the TRD.

$NDWI_{Gao,M2-5}$ for each pixel was calculated as:

$$NDWI_{Gao,M1-5} = \frac{\varphi_{red} - \varphi_{MIR}}{\varphi_{red} - +\varphi_{MIR}} \tag{42}$$

where ρ_{red} and ρ_{MIR} are the radiances (in reflectance units) in the red and mid infrared spectral ranges, extracted from bands 2 (841μm - 876 μm) and 5 (1230 μm - 1250 μm) of the MYD09A1 product.

To determine the index threshold that best differentiated between the flooded and dry areas, 1398 reference GPS points corresponding to 500 m by 500 m flooded or dry zones were acquired during two flood events (May 2010 and December 2011) and one rainy season when no floods occurred (May 2009) and were compared to the spatially and temporally coincident MYD09A1 pixels. These binary data were used to construct error matrices for $NDWI_{Gao,M2-5}$ values ranging from 0.05 to 0.12 (at a step of 0.01). The $NDWI_{Gao,M2-5}$ value that maximized the percent of correctly classified pixels (i.e., the overall accuracy of Congalton (1991) was retained as the threshold value. During the classification process, the misclassification of pixels in a flooded (resp. dry) state can be measured (the user's accuracy of Congalton (1991)) and was used here to estimate an uncertainty range for the resulting flood extents, A_o.

6.4.2.3 *Classification of pixels and image analysis*

Each pixel within the geographical mask was classified as flooded (resp. dry) when its $NDWI_{Gao,M2-5}$ value was higher (resp. lower) than this threshold value, or as clouded. The resulting MODIS imagery set was analyzed in three ways.

First, the empirical probability of flooded state, p_i, for each pixel, i, was calculated as:

$$p_i = \frac{n_{F,i}}{N_T - n_{c,i}} \tag{43}$$

where $n_{F,i}$ is the number of times the pixel i was classified as flooded, N_T is the number of images available and $n_{c,i}$ is the number of times that the pixel was classified as clouded at band 2 and band 5. This term expresses the fraction of times a pixel was classified in a flooded state, considering the observations of the pixel when it was classified as non-clouded. p_i was calculated for each pixel within the study site, and based on these calculations, we then drew an iso-contours map of p_i.

Secondly, a discrete time-series of flood extents was obtained from the images presenting less than 10 % cloud cover for all seven bands. Flood extent A_o was calculated as:

$$A_o = \gamma \cdot n_F \tag{44}$$

where γ is the area of a MODIS pixel (0.216 km^2), and n_F is the number of pixels classified in a flooded state. Then, to obtain uncertainty boundaries, 1000 numerical simulations, following a random sampling with replacement design, were undertaken for each image and each of the three classes. The probabilities that each selected pixel had been correctly classified (in a flooded or dry state or in a flooded state but clouded) were taken, respectively, as the user's accuracy for the flooded and dry classes from the error matrix and the ratio of pixels classified as flooded on pixels classified as non-clouded. The upper and lower uncertainty boundaries were then calculated as the 90th and 10th percentiles from the simulations centered around the previously calculated flooded area, so that a maximum $A_{o,x}$ and minimum $A_{o,m}$ flooded area were calculated for each image.

Lastly, the images were used to obtain an empirical probability of flood extent p using Eq. (45):

$$p = \frac{n_S}{N_T} \tag{45}$$

where n_S is the number of times the flood extent A_o was observed. To obtain a sufficient sampling size, we used all of the images that had less than 50 % cloud cover at bands 2 and 5 (342 images), and estimated flood extent A_o by taking into account the pixels classified as clouded. With the underlying hypothesis that the ratio of flooded to non-flooded area in the visible zone was identical to the same ratio in the clouded zone, A_o was calculated for each image as:

$$A_o = \gamma \cdot n_F \cdot (1 + \frac{n_c}{A_T - n_c}) \tag{46}$$

where n_c is the number of pixels classified as clouded and A_T is the area of the studied zone (1034 km^2).

6.5 THE TANA INUNDATION MODEL

6.5.1 *General structure*

The Tana Inundation Model (TIM, Fig.36) was composed of a non-linear flood routing model chained to a water balance model within the delta.

Input data were daily discharge rates at Garissa, Q_1 [L^{-3}.T^{-1}], daily precipitation at TDIP, R_D {L.T^{-1}], monthly precipitation at Garissa, R_{SB} [L.T^{-1}], and monthly potential evapotranspiration rates e [L.T^{-1}] for the delta (Woodhead 1968). Gaps in the Q_1 record were filled by linear interpolation, except for two periods when flood events occurred (05 May 2003-31 October 2003 and 31 March 2005-04 August 2005) for which this method is inappropriate. A 10-day moving average, which was more appropriate for the flood-routing model (Lamagat et al. 1993; Bader et al. 2003), was then used as the model input. State variables were daily discharge rates Q_2 at the delta inlet, daily discharge rates Q_3 at the delta outlet, daily evapotranspiration, infiltration and precipitation over the flooded area, E, I and R, daily overland flow L from the sub-basin between Garsen and the estuary, and daily flood extent A [L^2] within the delta. All fluxes are expressed in [L^3.T^{-1}].

Once calibrated and validated, the model provided a time series of flood extents for 2002-2011, as well as the number of flood peaks, their mean duration and flood frequency. Finally, a mean yearly water balance for the delta provided estimations of main water inflows and outflows.

6.5.2 *Flow propagation within the river stretch*

Discharge measurements, Q_2, were reconstructed using a flood routing model (Lamagat et al. 1993) that has been used to model many large rivers with overflow in Africa (Lamagat et al. 1993; Bader et al.

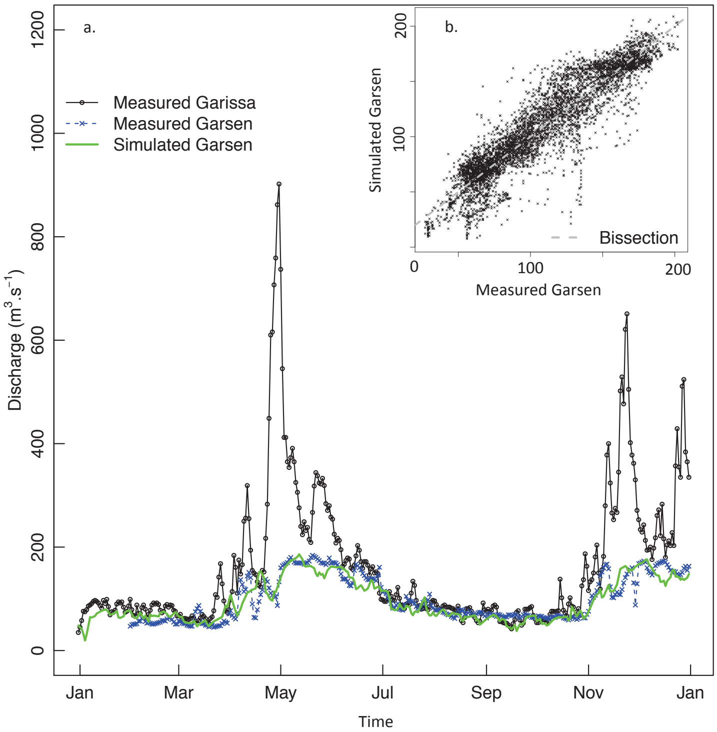


Figure 38: Discharge data for the Garissa, Q_1, and Garsen, Q_2, stations in 1988

2003; Belaud et al. 2010). This approach relies on a theoretical analysis of the diffusive wave equation and takes into account differences in propagation trends in low and high flow regimes.

According to this method, two empirical relationships were established between the upstream and downstream discharges (Q_1 and Q_2), and between the upstream station and a delay time, T. Calibration of the two empirical relations was performed with a subset of Q_1 and Q_2 discharge data (01 December 1986 to 29 June 1991). Upstream and downstream hydrographs were divided into 20 elementary intervals (Belaud et al. 2010), and then, a linear regression was performed between the discharge rates from the two stations for different delay times, T, and for each interval. The delay time T was chosen to minimize the Root Mean Square Error (RMSE) of the linear regression, thus maximizing the correlation between Q_1 and Q_2. A back-and-forth method was used to manually correct and smooth out the empirical data so that they exhibited the expected monotonous behavior. These relationships were then modelled with linear, second-order polynomial or logarithmic equations, by maximizing R^2 to obtain continuous functions relating Q_1, Q_2, and T. Discharge Q_2 was calculated as the resulting 10-day moving average daily discharge.

The Nash-Sutcliffe coefficient (NS), the Absolute Maximum Error (AME), the RMSE, and the Mean Absolute Error (MAE), as defined by Dawson (2007), were calculated for Q_2 for both the calibration (1986-

Table 13: Mean water flow per season (equivalent to half a hydrological year) at each station and the resulting water volume ratio between the stations. The number of seasons (Nb) used and the periods considered for each calculation are specified.

	Mean and sd	Nb	Period
Water flow per season at Garissa (km^3)	2.51 ± 1.34	115	1941-2009
Water flow per season at Garsen (km^3)	1.56 ± 0.46	23	1951-1992
Volume ratio	0.76 ± 0.28	22	1951-1992

1991) and validation (1963-1986 and 1991-1998) periods to assess the quality of the flood routing model.

6.5.3 *Equations and specifications of the water balance model*

The TRD was represented as a single reservoir, within which a daily water balance was calculated:

$$\frac{dV}{dt} = A \cdot \frac{dZ}{dt} = Q_2 + R + L - Q_3 - E - I \tag{47}$$

where V [L^3], Z [L] are the volume and the level of water within the reservoir.

In the absence of topographical data, the flooded area A was related to water level Z using a logistic equation:

$$A = \frac{A_{max}}{1 + a \cdot \exp^{-r \cdot Z}} \tag{48}$$

where A_{max} is the maximum flood extent, while a [-] and r [L^{-1}] determine the shape of the logistic curve.

Rainfall input, R, was calculated as:

$$R = R_D \cdot A \tag{49}$$

Overland flow, L, was calculated as a function of rainfall at Garissa, R_{SB}:

$$L = c_R \cdot R_{SB} \cdot (A_{SB} - A) \tag{50}$$

with c_R being the runoff coefficient [-] and A_{SB} being the sub-basin area after Garsen (13 700 km^2). In the absence of daily precipitation data for the sub-basin, R_{SB} was uniformly distributed daily values calculated from the monthly precipitation data at Garissa.

The outflow, Q_3, which is unknown in reality because of its diffuse character, was related to the level of the water stored above the reservoir's outlet at sea level, Z_{SL}, in a classical manner, i.e.:

$$Q_3 = \alpha \cdot (Z - Z_{SL})^{\beta} \quad (51)$$

$Z - Z_{SL}$ represents the head loss between the reservoir and its outlet. The value of β is typically between a minimum of 0.5 for a Chezy- or Manning-type flow and 1.5 for a free weir flow (Chow 1959), which is what would be expected here.

Evaporation was calculated in the same way as Wolski (2006):

$$E = e \cdot A \quad (52)$$

In the absence of more precise data, uniformly distributed values of daily potential evapotranspiration, e, were obtained from monthly estimates at Malindi (Woodhead 1968).

Infiltration was expressed through a linear relationship relating it to the flooded area, A:

$$I = c_I \cdot A \quad (53)$$

where c_I is the infiltration rate [L.T^{-1}].

The model was coded under R (R Development Core Team, 2008) and verified by checking the closure of the water balance model for all parameter sets. The minimum flooded area A_{min} was set to 1 km^2, and the maximal water level was set to 10 m to keep the reservoir shape conforming to the TRD. a was calculated from the area of permanent lakes A_L (4 km^2), the corresponding water level Z_L, A_{max} and r. Initial flood extent was set to A_L because the model was initiated at low flow. When the flood extent was minimal, evapotranspiration and infiltration were considered to be negligible. Equation (47) was solved iteratively using the fourth-order Runge-Kutta algorithm Atkinson 1989. For reasons of numerical stability, it was solved at an hourly time-step. Final output variables were averaged over 10 days so that the temporal resolution was close to that of the MODIS images and major input variables.

The water balance model had eight parameters (Table 14), which were estimated according to the equifinality concept (Beven and Binley 1992). This concept states that the uncertainty related to parameter estimations allows for multiple parameter sets to reproduce the observed behavior of a system. This uncertainty needs to be quantified in the modelling procedure (Beven and Binley 1992) because it affects the interpretation of the model.

6.5.4 *Calibration and validation strategy for the water balance model*

Calibration and validation of hydrological models are usually performed by comparing the simulated data with an independent set of data. Classical evaluation metrics include NS, AME, MAE and RMSE (Table 15).

Parameter	Signification	Range/Value	Unit
α	parameter for discharge Q3	0-10^6	$m^{3-\beta}.day^{-1}$
β	parameter for discharge Q3	0.2-1.7	-
A_{max}	maximum flooded area	300-700	km^2
r	parameter for logistic equation	1-40	m^{-1}
c_R	overland runoff coefficient	0-0.05	-
c_I	infiltration rate	0-25[1]	$mm.day^{-1}$
Z_L	water level of permanent lakes	0-2	m
Z_{SL}	water level at outlet	0-5	m

Table 14: Definition of water balance model parameters. [1] Parameter range from Clapp and Hornberger (1978).

Quality indicators	Abbreviation	Equation
Likelihood	L_ϵ	$1 - \frac{\sum \epsilon^2}{\sum (A_0 - \bar{S_0})^2}$
Absolute Maximum Error	AME	$max \mid \epsilon \mid$
Mean Absolute Error	MAE	$\frac{1}{n} \sum \mid \epsilon \mid$
Root Mean Square Error	$RMSE$	$\sqrt{\frac{1}{n} \sum \epsilon^2}$

Table 15: Evaluation metrics of the models, as defined by Dawson (2007). For the flood routing model, the error ϵ was defined using the observed and simulated discharges.

In this study, we were interested in 1/ selecting parameter sets during a calibration process, then validating each set, and 2/ assessing the final quality of the model, which includes the ensemble of parameter sets. In the first phase, point simulations were to be compared to an uncertainty range issued from the MODIS images, whilst in the second case, two uncertainty ranges were to be compared. To do so, we defined an evaluation metric $\mathcal{L}_\epsilon$ as:

$$\mathcal{L}_\epsilon = 1 - \frac{\sum \epsilon^2}{\sum (A_o - \bar{S}_o)^2} \tag{54}$$

where ϵ (Fig. 39) is the error defined in Eq.(55) or Eq.(56), A_o is the observed flooded area calculated at each date and $\bar{S}_o$ is the mean flooded area from the MODIS images. The likelihood $\mathcal{L}_\epsilon$ differs from the Nash-Sutcliffe coefficient because it compares flood extents rather than discharges and differs in the definition of the error ϵ. The latter is the difference between the value measured by MODIS and that simulated by TIM, taking into account the uncertainty ranges. In the calibration and validation of each parameter set, ϵ was defined between the value from TIM and the uncertainty range from MODIS, so that:

$$\text{If } A < A_{o,m} \text{ then } \epsilon_1 = A_{o,m} - A$$

$$\text{If } A_{o,m} \leq A \leq A_{o,x} \text{ then } \epsilon_1 = 0$$

$$\text{If } A > A_{o,x} \text{ then } \epsilon_1 = A - A_{o,x} \tag{55}$$

In the quality assessment phase, $\mathcal{L}_\epsilon$ was defined from the uncertainty ranges of both the TIM and the MODIS images because the equifinality concept states that all selected parameter sets are acceptable. Hence, ϵ becomes:

$$\text{If } A_{0.9} < A_{o,m} \text{ then } \epsilon_2 = A_{o,m} - A_{0.9}$$

$$\text{If } A_{o,m} \leq A_{0.9} \text{ and } A_{0.1} \leq A_{o,x} \text{ then } \epsilon_2 = 0$$

$$\text{If } A_{0.1} > A_{o,x} \text{ then } \epsilon_2 = A_{0.1} - A_{o,x} \tag{56}$$

where $A_{0.1}$ and $A_{0.9}$ are the 10^{th} and 90^{th} percentile boundaries for the calibrated hydrological model. The advantage of this approach is

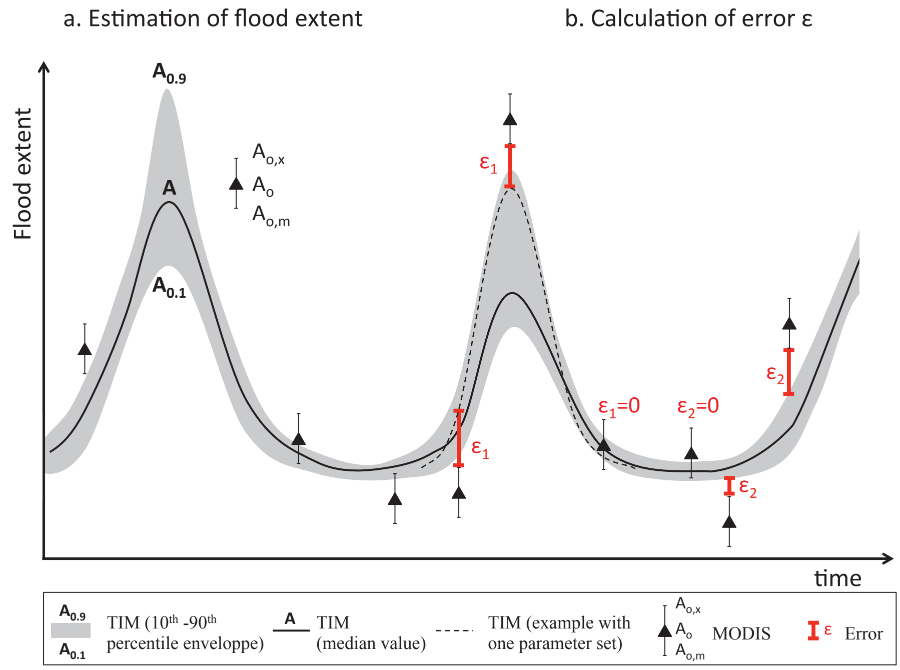


Figure 39: a. Simplified scheme depicting the flood extents from TIM and MODIS. b. Definition of the error ϵ_1 and ϵ_2.

that it increases the flexibility in the calibration process for a model that needs to be constrained using a very limited amount of data.

Model calibration was performed using the Generalized Likelihood Uncertainty Estimation (GLUE) methodology (Beven and Binley 1992; Beven and Freer 2001). Ranges were fixed for the model parameters (Table 14), and the parameter sets were randomly generated within these bounds, using a uniform distribution. The model was then run with each parameter set, and the results that did not meet our acceptance criteria were rejected. A first selection was conducted by retaining the sets yielding a $\mathcal{L}_\epsilon > 0.60$ and for which a full resolution of the differential equation could be achieved. Secondly, the parameter sets were further restrained to reproduce the observed conditions (a flood extent higher than 150 km^2 on 31 May 2010 or lower than 10 km^2 in May 2009).

This parameter selection was performed using a split-sample approach. The time-series was separated into two periods (01 January 2002 - 21 September 2006 and 22 September 2006 - 31 December 2011), each of which was used for the selection of a limited number of parameter sets. The initial pool consisted of 200 000 sets of parameters for each period. Finally, both reduced sets were combined, and the uncertainty ranges were defined by the 90th and 10th quantiles obtained from the likelihood-weighted output variables.

Each parameter set was validated by calculating the evaluation metrics ($\mathcal{L}_{\epsilon 1}$, AME$_\epsilon$, MAE$_\epsilon$, RMSE$_\epsilon$, with the error defined from ϵ_1) from the data not used during the calibration process. In the final assessment of the quality of the water balance model, including the ensemble of parameter sets, $\mathcal{L}_{\epsilon 2}$, AME$_\epsilon$, MAE$_\epsilon$, RMSE$_\epsilon$ were calculated for 2002-2011, with the error defined from ϵ_2.

6.6 RESULTS

6.6.1 *Satellite data*

The overall accuracy of the pixel classification was maximal (92.63 %) at NDWI$_{Gao,M2-5}$ = 0.09 (Table 16). For all the values of NDWI$_{Gao,M2-5}$ between 0.05 and 0.012, the overall accuracy pixels always exceeded 85 %, showing that the index was not sensitive near these values.

Seventy-six images (Fig. 41) presented a cloud cover of less than 10 %. The resulting set was well-distributed between the rainy and dry seasons. The maximum and minimum flood extents were 0-6 km^2 and 302-316 km^2 (10th and 90th percentiles). Only 19 images presented a flood extent over 100 km^2.

The contours of the preferential flooding zones, which are derived from the empirical probability of flooded state p_i, are mapped in Fig.40. The size of the area with an empirical probability p_i exceeding 0.01 was 450 km^2. The maximum empirical probability of flooded state was 0.41 in the south-eastern part of the delta, corresponding to a zone under tidal influence. The flooded zones mainly followed the active Matomba branch of the river and then spread out within the floodplain grasslands. On the contrary, zones surrounding the formerly active Oda branch were rarely flooded. The major lakes of the zone (Moa, Shakababo and Bilissa Boka lakes) were visible. Furthermore, ancient channels surrounded by riverine forests and other non-flooded zones effectively appeared to be dry. As expected, villages were out of the flooded zones, but close to them for easy access to pasture and farming land. The map corroborates well with our knowledge of the terrain.

Date	Groundtruthing data		NDWI threshold value							
	Status	Nb	0.05	0.06	0.07	0.08	0.09	0.10	0.11	0.12
25 May 2009	dry	410	407	409	409	410	410	410	410	410
25 May 2010	dry	270	167	186	213	230	244	255	261	264
19 December 2011	dry	253	196	226	238	245	246	248	249	251
25 May 2010	flooded	211	195	191	185	183	181	175	170	163
19 December 2011	flooded	254	238	233	230	224	214	207	196	179
User's accuracy (%)	dry		96.0	95.3	94.5	93.9	92.2	91.7	90.3	88.3
User's accuracy (%)	flooded		72.7	79.1	85.0	89.5	92.3	95.0	96.5	97.7
Overall accuracy (%)			86.0	89.0	91.2	92.4	92.6	92.6	91.9	90.6

Table 16: Evaluation metrics used for the calibration or validation steps of the water balance model. ϵ is defined in either Eqs. (55) or (56). A_o: flood extent measured from the MODIS imagery; $\bar{S}_o$: mean flood extent from MODIS imagery; n: number of concordant TIM and MODIS observations.

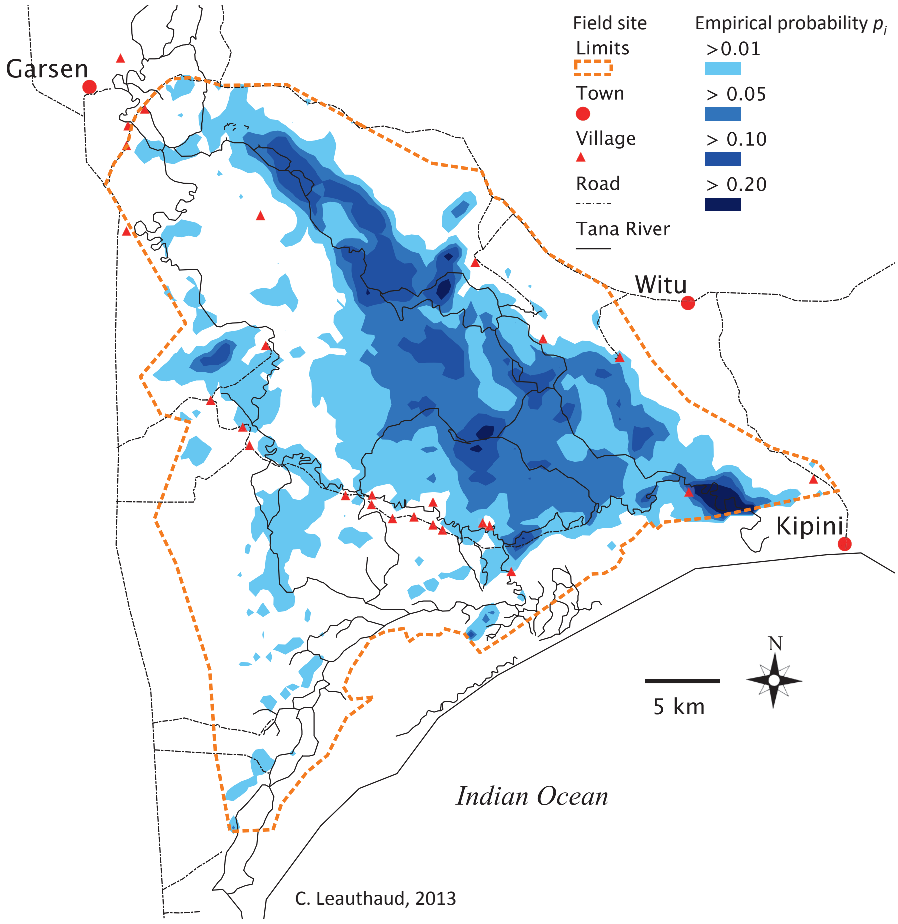


Figure 40: Map of the empirical probability of flooded state using the MODIS images from 2002 to 2011.

6.6.2 *TIM*

6.6.2.1 *Calibration and validation of the flood-routing model*

The model reproduces the observed discharges at the Garsen station to a satisfactory degree, with reasonable NS, RMSE, AME and MAE for both the calibration and validation periods (Table 17).

The discharge at Garsen (Q_2, $m^3.s^{-1}$) and the time delay (T, day) are described by Eqs. (57) and (58):

$$\text{If } Q_1 \in [0, 320] \text{ then } Q_2(t) = -0.0014 \cdot Q_1^2(t-T) + 0.9557 \cdot Q_1(t-T)$$

$$\text{If } Q_1 > 320 \text{ then } Q_2(t) = 0.04692 \cdot Q_1(t-T) + 145.69 \qquad (57)$$

$$\text{If } Q_1 \in [0, 36] \text{ then } T = 5$$

$$\text{If } Q_1 \in]36,78] \text{ then } T = 0.0033 \cdot Q_1^2 - 0.3715 \cdot Q_1 + 14.256$$

$$\text{If } Q_1 > 78 \text{ then } T = 3.5588 \cdot \ln(Q_1) - 10.085 \quad (58)$$

The resulting curves are typical of an overflowing river with a very low slope. Downstream discharge increased with upstream discharge. At high discharges, the slope of Eq. 58 decreased due to overflowing into the floodplains and the consequent evaporation. At high discharges, Q_1, time-delay T increased as water overflowed into the large floodplains. According to the model, a flood of 500 $m^3.s^{-1}$ required approximately 12 days to reach Garsen from Garissa.

