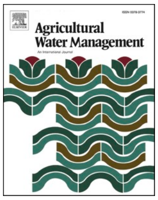
Agricultural Water Management 306 (2024) 109201

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat



An engineering approach to support user-led innovation in improving the performance of artisanal irrigation pivots in the Algerian Sahara

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ARTICLE INFO

Keywords:
Irrigation
Center pivot
Irrigation performance
Open innovation
Sahara
Algeria

ABSTRACT

Large-scale center pivots have been imported into Algeria since the 1980s to promote cereal production in the Sahara, but these pivots did not match either user needs or smallholder farming systems. In response, local artisans designed a smaller, cheaper, more robust center pivot in an incremental open innovation process that lasted 10 years. Currently, around 35 % of the Algerian potato production is irrigated by around 40,000 artisanal center pivots, each irrigating 1 ha. The aim of the study was to design and test an engineering approach to support local innovation actors in improving the performance of the artisanal irrigation pivot. Field observations and interviews were conducted with 24 users and 10 leading artisans to analyze the innovation process and judge which improvements would be acceptable. Experiments were then conducted *in situ* and in the national irrigation laboratory to analyze irrigation performance and test practical adjustments to improve it. Results showed that the distribution uniformity of pivots, less than 50 %, can be improved by adjusting the position of sprinklers along the pivot laterals and fine-tuning the nozzle aperture. This study opens new perspectives for engineering approaches to support user-led innovation.

1. Introduction

Food security relies to a great extent on smallholder farms that produce more than half food calories worldwide (Samberg et al., 2016). Smallholders also have an important role in the rapidly developing horticultural farming systems in the Algerian Sahara where the mild winter climate has allowed the development of a leading early-season horticultural sector (Côte, 2002; Amichi et al., 2018). It is estimated that 30–40 % of the national production of tomatoes, bell peppers and potatoes now come from the Sahara (Ould Rebai et al., 2022). Most of these small-scale horticultural farming systems rely on pressurized irrigation technologies, including drip and sprinkler irrigation, and, as we will show in this article, small-scale center pivots (Côte, 2006; Naouri et al., 2020). These technologies are often distributed as standardized, black-box kits manufactured by international companies, so for them to 'work' for small-scale farmers, it is increasingly recognized that there is a need for "translation" of the technology through local innovation systems (Garb and Friedlander, 2014).

This need has led to an emerging literature on user-led innovation systems in agriculture, including irrigation technologies, where "farmers are recognized as both the users *and* producers of innovations" (Ensor and de Bruin, 2022). For example, Mateos et al. (2018) showed how smallholders in Brazil improved the filtering system of drip irrigation while Duker et al. (2020) showed how smallholders actively intervened in an action research project on solar-powered irrigation in Mozambique and Zimbabwe, in particular to upscale the original pilot plots. In Algeria and Morocco, drip irrigation systems have been customized by small-scale farmers and artisans through user-led innovation involving both international companies and local actors (Benouniche et al., 2014a; Naouri et al., 2020). These different examples show how user-led innovation has enabled the emergence of local innovation systems, adapting, and indeed translating, standardized irrigation technologies into the specific yet diversified and evolving requirements of smallholders (Garb and Friedlander, 2014). More generally, Cloutier et al. (2015) showed that the "collective pooling of knowledge and experiences" of a wide range of actors, including engineers, local artisans, and

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https://doi.org/10.1016/j.agwat.2024.109201
Received 20 September 2024; Received in revised form 23 November 2024; Accepted 26 November 2024

end users, can provide tailored, specific, and adequate technologies to adapt, in their case, to climate change. However, to contribute adapted technologies requires engineers to reposition themselves in wider coalitions, thereby abandoning the posture represented by standardized black box technology (Naouri et al., 2020).

In this study, we designed and tested an engineering approach to support local actors (farmers, artisans) in improving the irrigation performance of an artisanal center pivot in the Algerian Sahara. The pivot was designed and constructed in an open innovation process that lasted 10 years and involved artisans and farmers, who successfully miniaturized imported large-scale irrigation pivots (Ould Rebaï et al., 2022). Currently, around 35 % of Algerian potato production is irrigated through around 40 000 artisanal center pivots, each irrigating 0.8 ha. However, farmers still wanted more uniform water distribution both to increase yields and to obtain more evenly sized potatoes. At the time, the actual irrigation performance of the artisanal pivot was not known since the technology was designed without recourse to established engineering processes. The aim of this study was thus to analyze the irrigation performance of the pivot and to suggest technical improvements that are acceptable and feasible for artisans and farmers. Our approach consisted in analyzing and then improving the irrigation performance by putting the authors engeeniring skills and facilities at the disposal of local innovation actors (Cloutier et al., 2015; Naouri et al., 2020). This participatory research approach is based on a thorough understanding of local innovation systems, and on the hypothesis that engineers can play a significant role in farmer-led innovation (Mateos et al., 2018).

2. Description of the case study and methodology

2.1. Case study

The study area is located in Wadi Suf Valley (Algeria), where the artisanal pivot was first constructed. The area is characterized by an arid climate, with 72 mm of rainfall and an annual reference evapotranspiration of 1731 mm (source: national meteorological service). The valley relies almost exclusively on groundwater resources for drinking, domestic and agricultural uses (Saibi et al., 2016). According to the official inventory, last updated by the National Agency of Water Resources in 2013, the extracted volumes are around 500 million m^3 per year, 20 % of which is destined for domestic uses, and 80 % for irrigation.

In the past, farming systems in the study area were mixed, multilayered, (date palms, fruit trees, annual crops) situated within small man-made depressions, called "*ghout*". *Ghout* are up to 10 m deep and 80–200 m wide, and are close to the water table. The ingenious *ghout* system, which has been proposed for the Unesco World Heritage Program, dates back to the 12th century. In 1998, there were about 9400 *ghout* in Wadi Suf (Côte, 2006). However, since then, the creation of a drinking water supply system and the introduction of 'modern' irrigation schemes based on pumped groundwater, have progressively led to generalized exploitation of deep, non-renewable, aquifers. In the absence of a drainage system and wastewater treatment, the shallow phreatic aquifer has been continuously recharged and polluted. In 2015, it was estimated that more than 50 % of the *ghout* in the valley had been abandoned due to waterlogging and pollution (ASD, 2015). The State has been building drainage infrastructure and wastewater treatment plants, but, since the 2000s, farmers have nevertheless increasingly turned to market gardening outside of the *ghout* and irrigated by artisanal pivots supplied with groundwater, particularly pumped from the shallow aquifer. According to the agricultural services (ASD, 2022), Wadi Suf Valley has more than 94,000 ha of irrigated area, 40 % of which is now irrigated by around 40,000 small-scale artisanal pivots, each covering 0.8 ha. During field surveys, representatives of government agencies and farmers pointed out that the water table is currently falling by 1–2 m/year in municipalities like Hassi Khalifa and Guemar, where many pivots are located.

