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## Assessing hydrologic changes across the Lower Mekong Basin

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## ABSTRACT

**Study region:** In this study, 33 catchments across the Lower Mekong Basin in Southeast Asia are examined to detect historical changes in their hydrological response via a model-based methodology.

**Study focus:** Intensive development over the past half century across Southeast Asia's Lower Mekong Basin has inevitably affected natural resources. Large areas have been converted from forests for subsistence and commercial agriculture, and urban development. We implement an innovative approach to screen hydrologic data for detecting impacts of such large-scale changes on hydrological response. In a first step, temporal changes in the rainfall-runoff relationship were assessed using the parsimonious, two-parameter GR2M hydrological model. In a second step, a distribution-free statistical test was applied to detect whether significant changes have occurred in the wet season (high flow) and dry season (low flow) conditions.

**New hydrological insights for the region:** Our results indicate that the majority of catchments (64% of those considered) with sufficiently long data records exhibited no discernable trends in hydrological response. Those catchments that did exhibit significant trends in hydrological response were fairly evenly split between increasing trends (between 21% and 24%) and decreasing trends (between 15% and 12%) with time. There was a lack of evidence that these changes were brought about by shifts in precipitation or potential evapotranspiration; however, catchments exhibiting significant increasing trends in hydrological behavior were found to have different land cover compositions (lower percentage of forest coverage and subsequently higher paddy rice coverage) than those exhibiting significant decreasing trends. The approach presented here provides a potentially valuable screening method to highlight regions for further investigation of improved mechanistic understanding. Without this connection, we might be blind to future hydrological shifts that can have significant impact on development.

## 1. Introduction

Surging economic growth in developing countries is often accompanied by the expansion of agriculture and infrastructure. Such expansion typically has both direct and indirect impacts on natural resources (Scanlon et al., 2007). For example, it is often seen that changes in land cover and land-use affect water yields (i.e. runoff, including groundwater outflow, and storage) within a catchment. This is typically due to the role land cover plays in the water cycling including evapotranspiration (e.g., Jaramillo et al., 2013) and

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recharge (e.g., Tessema et al., 2014) processes. Both groundwater recharge and streamflow generation in a basin are subject to change, especially when alteration of vegetation or agricultural expansion occurs over large areas, respective to the catchment size (Brown et al., 2005; Bruijnzeel, 2004; Andreassian et al., 2003). The magnitude and seasonality of hydrological impacts are, however, highly variable depending on regional conditions. As such, there is still clear need for studies that investigate techniques able to distill change in hydrological behavior and its potential relationship with land cover at regional scales – especially for regions targeted for development through exploitation of natural resources (e.g. Lyon et al., 2014).

Nowhere is this need more obvious than in southeast Asia where economic growth and increased land and water resource pressure have been substantial over the past half century. As the region's economies have soared, many natural resource stocks have declined. Across the Lower Mekong Basin (LMB), covering portions of Laos, Thailand, Cambodia and Vietnam, deforestation has been considerable ranging from land-clearing for strategic purposes during the Vietnam War (Lacombe et al., 2010; Lacombe and Pierret, 2013) to economic and population growth driving the logging and agriculture expansion for self-subsistence and markets. During the 1970s and 1980s, the region served as the principal source of timber for the trade of tropical hardwood internationally (Douglas, 1999). Deforestation rates have increased dramatically since the late 1980s, bringing the region's forest destruction rate on par with tropical Africa and tropical America (Bernard and De Koninck, 1996). Between 1990 and 2005, Thailand lost 1.5 million hectares of forest, while Laos and Cambodia lost 1–2.5 million hectares each year, resulting in the highest rates of deforestation in the region (MRC, 2010). However, this trend appears to have reversed in recent decades: according to the most recent Global Forest Resources Assessment (FAO, 2015), Laos and Vietnam are listed among the 13 countries globally which were likely to have passed through a national forest transition between 1990 and 2015, with a switch from net forest loss to net forest expansion.

While forest cover change has occurred over the past 50 years, agricultural irrigation and expansion has increased under growing populations. In 2000, irrigated area in southeast Asia reached 18 million ha, 80% of which was for rice cultivation extending traditional rainfed ventures. Large-scale irrigation systems now make up about 40% of the LMB area (FAO, 2007). Coupled to irrigation and agricultural expansion, construction of infrastructure such as roads and urban areas also took place during this time (Ziegler et al., 2004). These widespread activities have likely had an effect on the hydrological behavior (i.e. runoff response) of streams and rivers in the region through the reallocation and rerouting of existing terrestrial flows (i.e. internal catchment drainage). These and other influences on the hydrological behavior in the area have important social implications, as most of the region's population of 60 million relies closely on natural resources for survival. This is most concerning during the dry season as irrigation from agriculture tends to reduce flows whereby the current expanding demand could result in detrimental water shortages across the region (FAO, 2007). In addition to drought, large increases in runoff after rain events can lead to damaging floods, erosion, and downstream siltation, impacting local livelihoods.

Several simulation studies in the LMB region have been conducted with the intention to link the effects of land cover (and subsequent change) with hydrology using models of various levels of complexity (Kite, 2001; Thanapakpawin et al., 2006; Costa-Cabral et al., 2008; Homdee et al., 2011; Wang et al., 2016). Though some of these forecasts show decreasing resource availability results consistent with the expected relationships outlined above, conclusions are hard to draw due to the complex relationship of vegetation and land-use with hydrology (e.g., van der Velde et al., 2014). Previous research has highlighted the challenges of evaluating the connection between land cover and hydrology due to the complex role of underlying geomorphology (Douglas, 1999; Bruijnzeel, 2004), issues of scale and the roles of climate variability (Bruijnzeel, 2004), counteracting effects of different land-use changes (Bruijnzeel, 1990), and lack of adequate hydro-meteorological and land-use data in the region.

To try and overcome these issues, Lacombe et al. (2016) recently developed a methodology to isolate climatic impacts from other potential changes on water cycling. Specifically, they combined the monthly 2-parameter lumped GR2M model of Mouelhi et al. (2006) to represent hydrology with the distribution-free trend testing method of Andreassian et al. (2003) to identify changes in hydrology at a catchment scale. This approach allows for de-coupling of climatic change impacts from the resultant hydrological estimates. Lacombe et al. (2016) used this methodology to examine two relatively small catchments (< 1 km<sup>2</sup>) with contrasting but extensive land cover change in Laos and Vietnam for significant variation in runoff. The study revealed a correlation between afforestation and changes in hydrological behavior; however, the hydrological impacts differed depending on the afforestation strategy and vegetation types with increased and decreased flows in the catchment in Laos and Vietnam, respectively. Although the extent of the study was limited in spatial scale to the two catchments, the results highlight the complexity to be anticipated regionally with regards to the hydrological impact of large-scale shifts in vegetation cover and resource management.