Period	NS (-)	RMSE ($m^3.s^{-1}$)	AME ($m^3.s^{-1}$)	MAE ($m^3.s^{-1}$)
Calibration	0.89	14	74	10
Validation	0.87	16	107	12

Table 17: NS, RMSE, AME and MAE values for the calibration (1986-1991) and validation (1963-1986 and 1991-1998) periods of the flood routing model.

6.6.3 *Calibration and validation of the water balance model*

Calibrated parameters are presented in Table 14. They did not reveal any structure within the prior distribution space. However, Z_L and Z_{SL} were highly correlated (0.87), r and α showed a correlation of 0.50, and α and β showed a correlation of 0.43. The correlations (absolute values) between the other parameters were all less than 0.23 (and mostly less than 0.1). The correlation between Z_L and Z_{SL} was high because the water level within the delta is always higher than that at the outlet.

During the 2002-2006 calibration period, 463 sets of parameters were selected using the GLUE approach (Table 18). The likelihood, $\mathcal{L}_{\epsilon 2}$, was of 0.91 and 0.83 for the calibration and validation periods. During the 2006-2011 calibration period, 71 sets of parameters were selected (Table 18). $\mathcal{L}_{\epsilon 2}$ was 0.73 and 0.89 for the calibration and validation periods, respectively. The model seems better adapted to the 2002-2006 period, which has more parameter sets and higher $\mathcal{L}_{\epsilon 2}$ values compared to 2006-2011. After further restriction, 114 parameter sets were finally retained. The global model performance for each period and the entire 2002-2011 period are summarized in Table 18. $\mathcal{L}_{\epsilon 2}$, AME_{ϵ} and MAE_{ϵ} were, respectively, 0.91, 143 km^2 and 10 km^2 for the entire period. In light of these criteria, the proposed model performed well.

Calibration/Validation	Period	Np	AME (km^2)	MAE (km^2)	$RMSE$ (km^2)	$L\epsilon$
Calibration	2002-2006	463	72.7	10.8	20.7	0.91
Calibration	2006-2011	71	161.2	27.0	45.5	0.73
Validation	2002-2006	71	80.6	13.1	23.9	0.89
Validation	2006-2011	463	143.5	21.5	35.9	0.83
Validation	2002-2011	114	143.4	10.3	23.9	0.91

Table 18: Evaluation metrics of the water balance model. Np: Number of selected parameter sets.

Finally, a water balance for each selected parameter set was computed. The median total volume of water transiting through the system was 28.7 $\pm$ 0.5 km^3. A mean absolute difference of 0.85 % between the incoming and outgoing fluxes for all of the parameter sets was observed and attributed to the approximations of the numerical resolution. This difference is considered negligible.

6.6.3.1 *Quantification of hydrological variables*

Flood extents simulated by TIM for 2002-2011 are represented in Fig. 41. They corroborated well with the flood extents calculated from the MODIS imagery. The periodicity of the floods was well reproduced, with floods occurring during the rainy seasons. According to the hydrological model, the maximum flood peak of the past decade occurred in December 2007, with a medium and 90th percentile value of 340 and 481 km^2, respectively. On the contrary, the floods of May 2011 seem to have been negligible (<100 km^2). The last fact was confirmed in the field.

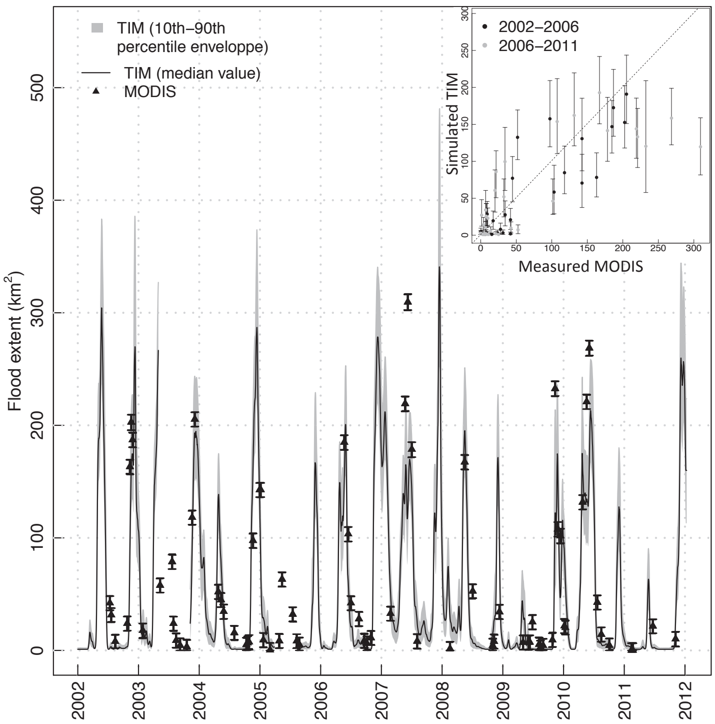


Figure 41: Flooded surface in the delta, 2002-2011, as computed by TIM or extracted from the MOD09A1 imagery.

Seventeen flood events with flood peaks over 100 km^2 (median value) were recorded for 2002-2011 (Table 19). Their duration was 43 days (median value). Among these floods, four lasted less than 20 days. These events were quite regular, with floods over 100 km^2 lasting more than 20 days occurring for an average of 2/3 of the rainy

Flood extent	10th percentile		Median		90th percentile	
	Nb	Duration	Nb	Duration	Nb	Duration
>100 km2	19	25±19	17	43±25	18	50±25
>200 km2	6	11±4	9	19±10	17	24±19
>300 km2	0	0	2	6±4	6	18±6

Table 19: Number of floods and their mean duration for 2002-2011.

seasons. However, because of the calibration procedure of TIM, small flood extents could be overestimated.

Flood events of a larger scale were more rare, with a median number of nine flood events over 200 km^2 for the 18 recorded potential flooding periods. These floods occurred on average once a year, even though there are two potential flooding seasons per year. Their mean median and 90^{th} percentile durations were 19 ± 10 days and 24 ± 19 days, respectively, with the longest 90^{th} percentile flood durations of 45 and 82 days having taken place in May 2002 and December 2007, respectively. Flood events over 300 km^2 were recorded 0 to 6 times and were of short duration.

The floodplains were considered to be in a dry state (flood extent < 10 km^2) 48 % of the time (Fig. 42). Flood extents over 100 km^2 were observed 22 % of the time, while floods over 200 km^2 were observed only 4 % of the time. The latter value corresponds to an average of 15 days in a year. These results corroborate with the empirical probability of flood extent calculated from the MODIS imagery (Fig. 42).

An empirical relationship relating the flood extent A with the incoming discharge Q_2 was also obtained from the TIM (Fig. 43). Confidence intervals (median values of the 10^{th} and 90^{th} percentiles of each data point) were calculated. Only three extreme rainfall events do not fall within these intervals. Floods exceeding 100 km^2 occurred for discharges higher than 130 $m^3.s^{-1}$. An increase of 30 $m^3.s^{-1}$ resulted in floods of 200 km^2.

Finally, the annual water balances were calculated for 2002-2011 using the median values of the parameter ensemble (Table 20). The total input discharge, rainfall, overland flow, output discharge, evapotranspiration and infiltration flows calculated in the water balance are represented in Fig.44. Mean annual water inflow into the delta was approximately 3.3 km^3. The minimum and maximum yearly inflows were observed in 2009 and 2007 at 2.6 km^3 and 4.1 km^3, respectively. The river discharges Q_2 and Q_3 corresponded to over 95 % and 98 %, respectively, of the mean annual water inflow.

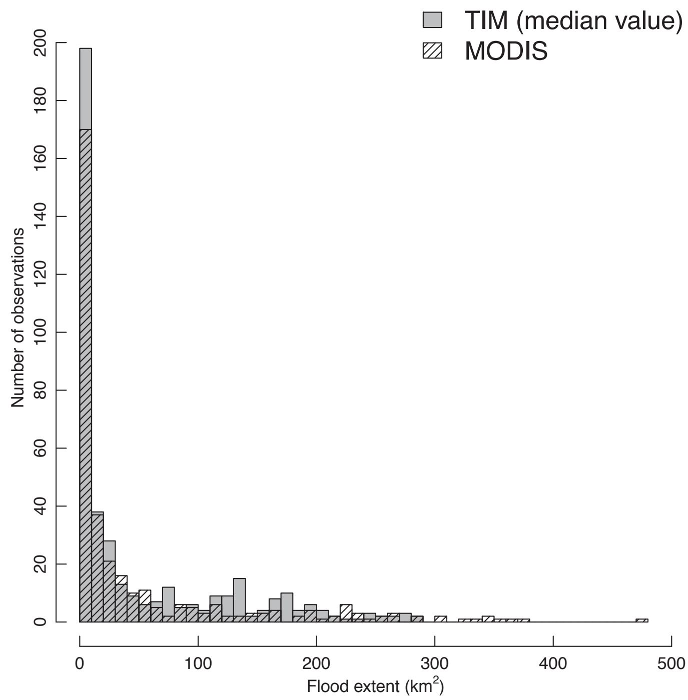


Figure 42: Frequency of calculated flooded days as a function of flooded surface for the MODIS imagery and the hydrological model. The median value and the 10^{th} - 90^{th} percentiles are depicted.

Flux	2002-2011[1]	2009[2]	2007[3]
Total discharge Q2	3.18	2.54	3.9
Total rainfall R	0.06	0.03	0.11
Total overland flow L	0.09	0.08	0.08
Total inflow (Q2+R+L)	3.33	2.65	4.10
Total discharge Q3	2.95	2.52	3.49
Total evapotranspiration E	0.12	0.04	0.20
Total infiltration I	0.22	0.08	0.39
Total outflow (Q3+E+I)	3.29	2.64	4.08

Table 20: Annual water balances, calculated from the median values of TIM (km3). [1]mean; [2]minimal value; [3]maximal value.

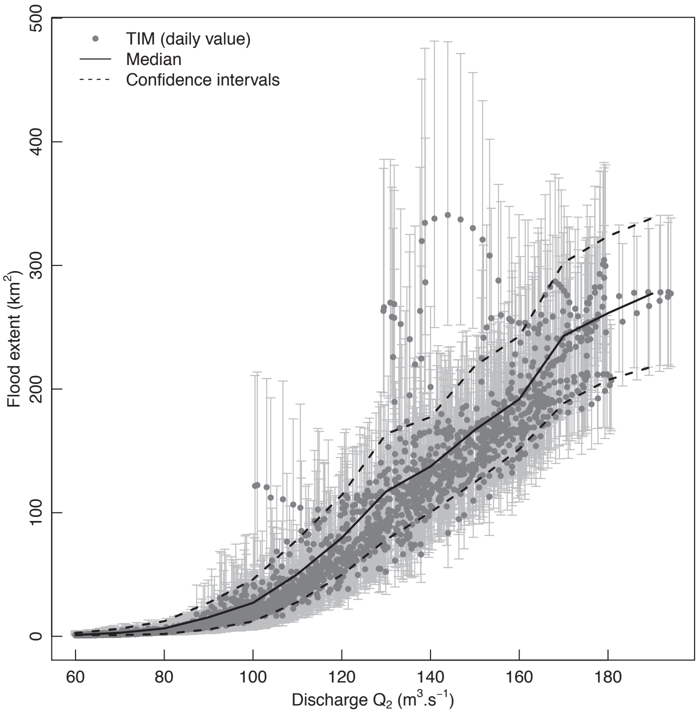


Figure 43: Relationship between discharge at the delta inlet Q2, and flood extent A, as computed by TIM. Error bars depict the 10th and 90th percentile values. "Median" and "Confidence intervals" depict the median values calculated from the median, 10^{th} and 90^{th} percentiles of TIM.

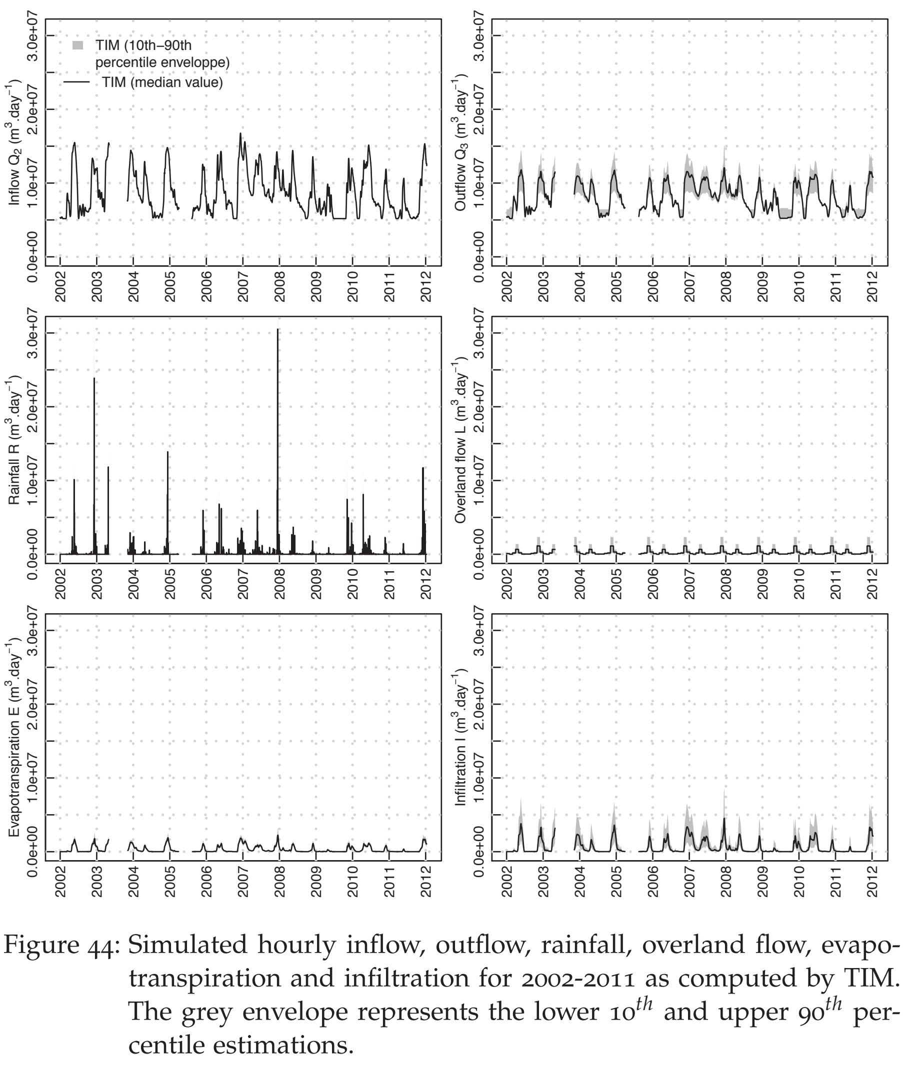


Figure 44: Simulated hourly inflow, outflow, rainfall, overland flow, evapotranspiration and infiltration for 2002-2011 as computed by TIM. The grey envelope represents the lower 10^{th} and upper 90^{th} percentile estimations.

6.7 DISCUSSION AND CONCLUSIONS

6.7.1 *Remotely sensed detection of flood extents*

The $NDWI_{Gao,M2-5}$ index properly distinguished the low-lying vegetated flooded surfaces from dry surfaces. Furthermore, this index can be calculated from many of the MODIS products, as well as from other optical sensors, such as LANDSAT, making it a good candidate to monitor flooded surfaces with low-lying vegetated cover, which is typically found in wetlands.

The use of the MYD09A1 composite product from the MODIS instruments allowed the characterization of the state of the surface despite a high cloud-cover. In particular, it gave the first estimation of the spatial flooding pattern and a time-series of flood extents, that are in good agreement with the water balance model. The disadvantages concerning its medium spatial resolution and 8-day uncertainty range are counter-balanced by its availability and high temporal resolution compared to many other satellite products. It can therefore be used in combination with the latter to characterize and monitor floods in medium- to large-scale wetland complexes.

6.7.2 *The Tana Inundation Model*

The use of a lumped model in combination with satellite data is a first-step in quantifying the flooding characteristics in the poorly gauged wetlands of the Tana River Delta. By doing so, this paper contributes to the growing literature on the use of hydrological modeling in ungauged basins and follows previous recommendations to use "tailor-made" and "site-specific" models (Savenije 2009).

The water balance approach adopted here was relevant to study the TRD system, for which information on the internal properties and processes was limited. The global fluxes generating floods and the flooding characteristics in the deltaic floodplains were quantified. These results have relatively high uncertainty ranges linked to the lack of essential data, such as a Digital Elevation Model and the scarcity of recent discharge measurements within the delta. Moreover, because of the chosen evaluation metric, the relative uncertainty for the low inundation extents is larger than for the high values. The model should therefore be better at capturing large flooded areas. Finally, the annual water balance confirms that the river discharge coming from Garissa, and therefore the upper basin, is the major process controlling the flooding events within the Tana River Delta.

In the future, semi-distributed or distributed models could be developed for the TRD. This study helps define which data are essential but unavailable in the zone, so that future research efforts concentrate on the acquisition of such data. Regular discharge or water level measurements at the inlet, outlet and other strategic locations (channel bifurcations, etc.) should be undertaken. A precise topographic map is necessary to describe the volume-area-water level relationships and hence the channel-overland flow dynamics. Lastly, in-situ or satellite measurements of flood extents are essential for parameter estimation and validation of future models.

6.7.3 *Management issues*

This study determined the major propagation characteristics within the Garissa-Garsen stretch. An understanding of these characteristics is essential for the management of water resources. These characteristics seem to have remained identical throughout 1963-2011, despite the construction of five dams. This finding is particularly interesting in the context of hydroelectric infrastructure development because it supports the idea that dams could have modified the volume of transiting water (Maingi and Marsh 2002) but not the propagation characteristics.

TIM provides an ensemble of flooding characteristics (flood extent, duration, timing, frequency of occurrence) that are essential in flood forecasting. The discharge-flood extent relationship also enables a rapid estimation of flood extents, which is information that can be used to monitor or predict floods in the delta. The MODIS images give complementary information concerning the spatial flooding patterns, which are also crucial for wetland monitoring. These images could be used to define the current flood-prone zones. Finally, this study highlights the idea that river fluxes are the main generator of floods within the delta. This result is important in the current context of hydroelectric infrastructure development on the Tana River.

Together, the results and the model developed in the study can help predict the consequences of the modification of the hydrological regime of the river on flooding events in the delta. Such prediction is essential because many ecosystems and local communities are dependent on the dynamic flooding regime of the Tana River.

Part IV

FOCUS 3: THE FODDER PRODUCTION

In the two previous parts, the general hydrological characteristics of the TRD and the growth processes of the floodplain grasslands were described. In this last part, I present a preliminary study on how this knowledge can be used to discuss the effects of changing hydrological regimes on the service of fodder production. There are however applicability limits relative to the previous results, which I explain in a small introductory section. I then focus, in **Chapter 7**, on calculating indicators of the ES of fodder production for different flooding scenarios representative of the past, the present and the possible futures.

Figure 45: An Orma woman preparing to milk one of her two cows. May 2009.

CHAINING THE HYDROLOGICAL AND PLANT GROWTH MODELS: JUSTIFICATION, CURRENT LIMITS AND THE WAY FORWARD

To study the effect of floods on fodder production, information is required relative to the hydrology and the growth processes of the floodplain grasslands. The previous chapters showed that flooding characteristics are important. Linking the growth patterns directly to the hydrogramme would add another level of understanding and bring answers to questions such as: what is the minimal discharge rate at which the grasslands are flooded? What type of hydrogramme is necessary to maintain the grasslands as prime grazing lands?

At this stage of the study, this practical implementation is not possible for several reasons. Firstly, the hydrological study was done at the scale of the delta and not of the grasslands. As it is not spatialized, the hydrological model does not indicate when the 200 km^2 of grassland are flooded. Secondly, biomass data at the scale of the floodplains, in combination with discharge rates and flood extents, are not available and are necessary to verify the results from the experimental plot. Thirdly, combining the models would also generate other challenges. Models both need to be at the appropriate timestep and feedbacks may need to be taken into account. Processes modelled in each sub-model should also be within the same order of magnitude (e.g. infiltration and evaporation). Uncertainty needs to be propagated: high uncertainty within the leading model generates large forks of uncertainty for the final outputs. Chaining the models would require that new parameters be defined, for which a rigorous sensitivity analysis should be provided. Without these steps, chaining the two models could lead to an erroneous estimation of the type of hydrogramme necessary to maintain pastureland within the delta.

Without going into the processes described above, it is none the less possible from this study to determine part of the hydrogramme-flood-growth-indicators equations The hydrological study gives the general characteristics of the floods, with an estimation of their duration, frequency and extent. Past and future hydrological infrastructure can have an impact on these, but within a maximal range determined by the rainfall within the catchment. From these flood characteristics, possible scenarios of change can be determined. The objective of the next section is to understand how the number of floods, their extent and duration can impact grass growth and the resulting ES of fodder production.

7

QUANTIFICATION OF THE IMPACT OF FLOODS ON THE ECOSYSTEM SERVICE OF FODDER PRODUCTION OF A FLOODPLAIN GRASSLAND

7.1 INTRODUCTION

The Tana River Delta (TRD), located in coastal Kenya, has recently been designated as a Ramsar site (Ramsar 1971). Its wetlands and adjacent ecosystems have a high biodiversity value with numerous vulnerable species (Hamerlynck et al. 2010; Hamerlynk et al. 2012). The wetlands also sustain some 100 000 people from the Orma and Pokomo communities (Republic of Kenya, Central Bureau of Statistics 2010) who use them to farm, fish, graze livestock, collect wood and local plants and hunt (Leauthaud 2009). Despite its productive potential, the TRD is one of the poorest parts of Kenya (United Nations Development Programme 2010) and has been the site of lethal conflicts over land and water during the last decade.

The past fifty years have brought major changes to the deltaic ecosystems and livelihoods of the local populations (Leauthaud et al. 2013a). In particular, the flooding regime of the river has been modified following the construction of hydraulic infrastructure (Maingi and Marsh 2002). Five dams have already been constructed and a sixth dam is planned for the near future that will further modify the hydrological regime.

Yet, floods provide important services (Hamerlynck et al. 2010) like the regeneration of forests, floodplain recession rice farming, grazing grounds for livestock, fishing and ground-water recharge. During the rainy seasons, the Tana River can overflow into its deltaic floodplains and give rise to important floods. A previous hydrological model provides the flood characteristics in the TRD for 2002-2011 (Leauthaud et al. 2012): it was estimated that the annual water input to the TRD was on average 3.3 km^3, of which approximately 96 % came from the river. Floods exceeding 200 km^2 occurred on average every two years, and lasted up to 44 days. The maximal calculated flooded surface exceeded 560 km^2.

The central floodplain grasslands, occupying an area of 200 km^2, are some of the most flooded zones of the delta. They are strategic grasslands for all the pastoralist communities of the region (Emerton 2003) as they are very productive compared to the surrounding grasslands (Leauthaud et al. 2013a; Leauthaud et al. 2012) and provide counter seasonal grazing grounds. An aerial survey in June 2010 (from Kenya's Department of Resource Surveys and Remote Sensing, DRSRS), just after an important flood event, showed that over 75 000 Tropical Livestock Units (TLU) were grazing within the Tana Delta grasslands (Figure 6). A large part of the livestock from the whole district (> 38 000 km^2) were concentrated within the deltaic floodplains and their surroundings. In parallel, Emerton (2003) estimated that over 2.5 million livestock depended on the Tana River's grasslands (deltaic and riverine floodplains) for dry-season pasture and water.

Past hydrological changes have already altered the TRD ecosystems. Land and water ressrouce scarcity have led to recent ltham conflicts in the zone, while future large-scale agricultural and biofuel projects are planned. It is important to assess the overall benefits that the deltaic environment provides for these different development scenarios. In particular, the impact of past and possible future changes of the flooding patternneed to be assessed. This study focuses on quantifying the impact of changing flooding patterns on the annual fodder production of the central floodplain grasslands of the TRD. Using our current knowledge on the grasslands and the hydrology of the TRD, simple flood and management scenarios representative of the past, present and possible futures are defined and indicators relative to yearly fodder production are calculated.

7.2 METHODOLOGY

To define flooding scenarios and their impact on fodder production, a 4-step approach was used:

1. define the range of possible natural and controlled flood events that occur in the TRD.
2. define contrasted flood and management scenarios, representative of realistic past, present and possible future events.
3. define important characteristics of fodder production using simple indicators.
4. and calculate the indicators of fodder production for the different scenarios.

7.2.1 *Linking the hydrogramme to the floods: defining possible flood events*

The number of floods, their extent and their duration are important hydrological characteristics that determine the annual fodder production of the floodplain grasslands. Floods occur twice a year in the TRD under natural conditions. As flood extent can exceed that of the grasslands, the maximal extent of central grasslands to be flooded is equal to 200 km^2. To simulate a wide variety of situations, zero to two floods a year, of different durations (0, 15 and 40 days) and extents (0, 50 and 200 km^2.) that are representative of those currently found in the TRD were chosen. The construction of a sixth dam could lead to a further control of the hydrological regime. In this situation, small floods could be artificially created at different times of the year, depending on the dam management strategies and the climatic conditions. Here, two small releases during both of the rainy seasons (50 km^2, 15 days each) were also selected.

7.2.2 *Construction of scenarios*

Nine scenarios, corresponding to possible past, present and future conditions were tested (Table 21).

- S1 mimics a drought year with reduced rainfall and no floods. This would occur during dry years like the La Nina years. Rainfall was reduced to 30 % of its original value.

- S2 corresponds to a year with no floods and average rainfall. This type of scenario occurs frequently with the current levels of infrastructure or could occur more frequently if another dam were constructed without any programmed flood releases.

- S3 to S6 correspond to years for which one flood occurs either during the long rainy season (LRS) from April to June or during the short rainy season (SRS) from November to December. Two different flood types were simulated corresponding to a small flood (S4 and S6) where only 50 km^2 of grassland is flooded for a duration of 15 days and a large flood (S3 and S5) where the whole central floodplains (200 km^2) are flooded for 40 days. The former correspond to what happens currently every two years on average. With a natural flow regime (no dams), this could be assimilated to flood events occurring during relatively dry years. On the opposite, if new dams were constructed, these scenarios could be reproduced through flood releases.