2.2. Methodology

The starting point of the study was that any improvement suggested to enhance irrigation performance needs to be consistent with local socio-economic and technical conditions. Therefore, the first step in our research approach was to analyze the innovation process that had enabled the co-design of the pivot by artisans and farmers, and the user conditions and practices. This was achieved through interviews and field surveys. During the first phase, we engaged discussions with 24 farmers and 10 main artisans in the study area to identify the main design and operational issues. These 10 artisans supply several thousands of farmers with artisanal pivots, while also continuously improve the pivot and handle after-sales services. This makes them very strategic actors in the innovation process and key resource persons for this study. At the same time, it was important to bring in the actual users, that is the farmers, in the study. Then, inspired by Cloutier (2015) and Naouri et al. (2020), we fostered a dialogue with 2 artisans and one farmer on the irrigation performance of the artisanal pivot that would last throughout this research, thus bringing together various (and complementary) knowledge and experiences. The first artisan had produced and sold the first artisanal pivot ever and both artisans were active in Wadi Suf as well as in its diffusion to other areas in the Sahara (Ould Rebai et al., 2017, 2022). At every step, the research results would be shared and debated with these innovation actors to design the next phase of the research. Next, the actual irrigation performance was analyzed *in situ*, as irrigation performance depends not only on the equipment but also on farmers' irrigation practices (Benouniche et al., 2014a). This was done in the presence of 2 artisans and a farmer, with whom the results were discussed and possible venues for improvement of the performance discussed. The sprinklers were subsequently tested in an expert laboratory to identify possible incremental innovations and quantify their impact on irrigation performance, inspired by Saretta et al. (2018). The last step involved simulating the distribution and discharges of the irrigation water from the artisanal pivot to increase the uniformity of water distribution (Dukes and Perry, 2006; Marjang et al., 2011; Baiamonte and Baiamonte, 2019), which had been identified as the farmers' main objective during the first step of our study. Molle et al. (1998) and Molle and Gat (2000) already demonstrated the complex irrigation water distribution pattern and the importance of appropriate distribution of nozzles along the pivot lateral. During the laboratory tests, the results were discussed frequently with the two artisans in order to plan the next steps.

2.2.1. Surveys and interviews

The first people interviewed were the main actors in the design, manufacture, and use of the artisanal pivot. Using semi-open interviews, this qualitative survey was carried out in the districts of Hassi Khalifa and Guemar in the Wadi Suf Valley. It targeted 24 farmers who use center pivots, plus 10 artisans and retailers (a scrap metal dealer, local spare parts suppliers) who were involved in the design, manufacture and installation of center pivots. The interviews focused on three main aspects: (i) the incremental design and innovation process (improvements that had already been made, why, when, and by whom); (ii) the organization of the pivot manufacturing sector and of the supply chain for the component parts so we could map all the actors of the center-pivot socio-professional network along with their skills; (iii) the requirements of potato growers, in terms of the type of irrigation regime, irrigation performance, and the cost and quality of service (Ould Rebai et al., 2017). The field surveys enabled to observe the whole process, from the manufacture and assembly, installation and fine-tuning, to maintenance of the artisanal pivots. These observations helped understand the local experts' rationale and led to a detailed study of the component parts of the pivot. Next, we shifted our focus to the local actors' perception of irrigation performance, and the actions already undertaken to improve the performance by adjusting the equipment or changing irrigation practices. Two aspects were analyzed in detail: (i) the adjustments to the spacing between sprinklers along the lateral made by artisans and how they tested the adjustments in the field; and (ii) how the farmers adjusted the nozzle opening. The rationale behind this approach was to analyze the influence of farmers' and artisans' practices on performance (irrigation volumes, uniform water distribution) and to include their views on how to improve the performance of the pivots.

2.2.2. *Tests and measurements*

2.2.2.1. In situ testing. Water distribution uniformity was measured on the most frequent pivot model in the valley, a recently installed 50 m long pivot made of a single well-maintained lateral, and was being used for its second irrigation season (Table 1). To focus on the intrinsic performance of the artisanal pivot, we evaluated it in calm air conditions ($< 2\ \mathrm{ms}^{-1}$).

Two radial rows of collectors were placed along the pivot, covering the whole 50 m long later lateral, considering the maximum range of each sprinkler is less than 10 m. A 2.5 m space was left between the collectors with an offset between rows according to ISO standard 11545. To check the accuracy of the results, three repetitions were carried out. Christiansen's Uniformity Coefficient (UC) was used to calculate water distribution uniformity (Dukes and Perry, 2006).

2.2.2.2. Laboratory testing. Measurements were carried out on five sprinklers in the national irrigation laboratory in Algiers. Two types of tests were conducted: flow versus pressure curve and water distribution (Table 1). The tests were conducted according to the ISO 15886 standards that specify the conditions and methods for testing the performance of irrigation sprinklers.

The sprinkler, imported from China and used in Wadi Suf Valley, has no written technical specifications, i.e. giving the operating range, minimum and maximum pressures (P_{min} and P_{max}), and corresponding flows and ranges. The sprinklers have an adjustable nozzle opening to regulate flow rate, but there is nothing to indicate the size of the nozzle opening. To get round this constraint, before any measurements were taken, the 5 sprinklers were identified and the nozzle open position was marked, making it possible to adjust and reproduce any nozzle opening as required. The flow-pressure tests were conducted on the spraying test bench, adjusted to obtain the desired combination of pressure (P) and nozzle opening (NO), and the corresponding flow rate for each combination was recorded. A pressure range from 0.1 to 0.4 MPa was applied with a 0.05 MPa step, the nozzle opening ranged from 0.5 to 3.5 turns, each step representing a 0.5 turn, resulting in a total of 245 measurements.

Table 1
Summary of the experimental setup.

Testing	*In situ*	Laboratory
Location	Wadi Suf Valley during calm weather (wind speed $< 2\ \mathrm{ms}^{-1}$), temperature ($T = 21^{\circ}C$) and humidity ($H= 31\ \%$).	National Irrigation Laboratory in Algiers, sprinkler test bench
Specific objective	Water distribution uniformity	Functioning of sprinklers
Physical layout	Recent mini-pivot, single 50-m lateral	Mini-sprinkler imported from China (and used in Wadi Suf), adjustable nozzle opening; range and flow adjustable simply by turning a screw
Useful guidelines	ISO 11545 to determine spacing between collectors, offset between rows	ISO 15886 specifies conditions and methods for testing the performance of irrigation sprinklers
Experimental settings	In situ water distribution uniformity: −19 collectors installed radially along the mini-pivot −3 repetitions	-Variation in P [0.1–0.4 MPa] and NO [0.5–3.5] and measurement of flow rate, 5 representative sprinklers giving a total of 245 measurements. - Variations in water distribution, 81 collectors (9 ×9 m grid, 1 m spacing, 1 m sprinkler height): First selective tests of 3 sprinklers (0.2 MPa, 2,5 NO), based on the average diqtribution curve, then using the same sprinkler for a total of 15 tests (fixed P or fixed NO)

Subsequently, tests were conducted to evaluate the water distribution pattern produced by the sprinkler at a fixed position, using different combinations of P and NO. The square grid methodology was applied, i.e. 81 collectors were placed in a 9 m x 9 m grid, with 1 m spacing. The sprinkler was positioned at a height of 1 m above the ground, consistent with the height of the field pivot. A total of 15 tests were conducted to assess water distribution symmetry, which was then used in the simulations (Bremond and Molle, 1995).