To this end, our study seeks to continue the exploration of the rainfall-runoff response using the modeling framework previously applied to the two catchments in Laos and Vietnam (Lacombe et al., 2016) and expand the analysis across the LMB. We do this using a subset of the large catchments (> 200 km<sup>2</sup>) from a study by Lacombe et al. (2014) considering only catchments where there were (1) at least 10 years of data and (2) relatively good GR2M model performance. Specifically, we test for the potential existence of trends (either increasing or decreasing) in the hydrological behavior of these catchments independent from trends that could be attributed to climatic changes. Due to data availability and scale limitations, we cannot explicitly quantify land cover change across all the catchments considered (as was done for the two catchments in Lacombe et al. (2016)); however, the catchments considered are classified static using 2003 land cover composition and geomorphologic catchment characteristics to investigate the possible connection between changes in hydrologic behavior and environmental factors.

## 2. Site description

The Mekong River Basin (795,000 km<sup>2</sup>) is one of the world's largest catchments, spanning over six countries in southeast Asia. With its headwaters in the Tibetan Plateau in China, the Mekong gains volume as it heads southwards through Myanmar, Laos,

Thailand, Cambodia and then Vietnam where it flows into the South China Sea. 4800 km long, its average discharge is 14,500 m<sup>3</sup>/s. Due to the tropical monsoonal climate, the Mekong experiences 75% of its total annual flow of 460 km<sup>3</sup> between July and October (MRC, 2005).

The LMB begins south of the Chinese-Lao border. It accounts for approximately 76% of the total Mekong basin area and 80–85% of the flow volume (MRC, 2005). It includes four different physiographic regions – the Northern Highlands, Khorat Plateau, Tonle Sap Basin and the Mekong Delta. The Northern Highlands include the north of Thailand, Laos and extend into Vietnam at the northern section of the Annamite Range. In this region, the tributaries and main stem Mekong flow mostly through steep, rock-cut valleys. Higher elevation and forest cover characterize the Northern Highlands. The Khorat Plateau covers most of Northeast Thailand with its northern and eastern margin in central Laos, and has a fairly consistent basin elevation around 300 m a.s.l. with a low relief. Flow in this low-gradient region is mostly dendritic. Further downstream, the Tonle Sap Basin is a dome-like structure of hills surrounding an alluvial plain. It covers the southern portion of Laos and most of Cambodia, and is distinguished by its large freshwater lake, Tonle Sap, which reverses its normal flow direction into the Mekong during the wet season. The Mekong Delta area begins near Phnom Penh, Cambodia, where the river becomes an expansive delta covering 62,520 km<sup>2</sup> of mangrove swamps, sand dunes, spits, tidal flats, and irrigated paddy fields.

The climate across the LMB is classified as tropical monsoonal, with warmest temperatures and highest moisture occurring during the wet season between April and September when the south-west monsoon brings humid air mass from the Indian Ocean. Rainfall patterns are seasonal (about 80% occurring during the wet season) and distributed by an east to west gradient; the highest rainfall quantities of more than 2500 mm/yr occur in the Highlands of Laos and the lowest of less than 1000 mm/yr over the Khorat Plateau in Northeast Thailand. Annual total rainfall typically varies within the order of  $\pm 15\%$  from year to year (MRC, 2010).

The population of the LMB is approximately 60 million, many of whom live in poverty and depend on the Mekong and its tributaries for their food security and livelihoods. Though poverty is widespread, all four countries in the LMB have recently moved to middle-income status in the UNDP's classification. Cambodia and Laos have the highest rates of poverty (> 30% of the population) whereas this rate falls below 20% in Thailand and Vietnam. Around 75% of the basin's population lives in rural areas, with an overall population density of 124 inhabitants per km<sup>2</sup>, unequally distributed between Thailand, Vietnam, Cambodia and Laos (125, 265, 80 and 25 inhabitants per km<sup>2</sup>, respectively) (MRC, 2010).

### 3. Material and method

In this study, we calibrate the GR2M model of Mouelhi et al. (2006) over successive 1-year periods using monthly precipitation, potential evapotranspiration and streamflow of catchments across the LMB. This results in a set of GR2M parameters for each year determined entirely by the hydro-climatology of each catchment. Then by holding these parameter sets from one year constant while simulating across the other years for the catchment, we isolate for inter-annual climatological variability within the catchment since precipitation and potential evapotranspiration changes are prescribed in GR2M. Any resultant inter-annual variations in flow simulated by the GR2M model reflect changes in hydrologic behavior that can be attributed to environmental changes not related to climate. The significance of these hydrologic behavior changes is assessed here using the distribution-free trend test of Andreassian et al. (2003). Last, the hydrologic behavior trends detected are compared to land cover and catchment physical descriptors to explore potential relationships. In the following, complete details of this approach as well as the data utilized across the LMB are presented.

#### 3.1. Data

##### 3.1.1. Temporal datasets

Based on the data set analyzed by Lacombe et al. (2014) (Fig. 1), including daily areal time series for streamflow, rainfall and potential evapotranspiration for non-regulated catchments, a subset of the catchments was selected based on model performance and the length of data records. Discharge data originates from the Mekong River Commission (MRC). Catchment-scale areal rainfall was derived by Lacombe et al. (2014) from the APHRODITE (Asian Precipitation Highly-Resolved Observation Data Integration Towards Evaluation of Water Resources) gridded database (Yatagai et al., 2012). The APHRODITE dataset comprises of interpolated ground-based daily precipitation data for the period 1951–2007 originating from the WMO Global Telecommunications System and stations across Asia, over a spatial resolution of 0.25° × 0.25°. Gridded values lying within a catchment were averaged, accounting for the reduced size of cells that overlap the catchment boundary.

Monthly areal value of potential evapotranspiration (PET) was computed across each catchment following the same aggregation methodology as that used for rainfall (Lacombe et al., 2014). Catchment-areal values were derived from the Climate Research Unit (CRU) data from Harris et al. (2014). PET was calculated using the FAO grass reference evapotranspiration equation (Ekström et al., 2007), using climate variables from the same CRU climate data package covering the period 1901–2009 with a spatial resolution of 0.5° × 0.5°. The monthly PET values inserted into the model allow removal the effect of inter-annual variability of potential evapotranspiration on the quantification of hydrological changes. As such, any change in the rainfall-runoff relationship caused by varied potential evapotranspiration is accounted in the GR2M simulated runoff directly while the change in actual evapotranspiration (manifested via change in land-use and land cover) is not accounted for and subsequently detected by the test of Andreassian et al. (2003).