- S7 corresponds to a scenario with two floods of 200 km^2 occurring for 40 days each during both the LRS and SRS. Scenario S7 is close to past conditions with no infrastructure.

- S8 corresponds to a situation where the construction of a dam leads to managed flood releases. Two small releases during both of the rainy seasons (50 km^2, 15 days each) were selected as possible flood events.

- S9 corresponds to an alternative scenario where dry season irrigation is tested as an alternative to floods. Irrigation of the grasslands could be undertaken by individual pastoralists who would invest in small water pumps, or collectively. In both cases, due to the investment and water availability during the dry season, it would be limited to small zones and short durations. An irrigation of 20 km^2 of grassland once every 8 days (supplying 80 mm) just after the rainy season for 48 days was chosen as a representative scenario.

7.2.3 *Linking grass growth to fodder production: defining indicators*

The performance of grazing animals is controlled by several factors, mainly their genetics, their health status and their nutrition (Lambert et al. 2000). Concerning nutrition, the amount of pasture that an animal can eat (its intake) and the quality of their food (their nutritive value) are major determinants of live-weight gain, milk and fiber production, health and the reproductive performance of livestock (Lambert et al. 2000). In pastoralist societies, where livestock are mobile and forage for themselves, the availability of fodder throughout the dry season is also important as it determines the survival rate of the cattle from one year to another. The quantity, quality and availability of fodder in the TRD all depend on the flooding regime of the Tana River (Chapter 4 and 5).

Three indicators were chosen to assess the impact of various flood and management conditions on fodder production:

1. The amount of fodder produced, corresponding to the cumulated aboveground dry biomass (AGDB) removed from the grassland system through the action of grazing.

2. The quality of the pasture. The energy content of the grass and its N content are important concerning the quality of the fodder. Leaf N concentration is high throughout the year, with an average of 1.7 % (**Chapter 4**). N is probably also available from other sources, including the invasive species *Prosopis juliflora* (in drought years, women collect its pods to complement the livestock's nutrition). The energy content of *Echinochloa stagnina* is globally high (François et al.,1989), and can been measured by the amount of Feed Units (UF) provided per kilgramme of fodder (1UF corresponds to 1 kg of mature grains of barley). UF values for *Echinochloa stagnina* were between 0.53 $UF \cdot kgDM^{-1}$ and 0.78 $UF \cdot kgDM^{-1}$ for flooded stems, 0.42 $UF \cdot kgDM^{-1}$ to 0.66 $UF \cdot kgDM^{-1}$ for flooded leaves, 0.51 $UF \cdot kgDM^{-1}$ to 0.54 $UF \cdot kgDM^{-1}$ for grass that was flooded in the previous 72 days and of 0.38 $UF \cdot kgDM^{-1}$ to 0.4 $UF \cdot kgDM^{-1}$, 72 days after the end of the floods (François et al.,1989). Following these figures, the total amount of fodder units produced for the different scenarios was calculated using the decision tree presented in Figure 46.

1. The availability of fodder during the dry seasons. In pastoralist systems where livestock forrage for themselves, the dry seasons are bottleneck periods during which the health of livestock

Type	No floods		One flood per year				Two floods per year	Water management	
Scenarios	S1 "Dry year"	S2 "No floods"	S3 "Extensive flooding LRS"	S4 "Small flood LRS"	S5 "Extensive flooding SRS"	S6 "Small flood SRS"	S7 "Pre-dam"	S8 "Managed flow"	S9 "Irrigation"
Rain	- 30 % precipitation	Standard	Standard	Standard	Standard	Standard	Standard	Standard	Standard
Floods during the long rainy season	-	-	200 km^2, 40 days	50 km^2, 15 days	-	-	200 km^2, 40 days	50 km^2, 15 days from 01/05 & 01/06	-
Floods during the short rainy season	-	-	-	-	200 km^2, 40 days	50 km^2, 15 days	200 km^2, 40 days	50 km^2, 15 days from 01/11 & 01/12	-
Irrigation	-	-	-	-	-	-	-	-	80 mm every 8 days (01/07-25/08 & 01/01-10/02) on 20 km^2

Table 21: Simulated flood and management scenarios (S1 to S9), described by their types, rain, flood extent and duration, and irrigation.

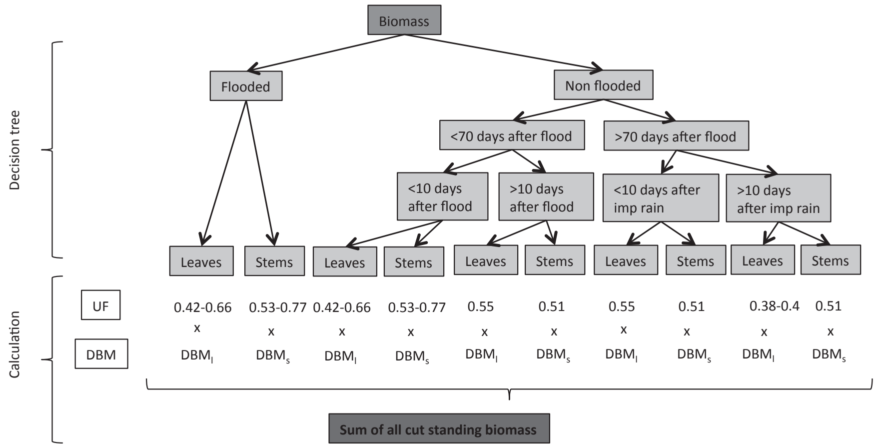


Figure 46: Decision tree to calculate the quality of the fodder. At each cutting date, flooded and rainfall conditions are determined for which Fodder Unit (UF) values are defined (François et al.,1989). Each sampled Dry Biomass (DBM) is then multiplied by this value, and the final value of the indicator calculated as their sum.

can deteriorate rapidly. Increasing the days where grass growth is available at a minimum therefore shortens this period. The number of days during which grass growth is very low was calculated as the number of days where the Net Primary Production (see **Chapter 5** for definition) of the grasslands did not exceed 10 $kgDM \cdot ha^{-1} \cdot day^{-1}$.

7.2.4 *Linking floods to indicators: calculation procedures*

A plant growth model for floodplain grasslands (**Chapter 5**) calculates the daily dry biomass growth of plant leaves, stems and roots. It was used to calculate the annual quantity, quality and availability of pasture on an assumption of grazing rate. To simulate grazing, aboveground dry phytomass was removed periodically from the modelled plant system. To stay within the validated range of the plant model, grazing during the non-flooded period was considered equivalent to cutting the grass to its minimal value (50 $kg \cdot ha^{-1}$) every 16 days, and no grazing was simulated during the flooded periods. The former corresponds to a grazing event evert 16 days during which the cattle ingest all the available phytomass. For the same reason, AGDB was cut to its minimal value the day following each flood. These conditions are close to those found within the TRD: the grasslands are grazed continuously during the non-flooded seasons and grazing within the floodplains is limited during the floods. The quantity of fodder produced corresponds to the cumulated AGDB removed by the cattle from the grassland. Stem and leaf dry mass removed for each grazing event were used to calculate the cumulated amount of UF produced for each scenario.

By recharging the soil with water, floods extend the growth period of the grasslands compared to a non-flooded situation. The current plant growth model does not reproduce this event accordingly (underestimation of AGDB after the floods for the non-irrigated modality, cf **Chapter 5**). For a similar grassland and soil type, in the Interior Delta of the Niger River, this drying phase was estimated at approximately 20 days (François et al., 1989). The number of days where growth exceeds 10 $DMkg \cdot ha^{-1}$, as calculated by the model, was corrected assuming that growth exceeds this value during the 20 days following a flood event.

The model was run on a hypothetical year (from 01/03 to the 28/02) during which only flood duration and the amount of rain or irrigation were changed according to each scenario. Even though rainfall could modify solar radiation or air temperature, identical climatic variables were used for all the scenarios as the aim is to assess the effect of the floods. Input data for the grass growth model were daily rainfall, minimal and maximal air humidity, minimal and maximal 24h air temperature, cumulated 24h solar radiation as well as flood extent and duration (as defined in the previous section). Floods were centered on the 01/06 or 01/12, corresponding to mid-rainy seasons. Precise specifications of the model have already been given in **Chapter 5**. Climatic data were obtained from the closest weather station (TDIP, 2°18′51.08"S, 40°12′39.84"E, 30/11/2011-29/10/2012). Missing data were linearly interpolated and ten-day moving averages were used for the radiation, temperature and humidity. For these simulations, rainfall from 01/08 to 01/10 and from 01/01 to 28/02 was set to zero. The growth model was run from 04/12 so that initial soil water content corresponds to that used during the calibration and validation process so that it was not necessary to re-calculate the initial soil water content.

The model provided an uncertainty range linked to the estimation of parameters with an upper and lower boundary (**Chapter 5**). The lower (respectively higher) estimation of the indicator was obtained by using the lower (higher) boundary of the plant model. The indicators are calculated for the whole period of simulation, i.e. one year.

7.3 RESULTS

7.3.1 *Description of scenarios*

During the non-flooded periods, grass growth occurred primarily during the rainy seasons, with a maximal AGDB of 560 - 670 $kg \cdot ha^{-1}$. Maximal simulated AGDB was attained for S5, at 4 - 5.2 $T \cdot ha^{-1}$ during a flooded phase of 40 days. For the flooded phases of 15 days, maximal AGDBs were variable, with values ranging from 0.95 - 1.14 (S6) to 2 - 2.36 $T \cdot ha^{-1}$. Mean daily growth rates varied from 11.5 $kg \cdot ha^{-1} \cdot day^{-1}$ (S1) to 33 $kg \cdot ha^{-1} \cdot day^{-1}$ (S7). Maximal Net Primary Productivities ranged between 200 and 250 $kg \cdot ha^{-1} \cdot day^{-1}$ for S5 and S7.

The 20-day period during which AGDB is underestimated by the plant model are depicted on Figure 47. Depending on the flooding characteristics, this period was more or less located within a rainy season.

7.3.2 *Effect on quantity indicator*

The total amount of removed AGDB for each scenario for the 200 km^2 of central floodplains is depicted in Figure 48 and summarized in Table 22. Minimal and maximal production ranged from $69 \cdot 10^3$ - $105 \cdot 10^3$ to $216 \cdot 10^3$ - $289 \cdot 10^3$ for S1 and S7 respectively. For this indicator, at the yearly scale, four types of scenarios appear:

1. low production (S1) when no floods occured and rainfall is limited.
2. medium production (S2, S4, S6, S8 and S9), for which cumulated AGDB ranges from $97 \cdot 10^3$ - $143 \cdot 10^3$ to $113 \cdot 10^3$ - $161 \cdot 10^3$ T.
3. high production corresponding (S3 and S5), with cumulated AGDB ranging between $152 \cdot 10^3$ - $210 \cdot 10^3$ and $163 \cdot 10^3$ - $223 \cdot 10^3$ T.
4. extremely high production (S7) ($216 \cdot 10^3$ - $289 \cdot 10^3$ T).

Scenarios with short flood durations (S4 and S6) do not increase this indicator compared to an average non-flooded year (S2). Similarly, irrigation as specified here does not increase production compared to S2.

7.3.3 *Effect on quality indicator*

The energetic value of the fodder for the different scenarios ranged from $33 \cdot 10^3$ - $47 \cdot 10^3$ to $67 \cdot 10^3$- $117 \cdot 10^3$ UF. The same groups as those described for the quantity can be distinguished, although the differences between the categories are not as constrasted (Figure 49). S1 and S7 remain the extreme scenarios, and S2, S4, S6 and S8 cannot be distinguished from each other using this indicator.

7.3.4 *Effect on availability indicator*

The indicator of availability ranged from 144-183 to 208-233 days. Minimal and maximal values ranged were attained for S1 and S9 (Fig-

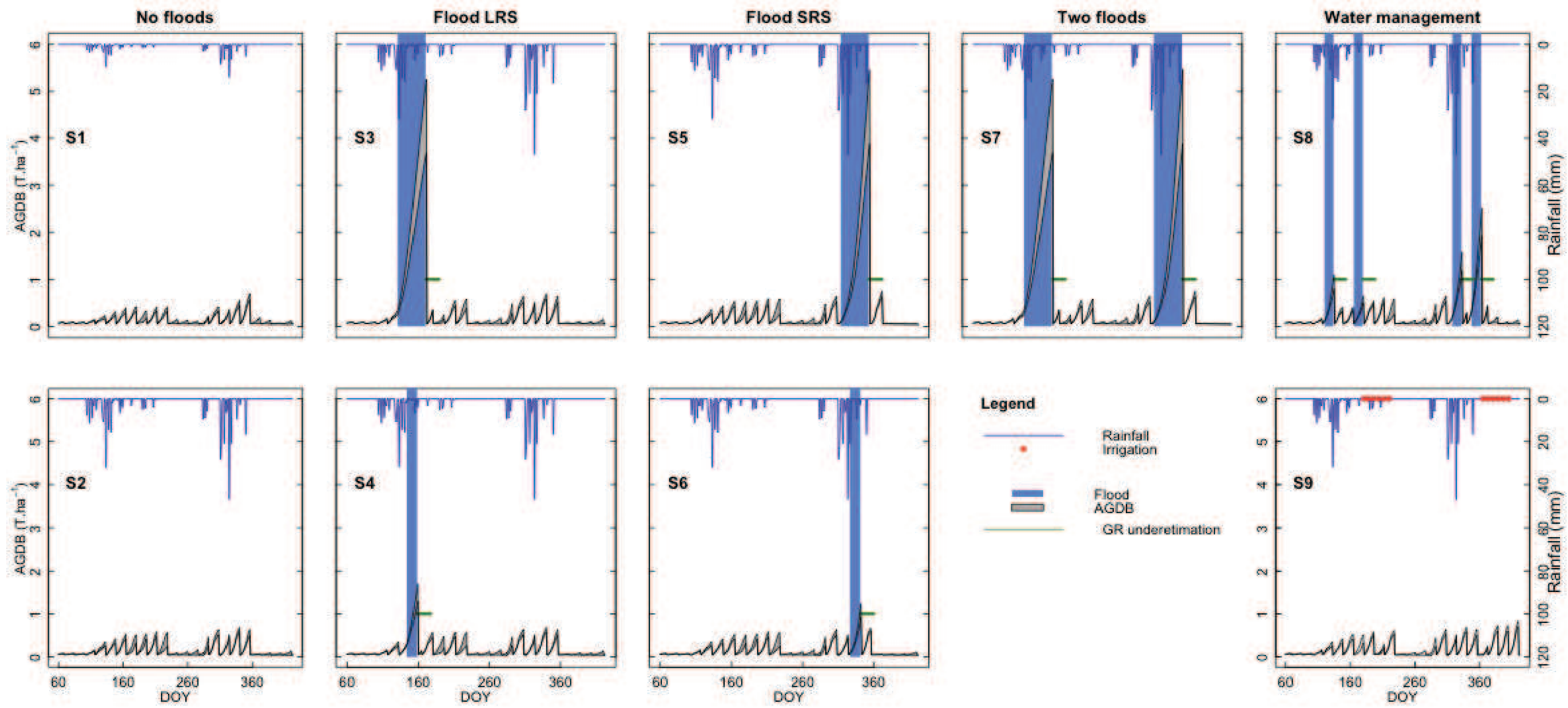


Figure 47: Daily Aboveground Dry Biomass (AGDB) for each of the nine simulated scenarios, represented by their rainfall, flood and irrigation characteristics. GR: growth rate; LRS: Long Rainy Season; SRS: Short Rainy Season.

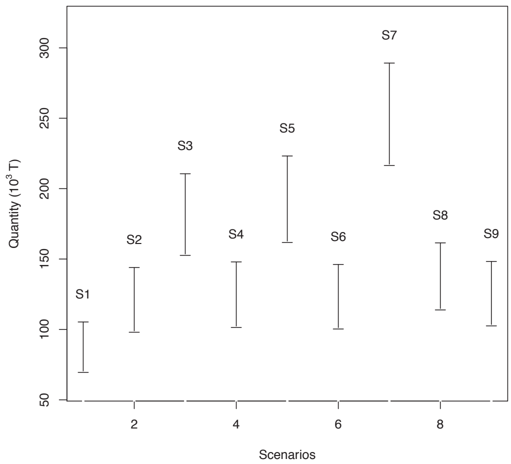


Figure 48: Yearly fodder production of the 200 km^2 of floodplain grassland for each of the nine simulated scenarios, representing the quantity of fodder produced as a first indicator of this ecosystem service.

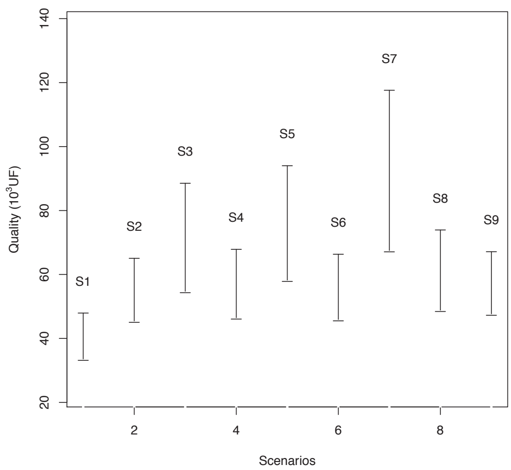


Figure 49: Yearly production of fodder units (UF) of the 200 km^2 of floodplain grassland for each of the nine simulated scenarios, representing the quality of fodder produced as a second indicator of this ecosystem service.

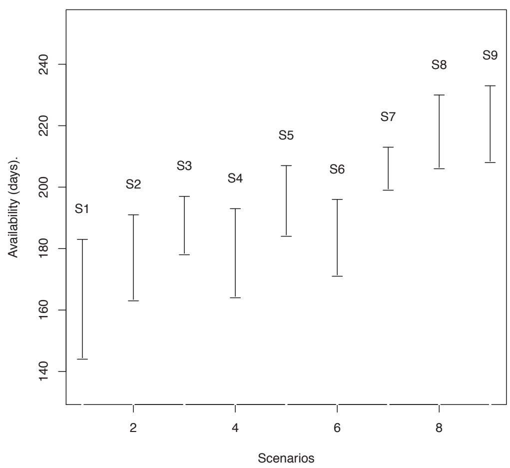


Figure 50: Total number of days in a year where Net Primary Production exceeds 10 $DMkg \cdot ha^{-1}$, representing the availability of fodder produced throughout the year as a third indicator of this ecosystem service.

ure 50). For S1, grass was not available for at least half of the year. In a non drought situation (S2), this availability slightly increased. S4 and S6, corresponding to unmanaged floods of short duration, did not increase the availability compared to S2. S3 and S5 slightly increased availability, with a maximal value of 184-207 days for S5. Differences between S3 and S5 can be due to the relative timing of the floods and rainfall. S7, S8 and S9 have the highest availability indicators with respectively 199-213, 206-230 and 208-233 days during which grass growth is sustained. This is because all three scenarios prolongate the grass growth period after the end of the rain.

7.4 DISCUSSION

7.4.1 *Approach*

In this study, nine different scenarios defined according to the past, present and possible futures were defined. It is a rather simplified representation of reality. However, it captures the major trends in fodder production and outlines the major differences between the different types of years simulated.

This study focused on the 200 km^2 of central floodplain grasslands found near the Bilissa Boka lake in the Tana River Delta. However, the grassland formation of *Echinochloa stagnina* extends beyond this central zone as a patchy formation mixed with wooded bushland. The extent of this patchy grassland has not yet been determined but it could double the current floodplain grassland area. Furthermore, in the past, a former river channel was more active and flooded the western side of the delta so that the grassland extent could have been higher. In these conditions, as the quantity and quality of fodder mainly depend on the extent and duration of the floods, the resulting indicators of the scenarios could even more contrasted.

Yearly production for the non-flooded scenarios are slightly higher than production estimations from other rain-fed pastures in Africa (0.8-2.5 $T \cdot ha^{-1} \cdot yr^{-1}$, Penning De Vries and Djitèye 1982). This could reflect differences in the other climatic variables or possibly be due to the absence of C3 plants within the TRD formation that have lower productivities at high temperatures. The high Net Primary Productivities are close to those found for floodplain grasslands in the Amazon, for which NPP was 259 $kg \cdot ha^{-1} \cdot day^{-1}$ (Piedade et al. 1991).

Even though improvements are possible for the models, they capture the major characteristics of the grasslands. The results of this study however have limits. Firstly, the grazing frequency was fixed at once every 16 days during the non-flooded period. In reality, grazing is continuous during the non-flooded period and the frequency can vary throughout the year. Secondly, the timing of the floods was fixed although the timing can largely modify the availability indicator. Thirdly, François et al. (1989) note that the sugar content of the stems is important which can make the stems appetizing for the cattle (Hiernaux and Diarra 1986). THis aspect was not taken into account to calculate the quality of the indicator. Finally, the plant growth model is not appropriate for extreme flood events linked to the El Niño Southern Oscillation (Bjerknes 1966; Bjerknes 1969) as they could lead to rapid increases of water that could impact the grassland. Similarly, *Echinochloa stagnina* enters an inflorescence and senescence stage after a while under flooded conditions, which is not simulated by the grass model. For this reason, and because the growth model has not been validated for longer flood durations, the duration of a flood was limited to a maximum of 40 days even though it could have been longer before the construction of the dams.

7.4.2 *Defining a best possible scenarios for fodder production ?*

The ranking of the scenarios changes depending on the indicator used. S3, S5 and S7 (one or two long flooded periods), seemed the best scenarios relative to the yearly quantity and quality of fodder produced. On the contrary, S8 and S9, corresponding to managed floods or irrigation, increased most the availability of fodder throughout the year. Actually, there is not one type of best possible yearly scenario, but a whole range of possible management possibilities to optimize livestock keeping activities in the region. It is rather at a pluriannual scale that dam management and livestock keeping strategies need to be considered. The livestock found in the TRD can adapt to drought periods by loosing weight and rapidly regaining it during the rainy seasons. However, frequent dry spells weaken the animals. Furthermore, the choice of a scenario can change depending on the climate conditions of the year, dams management and the provision of other services. In dry years, during which electricity production could become a priority compared to managed floods, small scale irrigation could be an option to increase grass growth during the dry seasons. In this case, the economic viability of irrigation in the TRD would need to be considered.

Alternative scenarios could also be imagined: store fodder produced during the rainy seasons or just after the floods, bring fodder to the cows, sedentarize the pastoralists and convert the grassland to agricultural land, or convert the pastoralists to farmers. These solutions were put forward after the recent conflicts, but the social acceptability of such scenarios needs to be verified. In fact, establishing multiple scenario types underlined the importance of establishing a dialogue between the stakeholders so that a concerted development model can be found that could maximize the benefits obtained from the ecosystems.

7.4.3 *Necessity to downscale and current limitations*

The study was undertaken at a yearly scale at which general indicators of fodder production were calculated. However, most of the livestock are out of the delta during the flooded period so that fodder produced during this period is mostly lost to the cattle. To provide a more realistic determination of the indicators, this study could be downscaled to the non-flooded period. Currently, the grass growth model does not allow this next step, although simplified assumptions about post-flood growth could be used as a first approach.

7.4.4 *Comparison to other services*

The floods and floodplain grasslands provide a wide range of services (Daily 1997). Other than fodder production for livestock, these grasslands are also important fishing grounds during the flooded period and floods can also recharge the groundwater which in turn sustains the adjacent forests and provides drinking water to the villages. The whole range of services would therefore need to be evaluated and the different management scenarios compared. Assuming a fish production of 40-60 kg fish per flooded hectare (Welcomme 1979) and a drainage rate of 0.027 $mm \cdot day^{-1}$ to 1 $mm \cdot day^{-1}$ **(Chapter 2)**, a very simplified estimation of fish production and groundwater recharge are provided in Table 22 for the considered scenarios. Considering these three services, the maintenance of two or at least one flood per year appears as crucial.

By integrating these quantified scenarios into the valuation process of the TRD, the estimation of the whole benefits provided by the wetlands and floods could be improved. To do so, these indicators could be translated into economic terms. Alternatively, a participative approach integrating the stakeholders would not require such a conversion as indicators relative to the quantities as used here would be better understood by the local populations. Finally, the methodology used here could be integrated into a participative approach in which the indicators and scenarios could be defined with the stakeholders and the outcome of the scenarios discussed as a verification process. This may not provide a best possible solution but would open the debate and favour discussion between the stakeholders.

Type	No flood		One flood per year				Two floods per year	Water management	
Scenarios	S1 "Dry year"	S2 "No floods"	S3 "Extensive flooding LRS"	S4 "Small floods LRS"	S5 "Extensive flooding SRS"	S6 "Small floods SRS"	S7 "Pre-dam"	S8 "Managed flow"	S9 "Irrigation"
Quantity of fodder (10^3 T)	69-105	97-143	152-210	101-147	161-223	100-146	216-289	113-161	102-148
Quality of fodder (10^3 UF)	33-47	45-65	54-88	46-67	57-93	45-66	67-117	48-73	47-67
Availability of fodder (days)	144-183	163-191	178-197	164-193	184-207	171-196	199-213	206-230	208-233
Fish production (10^3 kg)	0	0	800-1200	200-300	800-1200	200-300	1600-2400	400-600	0
Drainage (10^3 m^3)	0	0	360-8000	20-750	360-8000	20-750	720-16000	80-3000	0
Ranking of the scenarios	***9 9 9*** 9 9		2 2		***2 2*** 2 2		***1 1*** 1 1	***2***	***1***

Table 22: Quantifiction of three services provided (fodder production, fish production and drainage) by the floodplain grasslands for nine contrasted scenarios. The last line gives the ranking (1: best; 2: second best; 9: worst scenario) of the scenarios for fodder production (for all three indicators, in bold) and for the other services. Rank 2 appears 8 times as scenarios S3 and S6 have identical indicators for fish production and drainage.

Part V

GENERAL DISCUSSION, PERSPECTIVES AND CONCLUSION

The results of this PhD have been given. In **Chapter 8**, I summarize them for each Focus, then give their limits and perspectives. I end with a general discussion on my approach. **Chapter 9** forms the final conclusion.