2.2.2.3. Design and simulation. A simulator linked to a database using R software was developed to evaluate irrigation water distribution under the pivot as a function of various design options (table S2 and S3 in supplementary material). The database contained the flow-pressure and water distribution measured in the laboratory. The simulator used these data to (i) simulate the sprinkler flow rate; and subsequently to (ii) simulate the water applied while the machine is moving based on the flow-pressure tests of the five representative sprinklers. Simulations were run and the results compared with crop water requirements (for potatoes) to select the required combination of pressure (P) and nozzle opening (NO) and subsequent water application. The sprinkler flow rates (Q) obtained with different combinations of P and NO, resulting from the flow-pressure tests were compared with the required flow (Q_{req}). Q_{req} is based on the daily water volume and the surface area covered by a sprinkler, and represents the volume of water that needs to be supplied by each sprinkler outlet along the total length of the pivot lateral. This methodology was inspired by the standards used to model water uniformity under conventional pivots (Molle and Gat, 2000; Smith et al., 2008; Al-Agele et al., 2020, 2022).

After determining (P), the correlations obtained on the basis of flow-pressure tests (correlation coefficient $R > 98\ \%$) (see figure S1 in supplementary material) enabled the extrapolation of (Q_{spr}) for different NOs and a more appropriate distribution of the nozzles along the lateral was proposed. The water to be applied was adjusted accordingly to improve the performance of the pivot. The water applied by the sprinkler was simulated in 0.5 m steps for different openings of the nozzles mounted on the moving pivot. This profile corresponds to the average curve of the cumulative rows and columns of the volumes of water collected in the 81 collectors. Next, the irrigation water distribution was simulated by extrapolating to the entire moving pivot: (i) simulated applied water, in 0.5 m steps, according to the NO to be adjusted, and then (ii) the irrigation water distribution along the whole lateral was deduced by cumulating the water applied water, while accounting for the cumulative water volume between two successive sprinklers in the overlap area.

3. Results and discussion

3.1. *Continued improvement of the artisanal pivot through an open innovation process*

3.1.1. *From conventional to artisanal pivots*

The diffusion of the artisanal pivot in Wadi Suf Valley since its invention in 1996 by a local artisan (around 40,000 pivots on 40 % of the total irrigated area in 2022), is truly impressive. Its success is certainly due to the continuous adaptation and improvement of the pivot, through a process of open innovation involving artisans, traders and farmers, to meet the requirements of the end users, in tandem with active and personalized service to users. The design of the device was inspired by the conventional large-scale pivots that were imported to expand cereal production in different pilot sites in the Algerian Sahara. At the end of the 1980s, three large pivots, 350 m long, each covering 30 ha, were provided to three farmer-entrepreneurs in Wadi Suf Valley. However, lack of knowledge concerning, for instance, automatic adjustment of the alignment of the laterals, as well as lack of maintenance resulted in breakdowns. In addition, no spare parts were available on the market, nor was there a skilled support sector to repair the pivots. Consequently, after two years, the entrepreneurs abandoned the pivots. Large-scale pivots did not match local farmers' farming objectives, crop choices or technical capacities: *"We didn't have enough land to use this type of device, or enough money to get them on credit and reimburse the loan, even though they were 50 % subsidized. What is more; even if we had had the money, having seen them fail, we didn't want to run the risk of investing*" (Interview with a 58-year old farmer, owner of 5 ha of land irrigated using artisanal pivots).

More generally, due to high investment costs, the economic results of cereal production under pivots were disappointing across the Sahara (Pérennès, 1993; Otmane and Kouzmine, 2013). Additionally, the creation *ex nihilo* of an agri-business model that mirrored the living conditions for oil exploitation, with farm managers and employees located in base camps, failed to connect the technology to local communities, who may have been able to adapt the technology to local conditions (Bendjelid et al., 2004; Hamamouche et al., 2018). Experiencing the unsuccessful adjustment of imported conventional pivots to local conditions may have discouraged farmers, but in the early 1990s, it inspired local Wadi Suf artisans to design a low-cost, miniaturized, artisanal pivot using some of the equipment dumped in the hydraulic 'cemetery' in Gassi Touil (Côte, 2006). The design emerged from the difficulties encountered using furrow irrigation on horticulture plots that were only one to two ha in size, whose number was rapidly increasing with the decline of the traditional farming systems in the *ghout*.

The first artisanal pivot was designed in 1995, and the first pivots were already being sold to local farmers in 1996. Over a period of 10 years, the artisanal pivot was improved by local artisans in close collaboration with local traders and farmers via an open innovation system (Ould Rebaï et al., 2017). Indeed, different types of artisans were required (welders, turners, electricians) to tackle the many difficulties encountered, for instance, when reinforcing the pivot lateral by replacing the steel wires with a steel strut; designing an artisanal speed reducer to ease the settig and improve the regularity of the movement and by replacing the engine flywheels that blocked the rotation system; by designing a control unit connected to the electric motor to allow automatic programming of the pivot to replace the simple timer whose cycles were too slow and required constant attention. This collective open innovation process made the artisanal pivot increasingly robust and as a result, demand from farmers in the valley continued to grow. The typical lifespan of the pivot is eight years and part of the pivots will then be reused for new pivots, while the remaining components will be sold to scrap merchants for recycling (Ould Rebaï et al., 2017). From the year 2000 onwards, the pivot even travelled from the Suf Valley to other regions in Algeria's Sahara, including Adrar, Ghardaïa and Tamarasset, and to countries like Saudi Arabia and Sudan (Ould Rebaï et al., 2022).

The pivot is made up of different parts, many of which are purchased from local scrap metal companies and recycled. The current model comprises a 50-m long pipe with a diameter of 60 mm, stiffened by steel struts and assembled in a single lateral with a 50 m span, thus avoiding the need to adjust the alignment of multiple laterals as is the case with conventional pivots (Fig. 1 and table s1 in supplementary material). The lateral supports a pipe of the same diameter that supplies the water. The middle of the lateral is supported by a tower that rests on two wheels and is driven by a geared motor that allows the whole device to rotate. The irrigation water comes from a well located less than 10 m away, through a PVC pipe buried at very shallow depth. The pipe from the well is connected directly to the pipe inlet in the central element of the pivot.