##### 3.1.2. Land cover and geomorphologic characteristics

Land cover data across the catchments were taken from the full suite of catchment characteristics in Lacombe et al. (2014). Due to

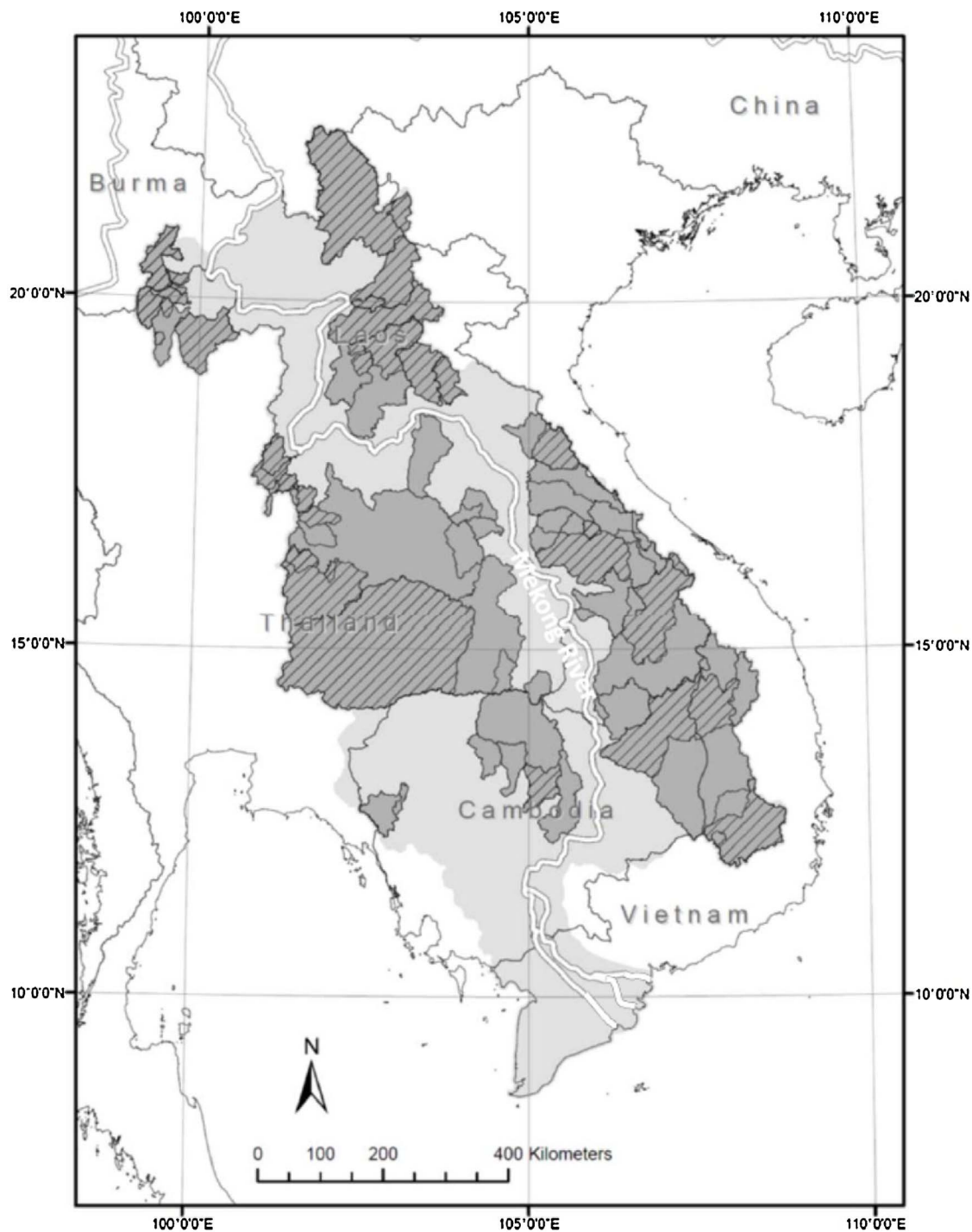


Fig. 1. Location of the 33 catchments retained in this study (simple hatched) as a subset of the 65 catchments considered within Lacombe et al. (2014) across the Lower Mekong Basin (light gray).

limited data availability at the resolution of our analysis covering the extent of the LMB, we only use land cover in this study as a manner to classify catchments rather than try to quantify the full potential and impact of land cover changes (as was done in Lacombe et al., 2016). Specifically, we focus here on forest and paddy rice coverage data as these have previously been found to have good predictive power among the land cover characteristics for low flow dynamics across the region (Lacombe et al., 2014).

For each catchment, the percentage area covered by either forest or paddy rice was computed using the digitized 2003 land cover map of the LMB prepared by MRC (2011). Paddy cover mainly consists of bunded rainfed lowland rice paddy fields, the majority of

which is never irrigated. Forest cover was created by merging the four forest types available as separate land cover classes in the published map: “coniferous forest”, “deciduous forest”, “evergreen forest” and “forest plantation”. We also consider catchment areas, perimeters, drainage densities and average slopes as potential predictors of hydrological behavior changes given their potential as first-order controls in catchment hydrology (e.g. Broxton et al., 2009) and in this region (Lacombe et al., 2014). These physical catchment characteristics were taken from Lacombe et al. (2014) derived via HydroSHEDS, a quality-controlled 90-m digital elevation model (Lehner et al., 2006).

### 3.2. GR2M hydrological modeling setup

The monthly lumped rainfall-runoff model GR2M of Mouelhi et al. (2006) used in this study is a two-parameter model empirically developed using a sample of 410 basins ranging in climatic conditions. This model was chosen due to its good performance in previous utilizations and parsimony, which allows a region with limited data availability to be analyzed (see Lacombe et al., 2010). Full description of the model development is provided in Mouelhi et al. (2006).

GR2M estimates monthly streamflow from monthly areal averages of rainfall and potential evapotranspiration. For this current study, following Lacombe et al. (2016) and most LMB studies, hydrological year begins with April and ends with March of the following calendar year. The two parameters of the model relate to (1) the capacity of the soil moisture reservoir and (2) the movement of underground water outside the catchment, respectively (see Fig. 3 in Mouelhi et al. (2006) for schematic). For model initiation, we set initial reservoir water level values to long-term inter-annual average at the beginning of the first year of modeling. Then, for each successive year, the previous year’s reservoir values provided initial condition. The model was calibrated over successive 1-year periods for each of the catchments considered. Previous work in the region with the GR2M model by Lacombe et al. (2016) has explored the sensitivity of the resultant parameter to the length of the calibration period considered. Based on that study, we adopt this length of calibration as suitable for defining parameters in GR2M modeling.