Figure 51: The floodplains provide multiple services. Photos: C. Leauthaud, S. Krasser, C. Ledéaut

8 SUMMARY OF RESULTS, PERSPECTIVES AND GENERAL DISCUSSION

Fodder production in floodplain grasslands depends on a multitude of processes. Considering its socio-economic and environmental importance for pastoralists in Sub-Saharan Africa, it has been studied from various angles using tools from different disciplines, including agronomy, ecology, geography, while other fields like hydrology or pedology largely contributed to our understanding of the processes. Each discipline addresses different questions and approaches them with their own conception of reality, their own time and spatial-scales and their own tools. These different perspectives enhance our understanding of the grasslands, their processes, and their uses.

This PhD contributes to the understanding of how floods can impact grass growth and the resulting fodder production in an East African coastal wetland. Field work was undertaken in the Tana River Delta, where these questions are relevant. Two models and some preliminary simulations were developed. Scientific questions emerged during and after each step of this research, concerning the approach used, and more generally on model use and development. In these final sections, I first summarize the main results, and give their limits and some perspectives for each section. I then end this manuscript with some general reflections on models and on their use to understand complex systems.

8.1 IN A NUTSHELL

8.1.1 *Contribution to knowledge*

Looking back at the three objectives defined in **Chapter 3**, the contribution to knowledge of this PhD falls within three broad fields (Table 23):

- Ecology/agronomy
  - This research characterized the aboveground biomass production of the floodplain grasslands of *Echinochloa stagnina* (Retz) P Beauv. More specifically, the daily growth rate and annual aboveground biomasse production under different cutting and irrigation treatments were measured in the Tana River Delta.
  - A plant model was developed adapted to floodplain grasslands. In this process, mathematical functions character-

izing the impact of floods on the energy conversion efficiency, on the allocation of photosynthetates within the plant and on the senescence rates of the plants were defined.

- Hydrology
  - A hydrological model was developed in a context of scarce data that contributes to the growing literature on the use of hydrological modeling for prediction in ungauged basins (Sivapalan et al. 2003).
  - I assessed the use of a specific MODIS satellite product (MYD09A1) and of the Normalized Difference Water Index (Gao 1996) to measure flood extent in a cloud-covered zone where water is mixed with flooded vegetation.
  - The hydrological model was calibrated and validated on inundation extent rather than on discharge measurements. Two cost functions to define the quality of the calibration procedure were defined. These are similar to the Nash-Sutcliffe coefficient but use the inundation surfaces modeled and measured with remote sensing techniques rather than the usual discharge measurements.
- Ecosystem service science
  - Two biophysical production functions were constructed and enable a first estimation of the effect of the changing hydrological regimes on the ecosystem service of fodder production at a yearly scale.
  - The ecosystem service framework was implemented in the specific context of the Tana River Delta. This research was socially relevant and user inspired.

In summary, looking at different mechanisms at different levels was of help to get a broader understanding of the determinants and processes that lead to fodder production in the TRD (Figure 52).

8.1.2 *The next step forward*

This PhD explored certain aspects of the linkages between the hydrology and fodder production of a floodplain grassland. Doing so, certain facts were established, while others need further investigation. This research also raised other questions and points out major aspects that still need to be studied. These are summarized in Table 24.

Main result	Related Part of the manuscript
Grass growth rates in flooded and non-flooded situations	2
Grass growth rates under different irrigation and cutting treatments	2
Leaf-Stem allometry relationships	2
Annual aboveground dry biomass for 2011	2
Flood propagation from Garissa to Garsen	3
Use of MYD09A1 and the $NDWI_{Gao}$ to distinguish flooded vegetation	3
Time-series of floods at a medium spatial and temporal resolution (2002-2011)	3
Spatial frequency of the floods (2002-2011)	3
Water balance model (1 reservoir)	3
Mean flood extent, duration and frequency	3
Yearly indicators of fodder production	4

Table 23: Main results of this PhD and their related part in the manuscript.

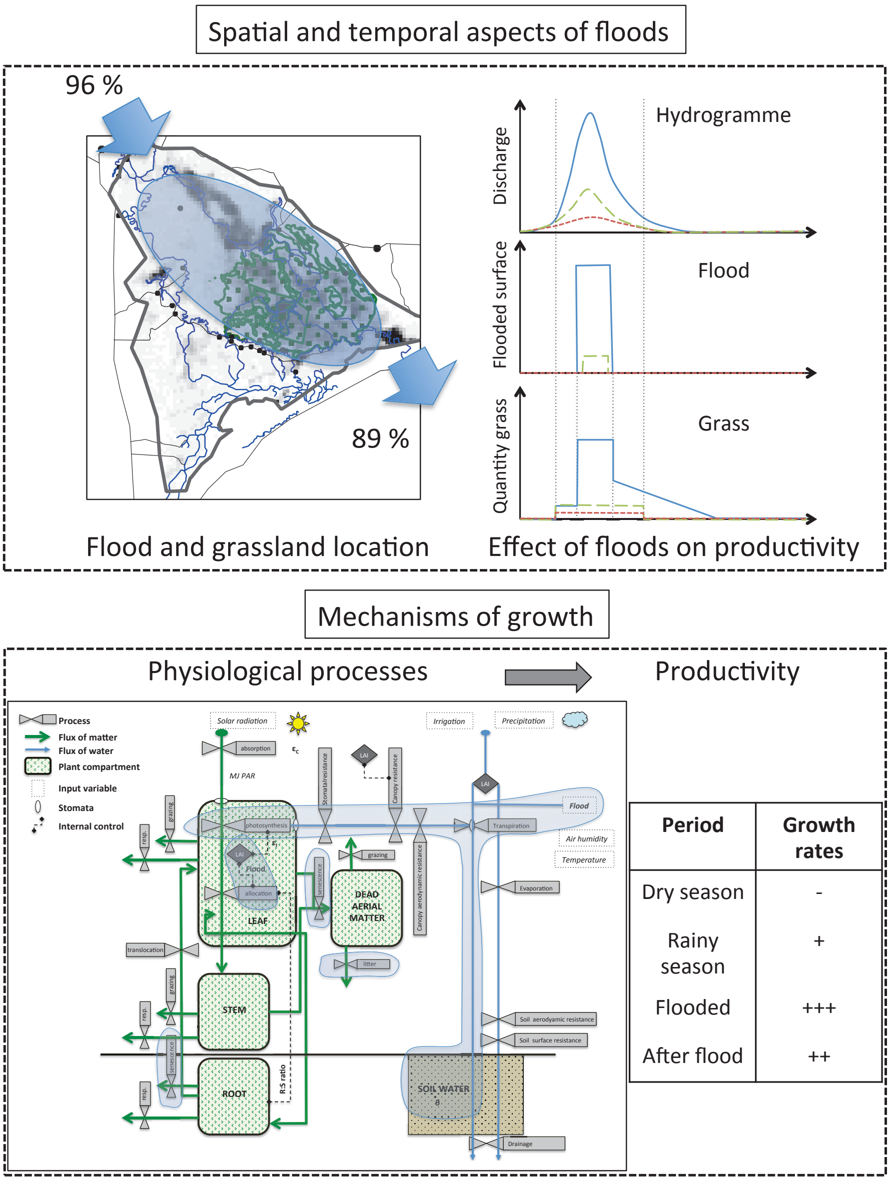


Figure 52: Illustration of the main results of this study. The Tana River is the main provider of water in the Tana River Delta and floods the grasslands (upper left). Different seasonal hydrogrammes result in various flood extents and extremely different productivities of the grassland (upper right). This can be explained by the physiological response of *Echinochloa stagnina* (Retz) P. Beauv. (lower left) and the resulting growth rates (lower right).

Table 24: Further research topics to achieve a complete view of the problematics. Topics are classified per Focus and by main disciplines concerned. Explored: aspects already explored (Y) or not (N) during this PhD.

Focus	Further research	Explored	Hyd.	R.S.	Ecophy.	Eco.	Pedol.	Zool.	E.S.	Geog.	Socio.	Econ.
Grasslands	Effect of flood height, speed and duration	N			x	x						
	Physiological changes for long floods ?	N			x	x						
	Water dynamics in the soil	Y	x				x					
	Root system	Y			x		x					
	Long-term changes in vegetation composition	N				x						
	Effect of floods on plant traits	N				x						
	Effect of livestock other than grazing	N				x		x				
Floods	Past changes in flooded surface	N	x									
	Temporal and spatial resolution of flood characteristics	Y	x	x								
	Grassland flooding characteristics	Y	x	x								
	Topography	N	x	x						x		
	Spatial rainfall patterns	N	x	x								
	Contribution of surface inflow	Y	x									
	Infiltration and underground water	Y	x									
	Discharge rates	Y	x									
Fodder production	Seasonal indicators of fodder production	N							x			
	Explore user-defined scenarios	Y							x		x	
	Fodder production in dry-land grasslands	N		x	x	x			x			
	Livestock movements	N		x				x	x	x	x	
	Quantification of other services	N							x			
	Economic valuation of livestock activities	N							x			x

Hyd: Hydrology; R.S.: Remote Sensing; Ecophy: Ecophysiology; Eco.: Ecology; Pedol: Pedology; Zool: Zoology; E.S.: Ecosystem services; Geog: Geography; Socio: Sociology; Econ: Economy

8.2 SYNTHESIS OF RESULTS AND PERSPECTIVES PER FOCUS

8.2.1 *Growth characteristics of the Echinochloa stagnina grasslands: approach, results, limits and perspectives.*

8.2.1.1 *Approach and results*

At the beginning of the PhD, information relative to the Tana River Delta grasslands was scarce... and even non-existent. The first step of the study consisted in describing them. A botanical survey of the grasslands showed that the grasslands were mainly composed of *Echinochloa stagnina* (Retz) P. Beauv. and *Vossia cuspidata* (Roxb.) Griff.. Secondly, the central floodplain grasslands was delimited using a high resolution satellite image (SPOT).

In a third step, the productivity of the grasslands was measured for different management practices to capture a whole range of growth situations. To do so, I set up an experimental plot to study the effect of floods, irrigation and the frequency of cutting on the standing aboveground biomass. Through a statistical analysis of the data, this study showed that floods have a strong positive effect on grassland productivity during and after the floods. The grasslands also showed adaptations to flooded conditions, including a higher allocation of the photosynthates to the stems. Cumulative annual aboveground dry biomass reached 10 $T \cdot ha^{-1}$ to 45 $T \cdot ha^{-1}$ and maximal daily growth rates exceeded 20 $g \cdot day^{-1}$ under flooded conditions. These high productivities are mainly explained by the floods and irrigation. They are much higher than those encountered in the surrounding semi-arid grasslands. Other than the floods, climate and management strategies also influenced the productivity of the grasslands. Frequent cutting combined with no irrigation led to a very low annual productivity. However, these same quadrates maintained high growth rates during and after the floods, which suggests that intense grazing may not affect the long-term maintenance of the grasslands and their productivity as long as regular floods occur. Interestingly also, irrigation maintained high growth rates during the dry season, which could be an alternative solution to provide fodder during these seasons. This first phase highlighted the important factors that influenced the growth rates of the grasslands.

From this understanding of the grassland, a plant growth model was constructed. In particular, special attention was paid to incorporate the effect of floods on the modelled processes (growth efficiency, senescence and allocation of photosynthetates). As the precise mechanisms were not studied, the model was also based on a literature review on similar grasslands along the Amazon river. The model reproduced reasonably well the seasonal growth patterns observed within the experimental plot. The best adequation between the observed and simulated data was obtained for well-irrigated and frequently cut vegetation, suggesting that further in-depth studies are still required. In particular, adequation was poorer for the post-flood period in the non-irrigated situation.

The added value of the model compared to the statistical analysis done beforehand is to set a physiological basis to our understanding of the processes that describe the growth of the grasslands. It also enables to explore a wider variety of possible scenarios with alternative irrigation, cutting and flood durations.

8.2.1.2 *Limits and perspectives*

The results pertaining to the growth characteristics of *Echinochloa stagnina* (Retz) P. Beauv. were obtained at the scale of an experimental plot with 14 months of data. Even though an attempt to reproduce a variety of situations (different irrigation and grazing states) was made, the results do not capture the complexity of the grassland ecosystem. Livestock also have other effects on the grasslands, including transfer of N and trampling. Trampling of the grasslands just after the floods probably leads to a better regrowth than that observed in the experimental plot, as the stems are pushed into the muddy ground and rerooting would be facilitated. Neither does the study take into account the possible compositional changes of the vegetation.

A better understanding of water movement within the soil would greatly improve the plant growth model. No soil humidity data was available for verification of the current soil module. Due to this, only a simple representation of the soil water was undertaken. Vertisols are however specific soils because of their high clay content. In particular, they crack when drying. In the TRD, these cracks had a width attaining at least 10 cm and a depth that could reach 1.2 m. As such, evaporation does not only take place at the surface of the soil but also within the cracks. Similarly, rainfall penetrates the lower soil horizons directly by the cracks. To model this, the soil could be considered as a juxtaposition of small units that pass from a rectangular shape during the rainy seasons to a trapezoidal prism during the dry seasons, with sides that contribute to evaporation or receive rainfall. Another specificity of vertisols that was not taken into account is their impermeability when saturated: drainage is limited in this situation. When we dug the pit holes in May 2011 to characterize the soil after a small flood that inundated the zone for less than a week, the water front had not reached 2 m in depth.

Another aspect that would require further investigation is their spatial differentiation. In this study, considerations about spatial variations of the grassland formation were not taken into account, as our knowledge on essential hydrological and ecosystem characteristics was too limited. However, the grasslands are not uniform formations. Micro-topography plays an essential role (Figures 63, 64 and

65 in **Appendix D**), with multiple small channels that are a preferential pathways for the water. Even though differences in elevation are probably less than 1 m within the central grasslands, small floods can be contained within these lower zones. This micro-topography could be important at the end of the floods and at the beginning of the dry season as small patches of grass could maintain the availability of fodder throughout part of the dry season.

Data acquisition needs to be continued. Other than the soil water content, collecting biomass samples is essential. Experimental data from this study was essentially taken from one site, then considered as representative of the whole grassland. This assumption needs to be verified, even though this is practically challenging. Similarly, underground phytomass was not measured and now appears as an essential variable to study.

Other approaches to study the grasslands exist and can be implemented in the future. For example, analysis of satellite images could give new perspectives. Knowing the flood duration, it would be possible to see how long grass growth is sustained after the flood by following a vegetation index, such as the NDVI. LAI measurements could also be extracted and integrated into a spatialized growth model, either as a calibration/validation of the model or to update the model. Specific measurements of $C0_2$ absorption, photosynthesis and respiration at the plant level would strengthen our assumptions or maybe invalidate them.

The functional diversity of the grasslands was not taken into account in this study, because the three dominant species have basically the same functional traits. However, functional diversity can control soil water availability and comes into account when considering the quality of the fodder produced (Le Roux et al. 2008). Water quality can also be influenced and the control of invasive species can also increase with species richness. Growth models based on functional traits have been developed for grasslands (Duru et al. 2009). Such an approach could highlight the adaptive traits of the grasslands to both flooded and semi-arid conditions.

Finally, a comparison between the deltaic grasslands and the adjacent dry-land grasslands would be interesting. Figure 53 shows that the NDVI value of the delta is most of the time higher than that of the surrounding zone. Understanding the transhumant patterns to and from the drylands and floodplain grasslands, the former's fodder quantity, quality and availability, the influencing climatic variables and their changes in recent years would help understand the livestock keeping strategies as an ensemble.

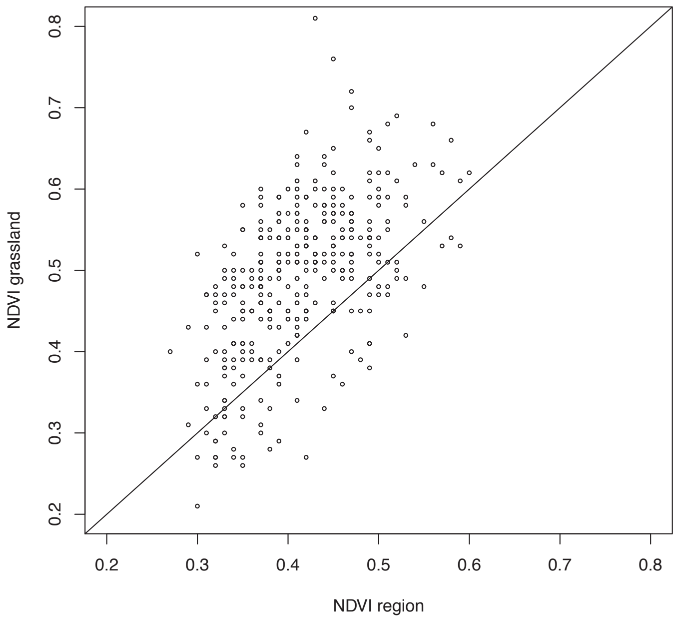


Figure 53: Mean monthly NDVI values of the central zone of the Tana River Delta versus those of the surrounding 100 km radius region for 1982 to 2009. Dots represent the NDVI values of these two zones at different dates. The NDVI value for the central part of the Tana River Delta is often higher than that of the region. Data extracted from the NOAA/AVHRR and MODIS satellites, during a collaboration with the PEL department of ILRI.

8.2.2 *Flooding characteristics of the Tana River: approach, results, limits and perspectives.*

8.2.2.1 *Approach and results*

I then explored the flooding dynamics of the Tana River. The main challenge that arose was the lack of data as only historical discharge rates were available at Garsen, and remote sensing studies were limited due to high cloud cover. The water balance model was instrumental to get a general understanding of the flooding dynamics. To calibrate and validate the model, two preliminary studies were necessary, which can be seen as results of their own.

1. Upstream discharge data at Garissa were correlated to the available historical discharge data at the TRD inlet using a non-linear flood propagation model. Between Garissa and Garsen, there is a general loss of 75 % of the volume of the water, and peak discharge decreases, with a variable time-delay going up to two weeks depending on discharge rates.

2. A time series of flood extents was extracted from MODIS satellite imagery. The $NDWI_{Gao,M2-5}$ index distinguished the flooded and non-flooded vegetation with a 8 % error when compared to three sets of verification points from the field, at contrasted stages of flooding. The analysis of the satellite imagery gives a satisfactory spatial representation of the extent of the floods.

Using this data and some simplifying assumptions about the geometry of the delta, I showed that a water-balance approach could give a first estimation of the hydrological processes that occur within the TRD. In particular, I showed that over 95 % of the volume of water arriving within the TRD comes from the river: the river is the major purveyor of floods within the zone. Flood extent, duration and frequency characteristics were determined for the 2002-2011 period. Floods are generally of short duration (5 to 7 weeks for floods over 100 km^2 and have occurred on average once every two years in the past decade.

8.2.2.2 *Limits and perspectives*

The Tana Inundation Model, TIM, was constructed using certain assumptions and specific data which restrict its use.

Firstly, TIM was not spatialized because precise topographic data were not available. The delta was represented as a reservoir with a logistic curve relating the flood height within a unique reservoir to the flooded surface. In reality, the topography of the delta is much more complex, with multiple channels, river banks and various types of soils and vegetation. To explore these spatial characteristics of the floodplains, the model could be improved to include multiple reservoirs. Indeed, the satellite imagery show that floods first occur within the northern zone of the delta before propagating into the southern part (Figure 54). Complexifying the model would require, beforehand, defining the reservoir units based on topographical data. In the research undertaken here, only the MODIS images with less than 10 % cloud cover above the whole delta were selected (app. 70 impages out of over 430). By spatially restricting the study zone to smaller units, more MODIS images would be usable. Indeed, by zooming in on smaller reservoir units, the probability that the sky is clear over some of these units is higher as cloud cover is patchy. The counterpart is that the relative error made when measuring flooded surfaces increases for smaller units, so that MODIS images are of limited use to study very small units. Medium-size reservoirs (I would suggest three to four, see Figure 54) could be defined and studied using the MODIS images. For smaller units, other satellite images with a finer spatial resolution would be required. Integrating multiple reservoirs into the model also poses the problem of defining the transfer processes between the units. Because of the diffuse character of the water flow for flooded periods, these parameters are not measurable and would need to be calibrated using similar assumptions to those in **Chapter 6**.

Secondly, the temporal resolution of TIM is related to that of the MODIS satellite imagery used. As MYD09A1 images are constructed with the best possible pixels (minimal cloud cover and aerosols) within an 8-day window, each pixels is "visioned" in the worst case with a 16-day interval. As such, we cannot expect the model to have a temporal precision better than sixteen days.

A third limit is the temporal validation period of the model. It has been cross calibrated for the 2002-2011 period and would need further verifications before being applied to the historical dataset for which the hydrological characteristics are different (Maingi and Marsh 2002). Furthermore, the flow path of the river changed in the 1990s so that the flooding zones have probably shifted. Finally, simplifying assumptions have been made about the rainfall (at the sub-catchement and local level), infiltration and evaporation processes.

Focusing on the grasslands, TIM also has some restrictions. To take into account the equifinality concept in the parametrization process, and give more flexibility to the equations, to each time-step of the model is related a range of possible flooded surfaces. Mean 10^{th} and 90^{th} percentiles are 65 and 32 km^2 , and there is a maximal difference of 285 km^2 between these two percentiles for the maximal observed peak flood. With a grassland surface of 200 km^2, this model is not precise enough to give flooded surfaces within the grassland, even thought it gives an idea on whether the grasslands are flooded or not. This limitation was to be expected, considering the scarce data

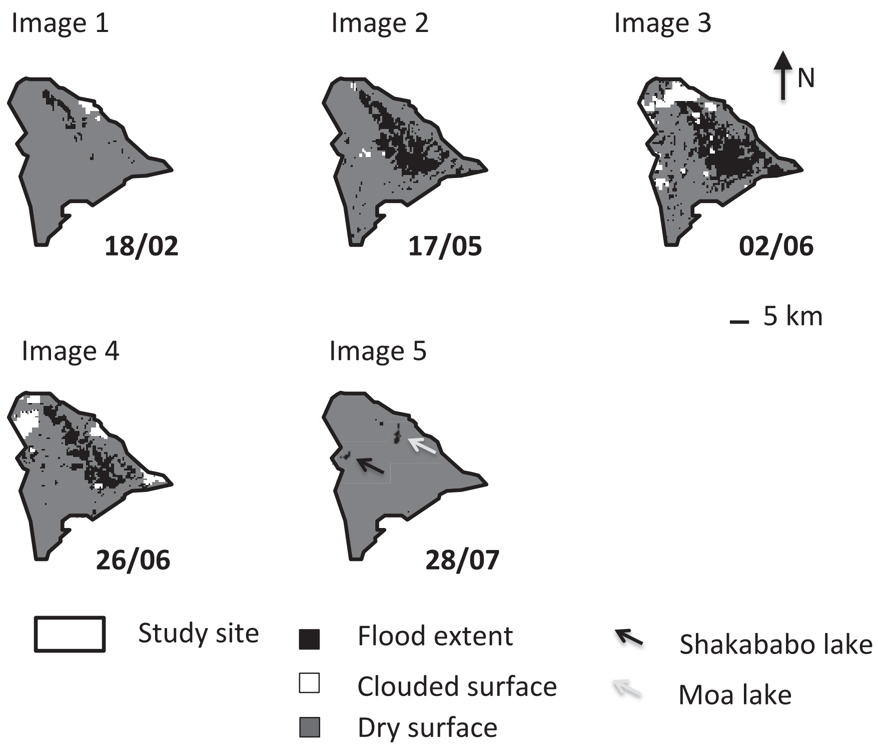


Figure 54: Flooded surfaces as extracted from the MODIS satellite images in 2007, at contrasted stages of flooding. The grey surface corresponds to the study area in Figure 55. One can see that the delta may first be flooded in its upper part (image 1) before flooding the central floodplains (images 2-3). The floods then seem to propagate on the western side (image 3) through the Oda branch, bringing water to Shakababo lake (image 4) before receding (image 5). Shakababo lake stays full after the end of the floods in the central floodplains.

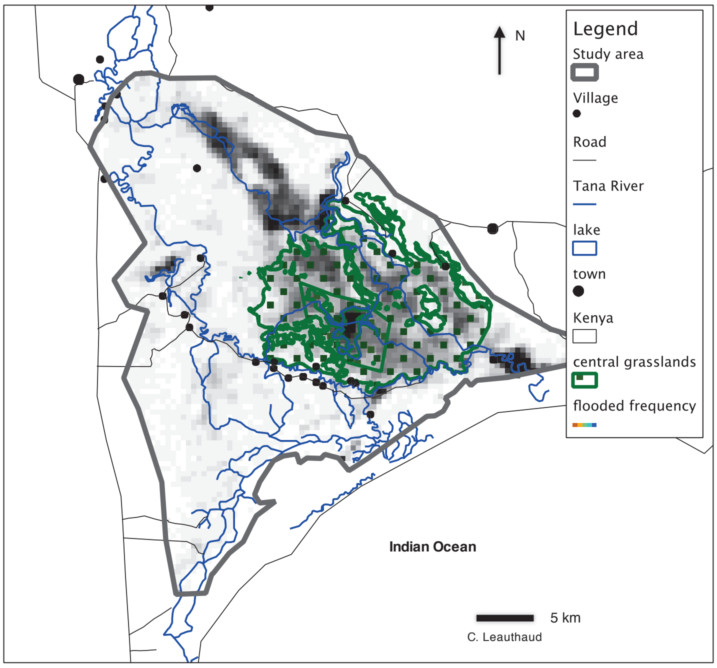


Figure 55: Location of the floodplain grasslands in the Tana River Delta in relation to the flooded frequency of the zone, as calculated in **Part III** of this manuscript.

available (discharge rates 200 km upstream and flooded surfaces of medium spatial resolution from MODIS satellite imagery). All in all, TIM's uncertainties are too high to consider using it solely on the grasslands.

This study however highlights some interesting aspects concerning the hydrology of grasslands. Firstly, the grasslands are within the frequently flooded zones (Figure 55). They are therefore within the lower zones of the topography (not corrected for the hydrological gradient from upstream to downstream) and we can reasonably say that they are among the first zones that are flooded and for which flood durations are the highest. Secondly, the general idea that the river discharge is the main determinant of floods within the delta is also applicable to the grasslands. Changes that impact the flooding regime of the river directly affect the grasslands. Finally, as the presence of floods is an important environmental variable probably limiting the establishment of many non-flood tolerant species, the decrease of flood frequency and height could induce changes in the floristic composition of the grasslands.