Stabilizing the design of a robust but nevertheless inexpensive, easy to operate artisanal pivot, increased the expansion of market garden crops, particularly potatoes. For instance, in the municipality of Hassi Khalifa, land used to grow potatoes increased from 125 ha in 2004–8000 ha in 2013 (ASD, 2015). The farmers obtain good yields (30–40 t/ha) since there are few diseases in this dry desert area, and, thanks to mild conditions in winter, they can grow off-season potatoes in December and January that fetch high prices on wholesale markets. Local extension services advised the use of sprinklers, but farmers preferred the artisanal pivot for several reasons: (i) its modest price: 1000 € for a pivot that irrigates one hectare, compared with a sprinkler kit for the same surface area that costs between 2000 and 5000 €, depending on the quality; (ii) the quality of service: the artisanal pivot is produced locally and is consequently readily available, and, at the same time, is adapted to the requirements of each user, guaranteed for one whole potato season, and includes after-sales services and improvements, in comparison with imported sprinklers that were not readily available and did not meet the farmers' needs; and (iii) ease of use: while the sprinklers have to be removed to enable access by plows and other implements, the artisanal pivot can be left on site.

3.1.2. User-led improvement of distribution uniformity

We were in an ideal position to observe an improvement that both farmers and artisans were working on during our field surveys: the farmers had noticed that sprinkler kits produced more uniform water distribution than the artisanal pivot, resulting in more evenly sized potatoes that fetch a higher market price. Thanks to the pale color of the sand, the farmers could easily judge water distribution uniformity, so once the mechanical performance of the pivot had been improved, farmers asked the artisans to improve the pivot's water distribution uniformity. The choice of spacing between sprinklers was the focus of the exchanges between the farmers and the artisans at the time, so we were able to witness the farmers' irrigation practices, the artisaens' fine-tuning of the equipment in the field, and the different interactions

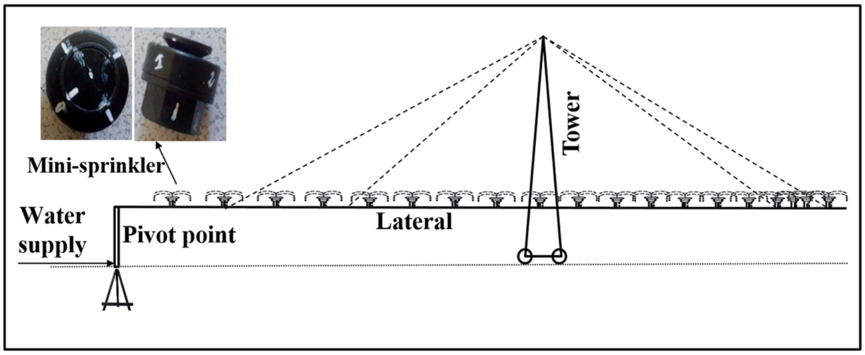

Fig. 1. Structure and main component parts of the artisanal pivot.

between the two.

First, we saw how the artisans tested the effect of the position of the outlets to which the sprinklers are fixed on the lateral, and the narrower the gap between the outlets, the easier it is to adjust the overlap and hence to ensure uniform water application: "*Originally, we put in 5 outlets, one every 10 m. But even when the nozzles were set to the maximum opening, there were patches of dry ground, so we decided to reduce the spacing by half, i.e. to put an outlet every 5 m, making 10 outlets in all. Even so, there were still dry patches and those at the end of the lateral were the biggest. We concluded that the spaces has to decrease progressively from the center to the end: we left a space of 4 m between the center of the pivot and the first outlet, and then reduced the space by 10 cm at each step up to 45 m from the center (that is, the 16th outlet). Then, in the last 5 m, where originally there was only one sprinkler, we added two more (making 3 in all) to avoid the biggest dry patches under the pivot*" (Interview with a 52-year old artisan).

Second, although the selection of the sprinkler is important for water distribution, it is not the only important criterion for farmers. In Wadi Suf Valley, a particular model of sprinkler is currently in use because the farmers find it easy to control water distribution, plus they can adjust it to their own field conditions and to their own pivot, because, unlike more sophisticated sprinklers, the nozzles are designed so they are easy to adjust. What is more, the droplets are fine so they do not disperse the sand particles excessively, meaning the potatoes remain covered by sand until they reach maturity, which prevents them greening. For these reasons, 12 out of the 24 farmers interviewed consider this model suitable for sandy soils and for their potato crop. The other criteria that influence the farmers' choice are not directly connected with water distribution. At the time of the survey, the price of the sprinkler component was 4–5 times cheaper (€ 0,34) than other models on the market, and it was readily available, as it was imported directly from China, or through Libya, by informal traders in this border region.

Third, the farmers' irrigation practices are the result of their own observations and are inspired by their previous experience using conventional equipment (mainly sprinkler irrigation) and compared with artisanal pivots. Particularly when adjusting the opening of the nozzles, the farmers applied the same logic: *"we make the opening of the nozzles of the first sprinklers bigger than those at the end"*. These decisions were linked to the reduction in the distance between the sprinkler along the pivot lateral used by the artisans, meaning the extent of the wetted area decreases progressively from the pivot to the extremity.

The fine-tuning of the nozzle, the selection of the sprinkler, and the adaptation of irrigation practices, mean that the design and the use of the pivot never stops changing and coinsequently does not become standardized. For the artisans, the farmers' plots represent a permanent opportunity to improve the mechanical and hydraulic performance of the pivot and adapt it to the farmers' needs.

3.2. Assessing the irrigation performance of artisanal pivots

3.2.1. In-situ performance of the artisanal pivot

To establish Christiansen's Uniformity Coefficient (UC), the uniformity of water distribution was measured under a pivot chosen in consultation with the artisans involved in the study. This particular pivot was selected for the following reasons: (i) it was the most widely used model with a 50-m span (at the time of the interview, it accounted for 95 % of pivots used in Wadi Suf), (ii) it already had the most recently introduced improved spacing between nozzles, (iii) it was in a very good condition, as it was only being used for its second irrigation season. It would be interesting to do a further comparative study of the irrigation performance of different pivots (for example recent versus older equipment) to understand the effect of wear and tear in this arid environment.

The measurements taken revealed uneven distribution corresponding to a UC of 42 %, 47 % and 48 % i.e. below the minimum threshold (UC < 80 %) recommended by Christiansen for sprinklers, thereby confirming the farmers' reports concerning the uneven size and shape of the potatoes across their plots. According to a farmer (44 years) that we interviewed, *"our tests based on the sand wetting zone highlighted the heterogeneity of water distribution, but we were unable to solve the problem"*. The results of our measurements supported their request to improve the uniformity of water distribution (Fig. 2), and actually acted as an incentive both for artisans and farmers, and for engineers to contribute to the incremental innovation process.

3.2.2. Performance of the artisanal pivot in laboratory tests

In the absence of technical data on the pivot (operating range, radius of throw according to nozzle opening, etc.), a series of laboratory tests was performed.

3.2.2.1. Flow-pressure behavior. First, the conformity of the results was checked by calculating the deviation of the flow rates of the 5 sprinklers from the average, for each of the pressures (P). We obtained $\sigma \in$ as recommended in ISO 15886.