Calibration of the two parameters in the GR2M model was conducted by optimization of two efficiency criteria similar to what was done in Lacombe et al. (2016). The Nash-Sutcliffe efficiency criteria calculated on flow ( $NSE_Q$ ) and calculated on the logarithm of flow ( $NSE_{lnQ}$ ) were used for the evaluation of wet (April through September) and dry (October through March) season streamflow simulations, respectively. While each of these two efficiency criteria are calculated here with the 12 monthly flow values of each 1-year calibration period (including wet and dry season streamflow) following Lacombe et al. (2016),  $NSE_Q$  and  $NSE_{lnQ}$  give more weight to high and low flow values, respectively. Therefore, the former and the later are adopted as suitable for evaluating high and low flow simulations, respectively (Pushpalatha et al., 2012). Optimization was carried out using the Generalized Reduced Gradient (GRG) Nonlinear Solving Method for nonlinear optimization within the solver functionality of Excel.

From these 1-year calibration periods, we were able to obtain unique (optimal) values for the two model parameters of GR2M for each year of available data, for the wet and dry seasons, and for each of the catchments from Lacombe et al. (2014). Following the methodology from Andreassian et al. (2003), the optimized parameters from a given year were used to simulate wet and dry season flows on all other years of available data. The end product of such an analysis is a  $n$ -by- $n$  cross-simulation matrix where  $n$  is the number of years with available data, specific to each catchment and each season. Each cell in the matrix corresponds to the model simulated flow  $q_{ij}$  found in the  $i$ th row and the  $j$ th column. The  $j$ th column corresponds to the year in which the optimal parameters were calibrated and the  $i$ th row corresponds to the year in which the model forcing data were observed. Note, the diagonal of such a cross-simulation matrix (where  $i = j$ ) includes the optimal model result for a given year since it is simulated by the model calibrated with the actual observed forcing for that year. Given the seasonality consideration in the calibration setup, cross-simulation matrices were produced for both wet and dry season simulated flows, for hydrological change detection consistent with Lacombe et al. (2016).

### 3.3. Distribution-free hydrological change test

For each pair of cross-simulation matrices obtained for each catchment, a statistic  $S$  quantifying the temporal trend in the rainfall-runoff relationship is calculated as follows:

$$S = \sum_{i=1}^n \left[ \sum_{j=1}^{i-1} (q_{ii} - q_{ij}) + \sum_{j=i+1}^n (q_{ij} - q_{ii}) \right] \quad (1)$$

Negative and positive  $S$  values imply a decreasing and increasing trend over time, respectively. The expected distribution of the statistic  $S$  can be obtained explicitly by randomly shuffling the columns in the original matrix and recalculating a  $S$  value for each resampled matrix (Andreassian et al., 2003). Implementing a Monte-Carlo approach, we carried out 10,000 random realizations of the two cross-simulation matrices for each catchment to generate the expected distribution of the  $S$  statistic. These distributions give an explicit definition from which to identify significance in a trend. Here and throughout this study, we adopt a p-value of 0.05 for significance such that the positive (negative) trend in simulated flow is statistically significant if the original  $S$  value is higher (lower) than 95% (5%) of all  $S$  values derived by permuting the matrices. A thorough description of the test and methodology is available in Andreassian et al. (2003).

The cross-simulation matrices developed by Andreassian et al. (2003) can be used to isolate the hydrological impact of non-climatic factors. To do this in this current study, and following Lacombe et al. (2016), we use the median year of observed rainfall across the period of record to simulate flow with each GR2M model parameter set. From here forward we refer to this as the median rainfall modeling result. This result is consistent with identifying the row in the cross-simulation matrix that corresponds to the

**Table 1**

Summary characteristics for the subset of 33 catchments from those considered by Lacombe et al. (2014). Latitude and Longitude refer to the location of the stream gauge.

Statistic	Latitude North	Longitude East	Catchment Area (km <sup>2</sup> )	Annual Rainfall (mm)	Annual PET (mm)	Annual streamflow (mm)	Years with streamflow Data
All (33 catchments)							
Max	20.70	107.93	49650	2093	1330	2347	41
Min	12.61	99.35	207	880	1039	128	10
Average	17.91	102.41	7389	1339	1162	740	23
Cambodia (2 catchments)							
Max	13.55	106.05	49650	1658	1330	998	29
Min	12.71	104.87	13675	1265	1208	504	14
Average	13.13	105.46	31663	1461	1269	751	22
Laos (13 catchments)							
Max	20.70	106.84	19475	2093	1247	2347	41
Min	14.81	102.18	384	1231	1039	360	10
Average	18.50	103.58	6641	1601	1107	1161	19
Thailand (17 catchments)							
Max	20.23	104.16	44785	1471	1310	740	37
Min	15.33	99.35	207	880	1106	128	16
Average	18.34	100.84	5043	1110	1192	409	27
Vietnam (1 catchment)							
Value	12.61	107.93	8441	1581	1143	886	20

median rainfall year. As we are controlling for climatic inter-annual variability in this regard, any resulting deviation or trend in the model simulation (i.e. between the columns of the matrix) is driven by other environmental conditions (i.e. not related to rainfall or potential evapotranspiration). The non-parametric test of Andreassian et al. (2003) enables the significance of trends caused by non-climatic conditions to be quantified in our simulations for both the wet and dry seasons. Further and to allow for comparison, we also calculated the Theil-Sen's slopes (e.g. Gilbert, 1987) of the GR2M simulations for the wet and dry season, respectively, for each catchment. Under the assumption of long-term unidirectional changes, trends could be investigated over the entire period of simulation in each catchment from Lacombe et al. (2014) for both the wet season and dry season.

However, in practice, we start by filtering the catchments to retain only those with good GR2M model performance and where there is likely enough data for trend detection. To ensure the robustness of modeling and subsequent analysis, we only retain a subset of the catchments from Lacombe et al. (2014) to be analyzed for trend detection based on model performance and data availability. First, only catchments with NSEQ and NSElnQ greater than 0.50 were retained. Second, since we are considering trends, only catchments with a minimum of 10 years of data were considered. This length of record was selected because it provided a potential balance between the robustness of the results and the number of catchments considered (see section 4.2). Based on these two steps, 33 out of the 65 catchments presented in Lacombe et al. (2014) were retained for GR2M modeling and trend detection. Their characteristics (Table 1) and spatial coverage (Fig. 1) span the LMB.