Alongside the previously mentioned multi-reservoir model, another promising field is radar satellite technology. Many radar images (like those from the PALSAR sensor aboard the Advanced Land Observing Satellite, ALOS) offer a better spatial resolution than the MODIS products. This is particularly interesting as the temporal resolution would be high enough to precisely delimit the flood extent and flood progress within the floodplains. Additionally, they are not sensitive to cloud cover and can therefore be used in the rainy seasons. Radar altimetry could also give a first measure of the topography by identifying curves of iso-floods. On the other hand, most products historically available have a low temporal resolution, so that few images are currently available. This can be overcome now as some agencies offer the possibility to frequently overfly a required zone so that images could be available at a much better resolution for some flooded periods. Another limit may be their ability to distinguish flooded zones with a high vegetation cover from high-cover non-flooded vegetation, as their reflecting characteristics in the microwave bands could be similar.

These remotely-sensing products also need to go with field measurements of hydrological processes and of the topography. Discharge measurements at minima at the delta inlet are currently being undertaken by the Kenweb/IRD team but need to be extended to other strategic locations (i.e. channel bifurcations). Water height measurements within the floodplain at different flooded periods would also be helpful but are challenging to acquire due to access restraints during the floods (and automatic equipment have a short life expectancy in the zone).

8.2.2.3 *Choice of a conceptual hydrological model*

The choice to construct a conceptual hydrological model at a medium scale resolution was firstly led by the objectives set and the constraints linked to our scarce knowledge of the river and the topography of its floodplains. This can first be considered as a drawback when considering the study as a whole as it was not possible to zoom down to the grassland level. However, this also presented an advantage other than the results made explicit in this study. Indeed, understanding the hydrology of the Tana River is not only essential for the grassland system but for each ecosystem of the delta and basically each service. It recharges the underground system, feeds the livestock, is essential to grow rice, sustains the forests, is needed for fish production, etc. As such, it was important to acquire a better knowledge of the hydrology of the grasslands, but even more for the whole delta. The modeling undertaken here was helps in this direction.

8.2.3 *Coupling the models: limits and perspectives*

This study focused, on one hand, on the hydrology of the TRD, and on the other, on the grasslands, and does not attempt to combine the resulting models. This integration, however, would be the most important from a decision maker's point of view as the hydrogramme would directly be linked to grass growth. Previous to **Chapter 7**, I rapidly explained why the models were not chained. Basically, the temporal and spatial scales at which each model was constructed does not allow it (see also **Section 8.2.2.2**).

This chaining could be done by incorporating multiple reservoirs into TIM. A specific reservoir unit for the grasslands could, and should (as they form a specific topographical entity) be defined, so that water height, flood extent and duration specific to the grasslands could be calculated.

When combining the models, attention would need to be focused on choosing the appropriate time-step, on propagating the uncertainty of the leading models and on the definition of the new parameters. Validation data concerning both the hydrology (flood extent and height) and the plants (standing biomass) would be necessary.

8.2.4 *Scenario building: preliminary study on the effect of floods on the ES of fodder*

8.2.4.1 *Approach and results*

With knowledge acquired on the hydrology and the grasslands, and having defined the limits of the models, my final goal was to take a step back from the precise mechanisms influencing these factors and to understand how the flooding pattern influences the ES of fodder production at the grassland scale.

In doing so, I followed 6 out of the 8 recommendations listed in the research arena of the ES field (**Chapter 1**):

1. implement rigorous measurements, modelling and monitoring of ecosystems functions (Costanza et al. 2011, Seppelt et al. 2011).
    a) A biophysically based grass growth model describing the main processes of growth was used to simulate fodder production. Data acquisitions were performed to validate the model.
2. represent realistic biological processes (Nicholson et al. 2009).
    a) The main biological processes relevant to fodder production were incorporated into the study. Furthermore, realistic hydrological processes were determined from the TIM model.
3. involve stakeholders when defining services and implementing the concepts.
    a) The communities of the TRD were present at each step of the study. During the very first phase (see Appendix A), interviews enabled us to define the major services the ecosystems provided, so that this study focuses on issues relevant to local stakeholders. Grassland monitoring and data acquisitions were also done with them.

   b) We use indicators (e.g. Feld et al. 2009) that are simple enough to be used elsewhere and that englobe the different important aspects of fodder production in a pastoralist society.

4. widen the studies on different services and have a more diverse representation of the ecosystems, and especially in underrepresented parts of the globe (Vihervaara et al. 2010).

5. integrate the measurement of uncertainty (Nicholson et al. 2009).

   a) At different (although not all) steps, the uncertainty relative to the hydrology or the grasslands was incorporated.

6. favour interdisciplinary approaches (Nicholson et al. 2009; Vihervaara et al. 2010).

This final study gives preliminary results on quantifying the effect of floods on fodder production. At a yearly scale, the different scenarios yielded contrasted results showing how floods affect grass growth and consequently fodder production. Alternative solutions were also tested, such as managed floods and irrigation.

Floods appear as a cornerstone to the livestock keeping activities of the TRD. They improve, at the same time, the quantity, the quality and the availability of fodder. In particular, by providing additional fodder during the dry seasons compared to the surrounding zones, they help the livestock keepers pass the bottleneck periods. As such, they appear as the only viable long-term solution for the livestock keepers. However, small-scale, alternative initiatives and solutions could emerge that would improve the situation. For instance, irrigation sustains the growth of the grasslands even during the dry seasons. This solution could be implemented at a smaller scale as an emergency solution.

8.2.4.2 *Limits and perspectives*

As stated in the **Chapter 7**, this study was a first-step analysis aimed at a rapid assessment of the impact of floods on fodder production. It will be interesting to use this approach within the participatory framework of the GEOPAR and PACTER projects where workshops are bringing together researchers, NGOs, decision makers, and local populations to build up a dialogue on the management of the delta. The results could feed some Scenarios to be tested, with indicators used that could be directly defined by the stakeholders. In this study, only three variables (flood duration, extent and the number of floods) were tested, whereas the timing of the floods, the timing of the rains and other climatic aspects are also important.

One limit of the study is the temporal scale at which it was undertaken. Seasonal indicators, rather than yearly ones, appear more appropriate as they would account for fodder production during the periods in which cows are present in the floodplains (i.e. the non-flooded period). This should be possible with an improvement of the grass growth model.

Additionally, the practical implementation of alternative scenarios needs to be considered. Irrigation could cause problems of land ownership or cause conflicts with wild herbivores. Irrigation may also lead to salinization of the soils. Other solutions may also exist. For instance, in the Inner Delta of the Niger River, where the same flooding system exists, people harvest the grass just after the floods, thus constituting reserves for the dry season. Similarly, it should be possible to store fodder from the rainy season. Finally, a ranching system, where access to different zones is restricted to allow grass growth, may optimize fodder production. These societal choices need to be done in concertation with the pastoralists and their advantages and disadvantages weighed. An economic valuation of the wetlands would help in this way and government aid or compensatory mechanisms from the dam management companies could be imagined.

Floodplain grasslands, other than fodder, provide a multitude of other services. They store carbon, as a significant part of their phytomass is stored underground. Floodplain grasslands also contribute to the cultural identity of the pastoralists. An original additional benefit compared to dryland grasslands is that, by flooding periodically, they also become important feeding and nursery grounds for fish and birds. Optimizing one component of the system as a whole does not necessarily lead to a "best" option. This is what I pointed out with the irrigation scenario which may seem as a viable solution for livestock keeping, but where the loss of fishing activities are drastic. It is the same for the conversion of the grasslands into large-scale agricultural lands. The leaders of these kind of projects are optimizing one aspect, i.e. cereal/sugar production, while occulting and hence destroying the other benefits brought by the system as a whole. These other services need also to be studied and taken into account when managing the grasslands.

In a similar way, in this PhD, the grasslands are studied as an independent entity, when in reality it is interconnected with the other ecosystems. Livestock keepers use the drylands for grazing and farming, drink the underground water and interact with the other communities through trade. Their interactions need to be specified. A good illustration of this is the way the Orma have set up a flexible, dynamic and adaptable system to face environmental challenges. Cattle raids, diseases or severe droughts have already led in the past to the collapse of their herds. To face this, they converted temporarily to other activities. As such, the system can be considered as resilient: different stability domaines (livestock keeping as the predominant system, other strategies as the dominant system, etc.) exist and one can pass from one domain to the other. However, the resilience and capacity to pass from one state to another (considered as better) can break down. It is not only the repeated failure of the livestock keeping strategies, but its combination with failures in farming, fishing, and the disappearance of drinking water that is making the system collapse.

This type of thinking can appear as a novel management type for some decision makers, but it has been put in place in other wetland systems. For example, the delta of the Senegal river was faced with the decrease of its water resources after the construction of the Diama dam. A concerted decision led with the locals ended with periodical flood releases that restored the wetland system and the services provided (Duvail and Hamerlynck 2003). For such an effort to take place, a framework to learn, concert each other and interact seems necessary. Good governance, transparent actions, law abiding decisions, consensus-oriented and equitable choices seem like essential requirements (Borrini-Feyerabend et al. 2004). The recent nomination of the TRD as a Ramsar site is one step in this direction, for which local management and the wise use of wetlands are priorities.

8.3 general discussion

8.3.1 *Some reflections on the conceptualization and development of models*

Modelling flood dynamics or plant growth processes is a complex issue that requires knowledge in hydrology, ecology, agronomy, plant physiology, in programming, in logic, etc. At the end of this type of study, one problem is that the final model results always differ, to a certain extent, from those measured. One can then legitimately ask what can be actually done with models. Or more precisely, how can we use models and what confidence can we give them?

In most cases, the construction of a model answers specific objectives, as it was done in this study. Defining the objectives was particularly important as it then determined the applicability, use, the mechanisms, etc. of the model. The development of the models also depended on the scale (spatial, temporal), the mechanisms represented and the availability of data. These reflections of model development helped me address the conceptual and practical aspects of modelling.

In this study, modelling helped to characterize the different systems under study and to identify our gaps in knowledge. Models were a tool to understand a system and to test our hypothesis on how this system worked. However, as they are used to describe the reality, they quickly became very complex. I tried to use a parsimonious approach, but still have a realistic description of the precesses. For example, in the TIM model, we used a logistic curve showing that floods propagate rapidly at the beginning to finally attain a surface plateau corresponding to the floodplain zone.

The exploratory phases of model development made me look at the scale at which the models were developed and their validity range. For these matters, and more generally to evaluate the quality of the model, sources of error and uncertainty needed to be defined. Sources of error in a model are numerous, spanning from input data to coding errors during the programming phase. Rigorous and repeated verifications needed to be undertaken at each step of model construction to limit sources of error.

During the development of the models, questions aroused concerning the sensitivity analysis procedures. The sensivity of a model not only depends on the equations within the model but also on the output variable(s) studied. It seemed important for me to look at several output variables at different scales. In the case of the plant model, parameters coming into account in the photosynthesis or the allocation were sensitive, as could be expected, but the multi-output variable approach also showed that other parameters, especially concerning the flooded period, were also important.

Because of our limited knowledge on the modelled system, it was often necessary to calibrate the models to a specific context. Classically, the parameters are estimated by using data points, generating sets of parameters and the set for which the result and the observed values have the least difference is retained. In the equifinality framework, not one but several sets of parameters are selected as they all respond correctly to the selective criteria. In both cases, expert opinion is important to keep the final parameter sets within their probable physical range. In the calibration phase, the choice of criteria function was important as it defined which data points are given priority to. For example, RMSE, as it looks at the quadratic error, gives more importance to large differences and gives good estimations of the peak values of a function. To bypass this effect, I sometimes defined several criteria functions, each favouring a different section of the function. With two functions, the Pareto front defines the best parameter sets. This approach is limited to a low number of functions as the selection of the best parameters becomes more complex.

All in all, modelling is an essential step during which we test our knowledge of the system under study and identify essential mechanisms that need further development. This would not have been possible without the knowledge of the terrain I acquired during the numerous field trips in the TRD.

8.3.2 *Approaching complexity*

The general problematic of the study was:

HOW DOES THE HYDROLOGICAL REGIME OF A RIVER, AND ITS CHANGES, IMPACT THE BENEFITS LOCAL STAKEHOLDERS OBTAIN

FROM WETLAND ECOSYSTEMS?

... with a special attention on floodplain grasslands. Ecosystems, and more especially when integrated into a socio-economical system form complex systems to study. Complex systems are characterized by feedbacks, stability domains and multiple stable domains to which the systems are attracted to and for which it is necessary to understand the passage from one stability domain to another. In front of such a complex object to study, answers can be brought using different perspectives, by analyzing different axes and by using different approaches. At the beginning of the study, I deliberately focused my work on specific parts of the problematic and chose one driver of change, one ecosystem and one ecosystem service. This choice was first piloted by a scientific approach consisting in untangling complex systems by studying specific processes then by putting the blocs back in place to understand the system as a whole. The choice was also done based on social relevance. As explained in the bibliographical review, wetlands are under pressure from many sides and the dynamic flooding system is the heart of the ecosystems. In the Sub-Saharan context, these wetlands are particularly important for pastoralists. The floodplain grasslands therefore appear as the major link between the river and the pastoralists. This link in some way is at the base of these pastoralist systems and allow them to explore extreme environmental zones during the rainy season when climatic conditions are a bit more clement/mild, while moving back into these wetland buffer zones when the climate is harsh. The loss of these wetlands contributes to the collapse of these systems. Lastly, major choices concerning more the methodological aspect were also done considering the constraints of the zone, and especially remoteness, access difficulties and scarcity of data.

My approach to these questions was therefore a simplifying approach. Based on literature and on previous work done in the TRD, I defined the major links, the first order interactions, between the hydrological system, the grassland and the pastoralists. This was combined with a modelling approach undertaken at different spatial and temporal scales depending on the sub-objectives. The proper quantification of the dynamics of the system was also set as a priority.

This approach has several advantages. It helps to specify the objectives and express the linkages and dynamics between different entities. it also makes explicit the limit of the system under study and is a way to test hypotheses. Mathematical models allow to apprehend the sensibility of the model and define its domain of applicability and our uncertainty concerning the questions we address. These aspects are particularly important when the models or knowledge are intended to be used in the "real world" and define actions. Quantification also allows comparison between different objects of the same nature.

Models can be used to test different situations within its limits of applicability. Connecting entities through mathematical functions and comparing them with field measurements also makes it possible to test and improve our knowledge of the system.

However, this approach also has limits. By limiting the processes under study, the significance/reach/range of the study can be restricted. Models too simple can lead to erroneous recommendations when important factors are be omitted. Models are also constructed for specific objectives so that their use if often constrained to a certain dataset, context and use. It also provides a partial vision of the entity as many objects or linkages cannot or are difficult to define precisely, delimitate and represent through mathematical equations. Finally, this approach is not always applicable, especially for non-quantifiable services (how to quantify cultural services, for example?). Mathematical modelling can also become very complex when there are not one to a couple of strong linkages between the driver(s) of change and the properties and services but numerous more or less weak linkages between several of them. Hence, proper feedbacks may not be taken into account.

Another difficulty with mathematical modelling is related to simplification. Simplicity allows understanding of a system, but keeping things simple is not always easy. For example, during the sensitivity analysis of the plant model, 40 parameters and 81 output variables were studied. Even though I tried, at each step, to keep the system under study simple by representing just the major processes, the final models could become quite complicated. This was driven by the necessity to represent realistically the processes so that the causality effects could be explained. For example, the plant model ended up with over 40 parameters with numerous boxes, linkages, input and output variables. Complexity also implies costs: costs of time, money and costs through duplicated errors. So how far should we go into complexity? Would it not have been possible just to ask the locals and experts about the causality effects between the floods and grasslands? Another disadvantage about complex modelling is that , at the end of the day, we are not interested in one specific process, but in the multiple facets and benefits of the floods. Making a mathematical model for each service, each ecosystem, each driver of change is quasi impossible.

An alternative approach would therefore to do a more qualitative study. Through historical interviews, diagrams, participatory discussions with the stakeholders, an understanding of the system as a meta-system can be obtained. A multi-service approach could also have been used by defining several services, and loose linkages between them obtained through literature or extrapolation techniques. This is what we could call a more holistic approach to understand the system and calls on quite different disciplines. However, these approaches also have their limits... which are, at the end of the line, the advantages of the first approach.

Finally, these two approaches seem complementary. One explore the precise mechanisms through mathematical equations while the other approach explore more globally which objects are important to study, how they are linked together and which aspects, objects or linkages can change through time. Both approaches bring different answers concerning the same object under study and each can use the knowledge generated by the other to improve the concept and general understanding of the system. These thoughts are depicted on Figure 56. They are certainly not revolutionary, but the three years I passed trying to understand the grasslands of the TRD gave me a concrete example on which to sculpt these notions.

Environmental and socio/human spheres are complex systems. On one hand it seems unrealistic to be able to answer complex questions with a simplified approach, as one needs to account for social, economical, political and environmental aspects. On the other hand, constructing complex mathematical models is a daunting task, not feasible for many problems. In such a situation, a good way forward seems to be to set up a general understanding of the system and to use process modelling to study specific questions concerning a limited number of important aspects. This in turn brings light to important processes to take into account, and also highlights gaps in knowledge. Continuously changing scales of study and scales of complexity to hypothesize, test, and compare ideas can make one dizzy but seems like the most promising way to improve our understanding of complex objects.

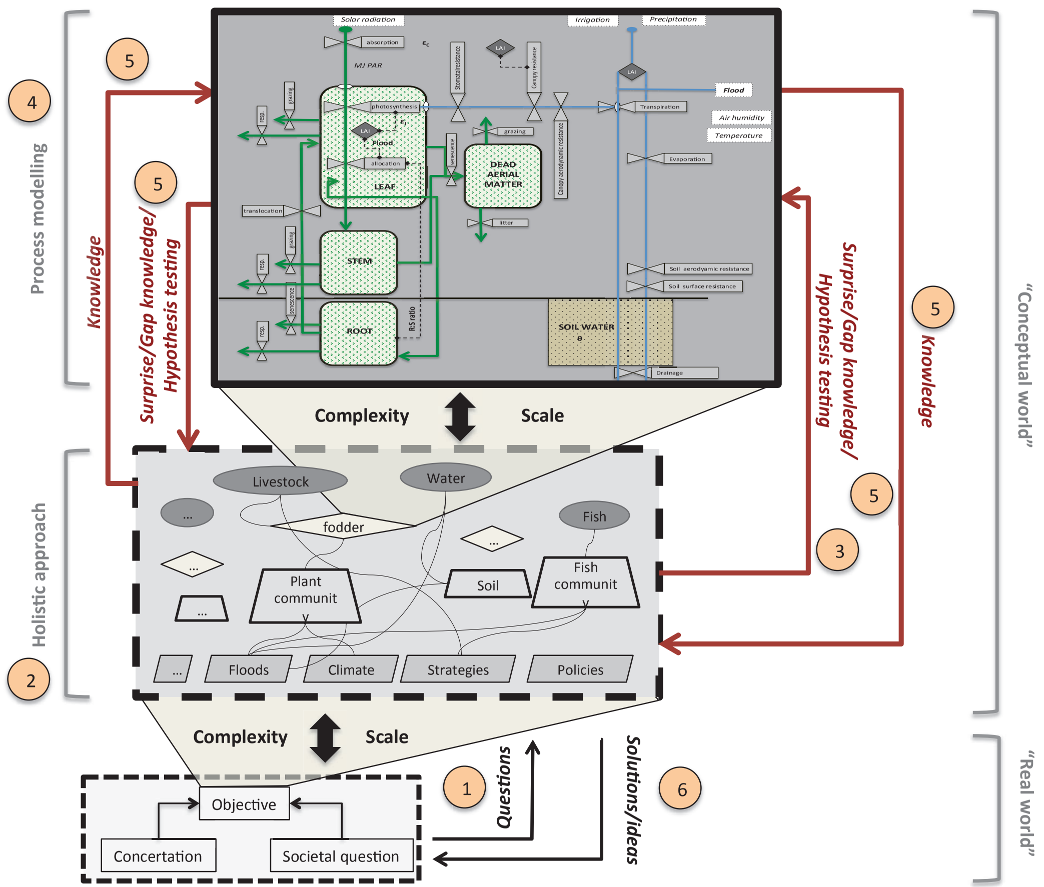


Figure 56: Illustration of the approach used in this PhD to understand the complexity of the grasslands. Interconnected models were studied at different scales in a "conceptual world", to bring answers to a question emanating from the "real world".

9 FINAL CONCLUSION

The Tana River Delta is at a turning point. Past dams have altered the hydrological regime of the Tana River, which is one of the vital pulses of the wetland. In turn, the ecosystem properties and functioning of the wetlands were changed, leading to a degradation of the environment and a decrease of the consequent services. The zone is also poverty stricken and new types of conflicts over land and water resources have emerged. An encouraging point is that is was designated as a Ramsar site in 2012. The associated convention recognizes the importance of the wetlands and encourages their wise-use and good management. Indeed, the wetlands provide multiple services, including fishing, livestock keeping and farming grounds, biodiversity conservation, carbon storage, groundwater recharge, coastal protection, and sea fisheries.

Within the Tana River Delta, the floodplain grasslands form an essential ecosystem. Firstly by their extent, with a surface of at least 200 km^2 of prime grasslands surrounded by a patchy mix of grasslands, bushland and woodlands. Secondly by the services they provide to the local population: pastureland, fishing, groundwater recharge, and many others. These grasslands are vital for the livestock keepers of the zone, with over half of the 100 000 residents and many semi-nomadic or transhumant livestock keepers from the whole region who use these grasslands as counter seasonal grazing zones, and even more during drought years.

To understand the impact of the changing hydrological regime on the ecosystem services that the wetlands provide, many questions need to be answered. In particular, the hydrological regime, and especially the flooding dynamics of the river, need to be determined. For the livestock keepers, it is important to quantify the impact of floods on grass growth. This PhD brings some answers to these two aspects. In a first step, the productivity of the floodplain grasslands of *Echinochloa stagnina* (Retz) P. Beauv. were determined for different flood and management treatments. A plant growth model adapted to floodplain grasslands highlights the probable mechanisms explaining the high growth rates measured. In a second step, the major flooding characteristics of the Tana River in its deltaic floodplains over the past ten years were determined. Doing so, hydrological processes of ecological importance such as flood extent, timing, duration, frequency, and a spatial map of the floods were provided. In a third step, a preliminary analysis explores different flooding scenarios and their impact on fodder production.

Scientifically, this PhD uses approaches and tools from several disciplines. The combination of remote sensing techniques and a water balance model enabled the determination of major flooding characteristics in a poorly gauged basin. Flooded surfaces were determined with MODIS satellite imagery and a water index, despite a high cloud cover. A water balance model reproduced the main flooding patterns despite the lack of precise knowledge on the discharge rates and on the topography of the zone. Concerning the grasslands, a first step quantification of the productivity of these grasslands was achieved. This kind of data is scarce for floodplain grasslands in Sub-Saharan Africa. Secondly, a plant growth model adapted to tropical floodplain conditions and perennial C4 grasses was developed. It is the first known physiologically based model for grasslands that takes into account the responses of these specific grasslands to floods. Even though it is a rather simplified representation of reality, it simulates the main mechanisms so that a realistic description of the growth processes is possible. Finally, within the ecosystem service domain, this PhD contributes to the ecosystem services research field. First, it describes a major service provided by floods in tropical floodplains. Secondly, two biophysically based simulation models were developed. Thirdly, possible ranges of scenarios that are a descriptive narratives of the past, present and possible futures are explored. Lastly, the study is located in region of the world and ecosystem where these type of ecosystem service evaluations are rare.

This study raises further questions and points out the necessity to obtain more precise knowledge about the flooding patterns within the delta, the growth processes of the *Echinochloa stagnina* floodplain grasslands and their uses. In a next step, the spatial and temporal characteristics of the floods could be further defined by developing a multiple reservoir model and by studying radar images. The most urgent, however, is to have a better knowledge of the system itself and keep up the effort of collecting data through field work and by remote sensing techniques. The same is true for the grasslands. Empirical data on the growth processes, changing vegetation patterns, grazing patterns and frequency are required. In particular, a better knowledge of water movement within the soils would significantly improve our understanding of the growth processes. Further characterization of the flooding dynamics, and their effects of *Echinochloa stagnina* (Retz) P. Beauv. are also necessary. Finally, integrating this knowledge into a larger framework where multiple services and multiple development scenarios are compared, with the participation of the stakeholders, seems a key issue. *In fine*, these axes could lead to redefining the economical and ecological benefits of the Tana River catchment and highlight that the currently un-evaluated costs of hydro-electric infrastructure on the Tana River, through the destruction of vital ecosystems, could be much higher than the benefits obtained.

The research projects undertaken in the Tana River Delta, lead by the IRD-Kenweb team, are continuing their efforts in these directions. The designation of the delta as a Ramsar site is a big step forward. Wise use of the water and wetlands, along side further scientific research, will improve our knowledge of this unique system.

Part VI

APPENDIX

A

FLOODS AND LIVELIHOODS: IMPACT OF CHANGING WATER RESOURCES ON WETLAND AGRO-ECOLOGICAL PRODUCTION SYSTEMS IN THE TANA RIVER DELTA, KENYA

A.1 ABSTRACT

Wetlands are highly dynamic and productive systems that have been under increased pressure due to changes in land-use and water management. In Eastern Africa, they provide resources at multiple spatial and temporal scales through farming, fishing, livestock keeping and a host of other ecosystem services that sustain the local economy and livelihoods. In a broader effort to describe the future development scenarios of East African coastal wetlands, this qualitative research focuses on understanding the processes by which river-water depletion has affected local food production systems in the Tana River Delta, Kenya, in the past 50 years and how this has impacted livelihoods and human well-being. Interviews undertaken in six villages with various ethnic groups, locations and resource profiles show that the agro-ecological production systems were adapted to the dynamic flooding patterns of the river. As flooding characteristics changed, the local population diversified, abandoned or adopted various farming, fishing and rearing techniques. Despite their efforts, decrease in water availability affected each subcomponent of the productive systems, which led to their collapse in the 1990s. Water depletion has negatively impacted local human well-being through the loss of food security and by indirectly affecting its other components. The present study provides a detailed account of the dynamics of agro-ecological production systems facing river-water depletion problems in a wetland-associated environment in Sub-Saharan Africa.