The results of the tests were used first to study flow-pressure behavior, and second to deduce the operating range of the sprinkler. i.e. the flow rates (minimum flow rate Q_{min}, and maximum flow rate Q_{max}) corresponding to the minimum and maximum pressure (P_{min}, P_{max}) for each of the nozzle openings (NO), that is the number of turns of the sprinkler opening (Fig. 3).

The flow-pressure curves $Q = f(P)$ were juxtaposed and showed that for each pair of (P, NO) i.e. the same P and the same opening, the values of the flows of the 5 sprinklers are quite close. Variability is less than $0.08\ m^3h^{-1}$, this means that differences in the manufacture of the sprinklers has little influence on flow variability. Overall, the flow of the 5 sprinklers for the entire series (245 measurements) ranged from a minimum value $Q_{min} = 1\ m^3h^{-1}$ to a maximum value $Q_{max} = 2.66\ m^3h^{-1}$. The two limit values of the flow corresponded respectively to the pressures $P_{min} = 0.1$ MPa and $P_{max} = 0.4$ MPa. In addition, from the relation - $Q = f(NO)$ - the maximum opening (NO_{max}) was determined (Fig. 3) i.e. the value of NO, for a given pressure P_x, at which the flow rate of the sprinkler does not increase regardless of the size of the opening. This value was established at a NO of 2.5.

These results confirmed the good flow-pressure behavior of the model of the sprinkler component of the pivot used by the farmers. At the same time, the laboratory tests established the operating range by calculating the average minimum and maximum flow rate for each nozzle opening.

To assess the influence of farmers' practices on performance, in particular the approximate adjustment of the nozzle according to the logic 'the nozzles of the first sprinklers on the lateral (starting from the center) should be wider open than those of the last', the difference between the average flow rates corresponding to the NO_{min} (0.5) and NO_{max} (2.5) were calculated for different pressures. For example, at $P = 0.4$ MPa, the difference between the flow rates of the two openings NO_{min} and NO_{max} reaches $0.82\ m^3h^{-1}$. To achieve the objective of improved uniformity of distribution, both different nozzle openings and different spaces between the sprinklers were evaluated without changing the model of sprinkler preferred by the farmers.

3.2.2.2. Water distribution behavior. We illustrate the variability of water distribution among sprinklers by giving the results for three sprinklers (Fig. 4). Unlike the homogeneous flow-pressure behavior of the five sprinklers evaluated, these results revealed considerable differences in water distribution patterns among the sprinklers. This applied particularly at the periphery of the wetted zone and in the overlap zones (Fig. 4). The maximum range of each sprinkler is 4.5 m, which will be used when designing the new nozzle plan (nozzle openings and sprinkler spacing, see Section 3.3).

Distribution is clearly uneven, and symmetry sometimes poor (Fig. 4). The differences between sprinklers and the low symmetry for a

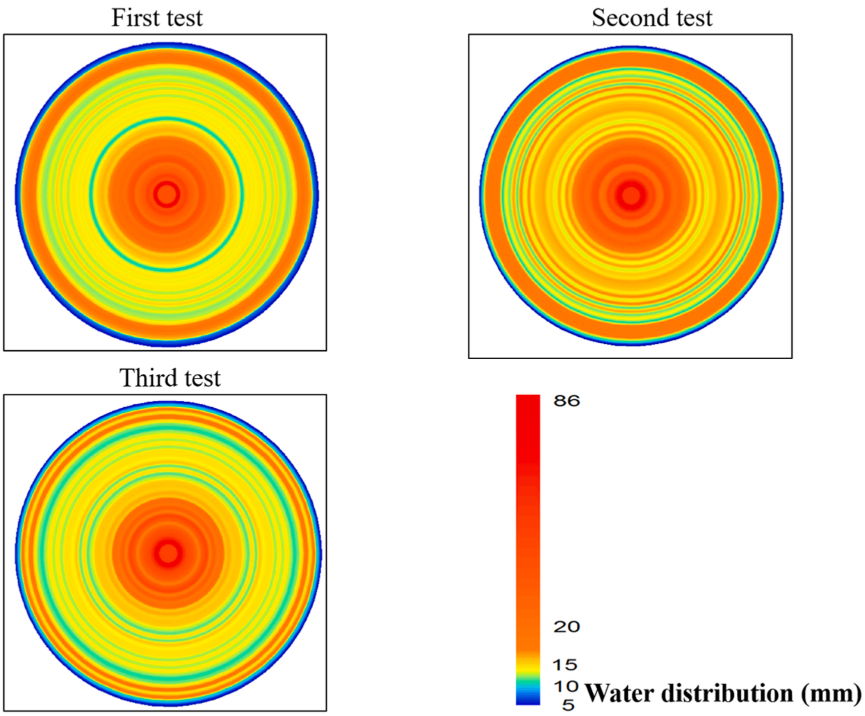

Fig. 2. Uniformity of water distribution under an artisanal pivot, based on in-situ measurements.

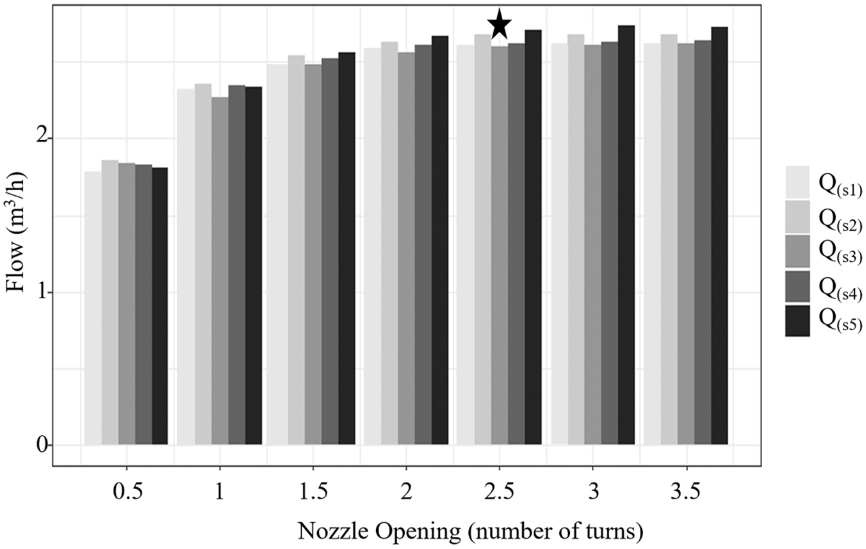

Fig. 3. Determination of the flow rate according to the nozzle opening, illustrated by the results of P = 0.4 Mpa, indicates maximum NO.

single sprinkler would cause poor water distribution under a stationary sprinkler, but the movement of the pivot as well as the overlap between neighboring sprinklers partially offsets this heterogeneity. The profile of applied water, caused by the movement of the pivot lateral, can be reproduced using the distribution profile of a sprinkler calculated from the distribution map. This profile corresponds to the two curves of the cumulative rows and cumulative columns of the network of water gauges during the sprinkler tests (Fig. 5), as if the sprinkler was moving over a set of collectors. This representation allowed us to choose the average sprinkler opening and also, as described in the following section, to choose the optimal spacing that allowed good coverage to simulate the applied water profile under the entire pivot.