## 4. Results

### 4.1. General GR2M model performance over Lower Mekong Basin

The GR2M model was able to reproduce the general hydrological behavior of the 33 study catchments (Fig. 2) with better performance for wet season flows. There was a slight skew towards over-prediction of wet season flow, particularly during lower streamflow years. This slight over-prediction was well distributed among the 33 catchments such that no discernable pattern explains it. The modeling error was rather well distributed (random) for the dry season modeling. These results are reflected in the modeling efficiency values across the catchments. For the wet season modeling, the average  $NSE_Q$  was 0.91 across all catchments, ranging from 0.58 to 0.99. For the dry season modeling, the average  $NSE_{lnQ}$  was 0.71 across all catchments, ranging from 0.52 to 0.89. Even after retaining only the “good” performing models, the overall modeling performance is considered fairly adequate especially considering the simplicity of the GR2M modeling approach. The poorest modeling performance typically occurred during the dry season when seasonal systems can exhibit more non-linear responses (Lyon et al., 2014). As such, the relatively reduced model performance can be somewhat expected for the dry season.

### 4.2. Trends in simulated flows across Lower Mekong Basin

When considering the entire period of simulation (Table 2), while the majority of catchments demonstrated no significant trend (either increasing or decreasing) in simulated flows, 36% showed significant trends (increasing or decreasing) in the wet season and 36% showed significant trends (increasing or decreasing) in the dry season. Of those catchments exhibiting significant trends, there was considerable consistency in trend direction and significance between wet and dry seasons flows. Of the 7 catchments exhibiting

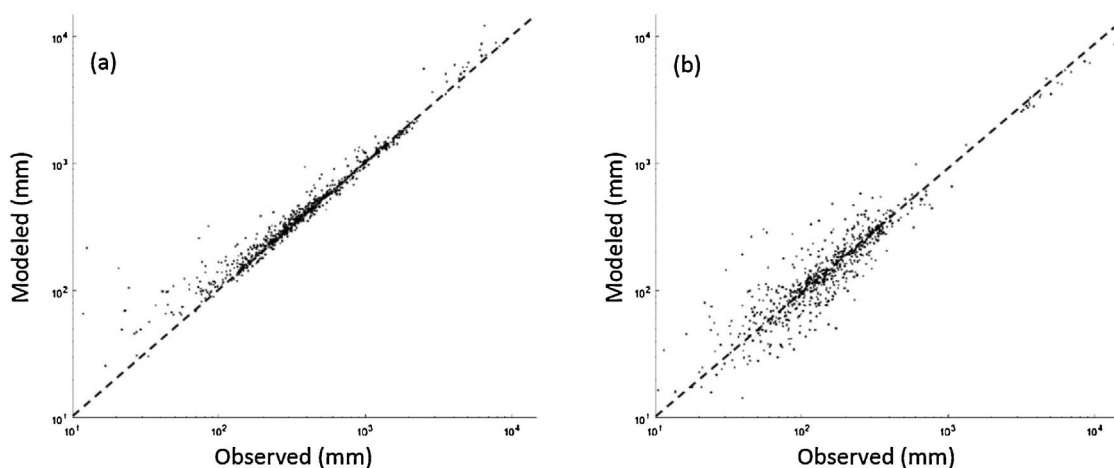


Fig. 2. GR2M annual modeled versus observed streamflow (specific discharge) for (a) wet seasons and (b) dry seasons for all 33 catchments considered in this study (note the log–log scale).

**Table 2**  
Number of detected significant trends in the simulated hydrological response for catchments.

	Wet Season	Dry Season
Significant Increasing Trend	7	8
Significant Decreasing Trend	5	4
No Significant Trend	21	21
Percentage Significant	36%	36%

significant increasing wet season trends, 5 of these also showed significant increasing trends in the dry season flows. Of the 5 catchments exhibiting significant decreasing wet season trends, 4 of these also showed significant decreasing trends in the dry season flows. None of the catchments exhibited a switch in their significant trend direction between the wet and dry season simulations.

To test the robustness of these results, an analysis on the impact of the length of record considered on the ability to identify significant trends was conducted (Fig. 3). As expected, as the minimum length of record considered increases, the number of catchments with enough data to be analyzed decreases. Still, the proportion of significant trends (either increasing or decreasing) relative to total number of catchments assessed remains rather constant independent of the threshold set for minimum length of record.

In addition, the locations of those catchments exhibiting significant increasing or decreasing trends in hydrological behavior were considered (Fig. 4). Independent of wet or dry season, the catchments exhibiting significant trends were well spread across the LMB. This lack of a clear pattern in significant trends was mirrored in the Theil-Sen’s slopes estimated across all studied catchments of the

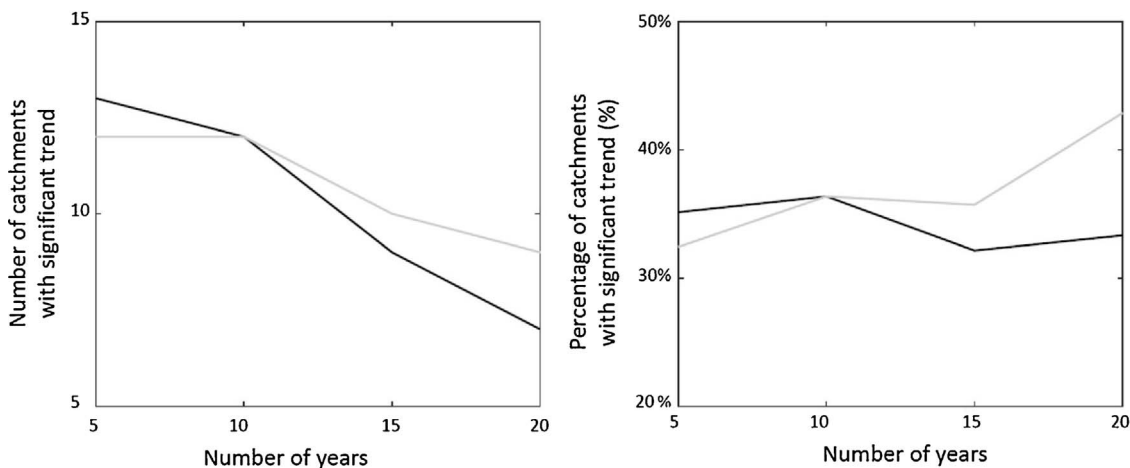


Fig. 3. Relationship between number of catchments showing significant trends (left panel) and the percentage of catchments showing significant trends (right panel) as a function of the length of observation record considered in the GR2M modeling and trend detection analysis. Black lines indicate significant trends in wet season and gray lines indicate significant trends in dry season calibration.