Keywords: River water depletion, food production, wetland, human well-being, sustainability, Sub-Saharan Africa

A.2 INTRODUCTION

Wetlands have long been recognized as valuable ecosystems for human beings as they provide a wide array of ecosystem services (Costanza et al. [1997]; Daily [1997]; Millenium Ecosystem Assessment (MA), 2005a; Maltby and Acreman, 2011). In particular, wetlands and the associated natural resources are used for small-scale farming, fishing and livestock keeping activities that provide some of the basic material for a good life through food production. Despite their services, wetlands have been continuously degraded in the past 50 years (MA, 2005a). Because of abundant water resources and generally fertile soils, many policy makers dream of converting these supposedly empty zones into large-scale intensive agricultural schemes. The latter can improve food security. However, they also require numerous inputs (capital, fertilizers, water, infrastructure etc.), are often detrimental for other ecosystem services and, especially, are not applicable worldwide (Horlings and Marsden, 2011). Of concern is also the construction of dams that modify the flood pulse of river systems (Junk et al. [1989]). Although hydraulic infrastructure has contributed to economic development, there is a growing recognition that dams have also had many adverse effects (World Commision on DamsWCD [2000]) as they alter key hydrological factors such as the timing, extent and frequency of floods, the associated sediment flow, the quality, temperature and chemistry of water (Olden and Naiman [2010]) and the morphology of river channels (Petts and Gurnell [2005]). In a cascading effect, this then affects the integrity of adjacent ecosystems (like the riparian forests (Hughes [1984]; Hughes [1990]; Shafroth et al. [2010]), floodplains, mangrove and coral systems (MA, 2005a)) and finally the local communities by depriving them of vital water resources. Numerous studies state that water depletion has impacted local farming, fishing and livestock keeping in Sub-Saharan wetlands (for example, see Bader [1998]; Emerton [2003]; Loth [2004]; Schuyt [2005]; Kgathi et al. [2006]) but few explicitly explore the precise mechanisms of change by which this occurs from a historical perspective (Verhoeven and Setter [2010]; Vilardy et al. [2011]. The objective of this study was to document the use of river-water resources and the impact of the decrease of river-water resources on small-scale, subsistence-oriented, agro-ecological production systems in wetland-associated ecosystems in Sub-Saharan Africa. We hypothesise that a decrease in river-water resources modified the local cropping systems (crop type, cropping season and crop location), changed the pastoralist system (transhumance, herd resistance to drought) and caused a decrease in fishing activities. To test these hypotheses, we explored the temporal dynamics of change in agro-ecological production systems in the light of varying water resources and analysed how water was used and whether its usage had changed over time. We then examined the local adaptive strategies and evaluated whether and how water changes had impacted the food production systems. Finally, we explored how this had affected the different components of human well-being. Our study focused on the farming, fishing and livestock components of the Pokomo and Orma communities' production systems in the Tana River Delta (TRD), Kenya, and on the changes that had occurred in the past 50 years.

A.3 CONCEPTUAL FRAMEWORK

A.3.1 *Ecosystem services, livelihoods and human well-being*

Ecosystem services, livelihoods and human well-being are all closely related. The term livelihood was initially defined by Chambers and Conway 1992 then by Scoones 1998 as comprising "the capabilities, assets (including both material and social resources) and activities required for a means of living". The concept, later broadened to include other assets (Wisner et al. [2004]), is closely connected to the notions of human rights, capabilities and sustainability (Bohle [2009]). The terms ecosystem services and human well-being (Holdren and Ehrlich [1974]; Westman [1977]; Daily [1997]) have become popular through the MA. The latter states that human well-being has five dimensions (basic material for a good life, health, security, good social relations, freedom of choice and action), all of which are linked to the supporting, provisioning, regulating, and cultural services rendered by ecosystems. The link between ecosystem services and human well-being is evident, but their sole provision is not sufficient: other determinants (Butler et al. [2006]; Carpenter et al. [2009]) such as social position, a sense of participation or belonging, context etc. all play a role in shaping how people perceive their lives. In on-going research, a key debate is how to "assess, project and manage flows of ecosystem services and effects on human well-being" (Carpenter et al. [2009]) and make these concepts more efficient through their integration into policy and decision-making. To do so, different valuation methods linking livelihoods, ecosystem services and human well-being have been developed (Costanza et al. [2011]). The one we chose is a qualitative approach based on understanding historical events, links and processes (Enfors and Gordon [2007]; Liu et al. [2008]) as they have legacy effects on present conditions (Liu et al. [2007]).

A.3.2 *Adaptive strategies, resilience and thresholds*

The impact of changing environmental, political and societal conditions on ecosystem services, livelihoods and human well-being is not a linear process, and the concept of resilience (Holling [1973]; Holling and Gunderson [2002]; Folke et al. [2004]; Folke [2006]) has helped gain insight in this domain. Living systems (very broadly taken) –individuals, communities, ecosystems or complex socio-ecosystems – present a robustness to change: they are able to absorb shocks so as to keep their major functions and services. Another property is their adaptive capacity which can make disturbances an opportunity for development and for new trajectories to emerge. Authors have documented the erosion of ecosystem resilience and the insufficient adaptive capacities of many socio-ecosystems (such as Enfors and Gordon [2007]). In such a case, systems can present abrupt changes switching from a productive to a degraded state from which it can be difficult to emerge (e.g. Folke et al. [2004]; Steneck [2009]; Cinner [2011]). Current research focuses on the mechanisms through which these traps appear, the thresholds involved, the consequences on human well-being and on how to make systems more or less resilient. In this study, these concepts are applied to river-water resources and to small-scale, subsistence-oriented, agro-ecological production systems. As our objective is to identify the major mechanisms by which river-water rarefaction has affected the latter, and hence livelihoods, we have restricted our study to the provisioning services of water and its link to food security.

A.4 CASE STUDY AREA

A.4.1 *General description*

The Tana River Delta (TRD) (Figure 57) is located in the coastal zone of Kenya and extends over approximately 1300 km^2. The Tana River is the main feature of the area. By overflowing periodically into the floodplains, it supplies water and nutrients to the natural and cultivated vegetation, which in turn provides food, grazing zones, building materials and other vital resources to the inhabitants. The Pokomo and the Orma are the main residents, alongside the Wardei, Somali and the Wata. The Pokomo culturally define themselves as farmers and fishermen; the Orma, Wardei and Somali groups as pastoralists; and the Wata as former hunter-gatherers. They have

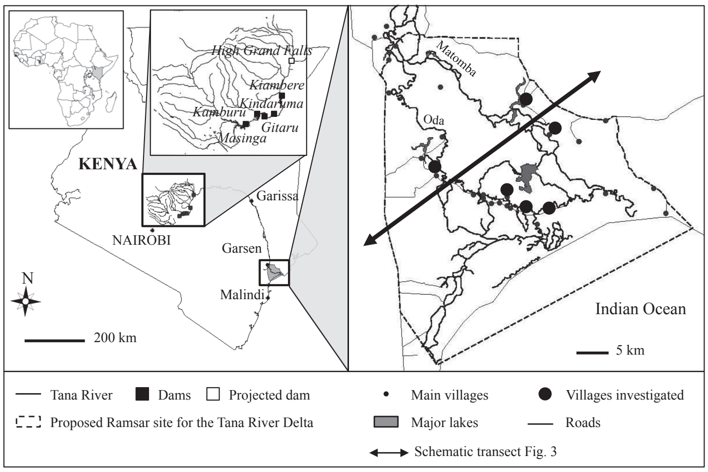


Figure 57: Left: location of the Tana River, its dams and its delta. Right: the Tana River Delta, its river, road system and main villages. The location of the six villages and the transect from Fig. 3 are also included. Source of maps: International Livestock Research Institute, World Resources Institute and Hamerlynck et al. (2010), compiled by the authors.

occupied the delta for centuries (Fitzgerald [1898]; Miller [1981]) and have been using the dynamic flooding system to cultivate, fish, graze, gather and hunt. The region and its 100 000 inhabitants (Republic of Kenya, Central Bureau of Statistics [2010]) are however poverty-stricken, and food distribution by the World Food Program is more than common. The 2009 indicators of human well-being (United Nations Development Programme, United Nations Development Programme [2010]) also indicate distress. The Human Development Index (HDI) was of only 0.389 compared to the already low national average of 0.561, while the Gender-related (GDI) and the Human Poverty Development Indices (HPI) were ranked in the ten worst nationwide. Human illiteracy was beyond 68 % and life expectancy was under 54 years - lower than the national average by nearly three years. Alongside the multiple ecosystem services that the wetlands provide, the TRD forms a biodiversity hotspot, with numerous vulnerable species, including two endangered primates: the Tana River Red *Colobus Procolobus rufomitratus rufomitratus* (Peters, 1879) and the Tana River Mangabey *Cercocebus galeritus* (Peters, 1879) (Hamerlynk et al. [2012]). As such, it meets all the criteria to be designated as a wetland of international importance by the Ramsar Convention (1971).

A.4.2 *Key water resources*

Rainfall is high on the Kenyan coast but rapidly decreases when moving inland, from 1098±306 mm in Malindi (1962-2008) to 530±202 mm in Garsen (1972-1986) to 373±202 mm in Garissa 250 km upstream (1962-2008, all data from the Kenya Meteorological Department, Kenya[1]. Years with over one month missing data were excluded). The rainfall pattern is bi-modal, with two rainy seasons extending from April to June and from November to De-

1 Republic of Kenya, Kenya Meteorological Department, 2008.

cember (Figure 58). The mean cumulated rainfall for each growing season is respectively of 230 mm and 124 mm in Garsen, which is not enough to grow major cereal crops, such as maize. Furthermore, rainfall is highly variable - both temporally and spatially - thus increasing the risk of dependence on rainfall events for farming and pasture. Most water, for productive uses, is therefore derived from the Tana River. With a catchment area covering over a sixth of the country, the river carries between 2.7 and 10.2 billion cubic metres yearly (Hamerlynck et al. [2010]). Its flowing pattern is bi-modal, with peak flows during the long and short rainy seasons (Figure 58). The consequent floods can either be productive or destructive inputs for agricultural activities, depending on their predictability, timing and force. Moderate floods sustain fishing, rice cultivation and dry season grazing land. Extreme (and often early) floods cause drastic losses for the farmers and livestock keepers by inundating the fields and blocking escape ways to higher lands for the herds. In East Africa, extreme flood events are often linked to the El Niño Southern Oscillation (Bjerknes [1966]; Bjerknes [1969]) and anomalies of the Sea Surface Temperature of the Indian Ocean associated with the Indian Ocean Zonal Mode. In particular, excessive short rains of October to December are tightly linked to these events (Black et al. [2004]). In the past 50 years, six flood events with discharges over 1200 $m^3.s^{-1}$ in Garissa have been recorded (data from the Water Resource Management Authority, Kenya) and the major catastrophic floods as perceived by the population were those of 1961 and 1997-1998. Five major reservoirs (Figure 57) were constructed between 1968 and 1981 in the upper basin to provide electricity (installed capacity of just over 500 MW) to urban centres and to develop irrigation schemes. The adverse effect is a modification of the hydrological regime of the Tana River, especially since the construction of the Masinga dam in 1981. Maingi and Marsh (2002) state a 20 % reduction in average peak May flows. In El Niño years, heavy rainfall in the upper catchment rapidly fills the successive dams, which, combined with rainfall in the mid to lower catchment can cause excessive floods in the delta. During dry and moderately wet years, water retention within the reservoir can stop the river discharge attaining the threshold at which floods occur. In 2010, Kenya proposed the construction of the High Grand Falls dam which is expected to bring an additional 700 MW to the national electricity grid, but for which downstream impacts on ecosystems and livelihoods are still uncertain.

A.5 METHODOLOGY

A.5.1 *Agrarian diagnosis*

The methodology employed was the first two sections of an agrarian diagnosis as defined by Dumont and later refined by Mazoyer and Dufumier (Cochet, Devienne and Dufumier, 2007; Cochet, 2011). An agrarian diagnosis provides a framework for the analysis of agricultural production systems. In a first step, it determines the landscape functional units in relation to agricultural production systems. In a second step, it characterizes the recent transformations of agricultural production systems and explores the major factors - ecological, sociological and economic - that determine their functioning, performance and development. In a third step, it establishes a typology of the major production systems and models their economic per-

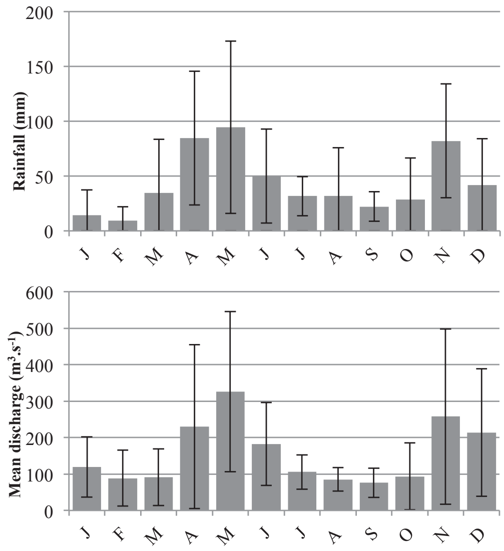


Figure 58: Top: mean monthly rainfall and its standard deviation at Garsen (1972-1986). Bottom: mean discharge and its standard deviation of the Tana River Delta at Garissa (1941-2010). Source: Water Resource Management Authority, compiled by the authors.

formances. In accordance with this methodology, a two-step and largely qualitative approach was used:

1/ Identification of relevant hydro-ecological landscape units in the TRD through field visits and the analysis of available maps and satellite images.

2/ A sociological and agronomic analysis of the changes in the production systems over the past 50 years as further detailed.

A.5.2 *Survey methodology*

Social interviews were conducted with village elders and key informants from different social categories (Table 25). The interviews focused on the productive activities of individual life trajectories. The state of a production system at different dates (i.e. what was cultivated, where, who, how, what animals he had, when, where and how he fished, etc.) and the major changes that had occurred between the different states were determined with each informant. When a detailed chronology of events was sought, it was based on time relative to the informant's history (i.e. how old he was, when he got married, etc.) then transposed to dates. As the focus of the interviews was on individual life histories rather than general trends, each person was able to provide relatively accurate data. To pass from the state and dynamics of individual production systems to a typology of the production systems and their dynamics, we then cross-referenced and interpolated between households of similar ethnic origins, structure and location. Finally, to correct and corroborate the gathered information, field observations of current and historical forms of land uses were noted and compared to the oral data. In the absence of reliable historical quantitative data such as mean yields from administrative records, we asked for minimum and maximum yields, then averaged for each category of production systems for different time periods. We also adopted a more qualitative method based on the perception that people have of changes in their environment. This approach can have biases, as perception is subjective. In order to diminish this bias, we interviewed multiple stakeholders with different origins and social categories and also confronted the data collected to former research. This methodology was applied in six villages (Figure 57) in the TRD between March and July 2009. The villages were chosen because of their different ethnic origins, locations and resource profiles. Kikomo and Chalaluma are Orma villages while Golbanti and Shirikisho are Pokomo villages. They were considered representative of the majority of the villages within the delta: of medium size (approximately 150 households each), established before the 1960s and located close to the river. In the 5th village, Moa, the main communities are the Luhya, Luo and Orma, of whom only the last were interviewed. Boramoyo was chosen because of its striking difference compared to the other villages: of Somali origin, it was set up in the 1990s and is the only place within the delta where water pumps for irrigation are regularly used. Residents from all age groups and social status were interviewed. Semi-directive interviews were conducted in the local languages, Kipokomo or Kiorma, or in Swahili, and translated into English by hired local guides fluent in these languages. Extensive interviews were conducted with fifty-six farmers, livestock keepers and fishermen.

A.6 RESULTS

A.6.1 *Identification of land and water resources through an agro-hydrological zonation of the delta and its surroundings*

The TRD landscape is a complex intertwinement of forests, wooded bush land, bush land, grasslands and lakes (vegetation maps, Kenya Soil Survey, KSS, 1984a and1984b). The landscape pattern derives from soil and water conditions controlled by the Tana River. The latter is highly dynamic, with its course shifting after important flooding events or redirected by human intervention. The Oda branch, like the other old river channels, has well-formed sandy levees, whereas the newly formed branches like the Matomba brook meander through the floodplains, forming braided channels with, as yet, minimal levees. A schematic agro-toposequence (Figure 7), perpendicular to the two main types of river channels, emphasizes the different environments encountered and the way people use them today. Riverine forests dominated by Ficus sycomorus and mango plantations are located on the levees of old riverbeds. Dry grasslands cover the upper floodplains, which are no longer or very rarely inundated, while the mid floodplains, still under water during important flood events, are cultivated. The lower floodplains, periodically under water, form grasslands composed of *Echinochloa stagnina* (Retz) P. Beauv, *Vossia cuspidata* (Roxb.) Griff., *Paspalidium obtusifolium* (Delile) N.D. Simpson and various species of sedges that offer good pasture land and fishing grounds. Other low-lying areas form permanent or temporary lakes, swamps or marshes. Here and there, remnants of ancient sand dunes are covered by Acacia and palm wooded bushland, mainly composed of *Acacia zanzibarica*, *Terminalia brevipes*, *Thespesia danis*, some *Borassus aethiopium* and the invasive *Prosopis juliflora* (Hamerlynk et al. [2012]). The delta itself is surrounded on both the eastern and western sides by an-

number of interviews	village	gender	age	tribe	comment	period
4	Shirikisho	woman	Y/M	p		06/04-11/04
3	Shirikisho	man	Y/M	p		06/04-11/04
2	Shirikisho	woman	E	p		06/04-11/04
3	Shirikisho	man	E	p		06/04-11/04
0	Boramoyo	woman	Y/M	oth		13/04-20/04
6	Boramoyo	man	Y/M	oth	3 Wata and 1 Orma	13/04-20/04
1	Boramoyo	woman	E	oth		13/04-20/04/
3	Boramoyo	man	E	oth	1 Orma	13/04-20/04
0	Kikomo	woman	Y/M	o		22/04-05/05
4	Kikomo	man	Y/M	o		22/04-05/05
1	Kikomo	woman	E	o		22/04-05/05
2	Kikomo	man	E	o		22/04-05/05
1	Chalaluma	woman	Y/M	o		15/05-23/05
5	Chalaluma	man	Y/M	o		15/05-23/05
2	Chalaluma	woman	E	o		15/05-23/05
3	Chalaluma	man	E	o		15/05-23/05
1	Golbanti	woman	Y/M	p		23/05-01/06
3	Golbanti	man	Y/M	p		23/05-01/06
0	Golbanti	woman	E	p		23/05-01/06
6	Golbanti	man	E	p	1 Wata	23/05-01/06
0	Moa	woman	Y/M	o		17/07-20/07
4	Moa	man	Y/M	o	2 Luo and 1 Pokomo	17/07-20/07
0	Moa	woman	E	o		17/07-20/07
2	Moa	man	E	o		17/07-20/07

Table 25: Number of interviews in each village, differentiated by their age, gender and tribe. The period during which the interviews took place in 2009 is specified. Y/M: Young or Middle aged, E: Elderly

cient alluvial plain terraces covered by degraded woods or wooded bush that periodically serve as pastureland. Lastly, at the interface with the Indian Ocean, high coastal dunes give way to an extensive mangrove system at the river's mouth (not shown in Figure 7). Most villages are located either on the river levees or on the more elevated sandy zones. Land-use is organised according a vertical differentiation along a topographic sequence and spatially around the villages. This vertical differentiation reflects the different water requirements of the crops while the distance reflects, to a certain extent, physical and frequency efforts related to the cropping system. Farming activities are located around the villages, fishing in the lakes and floodplains, and grazing within the bushland and floodplains.

A.6.2 *Dynamics of the agro-ecological production systems in the past 50 years*

A.6.2.1 *The Pokomo: the farmers and fishermen strategies*

A summary of the interviews is reported in Table 26. The river system, land cover and production systems in the 1960s was partially reconstituted through interviews with Pokomo village elders. At that time, the Tana River mainly ran through the Oda branch and overflowed into its floodplains twice a year. The lakes and floodplains located in the western part of the delta, such as Shakababo Lake, constituted fishing and farming grounds for the Pokomo. Their villages were located on the riverbanks sheltered from floods and surrounded by riverine forests, seasonally flooded grasslands on the upper floodplain, and swamps, marshes and lakes in the lower floodplains. Rice was planted biannually at the beginning of the two rainy seasons in small recession paddy fields, located on the upper floodplains. Water height and duration within these fields were managed by simple water control structures such as small channels, bunds and ditches. The influx of water and fertile loam and clays from the floods probably guaranteed yields of around 2 T.ha-1 per season (Table 26), typical for this type of small-scale rice recession farming. Banana plantations were common on the river banks, whilst on slightly sandier zones, maize was intercropped with beans, squash, sweet potatoes and cassava, and constituted an alternative, non flood-dependent, food source. As cultivation was entirely manual, the farmed surface was generally limited to around one or two acres per household. Regular fishing activities, using nets, hooks and spears, were also carried out in the surrounding swamps and more distant lakes (Table 26). Throughout the 1980s, fishing activities gradually decreased (Figure 59). The six informants who moved to Shirikisho village in the 1960s to the 1970s all carried a fishing spear, which shows that fishing was a common activity. Four explicitly reported a decrease in fish load. Overnight, one informant would catch on average 150-170, then 10-20 and finally 5-10 fish with 200 hooks in, respectively, the 1970s, 1980s and 2009. Another reported average catches of 10-15, then 5-10 fish using hooks in 1986 and 2004. One more reported daily catches of 100-200 large fish in the late 1970s, then catches of 100-200 small fish nowadays, using a net. Evidently, these figures depend on the fisherman's experience, equipment, location, etc. but all note a decrease in fish load. In 2009, approximately ten out of 156 households regularly fished in Shirikisho. Similar trends and figures were reported in the other villages.

	Pokomo			Orma	
	1960s	1970s-1980s	1990s-2000s	1960s-1980s	1990s-2000s
Livestock keeping as the main activity	No	No	No	Yes	Yes
Farming as the main activity	Yes*	Yes	Yes	Rare	Sometimes
Fishing as the main activity	Yes*	Sometimes	Rare	No	Sometimes
Farming					
Rice as major cereal crop	Yes	Yes	No	Yes	No
Maize as major cereal crop	No	No	Yes	No	Yes
Average yields per season for rice (Tpaddy.ha^{-1}	2	2	1.3	-	-
Average yields per season for maize (T.ha^{-1})	-	-	1.3	-	-
Mango tree plantation	Rare	Sometimes	Yes	No	Rare
Number of cropping seasons	2	2	1	-	1
Additional livestock keeping activities	No	Yes	Yes	-	-
Livestock keeping					
Seasonal migrations to the hinterland	No	No	No	Yes	Yes, if possible**
Grass height (after flood/ end of rainy season) (m)	-	-	-	2/0.6	0.6/0
Additional farming activities	-	-	-	Rare	Yes
Additional fishing activities				No	Sometimes
Milk production per cow in the rainy season (L)	-	-	-	5	2-5
Fishing					
Regular fishing expeditions to the nearby floodplains	Yes	Yes	Rare	No	No
Fishing as a daily activity in the river	Yes	Sometimes	Rare	No	Rare
Fishing in the lakes	Yes	Sometimes	Rare	No	Sometimes
Daily fish catch compared to today	"very high"	"higher"	-	-	-
Total number of interviews	11	11	12	11	11

Table 26: Summary of the main interview responses conducted in the Tana River Delta, differentiated according to tribal group and chronology. Common: over 50 % replies were positive, Sometimes: 20-30 % positive replies, Rare: less than 10 % positive replies. * in the 1960s, the Pokomo practiced both farming and fishing activities on a regular basis, ** the non-milked herds are brought to the hinterlands as soon as grazing there is possible.

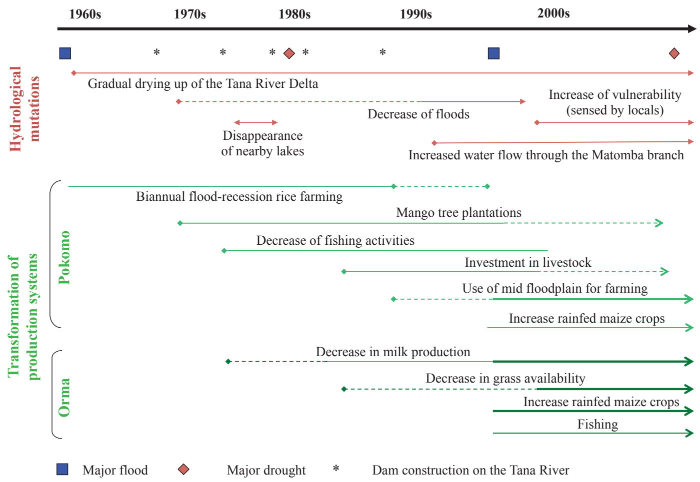
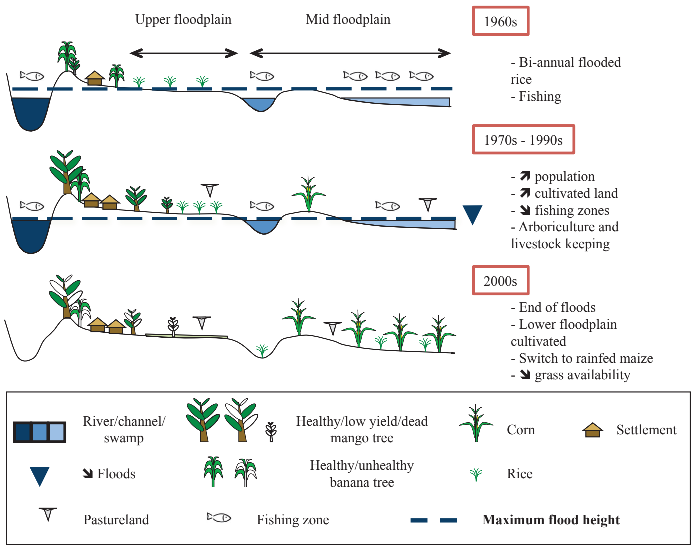


Figure 59: Chronology of the major hydrological changes and transformations of the agro-ecological production systems from the 1960s to today.