Then, by calculating the average volume of irrigation water as well as the minimum and maximum volume distributed by each sprinkler, while keeping the same nozzle opening (2.5 turns) and pressure (0.2 MPa), it was possible to evaluate and express the variation in the volume of water distributed by the different sprinklers (Fig. 5). The third sprinkler produced the most even water distribution, which is why it was chosen as the reference sprinkler for the following round of measurements.

3.3. Re-engineering: improving the performance of the artisanal pivot based on real field conditions

In this section, we present the results of our simulated re-engineering of the artisanal pivot to improve irrigation water distribution. The simulation allowed us to analyze different combinations of pressure [P_{min}, P_{max}] and speed of movement of the pivot (V). In the field, the

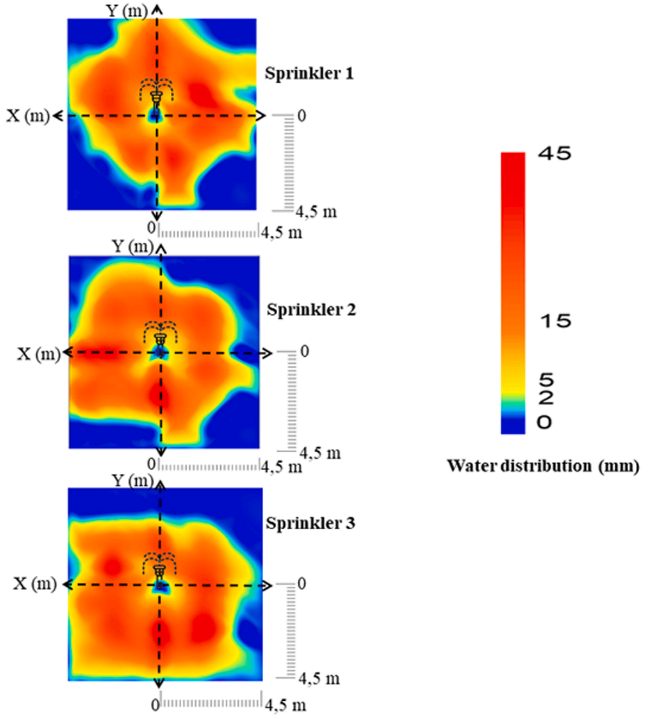

Fig. 4. Water distribution from three sprinklers with nozzles adjusted to the same opening (2.5 turns) and the same pressure (0.2 MPa).

speed can be modified by simply adjusting the speed reducer pulley. Two diameters are available on the market, allowing two travel speeds, 3 and 4 hturn^{-1}. The speed used for *in-situ* measurements was 3 hturn^{-1}, which is the usual speed used in the study area.

The results of the simulation showed that changing the travel speed would not significantly affect the uniformity of distribution of irrigation water in the artisanal pivot. This is in line with the results obtained by Molle et al. (1998) for a conventional pivot. In their study, the ratios of the over and under-watered zones, compared to the total area covered by the pivot, remained similar in the simulations run using the same pressures but different speeds. For example, with the same pressure of 0.2 MPa, over-irrigation, i.e. areas where the minimum output (Q for $NO_{min} = 0.5$) is greater than the crop water requirements (Q_{req}), represented respectively 12 % and 12.3 % of the total surface area in simulations run using travel speeds of 3 and 4 hturn^{-1}. Under-irrigation with the same sprinkler settings, i.e. the area where the water applied covers less than 80 % of crp water requirements crop water requirements (Q_{req}) exceeded the maximum output (Q for $NO_{max} = 2.5$), represented respectively 15.5 % and 13.8 % of the total surface in both cases. These results mean the speed of the pivot can be kept at 3 hturn^{-1}.

In terms of pressure, the simulation run using 0.3 MPa made it possible to satisfy crop water requirements over almost the entire surface area, while simultaneously saving water. Compared with simulations using lower pressure ($P < 0.3$ MPa), this simulation resulted in the smallest under-irrigated area, less than 0.5 % (Fig. 6). The over-irrigated area represented 17 % of the total surface, compared with the simulations run with $P > 0.3$ MPa, where the ratio reached 36 %.

However, the operating range of large conventional pivots with a 350-m long lateral or even longer that irrigate 30 ha or more, is around 0.2 MPa. Thus, in terms of energy, operating this small 50 m pivot with $P = 0.3$ MPa is not energy efficient. To get round this issue, we suggest a pressure of 0.1–0.2 MPa for 50-m pivots. Consequently, the simulation run with a pressure of 0.2 MPa was used as a basis to propose adjustments to improve both irrigation water distribution and energy performance.

Next we simulated adjusted nozzle openings for the almost 40,000 artisanal pivots that were already installed. First, the pressure was lowered to 0.2 MPa, which is the usual pressure provided. Second, three additional outlets were added to the lateral to mount three additional sprinklers.

These adjustments improved both the energy performance and the simulated irrigation water distribution. In practice, in the field, the over-

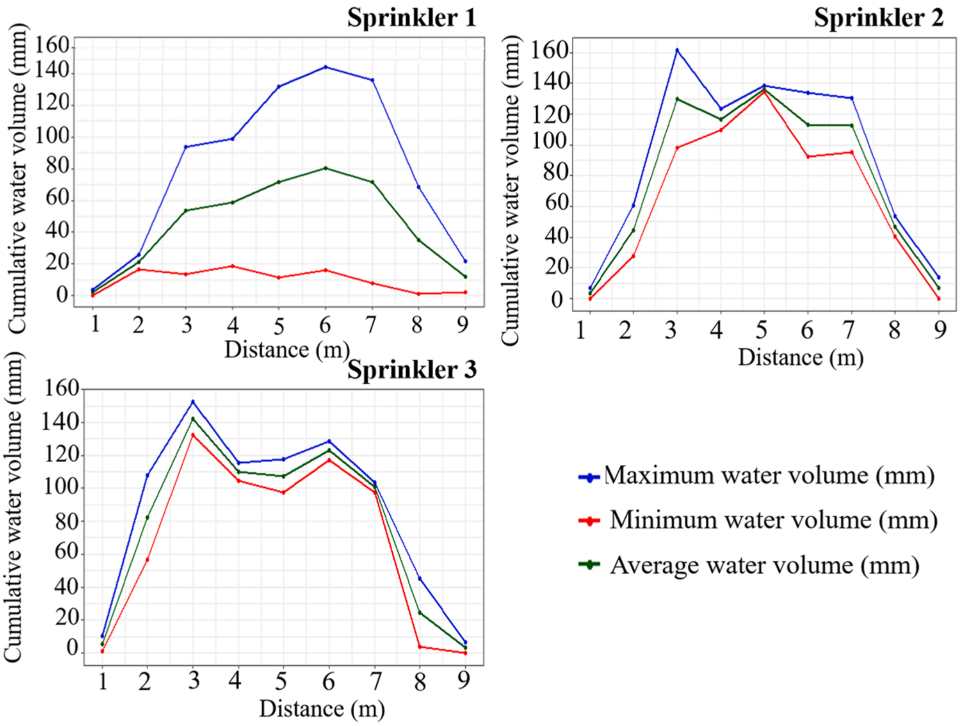

Fig. 5. Average, minimum and maximum cumulative water curve of the sprinklers, adjusted to the same nozzle opening (2.5 turns) and with the same pressure (0.2 MPa).