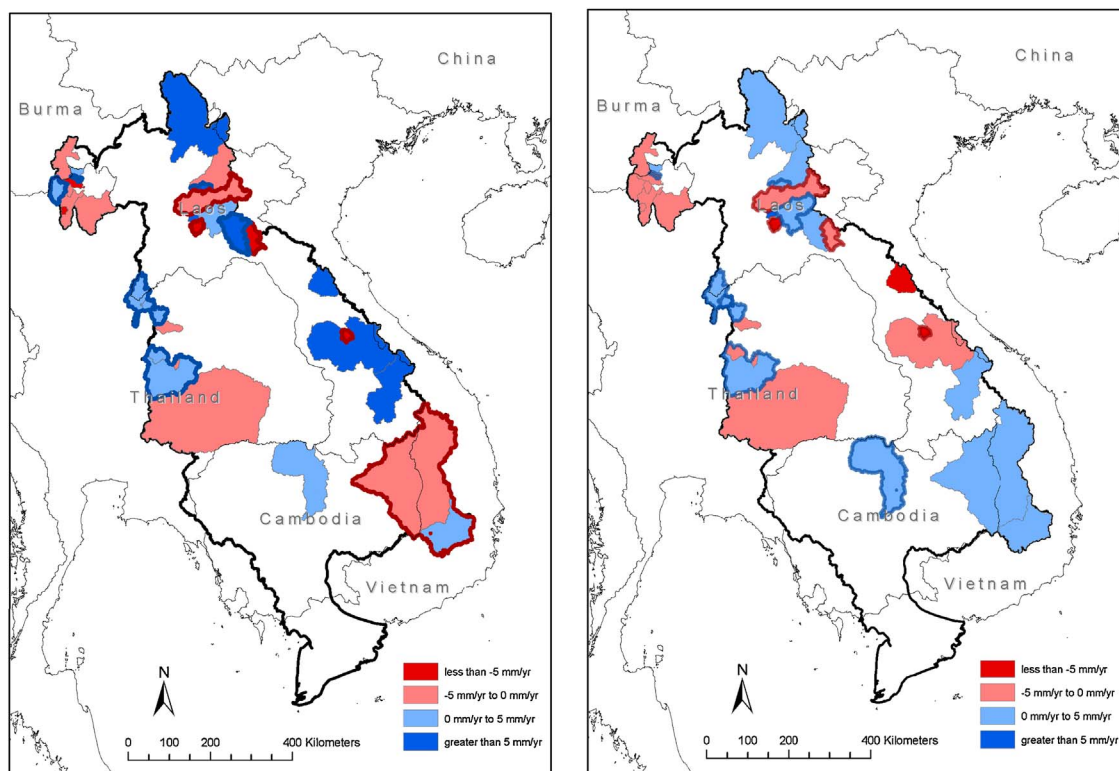


Fig. 4. Locations of the catchments exhibiting significant increasing (outlined blue) and decreasing (outlined red) trends in hydrological behavior in the wet season (left panel) and dry season (right panel) relative to the estimated Theil-Sen slopes for the GR2M simulations. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

LMB from the GR2M simulations for the wet and dry seasons, respectively. There was consistency in the directions of trends detected with the non-parametric test of Andreassian et al. (2003) and of those defined using the Theil-Sen's slopes.

#### 4.3. Potential controls on hydrological change

##### 4.3.1. Precipitation and potential evapotranspiration

We can start by considering the potential for trends in the rainfall or potential evapotranspiration amounts in the region as the main driver of hydroclimatic response. Specifically, since the methodology considered isolates any potential effects of climatic variability from other environmental changes at the catchment scale, we want to rule out the potential existence of long-term trends that could confound interpretation of results. This provides somewhat of a verification that the methodology is not identifying climatic-driven trends.

Only 4 out of the 33 catchments (12%) exhibited a significant long-term trend in their precipitation records (here assessed as a linear trend with  $p < 0.05$ ). In addition, only 3 catchments out of the entire 33 catchments (9%) exhibited a significant long-term trend in their potential evapotranspiration. Further, only one of the catchments with a significant trend in hydrological behavior corresponded to a catchment with a significant trend in either rainfall or potential evapotranspiration. When looking across all the catchments and all the trends (even those that are not significant), the directions (increasing or decreasing) of the trends in precipitation or potential evapotranspiration were not entirely consistent (from the perspective of a water balance) with the directions of the trends detected in the hydrological behavior. As such, neither precipitation nor potential evapotranspiration changes appear to be significant in the region when considering these data at the catchment scale – at least not significant enough to have had clear impact on the hydrological behavior changes identified with the cross-simulation method considered.

##### 4.3.2. Land cover

Based on a paired  $t$ -test ( $p < 0.05$ ), catchments with significant increasing trends in hydrological behavior had significantly lower forest coverage area than those with significant decreasing trends in hydrological behavior (Fig. 5). This is seen independent of wet season or dry season analysis. The average forest coverage for catchments exhibiting increasing trends in hydrological behavior varies between 62.2% (dry season trend) and 65.6% (wet season trend), while decreasing trends were observed in catchments with average forest coverage varying between 84.5% (wet season trend) and 88.5% (dry season trend). There was a statistically insignificant relationship between the presence of significant trends and paddy rice coverage (Fig. 5); however, the catchments showing significant increasing trends in hydrological behavior had higher paddy rice coverage relative to those exhibiting decreasing trends in



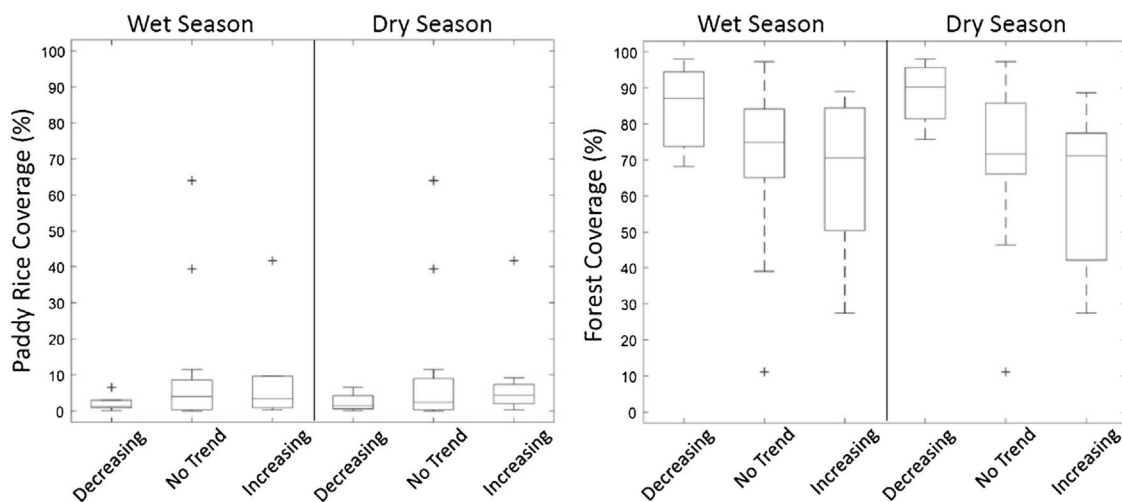


Fig. 5. Box plots showing paddy rice and forest coverage differences between catchments exhibiting significant decreasing trend, no trend and significant increasing trends under wet season and dry season across the LMB.

hydrology. Specifically, catchments exhibiting significant increasing trends in hydrologic behavior had an average paddy coverage ranging between 9.6% to 8.7% between the wet and dry season analysis, respectively, relative to those exhibiting decreasing trends where the average paddy coverage ranged between 2.2% and 2.4% between the wet and dry season analysis, respectively. This difference can be related to some extent to the complimentary relationship between paddy rice and forest coverage for this region.