The decrease in fishing activities was accompanied by increased rice and mango cultivation along the riverbanks. Most mango growers interviewed started planting mango trees (Ngowe, Punda and more recently Apple varieties) in the 1970s. The development of commercial arboriculture in the 1970s and 1980s, favoured by road extension, enabled some families to invest in livestock keeping. As a gradual decrease in rice yields was noted, larger portions of land were cultivated around the villages. Population growth in the 1980s also favoured the increase of cultivated areas. This extension was accompanied by a translation of the fields to lower zones, as flood amplitude decreased following the construction of the Masinga dam. Rice paddies were progressively translated down the floodplain and the mango plantations, first located only on the riverbanks, were advantageously extended in their stead (Figure 60). Animal rearing was also developed at the same time as live capital, compared to mango and rice farming, provided higher revenues and could rapidly be transformed into cash for emergency purposes. These small herds of sheep, goat and sometimes cattle would graze around the village all year round and in the mid floodplain during the dry seasons.

The 1990s were marked by the 1997-1998 El Niño event that caused a major flood. Crop and livestock losses were accompanied by a gradual shift of the main branch of the Tana River, as it migrated eastwards by breaching a large hole through the riverbank. As a result, both of the switch of riverbeds and of the changing flooding pattern linked to dam constructions, the western part of the floodplains of the Tana Delta is now very rarely flooded. The farmers operated a drastic switch from cultivating flooded rice twice a year in the upper floodplains to once-a-year rainfed maize in the mid floodplains (Figure 59), where enough rainwater through runoff accumulates to plant maize. Only one of the informants reported planting solely rice in a field nowadays whereas all farmers (including the Orma farmers) did in the 1960s and 1970s. The upper floodplains, no longer suitable for farming because of insufficient water and its decrease in fertility, were converted into grazing land for the village herds. In 2009, Pokomo production systems were mainly based on cropping systems, combining maize and rice in the

Figure 60: Land-use changes in a Pokomo village from the 1960s to today.



mid-floodplains, and mango and banana plantations on the riverbanks (Table 27). Out of 14 farmers in Shirikisho and Golbanti, five had maize (sometimes mixed with rice) fields, mango plantations and cattle; seven reported maize (sometimes mixed with rice) fields and mango plantations, and two maize fields. Seven of them had used a tractor at least once. Seven also carried out other activities (casual agricultural labour, fishing, other). Crops were rainfed, work manual, and harvests were mainly used for household consumption. The total surface per household dedicated to cereal growing was generally inferior to 1 ha. Mean yields for maize and rice were respectively around 1.3 T.ha-1 and 1.3 Tpaddy.ha-1. Lack of cash flow prevented farmers from using any form of fertilizer, herbicide or pesticide. Depending on the availability of capital for the initial investment, herd size varied between 0 and 100 heads. The sheep, goat and sometimes cattle, would graze in the upper floodplains around the villages and in the lower floodplains after the harvest. These herds constituted a major monetary income for the informants. Cash flow was also partially provided by the mango plantations located on the riverbanks. Informants reported a highly variable production with a mean production of 100 to 400 mangos per tree per season. This crop is vital as an important source of energy and vitamins (Litz [1997]) and can constitute the main food source during droughts. The informants were of the opinion that fishing activities, although still present, were in decline.

A.6.2.2 *The Orma: the livestock keepers strategies*

On the livestock keepers' side, two main phases in production organization can be distinguished, spanning roughly from the early 1960s to the 1984 La Niña drought, and then from 1984 to today. For the Orma, cattle are the social representation of wealth and status and most of the economic and cultural activities are centred on livestock keeping. In the 1960s, sedentary as well as semi-nomadic groups co-existed (Ensminger and Rutten [1991]) within the delta. Sedentary groups had settled on the eastern side of the main Oda branch, close to or within the flooded grasslands of the inner floodplains, and the semi-nomadic groups would graze their animals in the

	Agro-ecological production systems										
Characteristics	P1	P2	P3	P4	O1	O2	O3	O4	O5	B1	B2
Farming component											
Mango plantation (ha)	4	2	1.3	0.3	0	0	0	0	0	2.5	2.5
Cereal crops (ha)	4	2	0.8	0.5	1.6	1.2	0.8	0.4	0.2	2	2
Market gardening (ha)	0	0	0	0	0	0	0.4	0	0	0	0,8 (2)
Sugar cane (ha)	0	0	0	0	0	0	0	0	0	2	0
Irrigated banana plantation (ha)	0	0	0	0	0	0	0	0	0	2.4	0
Livestock component											
Head of cattle (1)	30 ♂	4 ♂	0	0	40 ♀, 15 ♂	20 ♀, 4 ♂	2 ♀	1 ♀	0	10 ♂	0
Head of goat and sheep	70	20	10	0	70	50	5	5	5	0	0
Fishing			occ	occ				reg	reg*		
Equipment	T + M	M	M	M	T + M	T + M	M	M	M	T + M	T + M
Hired workforce	+++	++	+	-	++++	+++	-	+	-	+++	+++++
Investment ability	++	+	-	0	++++	++	0	0	+	+++++	++
% estimated population	5 %	15 %	20 %	5 %	5 %	10 %	20 %	10 %	10 %	rare	rare

Table 27: Typology of the encountered agro-ecological production systems. P1-P4 correspond to Pokomo production systems, O1-O5 to Orma production systems and B1-B2 to those found in Boramoyo village. (1) Number of milking cows or bulls (2) irrigated. occ: occasional, reg: regular, reg*: regular and owner of a canoe. In places where fishing was difficult, small-scale, non-irrigated market gardening replaced fishing for monetary income, M: manual, T: tractor.

floodplains during the dry seasons. The livestock keeping strategy was similar in both cases: to increase the size of the herd to compensate losses that occurred in extreme flood and drought years. One informant in Kikomo reported a loss of 50 out of 170 heads in 1984 and 130 out of 175 in 1997. Although the herds already varied considerably in size between different families (4-5 up to 200), most people could live solely from livestock-related activities. Livestock keeping was characterized by a high mobility of the herds so as to take advantage of the different environments in the surrounding areas. Herds would complete seasonal migrations of several hundred kilometres back and forth from the deltaic floodplains during the dry seasons to the drier hinterlands during the rainy seasons. The herds in the hinterlands as long as rainfall allowed grass growth. The cattle thus avoided the floods within the delta and only came in after the floods when the grasslands were productive. In sedentary villages, small herds of milking cows were kept permanently for the household food supply. Cows could produce a maximum of 5 L of milk per day (Table 26) when grass was abundant, demonstrating the richness and quality of the deltaic pasturelands. Farming activities, similar to those of the Pokomo, were undertaken by the more vulnerable village members to constitute a supplement to the livestock keeping activities. This cyclical accumulation and strategy of livestock keeping continued throughout the 1970s and 1980s. Although some livestock keepers noted a slight decrease of local butter production (which was made using excess milk supplies) in the late 1970s, and that herds spent less time on the hinterlands, there were no marked changes by the livestock keepers until the mid-80s. The La Niña drought of 1984, in conjunction with the reduction of the flood peaks after the construction of the Masinga dam, marked a turning point, after which the cyclical accumulation process gradually broke down. By the end of the 1980s, livestock keepers noticed that grass biomass was decreasing (Figure 59). An elder woman reported that the grass locally known as Oba lesa or Oba kawisa, an important fodder producing grass (*Echinochloa stagnina* (Retz) P. Beauvoir), used to grow over 2 m and 60 cm high in the rainy and dry seasons. Since the early 1990s, this grass reaches knee height during certain rainy seasons and disappears in the dry seasons. After the 1984 drought, the livestock keepers took up farming as a secondary activity. Many Orma were still cultivating in the early 1990s, as they had been unable to recover a sufficient number of cattle. The El Niño of 1997-98 was a dramatic event for the Orma community with the disappearance of large portions of herds. In Chalaluma and Kikomo, six informants reported a 40 % to 74 % loss of cattle herds. Cattle loss forced the remaining population into farming activities and sometimes fishing. The regular transhumance pattern from the inner floodplains of the delta in the dry seasons to the hinterland stopped and the majority of the cattle lingered within the delta or the surrounding wooded bush land all year round following the variable rainfall pattern. Nowadays, the Orma mainly use the lower floodplains as grazing land and the floodplains around the village as well as the ancient sand dunes for farming purposes. Although many have a low number of cattle, the informants are all adamant that livestock keeping is still the founding activity for the Orma. Monetary inflow is provided by selling milk, animals, or by selling fish. To increase their revenues, some Orma have either invested in fishing activities if their village is located close to a lake, or have taken up small-scale market gardening. Others have succeeded in keeping a relatively large herd and in increasing their cultivated land by hiring a tractor and labour work (Table 27). Farming activities are mostly used for household consumption.

A.6.2.3 *Boramoyo village: local agro-ecological initiatives through irrigated systems*

The village, created in the late 1980s, is located at the Southern end of the Oda branch where river water is still partially flowing by back-flow from the Matomba branch. Since the mid-1990s, two households (Table 27) have been using water-pumps to produce crops for the local market (tomatoes, kale, onions, bananas and sugar-cane). By sidestepping crop dependency on rainfall, they were able to maintain two (and sometimes three) harvests a year and increase their income (with a two to ten fold increase compared to the other production systems). This was possible because of the initial investment in irrigation equipment and the subsequent continuous availability of river water. These irrigation techniques have not spread within the delta, despite some experienced farmers having the investment capabilities, mainly because the major requirement is available river-water: this system is limited to the zones where the river is still flowing close to potential crop land.

A.7 DISCUSSION

A.7.1 *Mechanisms of change and local adaptive strategies*

Two main economic production systems coexisted within the TRD in the 1960s: the Pokomo combined rice farming, fishing and occasional hunting and gathering to secure their livelihoods while the Orma relied on the rich floodplain pastures during the dry seasons. Although extremely different in their underlying mechanisms, both were based on the highly productive ecosystems found within the wetlands that resulted from abundant water and fertile sediments brought by the floods. As fishermen, rice cultivators or livestock keepers, the Pokomo and Orma set up flexible production systems by taking advantage of the diverse local agro-ecological zones and dynamic flooding patterns. The different communities perceive this period as a sort of golden age, even though it was a decade of instability and social battles nationwide (Kenyan Independence was obtained in 1963). The decrease in water availability led the farmers to diversify their crops and associate new subsystems. Crops were selected according to water requirements, planted along the hydrological upper floodplain-lower floodplain gradient and gradually followed the water as this gradient moved downwards. Mango plantations spread out as the water table lowered and rice fields migrated down the floodplain. This increase in mango plantations is consistent with national data, with an increase from 500 ha cultivated nationally in 1970 to approximately 15000 ha in 2000 (Ministry of Agriculture, 2001, in Griesbach [2003]). In 2003, 1300 ha were under cultivation along the Tana River producing 12000 T of mangoes yearly (Food Agricultural Organisation, FAO, 2004). Considering 100 to 400 mangoes per tree per season as previously reported, an average weight of 570 g per mango (Griesbach [2003]), a density of 60 trees.ha-1 and one productive season per year, the yields in this study are between 3.4 $T.ha^{-1}.year^{-1}$ and 13.6 $T.ha^{-1}.year^{-1}$. These yields are consistent with the FAO figures, and on the lower end compared to previous assessments (Ndungu et al. [2008]). The Tana River District has a comparative advantage in mango growing within the Coast Province as floodwaters advance the harvesting season (FAO,2004). This, combined with a working calendar compatible with cereal crops, could explain the rapid increase of mango production in the Tana River District. The TRD communities adopted a whole array of strategies to face the decrease in flooding duration and frequency. They changed their production systems by diversifying, abandoning or adopting various farming, fishing and livestock techniques. As people tried to adapt to their new environment, the spatial pattern of land and water use also changed. At first, the decrease in flood extent, frequency and duration was partly beneficial to the Pokomo as the lowering of the water table level made available new arable land. But as floods decreased, informants reported that rice cultivation became difficult. Farmers, instead of biannual cropping of rice, switched to maize or a combination of rice and maize, planted once a year. This technique highlights the creativity of the farmers facing serious water shortages. By doing so, they adopted a risk-spreading strategy that increases the chances of harvest as maize dominates in the field in the average rainfall years and rice in the good rainfall years. Despite these innovations, all informants noted a decrease in cereal yields throughout the past 50 years, and especially since the early 1990s with the harvest also being less predictable (28). The traditional fishing sub-component of the Pokomo activities was also affected by the change in inundation frequency and duration. The latter increase reproduction zones and nutrient availability (Welcomme [1979]). As the lakes nearby the villages dried up, fishermen migrated down the river to the more distant lakes and temporary fishing-grounds, but the overall productivity of their work seems to have declined. Okeyo (1991) notes that wetland fish populations in Kenya have dwindled since the mid-1960s. Of course, upstream industrial development, human population increase along with siltation and the use of modern fishing gear (Okeya [1991]) can explain some of this decline, but the major factor for the TRD seems to be a decrease in floods. With the decrease of fish load, the relation effort of fishing versus benefits of fishing probably inversed in the 1980s leading to a decline in fishing activities. Njuguna [1991] indicates a fish landing of 82 T from Shakababo and Kongolola lakes within the TRD in 1991. As these lakes are now dry most of the years, fish landings are close to nil. Fishing, once used to define the Pokomo identity, has now been relegated behind tree farming and livestock keeping. The decrease of floods within the delta also had a direct effect on the migration patterns of livestock and fodder production (28). The floods, by forcing the cattle out of the floodplains, contributed to the regeneration of the pasturelands twice a year. As the extent and duration of floods decreased, the pastoralists were no longer forced to move their cattle to the terraces but kept the herds within the delta, as the latter provided better quality pasture than the hinterlands. The disappearance of floods at first was beneficial to the livestock keepers, as grazing land was made available around the villages. But at the same time the productivity of the floodplain grasslands dropped as water and nutrient inputs decreased. The combination of an increase in livestock through population growth and the decline in productivity resulted in the emergence of overgrazing in the late 1980s. The advantages of staying within the delta, such as shorter travelling distances, were quickly counterbalanced by losses during the dry seasons and the appearance of new diseases. The productive systems of the TRD have undergone considerable changes in the past 50 years, primarily in terms of water and land-use. In the next sections, we set water rarefaction as the main driver of change in the TRD but also note the importance of integrating the other drivers into the analysis.

A.7.2 *Water rarefaction as a driver of change of wetland food production systems*

Changes in water availability have modified the productive systems of the TRD: river-water was the main water resource in the past and its rarefaction is felt as a loss by all communities. The rare existence of small-scale farming systems based on irrigated sugarcane, bananas or garden crop farming as in Boramoyo village supports the idea that if water is available, then some people can invest in farming equipment and improve their productive systems. River-water used to be abundant. When its supply dwindled from hydroelectric infrastructure and upstream conversions, the producers adapted their production systems, but no alternative water supply has yet been efficiently captured to secure sufficient food production. The main strength of the TRD productive systems was the existence of multiple subcomponents that were combined under different inundation or climatic scenarios. The existence of multiple subcomponents (farming, fishing, livestock keeping) within the production systems provided food security while maintaining a sustainable use of natural resources. The relative importance of each sub-component varied throughout the years and seasons depending on the seasonal floods. Water depletion not only affected one component but all of them at the same time, so that by weakening each sub-system, the resilience of the whole productive system was affected until its overall dynamic equilibrium collapsed. Enfors and Gordon (2007) argue that smallholder agro-ecosystems in drylands can pass from a 'productive' state to a 'degraded' state in short periods of time as key variables inherent to that system are modified. In this study, we find similar results transposed to a different socio-ecosystem. This modification of the system took place because 1/ Water availability is the major factor influencing the productive systems 2/ River-water decrease affected each sub-component, so that the overall resilience of the systems was affected. External incentives to build up the adaptive capacity of the local population were also probably lacking, although this factor was not studied. All in all, the changing environmental conditions made it impossible to perpetuate the former food production systems while the lack of other positive drivers of change impeded the development of alternative and viable solutions for food production. The process was clearly non-linear with progressive adaptations throughout the 1960s to 1980s (e.g. shift in and of the cropping systems, modification of the seasonal migratory movements) then an abrupt change in the 1990s (e.g. switch from two to one cropping seasons per year, adoption of farming activities for all the Orma). At first, disturbance was the opportunity for innovation and development in the productive sector, like the development of the mango sector or the combination of multiple farming and livestock keeping systems for the Pokomo. Then the social-ecological systems probably experienced a phase shift from a 'desired' to a 'less desired' state in the mid 1990s when the production systems were no longer adapted to low water supplies. This collapse had a major impact on food production. Although the mechanisms

		Agriculture	Fishing	Livestock keeping
Regular floods	Function	Good soil fertility Eradication of invasive species Full soil water recharge	Increased habitat and nursery zones Fish migration and spawning	High productivity and good regeneration of grasslands Fodder production throughout the year Maintains flood tolerant species and kills invasive species
	Land use	MFP: recession agriculture (rice) UFP: supplementary crops (bananas, etc.)	Floodplains, permanent lakes, temporary lakes, channels	LFP: dry season grazing Out of delta: rainy season grazing
	Production organization	Biannual cropping system with risk spreading strategy	Fishing all year round, in different ecozones	Seasonal migration of livestock
	Productivity	≈ 2 T.ha^{-1}.season^{-1} (1)	40-60 kg fish per flooded hectare (2)	Rainy season: 60 kgDM.ha^{-1}.day^{-1} (3) Dry season: 5-40 kgDM.ha^{-1}.day^{-1} (3) Flooded: 200-250 kg DM.$^{-1}$ha^{-1}.day^{-1} (4)
Rain	Function	Partial recharge of soil and ground water Low and medium rainfall: crops fail Low water table: low yields of tree crops	No spawning nor nursery zones	Dry years: limited growth Rainy years: partial growth Limited regeneration of grasslands
	Land use	MFP (rain runoff zones): rainfed crops (maize) UFP (sufficient water table): arboriculture	Only in permanent lakes and channels	Floodplains: grazing all year round Out of delta: occasional grazing during rainy seasons
	Production organization	Cropping: April-July Increase in cultivated land High yield variability	Rare	Livestock follow highly variable rainfall
	Productivity	1.3 T.ha^{-1} *	0	15 ± 5kg DM.ha^{-1}.day^{-1} **

Table 28: Changes in water resources and their consequences on production systems in the Tana River Delta. UFP: upper floodplain, MFP: mid floodplain, LFP: low floodplain. *: derived from the interviews. **: data collected from 04/12/2010 to 20/05/2011 in the Tana River Delta. References: (1) Mollard and Walter [2008] (2) Welcomme [1979] (3) Hiernaux and Diarra [1986] (4) Francois et al. [1989].

that played vary between the communities, all experienced food and water shortages.

A.7.3 *Integrating other drivers of change*

Agro-ecological production systems are complex assemblages resulting from strategic decisions on land and resource uses but also various social and economic incentives, cultural influences and market and political forces. To analyse the complex systems prevalent in the TRD, we adopted a disagregative strategy and analysed the impact of one major factor. However, it has been argued that complex socio-ecosystems are controlled by a number of key variables, the latter often somewhere between three and five (Holling and Gunderson [2002]). Other factors have certainly played a major role in shaping the current agro-ecosystems of the TRD, in particular population growth, land rights and market incentives. In the TRD, population has increased from 47 000 in 1989 to 100 000 inhabitants (Kenyta Population Census,2010) leading to an increased strain on natural resources. In particular, population increase has encouraged settlement in remote areas where infrastructure is scarce and the environment inappropriate for farming. Livestock numbers have also undoubtedly increased, thus requiring more pasturelands. Concerning land rights, the Pokomo and Orma do not have legal titles on the central floodplain although they have been using it for centuries. The recent tendency is toward acquisition of their land by public and private companies for large-scale biofuel projects (Duvail et al. [2010]). This leaves little opportunity for the locals to invest in a long-term management of their ressources. Economic growth (Ensminger and Rutten [1991]), market incentives, governance issues, infrastructure development and many other factors also shape the development trajectories of small-scale production systems. As this was not the scope of our research, future studies will need to extend our results through a more holistic approach. It will also be important to combine several levels of analysis from different research fields, like economic evaluations (Barbier et al. [1991]; Barbier [1993]; Barbier and Thompson [1998]; Emerton [2003]), modelling of water-demand scenarios (Duvail and Hamerlynck [2003]; Murray-Hudson et al. [2006]; Singh et al. [2011]) and climate change projections (Beck and Bernauer [2011]) so that a common consensus emerges.

A.7.4 *How changing water resources have impacted human well-being*

Human well-being has several constituents, including basic materials for good life (MA, Millennium Ecosystem Assessment [2005a]). The latter encompasses food supply, which is one of the essential needs for a society (Butler et al. [2006]). Decrease in water availability - accompanied by a degradation of the productive capacities within the delta - has deprived the communities of their ability to produce their own food, or to secure an income to buy food and other assets. As such, it has clearly impacted local human well-being. But water depletion has also affected the other components of human well-being in a cascading effect. Unreliable local food production led to a stronger dependency on external food supplies. As many families are nowadays unable to produce or buy food, they receive aid through the World Food Programme. This, in turn, has generated a sense of dependency and helplessness within the population. Boreholes have dried up, obliging some villagers to use river-water as drinking water, which has most probably affected their health. Changes in the inundation regime also hindered the economic development of the zone by blocking small scale irrigation systems, tree plantations and milk production that could supply the surrounding towns with local and highly demanded produce. As such, opportunities through which people could increase their assets have been blocked. Furthermore, water-scarcity has led to an increased competition over natural resources. In 2001, violent conflicts between the Pokomo and Orma communities started. The underlying causes of these conflicts are the degradation of the environment and the depletion of natural resources. In turn, this contributes to the loosening of social cohesion within and in between the TRD communities.

A.8 CONCLUSION

During the past 50 years, Kenya's strategy for energy production has been to construct large-scale hydroelectric reservoirs. As a consequence, downstream wetlands have undergone drastic environmental changes. These changes in water resource distribution have affected local food production systems leading to a decrease in human well-being in the TRD. The agro-ecological production systems in the TRD that were once adapted to and based on the dynamic flooding patterns of the river have undergone drastic changes. As the flooding time, duration and frequency diminished, the local population diversified, abandoned or adopted various farming, fishing and rearing techniques, extended land cultivation or even shifted. Despite all of this, decrease in water availability affected each subcomponent of the productive system leading to their collapse in the 1990s.Water depletion has lead to a decrease in human well-being through the loss of food security and also indirectly by restricting the freedom of choice and action, probably by affecting the health of the communities and loosening social cohesion. The next step of this research is to undertake a quantitative assessment of the changes related to flow regimes. This would provide a guideline to decision-makers and major stakeholders, in order to manage the wetland in accordance with national objectives and with local human and environmental requirements as specified under the Ramsar convention (1971) to which Kenya is a signatory. As the main ecosystem services of the TRD wetlands are food-oriented, these assessments should first focus on crop, fish and fodder productions and propose different flooding scenarios that would restore and improve the resource uses of the delta.