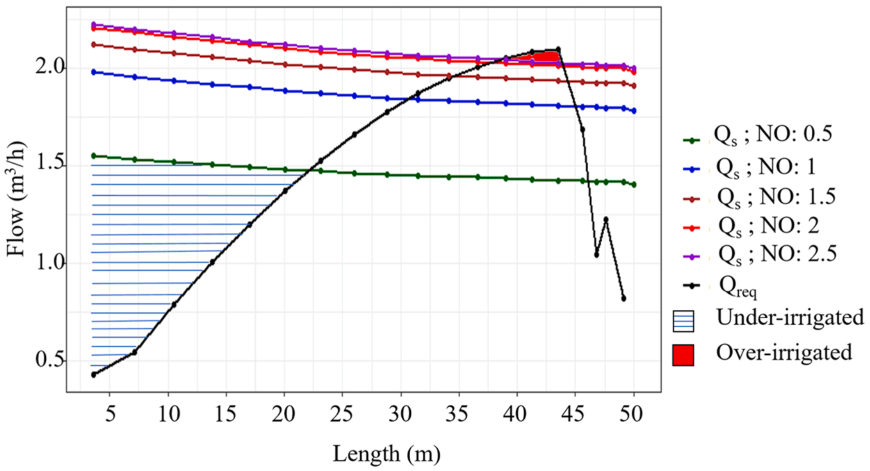

Fig. 6. Simulated flow of the artisanal pivot to illustrate for results obtained with P = 0.3 MPa.

irrigated area would be reduced by more than half, to 12 % of the total surface area instead of 27.5 %, while the under-irrigated area would be reduced to less than 2.5 % of the total area. The adjustments, which can be made by the farmers themselves with minimum assistance from artisans, consist in: 1) installing a pump that provides lower pressure (0.2 MPa); and 2) adding three additional sprinklers. To ensure the farmers can open the nozzles to the recommended opening size, it is necessary to mark the right spot on all the sprinklers, as we did during the tests.

For new pivots, re-engineering with a new nozzle plan was simulated to improve their performance. This was possible through a simple readjustment of the spacing between the outlets on the lateral to which the sprinklers are attached. The nozzle openings were adjusted starting from a pressure of 0.2 MPa, along with all other input parameters detailed in Section 3.2. The simulation started by determining the spacing required to maintain the flows as close as possible to the flow that matched crop water requirements (Q_{req}), after which the appropriate openings were chosen.

After simulating the proposed re-engineering, we simulated the irrigation water distribution pattern supplied by the improved pivot. Figs. 7 and 8 show the possible progress in the irrigation performance of the artisanal pivot, which will indeed enable remarkable water savings and a considerable improvement in irrigation water distribution.

Two important points emerge from the comparison of in-situ irrigation water distribution pattern and that simulated under a pivot, First, in the simulation, and for 70 % of the total irrigated surface area, the improved pivot makes it possible to satisfy 80–120 % of the average crop water requirements, compared with only 34 % of the total surface area *in situ*. Second, the improved pivot makes it possible to reduce the extent of over-irrigated area, i.e. that receives 120 % of the crop water requirements, to less than 12 %, versus 22 % of the total surface area *in situ*. However, despite the (encouraging) simulation results, there are still efforts to be made in relation to the nozzle map (beginning and end of the lateral).

Finally, the improvements that were tested in the research were co-designed with a small group of local actors (two artisans and a farmer) to ensure that these were adapted to the context of use and innovation. This ensured that the re-engineering, proposed here, can easily be carried out by artisans in their workshops. Also, the simple adjustments of nozzle openings can be made by the farmers themselves. Instead of aiming for hydraulic perfection of a pivot that cannot be used in local conditions, we were guided by the pragmatism of the artisans and farmers we

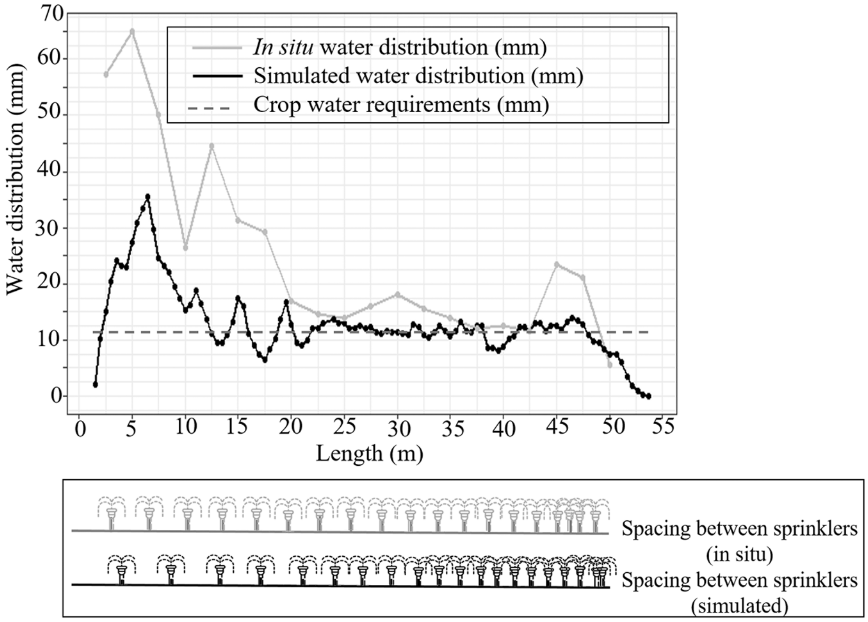

Fig. 7. *In-situ* and simulated patterns of irrigation water distribution provided by the artisanal pivot.