#### 4.3.3. Physical characteristics

No significant differences were found between drainage areas for catchments exhibiting significant increasing or decreasing trends in hydrological behavior (Fig. 6). As such, large and small catchments both had similar propensity to exhibit significant increasing or decreasing trends (or to not exhibit trends) in hydrological behavior. Catchment perimeter, which correlates with area for these catchments, showed similar lack of distinction between those catchments exhibiting significant trends and those exhibiting no trends. Drainage density also did not differentiate significantly based on hydrological trends detected. Finally, while the differences were not significant, catchments showing significant decreasing trends in hydrological behavior had steeper land surface slopes relative to those exhibiting increasing trends or no trend at all. Catchments with significant decreasing trends in hydrological behavior had average land surface slopes ranging from 21% to 24% between the wet and dry season analysis, respectively, relative to those exhibiting increasing trends where the average land surface slope range from 19% to 16% between the wet and dry season analysis, respectively, and those with no trends where the average land surface slope range from 17% to 18% between the wet and dry season analysis, respectively. We note this difference in land surface slopes as these values correlate somewhat with rice paddy coverage (and inversely with forest coverage) in the region.

## 5. Discussion

### 5.1. Can we use a 2-parameter lumped model with a non-parametric test to detect trends in hydrology?

The short answer here would be “yes” but of course there are clearly constraints to such a statement. To begin with, GR2M reproduces relatively well observed streamflow in the region (Fig. 2) particularly given the parsimony of the modeling approach. Further, the non-parametric approach of Andreassian et al. (2003) allowed for detection of hydrological behavior changes (Table 2) which were consistent in direction with, for example, Theil-Sen’s slope estimates (Fig. 4). Since the approach of Andreassian et al. (2003) allows for assessment of non-climatic conditions on hydrological response, these changes could likely be attributed to regional development (e.g. Molle et al., 2012) that is altering rainfall-runoff relationships. However, we did not explicitly assess regional development nor land cover change across the LMB over the period of time considered. As such, despite this lumped-modeling and catchment-scale success of GR2M in connection with the non-parametric approach, the complexity of interactions between climate, land, and people limit the clear establishment of a pattern across the LMB with regards to increases or decreases in hydrologic response despite likely widespread development and agricultural expansion in the region. Still the modeling framework proposed by Andreassian et al. (2003) – coupling the parsimonious model with a non-parametric test – is a good starting point since it can be set up in a rather objective manner and is simple enough to process through large amounts of data. The latter is important since this implies that the methodology can be used to highlight catchments experiencing significant hydrological change for follow up process-based investigations (i.e. explicit assessments of land cover change like in Lacombe et al. (2016)). This functioning as a screening tool is important as we seek to better manage resources under increased pressures of population and climate since it allows targeted action in catchments where we could potentially make impacts or improve our mechanistic understanding.

Our results indicate that the majority of catchments with long enough data records (here considered 10 years – see Fig. 3)

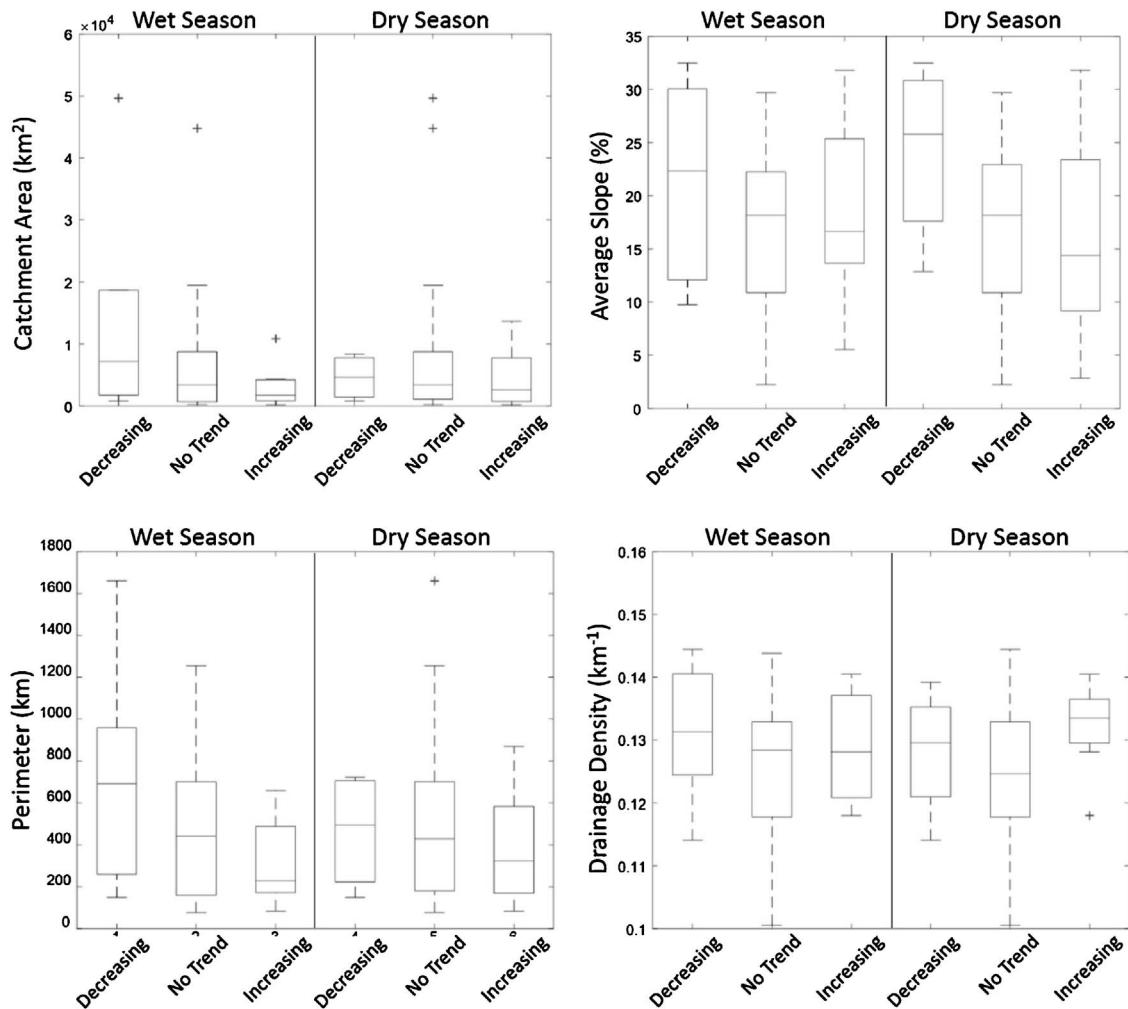


Fig. 6. Box plots showing catchment area, perimeter, drainage density and average slope differences between catchments exhibiting significant decreasing trend, no trend and significant increasing trends under wet season and dry season analysis across the LMB.