B

APPENDICES RELATED TO CHAPTER 4

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Coefficients: (1 not defined because of singularities)
                                               Estimate Std. Error t value Pr(>|t|)
(Intercept)                                   0.8194234  0.9695119   0.845  0.39848
Water_Supply_th                              -0.0776404  0.2223816  -0.349  0.72716
LogWat                                        0.4758310  0.2553990   1.863  0.06314 .
CuttingG2                                     0.9884716  1.4375429   0.688  0.49207
CuttingG3                                     2.2174819  1.9897139   1.114  0.26570
Mean_Radiation                                0.0158524  0.0454252   0.349  0.72728
Mean_Rainfall                                 2.4352440  0.5890603   4.134 4.29e-05 ***
AF1                                           0.2180987  0.2244184   0.972  0.33168
Temps                                         0.0015511  0.0006070   2.555  0.01096 *
Water_Supply_th:CuttingG2                     0.6865573  0.3104397   2.212  0.02753 *
Water_Supply_th:CuttingG3                    -0.3322901  0.4601332  -0.722  0.47059
Water_Supply_th:Mean_Radiation                0.0094907  0.0104447   0.909  0.36404
Water_Supply_th:Mean_Rainfall                -0.2747759  0.1324912  -2.074  0.03869 *
Water_Supply_th:AF1                           0.1971937  0.0480784   4.102 4.92e-05 ***
LogWat:CuttingG2                             -1.0721735  0.3650154  -2.937  0.00349 **
LogWat:CuttingG3                              1.0669702  0.5278264   2.021  0.04386 *
LogWat:Mean_Radiation                        -0.0175329  0.0119605  -1.466  0.14341
LogWat:Mean_Rainfall                         -0.3067002  0.1478916  -2.074  0.03870 *
LogWat:AF1                                   -0.4562610  0.0593384  -7.689 1.03e-13 ***
CuttingG2:Mean_Radiation                     -0.0387552  0.0690260  -0.561  0.57478
CuttingG3:Mean_Radiation                     -0.0924420  0.0928343  -0.996  0.31993
CuttingG2:Mean_Rainfall                      -2.1529861  0.5280332  -4.077 5.44e-05 ***
CuttingG3:Mean_Rainfall                       0.2819882  0.0626670   4.500 8.79e-06 ***
CuttingG2:AF1                                 0.3439263  0.1911979   1.799  0.07276 .
CuttingG3:AF1                                 0.5711167  0.3076777   1.856  0.06411 .
Mean_Radiation:Mean_Rainfall                 -0.1221438  0.0302353  -4.040 6.35e-05 ***
Mean_Rainfall:AF1                            -0.2736181  0.1155884  -2.367  0.01837 *
Water_Supply_th:Temps                        -0.0007731  0.0001352  -5.718 2.04e-08 ***
LogWat:Temps                                  0.0008162  0.0001616   5.050 6.56e-07 ***
CuttingG2:Temps                               0.0001482  0.0005265   0.281  0.77852
CuttingG3:Temps                              -0.0008772  0.0011572  -0.758  0.44887
Water_Supply_th:CuttingG2:Mean_Radiation     -0.0359909  0.0150213  -2.396  0.01701 *
Water_Supply_th:CuttingG3:Mean_Radiation      0.0147408  0.0224210   0.657  0.51124
Water_Supply_th:Mean_Radiation:Mean_Rainfall  0.0145173  0.0068277   2.126  0.03406 *
LogWat:CuttingG2:Mean_Radiation               0.0454690  0.0172686   2.633  0.00877 **
LogWat:CuttingG3:Mean_Radiation              -0.0452570  0.0242286  -1.868  0.06246 .
LogWat:CuttingG2:Mean_Rainfall                0.0027863  0.0117255   0.238  0.81229
LogWat:CuttingG3:Mean_Rainfall               -0.1000914  0.0206108  -4.856 1.68e-06 ***
LogWat:CuttingG2:AF1                         -0.1758657  0.0620866  -2.833  0.00484 **
LogWat:CuttingG3:AF1                         -0.2803017  0.1070678  -2.618  0.00916 **
LogWat:Mean_Radiation:Mean_Rainfall           0.0145598  0.0076045   1.915  0.05621 .
CuttingG2:Mean_Radiation:Mean_Rainfall        0.1147677  0.0276321   4.153 3.96e-05 ***
CuttingG3:Mean_Radiation:Mean_Rainfall               NA         NA      NA       NA
LogWat:CuttingG2:Temps                        0.0008139  0.0001765   4.612 5.28e-06 ***
LogWat:CuttingG3:Temps                        0.0005002  0.0003877   1.290  0.19773
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

Figure 61: Parameter estimations for the final model (g11) explaining daily growth rates (GR) in non-flooded conditions as a funtion of various practives and climatic variables.. Parameter estimators (log transformed), their standard deviation and their respective p-values are specified.

model	*K*	*AIC*	*AICc*	*ΔAICc*	*exp(-ΔAICc/2)*	*wi*	*Parameters*
F1	3	2734.60	2734.65	0	1	1	*F*
F2	1	2803.50	2803.51	68.86		00	

Table 29: Tested models (F1 and F2) to study the effect of floods on daily growth rates (GR). K: number of parameters; F: flood status. Dispersion parameter and R^2 were respectively 0.37 and 12.2 % for the best model (F1). $w_i = \frac{exp(-\Delta AICc/2)_i}{\sum exp(-\Delta AICc/2)}$.

model	*K*	*AIC*	*AICc*	*ΔAICc*	*exp(-ΔAICc/2)*	*wi*	*Parameters*
M1	4	223	223.09	0.00	1.00	0.82	W*NfD
M3	2	227	227.03	3.94	0.14	0.11	NfD
M2	3	228	228.05	4.97	0.08	0.07	W:NfD
M4	2	239	239.03	15.94	0.00	0.00	W

Table 30: Tested models to study the effect of irrigation, W, and the number of non-flooded days, NfD, on daily growth rates for flood modality F. K: number of parameters. $w_i = \frac{exp(-\Delta AICc/2)_i}{\sum exp(-\Delta AICc/2)}$. "*": effect of the factors and all their interactions; ":": effect of the interaction between two variables

Tested effect	Model 1	Model 2	res.Df	Df	SS	F	p-value
AGDB:Fl	AGDB*Fl	AGDB+Fl	89	2	13772	4.0195	0.02132
AGDB	AGDB*Fl	Fl+AGDB:Fl	89	2	2333.8	0.6812	0.5086
AGDB	Fl+AGDB:Fl	Fl	91	1	749666	410.37	< 2.2e-16
Fl	Fl+AGDB:Fl	AGDB	91	2	90165	24.678	2.737e-09

Table 31: Tested effects (Above ground dry biomass, AGDB, Flood status, Fl, and their interactions) on leaf biomass B_L, uging F-tests. res.Df: residual degrees of freedom, Df: degrees of freedom, SS: tested sum of squares, F: Fisher's value, p-value: p-value from Fisher's test. "*": effect of the factors and all their interactions; ":": effect of the interaction between two variables.

model	*K*	*AIC*	*AICc*	*ΔAICc*	*exp(-ΔAICc/2)*	*wi*	*Parameters*
N1	6	323.96	324.15	0.00	1	1	B_L*Fl
N2	4	338.65	338.74	14.59	0	0	B_L+Fl
N3	2	384.69	384.72	60.57	0	0	B_L
N4	2	558.26	558.29	234.14	0	0	Fl

Table 32: Tested models to study the effect of floods (Fl) and leaf biomass (B_L) on leaf N concentration. K: number of parameters. $w_i = \frac{exp(-\Delta AICc/2)_i}{\sum exp(-\Delta AICc/2)}$. "*": effect of the factors and all their interactions; ":": effect of the interaction between two variables. R^2 and dispersion parameter for N1: 79 % and 0.10.

model	K	AIC	AICc	ΔAICc	exp(-ΔAICc/2)	wi	Parameters
g1	97	1971.41	2022.59	163.98	0	0	W*WSq*C*Rd*Rn*Af
g2	55	1966.70	1981.57	123.04	0	0	W + WSq + C + Rd + Rn + Af + W:C + W:Rd + W:Rn + W:Af + WSq:C + WSq:Rd + WSq:Rn + WSq:Af + C:Rd + C:Rn + C:Af + Rd:Rn + Rd:Af + W:C:Rd + W:C:Rn + W:C:Af + W:Rd:Rn + W:Rd:Af + WSq:C:Rd + WSq:C:Rn + WSq:C:Af + WSq:Rd:Rn + WSq:Rd:Af + C:Rd:Rn + C:Rd:Af + W:C:Rd:Rn + W:C:Rd:Af + WSq:C:Rd:Rn + WSq:C:Rd:Af
g3	109	1866.41	1933.08	74.48	0	0	(W+WSq+C+Rd+Rn+AF)^3+T*W*WSq*C
g4	59	1857.34	1874.60	16.06	0	0	W + WSq + C + Rd + Rn + Af + T + W:C + W:Rd + W:Rn + W:Af + WSq:C + WSq:Rd + WSq:Rn + WSq:Af + C:Rd + C:Rn + C:Af + Rd:Rn + Rd:Af + W:T + WSq:T + C:T + W:C:Rd + W:C:Rn + W:C:Af + W:Rd:Rn + W:Rd:Af + WSq:C:Rd + WSq:C:Rn + WSq:C:Af + WSq:Rd:Rn + C:Rd:Rn + C:Rd:Af + W:C:T + WSq:C:T + W:C:Rd:Rn + W:C:Rd:Af
g5	71	1865.91	1891.59	33.06	0	0	(W+WSq+C+Rd+Rn+AF)^3+T*W*WSq*C
g6	52	1856.10	1869.31	10.78	0	0	W + WSq + C + Rd + Rn + Af + T + W:C + W:Rd + W:Rn + W:Af + WSq:C + WSq:Rd + WSq:Rn + WSq:Af + C:Rd + C:Rn + C:Af + Rd:Rn + Rn:Af + W:T + WSq:T + C:T + W:C:Rd + W:C:Rn + W:C:Af + W:Rd:Rn + WSq:C:Rd + WSq:C:Rn + WSq:C:Af + WSq:Rd:Rn + C:Rd:Rn + W:C:T + WSq:C:T
g7	52	1856.10	1869.31	10.78	0	0	W + WSq + C + Rd + Rn + AF + T + W:C + W:Rd + W:Rn + W:AF + WSq:C + WSq:Rd + WSq:Rn + WSq:AF + C:Rd + C:Rn + C:AF + Rd:Rn + Rn:AF + W:T + WSq:T + C:T + W:C:Rd + W:C:Rn + W:C:AF + W:Rd:Rn + WSq:C:Rd + WSq:C:Rn + WSq:C:AF + WSq:Rd:Rn + C:Rd:Rn + W:C:T +WSq:C:T
g9	56	2005.19	2020.64	162.11	0	0	(W+C+Rd+Rn+AF)^3+WSq+T*W*WSq*C
g10	71	1865.91	1891.59	33.06	0	0	(W+LW+C+Rd+Rn+AF)^3+T*W*LW*C
g11	46	1848.31	1858.53	0	1	0.99	W + LW + C + Rd + Rn + AF + T + W:C + W:Rd + W:Rn + W:AF + LW:C + LW:Rd + LW:Rn + LW:AF + C:Rd + C:Rn + C:AF + Rd:Rn + Rn:AF + W:T + LW:T + C:T + W:C:Rd + W:Rd:Rn +LW:C:Rd + LW:C:Rn + LW:C:AF + LW:Rd:Rn + C:Rd:Rn + LW:C:T
g12	42	1883.99	1892.45	33.91	0	0	W + LW + C + Rd + Rn + AF + T + W:C + W:Rd + W:Rn + W:AF + LW:C + LW:Rd + LW:AF + C:Rd + C:Rn + C:AF + Rd:Rn + Rn:AF + W:T + LW:T + C:T + W:C:Rd + W:Rd:Rn + LW:C:Rd + LW:C:AF + C:Rd:Rn + LW:C:T
g13	14	2250.50	2259.81	405.28	0	0	(W+C+Rd+Rn+AF)^3+T*W*C
g14	103	1866.4	2029.93	171.40	0	0	(W+LW+ C+Rd+Rn+AF)^6+T*LW*W*C
g15	97	1971.41	2022.52	7.41	0	0	(W+LW+ C+Rd+Rn+AF)^6

Table 33: Tested GLM models to explain daily Growth Rates (GR) as a function of floods, pratices and climatic variables. The best model, g11, is given by the highest w_i. K: number of parameters; W: Irrigation, WSq: Irrigation^2; LW: log(Irrigation; C:Ccutting frequency; Rn: mean daily rainfall during growth period ($mm \cdot day^{-1}$), Rd: mean radiation during growth period ($MJ \cdot day^{-1}$); AF: qualitative factor indicating whether the sample was taken before or after the floods; T: time; "*": effect of the factors and all their interactions; ":": effect of the interaction between two variables; "()^x": inclusion of all variables and all their interactions up to the xth order. $w_i = \frac{exp(-\Delta AICc/2)_i}{\sum exp(-\Delta AICc/2)}$. R^2 and dispersion parameter for g11: 77 %, and 0.16.

C

APPENDICES RELATED TO CHAPTER 5

Parameters	Symbol	Min - Max value	Value	Unit	References
Daily senescence coefficient of leaves or stems, non flooded	$s_{l,NF}$,$s_{s,NF}$	L:00074-0.01; S:00074-0.01	L:0.003 S: 0.003	$gDM \cdot gDM^{-1} \cdot day^{-1}$	Nouvellon et al., 2000;Cayrol et al., 2000
Daily senescence coefficient of roots, non flooded and flooded	$s_{r,NF}$,$s_{r,F}$	0.00078-0.01	0.003/0.0078	$gDM \cdot gDM^{-1} \cdot day^{-1}$	Nouvellon et al., 2000;Cayrol et al., 2000
Daily senescence coefficient of leaves, flooded	slF	0.108-0.162	0.135/	$gDM \cdot gDM^{-1} \cdot day^{-1}$	Piedade et al., 1991
Daily senescence coefficient of stems, flooded	ssF	0.0054-0.008	0.0067	$gDM \cdot gDM^{-1} \cdot day^{-1}$	*(1)
Remaining leaf dry biomass after cutting, for R_0, R_1, R_2, stem and dead	$B_{l,i,min}$	0-10/0-20/0-20/0-10/0-10	5/10/15/0/0	gDM	(1)
Maximal conversion efficiency coefficient, flooded	ε_{Emax}	4-5.5	4.9-5.4 **	$g \cdot MJ$	Piedade et al., 1991; Zhu et al., 2008; Long et al., 2006(2)
Maximal conversion efficiency coefficient, non flooded	β	3-4.5	3.49-4.5 **	$g \cdot MJ$	Mougin et al., 1995; Heaton et al., 2008(2)
Coefficient defining conversion efficiency coefficient	α	0.8-0.99	0.95	$m^3 \cdot m^3$	(1)
Initial root dry biomass	$B_{r,initial}$	20-100	25	gDM	(1)
Root to shoot ratio	$r_{r:s}$	0.01-3	0.90-2.25 **	-	
Maximal translocation rate from roots to leaves	$T_{r:l}$	0.008-0.012	0.01	$gDM \cdot m^{-2} \cdot day^{-1}$	
Surface Leaf Area	SLA	0.019-0.029	0.024769	gDM^{-1}	*(1)
Maximal LAI, flooded	LAI.max	5-7	6	$gDM \cdot gDM^{-1}$	Piedade et al., 1994
Coefficient for respiration	Y_G	0.7-0.89	0.75	-	Amthor, 2000
maintenance respiration coefficient	m_R	0.0004-0.1	0.02	$g \cdot g^{-1} \cdot day^{-1}$	Amthor, 1989(2)

Table 35: Parameter specifications for the plant growth model (part 1). Value: value given to the parameters after the sensitivity analysis. **: parameters adjusted during the calibration process. *: measured from field data.

Parameters	Symbo1	Min - Max value	Value	Unit	References
Minimal stomatal resistance	rsmin	80-130	88	$s \cdot m^{-1}$	Piedade et al., 1994; Rambal and Cornet, 1982;Mougin et al., 1995;Cayrol et al., 2000[(2)]
Aerodynamic resistance for the soil and canopy	r_{as}, r_{ac}	5-50	50	$s \cdot m^{-1}$	
Resistance coefficients	a_r,b_r	3312-4968/644-966	4140/805	$s \cdot m^{-1}$	Camillo and Gurney 1986
Allocation coefficient to leaves, non flooded	$a_{l,NF}$	0.416-0.624	0.52	$gDM \cdot gDM^{-1}$	(1)
Allocation coefficient to leaves, flooded	a_l	0.2456-0.3684	0.307	$gDM \cdot gDM^{-1}$	(1)
Allocation coefficient to stems, flooded	a_s	(3)	(3)	$gDM \cdot gDM^{-1}$	(1)
Allocation coefficient to roots, flooded	a_r	0.044-0.066	0.055	$gDM \cdot gDM^{-1}$	(1)
Coefficient defining allocation, flooded	γ_a	1.01-1.3	1.1	-	(1)
Maximal allocation rate to leaves	a_{Lmax}	0.48-0.72	0.56-0.71 **	$gDM \cdot gDM^{-1}$	(1)
Litter formation coefficient, non flooded	l_{NF}	0.0016-0.0024	0.002	$gDM \cdot gDM^{-1} \cdot day^{-1}$	(1)
Litter formation coefficient, flooded	l_F	0.016-0.024	0.02	$gDM \cdot gDM^{-1} \cdot day^{-1}$	Junk and Furch, 1991
Coefficient defining vegetation cover	k_1	0.39-0.59	0.496		*
Root distribution in horizons	ϑ_r	0.3-0.9	0.3-0.51 **	$m^3 \cdot m^{-3}$	(1)
Soil water content at saturation H1, H2	$teta_{sat,j}$	40-70	60	%	Chow et al., 1988
Soil water content at field capacity H1, H2	$teta_{fc,j}$	38.4-57.6/37.6-56.4/	48/47	%	*
Soil water content at wilting point H1, H2	$teta_{wp,j}$	30.4-45.6,27.2-40.8	38/34	%	*
Initial soil water content H1, H2	$teta_{i,j}$	34.4-51.6/32-45	43/40	%	* (2)
Maximal drainage rate H1, H2	$D_{max,j}$	1-50	10	$mm \cdot day^{-1}$	

Table 37: Parameter specifications for the plant growth model (part 2). [(3)] calculated from a_l and a_r

Constant	Symbol	Value	Unit	References
Albedo	α	0.23	-	Allen et al., 1998
air density	ρ	1	$kg \cdot m^{-3}$	
specific heat of air	c_p	1	$MJ \cdot kg^{-1} \cdot {}^{\circ}C^{-1}$	
latent heat vaporization	λ	2.45	$MJ \cdot kg^{-1}$	
psychometric constant	γ	$0.665 \cdot 10^{-3} \cdot P$	$kPa \cdot {}^{\circ}\mathrm{C}^{-1}$	
Stefan-Boltzmann constant	σ	$4.903 \cdot 10^{-9}$	$MJ \cdot K^{-4} \cdot m^{-2} \cdot day^{-1}$	
Atmospheric pressure (5m altitude)	P	101.2409	kPa	Allen et al., 1998
coefficients for fraction of extraterrestrial radiation reaching the earth on clear-sky days	a_c, b_c	1.35/-0.35		Allen et al., 1998
Coefficients for calculation of net long wave radiation	a_e, b_e	0.34/-0.14	kPa/-	Allen et al., 1998
Depth of horizons H1, H2	z	5/65	mm	measured
Climatic conversion coefficient	ε_c	0.47	$MJ \cdot MJ^{-1}$	Szeicz, 1974

Figure 62: Constants used in the plant growth model.

Input variable	Symbol	Min-Max value	Unit
Daily irrigation	Ir	0-60	$mm \cdot day^{-1}$
Maximal daily temperature	T_{max}	30-38	$^{\circ}C$
Minimal daily temperature	T_{min}	19-24	$^{\circ}C$
Maximal daily relative humidity	RH_{max}	91-98	%
Minimal daily relative humidity	RH_{min}	36-61	%
Daily rainfall	R	0-47	$mm \cdot m^{-2} \cdot day^{-1}$
Daily radiation	I	16-24	$MJ \cdot m^{-2} \cdot day^{-1}$
Extraterrestrial radiation	Ia	32.6-38	$MJ \cdot m^{-2} \cdot month^{-1}$
Presence/Absence floods	F, NF	-	-

Table 38: Input variables for the plant growth model.

D

PHOTOS OF THE GRASSLAND

Figure 63: Aerial view 1 of the grasslands. The flooded area in dark green is probably receding. Groups of cows are visible as small white spots. In front: Bilissa Boka lake. A manyatta (temporary campment for the livestock) is visible in the mid upper left side. Photo: Coleen Jackson. January 2008.

Figure 64: Aerial view 2 of the grasslands. The lower parts of the grasslands, like the small temporary channels, are flooded. Photo: Coleen Jackson. January 2008.

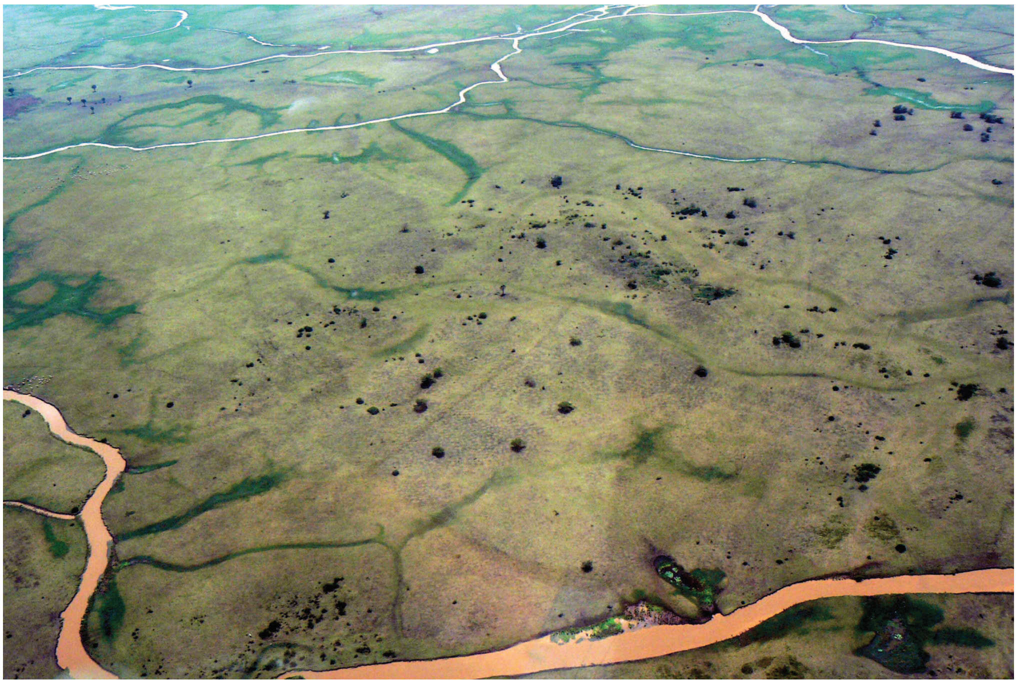

Figure 65: Aerial view 3 of the grasslands. The central part of the photo where bushes are visible is slightly elevated compared to the other zones. Photo: Coleen Jackson. January 2008.

Figure 66: Flooded grasslands of *Echinochloa stagnina* (Retz) P. Beauv. Very few cows graze in these conditions. The trees on the horizon (about 10 km away) mark the horizon. Mean flood height is 50-60 cm. May 2010.

Figure 67: Grasslands of *Echinochloa stagnina* (Retz) P. Beauv. during the rainy season. Cows graze the low vegetation. November 2011.

Figure 68: Grasslands of *Echinochloa stagnina* (Retz) P. Beauv. during the dry season. Large cracks in the soil are visible. March 2011.

Figure 69: Visible effects of floods 1. In front: grasslands that did not flood. Behind: Grasslands that were flooded for about a week. The only difference between the two areas is a slight difference in elevation (app. 10-20 cm). June 2011.

Figure 70: Visible effects of floods 2. Floods are increasing: a couple of days after this photo was taken, the zone in the lower part of the photo was flooded. As a result, the grass grew while the unpalatable dicotyledons died away. November 2011.

Figure 71: View of the experimental plot during the rainy season. Within the exclosure, the irrigation blocs and cutting sub-blocs, the irrigation system and the rain gauge are visible. See Figure 13 for a schematic diagram. December 2010.

(a) Experimental plot on the 29/11/2011, 8 days after the beginning of the floods. The plots that were cut frequently as well as the lanes are visible. Flood height: app. 20 cm

(b) Experimental plot on the 21/12/2011, 31 days after the beginning of the floods. In just over a month, the grass cover within the experimental site was homogeneous and extremely dense. Height of floods: app. 10 cm (decreasing).

Figure 72: View of the experimental plot in a flooded state.

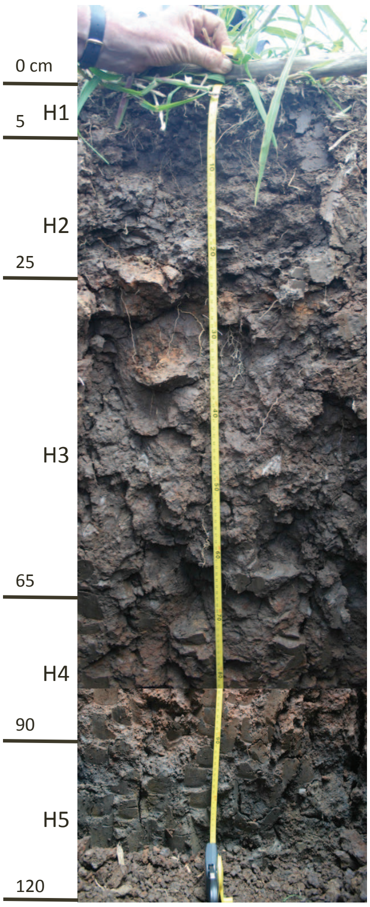

Figure 73: View of the soil profile at the experimental plot on the 27/05/2011. Roots are mostly concentrated in the upper horizons and are nearly inexistent in horizons H4 and H5. Small cracks are visible up to horizon H5.

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ACRONYMS

COLOPHON

This document was typeset using the typographical look-and-feel `classicthesis` developed by André Miede. The style was inspired by Robert Bringhurst's seminal book on typography *"The Elements of Typographic Style"*. `classicthesis` is available for both LaTeX and LyX:

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Final Version as of May 9, 2013 (`classicthesis` version 4.1).

Quantifying the impact of floods on fodder production in the Tana River Delta, Kenya

Wetlands are a vital resource for many pastoralists in Sub-Saharan Africa as they provide dry-season grazing zones. As floods are essential for wetland ecosystems, the assessment of water abstraction and hydroelectric infrastructure on downstream flooding dynamics is crucial. Yet, scarce data, environmental variability and the lack of models make this challenging. This research contributes to quantifying the influence of changing water resources on fodder production of floodplain grasslands in the Tana River Delta, Kenya. 1/ Growth characteristics of floodplain grasslands of *Echinochloa stagnina* (Retz) P. Beauv. for different flood and management options were determined and a quantification of their productivity achieved. This kind of data is scarce for floodplain grasslands. A plant growth model adapted to tropical floodplain conditions and perennial C4 grasses was developed, and is the first known physiologically based model for floodplain grasslands. 2/ Hydrological processes of ecological importance (flood extent, timing, duration, frequency) were characterized in a poorly gauged basin using a water-balance model combined with remote-sensing techniques, despite precise knowledge of discharge rates, topography and a high cloud cover. 3/ A preliminary analysis explored different flooding scenarios and their impact on fodder production through the use of simple ecosystem service indicators. This PhD contributes to the repertoire of wetland ecosystem services by building biophysically based simulation models and exploring possible scenarios in a region of the world and an ecosystem where these type of evaluations are rare.

Quantification de l'impact des inondations sur la production fourragère dans le delta du fleuve Tana, au Kenya

En Afrique Sub-Saharienne, les zones humides forment d'importantes zones de pâturages pour bon nombre de pastoralistes. Le régime d'inondation de ces plaines influence leur fonctionnement et leur productivité. Pour comprendre et maitriser ces régimes, il est donc essentiel d'évaluer l'impact de l'infrastructure hydro-électrique sur les dynamiques d'inondations en aval des barrages. Pourtant, le manque de données disponibles, l'absence de modèles validés et la forte variabilité environnementale rendent cet exercice difficile. Cette thèse contribue à quantifier l'impact du changement des ressources hydriques sur la productivité fourragère des prairies inondables dans le Delta du fleuve Tana, au Kenya. 1/ Les caractéristiques de croissance et la productivité d'une prairie inondable à *Echinochloa stagnina* (Retz) P. Beauv. ont été déterminées pour différents régimes de fauche, d'irrigation et conditions d'inondations. Ensuite, un modèle de croissance adapté à des Graminées en C4, tropicales et pérennes, de prairies inondables a été développé. Il constitue, à notre connaissance, le premier modèle éco-physiologique adapté à ce type de prairies. 2/ Des processus hydrologiques importants pour le fonctionnnement des écosystèmes (étendue, période, durée et fréquence d'inondation) ont été caractérisés grâce à un modèle de bilan hydrologique et à l'utilisation de techniques de télédétection, et cela en dépit de la faible instrumentalisation du bassin, du peu de données topographiques et d'un fort couvert nuageux. 3/ Une analyse préliminaire de l'impact de différents scénarios d'inondations sur la production fourragère a été effectuée en utilisant des indicateurs de services écosystémiques. Cette thèse participe à l'amélioration de nos connaissances des services écosystémiques des zones humides par la construction de modèles et par l'évaluation de scénarios dans une région du monde où ce type de données est rare.