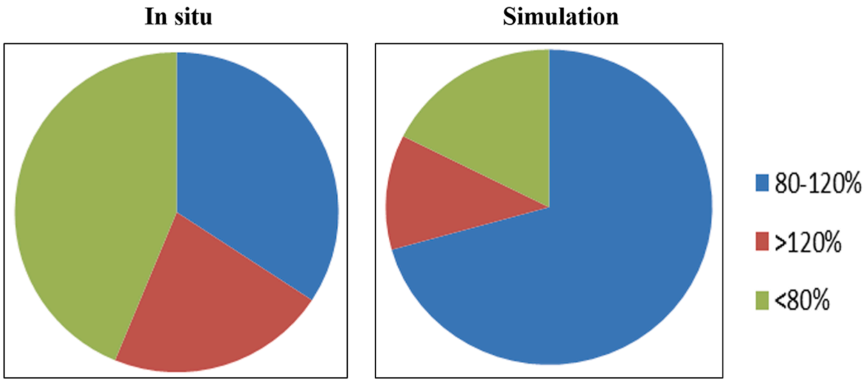

Fig. 8. *In-situ* and simulated irrigation water applied compared to the crop water requirements.

worked with. When we carried out behavioral tests in the laboratory, we jointly decided to improve the use of the existing model of the sprinkler, considered functional, widely available and cheap, rather than switching to alternative sprinklers that were not available locally. As indicated by an artisan (52 years old), "*The farmer does not expect you to make the perfect pivot, otherwise we go back to the bad experience of the large pivot. The mini-sprinkler costs four times less than other sprinklers, they are available and easy to adjust!*"

4. Conclusion: re-engineering through continuous negotiation with innovation actors

In this study, we designed an innovative (re-)engineering approach to support different innovation actors, including artisans, traders and farmers, in improving the irrigation performance of a small-scale artisanal pivot.

The approach was, first, developed around the conceptual perspective of supporting an incremental innovation process of local actors. This meant studying the irrigation performance of the artisanal pivot that was already widely used in the study area (more than 40,000 pivots already present), rather than focusing on the conventional imported pivot that was rarely used in the region. This conceptual perspective was informed by previous insights into the translation of irrigation technologies (Mateos et al., 2018; Naouri et al., 2020), and more generally by innovation studies on user-led innovations (Akrich et al., 2002; Ensor and de Bruin, 2022). Indeed, a technical innovation is embedded in a socio-technical network of innovation actors who "who take it up, support it, diffuse it" (*ibid*, p. 204). This "socialized" view of innovation of "embedded entrepreneurship" does not disqualify inventions by "alert individuals" (Garud and Karnøe, 2003), but draws attention to the fact that such discoveries then require the enrolment of a diversity of actors and skills to manufacture, sell, use and service the technology. It is the combination of the different interventions of all these people in the design, diffusion and use of the technology that will determine the irrigation performance in the field (Benouniche et al., 2014a). In other words, to improve the irrigation performance it is important to understand how the technology is going to be used and maintained in the field to avoid technological improvements that will only 'work' in the laboratory.

This conceptual perspective also relates to the fact that successful innovations are often obtained as a result of *bricolage* (in English, tinkering), i.e. by "the creation of new options through the recombination and transformation of existing resources" (*ibid*). In the case of the artisanal pivot, the technology was improved gradually over a period of ten years, through intense dialogue involving artisans, traders and farmers, and often via the recycling of locally available spare parts. This process can be compared to what Garud et al. (2021) refer to as a "neo-design approach", involving "repurposing, experimentation and collective learning". This explains why we took a functional artisanal pivot from the field to be tested in the laboratory, as it incorporated the different adjustments that had been made.

Second, our approach relied on a process of negotiation with the different innovation actors based on an intense dialogue and mutual respect. This started by considering the performance of the artisanal pivot as a dynamic rather than static process, countering a common pitfall in engineering studies (Benouniche et al., 2014a). In other words, 'under' performance of a technology should be seen as an opportunity to improve it, but only if (at least some of) the innovation actors consider under-performance as a problem to be solved. This means the engineers must have a thorough understanding of the innovation process of the (in this case) artisanal pivot and be convinced they can play a key role in improving its irrigation performance, as the engineers are progressively integrated in the socio-technical network surrounding the pivot (Benouniche et al., 2014b). This is in line with the conclusions drawn by Mateos et al. (2018), who pointed to the need to evaluate an artisanal filter designed by farmers in Brazil, rather than attempting to correct the deficiency of an imported conventional filter, in a specialized irrigation laboratory to further improve its functioning and to contribute to solving similar problems elsewhere. In the present study, after a thorough analysis of the innovation process, performance tests were undertaken on the artisanal pivot *in situ* on a farmer's plot, with the assistance of local artisans. This helped visualize the problem of uniform water distribution and revealed that this was a longstanding problem on which artisans had been working following farmers' request to produce more evenly sized potatoes thanks to more uniform irrigation. The sprinklers were then tested in the National Irrigation Laboratory, located more than 600 km away from the study area. However, contact with the artisans was regular via social media (photos, videos, explanations) to keep them informed about ongoing simulations. The different options for improving irrigation performance by improving the water distribution uniformity, while saving water and energy, were then discussed with both the artisans and the farmers. The involvement of local experts is indeed a crucial element in the process of adapting new technologies and making improvements (Stewart, 2007). However, it also led to arguments between members of the engineering team, as some team members suggested more radical changes to the nozzles on the pivot lateral or the use of more standard sprinklers, changes that were rejected by local actors. Yet, a common understanding was reached for the need for suitable positioning of the nozzles for better irrigation performance, which had already been pinpointed for conventional pivots (Molle et al., 1998). In our case, the objective of farmers to increase the uniformity of distribution was to obtain evenly sized potatoes to compete on the market, and not necessarily to save water. However, our results showed that it is possible to combine the two objectives. To broaden the scope of this study, it would be interesting to engage research and development organizations in such a negotiation process to collaborate in the improvement of artisanal irrigation systems and certify them for subsidy instead of continuing to provide subsidies for imported systems.

Finally, the third characteristic is the timing of our re-engineering approach. Our intervention happened 20 years after the original emergence of artisanal pivots. This meant that a robust technical device had already been gradually designed, tested and diffused, involving a diversity of skills and actors in a process characterized by multiple exchanges and feedback. Of particular interest is that the artisans were already in the process of improving the irrigation performance of the pivot in consultation with the farmers. Thus, on the one hand, we were able to build on existing efforts and ambitions, in a process in which all the actors were keen to learn from the engineering team in a process of collective learning (Garud et al., 2021) and the engineers considered themselves to be just one of many innovation actors. This positioned engineers as an integral part of society and not outside it (Riaux et al., 2023). On the other hand, the innovation actors' expectations were high and the engineering team had to come up with 'clever' improvements that could be shown to really work and were adapted to the local conditions. Our experience suggests that this is what (irrigation) engineering is - or should be – all about.

CRediT authorship contribution statement

Abdelkrim Ould Rebai: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Tarik Hartani:** Writing – review & editing, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Marcel Kuper:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Bruno Molle:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Data curation, Conceptualization. **Sami Bouarfa:** Writing – review & editing, Methodology. **Khalil Laib:** Writing – review & editing, Investigation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

Our thanks go to the artisans and farmers of Wadi Suf Valley who shared their experience and know-how on the artisanal pivot with us. We would also like to thank the engineers at the INSID laboratory who enabled us to carry out the tests. We are grateful to Pedro Gavilan Zafra and Kevin Daudin for their useful comments and suggestions on an earlier version of the paper. The research was supported by the Hubis project (Prima/0006/2019) and the Massire project (funded by IFAD/2000002013).

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agwat.2024.109201.

Data Availability

Data will be made available on request.

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