exhibited no discernable trends in hydrological response (Table 2). As the method outlined here attempts to isolate environmental (land cover) change impacts from climatic change impact, this may not be overly surprising. The explicit manifestation of land cover changes in hydrological behavior is often difficult to isolate (Scanlon et al., 2006), especially in large catchments ( $> 100 \text{ km}^2$ ) – like those included in our analysis, where complex combinations of counteracting land-cover changes generally render their hydrological effects difficult to detect. This is seen time and again across many regions globally and is a concern particularly in developing regions. For the latter case, this concern is because developing regions are typically those where the data needed to assess change are difficult to gather while at the same time the regions rely directly on understanding land-water interactions to allow sustainable development (Vörösmarty et al., 2000). Further, for this current study, those catchments that did exhibit significant hydrological trends were fairly evenly split between increasing trends and decreasing trends with time (Table 2). As there was a lack of evidence that these changes were brought about by shifts in hydro-climatology (Section 4.3.1), the results serve to highlight the role of hydrological processes for determining the magnitude and direction of hydrological response.

The direction of the hydrological behavior change implies that the loss of forest coverage in a catchment (i.e. conversion to paddy rice in the 1980s-90s) brings about different trend in hydrological behavior relative to that expected from a more forested (i.e. lower paddy cover) catchment (Fig. 5). Across the LMB, paddy rice fields tend to co-locate with low land surface slope and flooding landscapes underlain predominantly with poorly infiltration soils (e.g. Lacombe et al., 2014). In regions with high paddy coverage (and low forest coverage) there is potential for more influence of surficial flows on the resultant hydrology (Fig. 5). As water abstraction for paddy development via pumping or upstream allocations expand in the region (e.g. Thongmanivong and Fujita, 2006) and large-scale drainage patterns change through infrastructure expansion (e.g. Ziegler and Giambelluca, 1997), these expansion activities could tend to alter the uptake of water within the catchment or the retention of water as storage across the landscape. Therefore, as development and land cover changes occur in catchments, for example converting natural forested land to paddy coverages, there is likely more direct influence on the resultant streamflow allowing for changes at magnitudes detectable with the

approach considered.

This interpretation is somewhat consistent with Brown et al. (2005) who highlight how regions with high homogeneity of forest coverage (and subsequent change) exhibited hydrological changes more readily than those where land-cover changes occurred across smaller vegetation area (less than 20%). Through our analysis, we cannot explicitly distinguish the impact of land-cover change direction (i.e. de-forestation or re-forestation) on hydrological behavior but can see that catchments with lower percentage coverage of forest (likely more altered natural systems) respond differently than those with higher percentage of forest coverage (likely more pristine natural systems). As such, our cursory comparison with land cover data and physical catchment characteristics across the region can potentially help in development of an improved conceptualization to understand how hydrological changes brought about through development may manifest in the region. Further, it could also help in identifying target regions (Fig. 4) for future detailed investigation to isolate mechanisms that drive observable hydrological behavior change.

As must be noted, this current study did not assess land cover change or development changes in the region explicitly over the past 50+ years in relation to hydrological changes. Given the prevalence of spatiotemporal data limitations, the transnational nature of the basin, and the scale/extent of the region considered, such time-variable analysis was not possible at present. This is a potential weakness of the current study and limits to some extent our ability to interpret the results of the non-parametric trend test from Andreassian et al. (2003). In addition, and echoing statements that “one measure fits all” is appropriate neither in science nor in policy when it comes to the relationship between land-use and water (Bishop et al., 2012), we also emphasize the need for further investigation as to the mechanisms connecting development and hydrological change across scales in the LMB.

Another important aspect to be considered is the potential reliability of the hydro-meteorological data used in this analysis. While flow data had been initially screened and quality-controlled as part of the analysis reported in Lacombe et al. (2014), the APHRODITE rainfall data set includes inherent artefacts that could potentially bias the trend analyses. Rainfall time series were gap-filled by interpolation in order to produce a homogeneous gridded product from a spatially and temporally heterogeneous set of rainfall stations (Yatagai et al., 2012). This may have produced artificial trends. However, their influence on the overall hydrological assessment is likely to be negligible, accounting for the results of Lauri et al. (2014) who identified APHRODITE as one of the most reliable precipitation dataset to model discharge in the monsoon-driven large river basins in Monsoon Asia. Further, our retention of only those “good” performing models potentially limits the impact of extremely erroneous data.

## 5.2. Implications and concluding remarks

Obviously, there is a connection between climate and hydrology across the LMB as precipitation drives streamflow. This clearly needs to be considered as we project future climates and potentials for shifts in hydrological responses to assess the potential gains associated with development (e.g. agricultural expansion and infrastructure improvement). However, there is also the role of land cover and catchment characteristics in mitigation of climate and environmental changes that must be considered. Even when changes in climatic forcing are not evident, land cover and catchment structure composition appear to influence the potential for water allocation changes at the catchment scale (Fig. 5). Across the LMB, we have demonstrated this inherent complexity of interactions. By utilizing a parsimonious modeling concept and a non-parametric estimate of change, we were able to isolate significant trends in hydrologic behavior at the catchment scale. There are still, however, mechanistic gaps between the myriad internal shifts of water resource utilization and hydrological response. To close such gaps, it is crucial to consider internal catchment processes (i.e. surface-groundwater interactions) since only by appropriate mechanistic representation can we hope to develop accurate scenarios of future land-water interactions to inform policy and management.

To this end, we can conclude here with the call for incorporation of stakeholders and/or detailed hydrological processes within our management tools (and subsequent scenarios) to ensure reality is properly reflected. This call underlines the need to include people and how they interact with the landscape in our future planning. The approach presented here provides a valuable screening method to highlight regions exhibiting hydrologic change via land cover shifts for further investigation of improved mechanistic understanding and stakeholder engagement. Without such connection, we might be blind to future hydrological shifts that can have significant impact on development.

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