

CLIMATE-RESILIENT IRRIGATION DESIGN: TRANSITION FROM GRAVITY TO ON-DEMAND DRIP IRRIGATION IN MADAGASCAR

CONCEPTION D'UNE IRRIGATION RÉSILIENTE AU CLIMAT: PASSAGE DE L'IRRIGATION GRAVITAIRE À L'IRRIGATION GOUTTE À GOUTTE À LA DEMANDE À MADAGASCAR

Maria João Calejo¹, António Capelo¹, Sara Ruivo Santos¹, Catarina Bochechas¹,
and Maria Do Rosário Cameira²

ABSTRACT

The design of irrigation systems in climate-exposed and data-scarce regions is challenged by the absence of reliable demand data and uncertain future irrigation practices. This study addresses this issue using the Havelo–Mandrare project in southern Madagascar as a case study, where irrigation development is required under conditions of high climatic variability, limited farmer experience, and fragile soil systems. A modelling framework combining ISAREG, SRFR, and RZWQM was applied to analyse irrigation performance under contrasting scenarios. Soil characterization indicates a dominant hydraulic behaviour characterized by high infiltration capacity and limited water retention, leading to strong constraints on irrigation efficiency.

Results show that gravity irrigation can meet crop water requirements but results in substantial water losses due to deep percolation, particularly under large application depths. In contrast, drip irrigation enables better control of water application, resulting in improved alignment between actual and potential evapotranspiration and reduced losses. Although surface irrigation efficiency can be improved through reduced application depths and optimized field layouts, such configurations require very short irrigation durations and high-frequency interventions. At field scale, this implies significant operational complexity, making such solutions impractical under smallholder and manually operated conditions. The study demonstrates that irrigation performance is governed not only by hydraulic processes but also by operational feasibility. Based on these findings, a staged design approach is proposed, combining initial rotational delivery with preserved hydraulic flexibility to enable a transition towards on-demand operation. This approach supports the progressive adoption of more efficient irrigation systems while ensuring initial operability. More broadly, the results highlight the importance of designing irrigation infrastructure as adaptive systems capable of accommodating evolving practices under climatic and institutional uncertainty.

Keywords: Drip irrigation; Crop water requirements; High infiltration capacity; Hydraulic flexibility; Irrigation infrastructure.

RÉSUMÉ

La conception de systèmes d'irrigation dans les régions exposées aux aléas climatiques et pauvres en données est entravée par l'absence de données fiables sur la demande et par l'incertitude entourant les pratiques futures d'irrigation. Cette étude aborde cette question à partir du projet Havelo–Mandrare, dans le sud de Madagascar, où le développement de l'irrigation doit s'opérer dans un contexte de forte variabilité climatique, d'expérience limitée des agriculteurs et de systèmes pédologiques fragiles. Un cadre de modélisation combinant ISAREG, SRFR et RZWQM a été appliqué pour analyser les performances de l'irrigation selon des scénarios contrastés. La caractérisation des sols met en évidence un comportement hydraulique dominant marqué par une

1 AQUALOGUS – Engenharia e Ambiente, Rua do Mar da China, n.º 1 - Escritório 2.4, Portugal

2 LEAF - Linking Landscape, Environment, Agriculture and Food-Research Center, Associated Laboratory TERRA, Instituto Superior de Agronomia, Universidade de Lisboa, Lisbon, Portugal Corresponding author: mariacalejo@aqualogus.com

forte capacité d'infiltration et une faible rétention d'eau, ce qui impose de fortes contraintes à l'efficacité de l'irrigation.

Les résultats montrent que l'irrigation gravitaire peut satisfaire les besoins en eau des cultures, mais qu'elle entraîne d'importantes pertes d'eau par percolation profonde, en particulier lorsque les lames d'eau appliquées sont élevées. À l'inverse, l'irrigation goutte à goutte permet un meilleur contrôle de l'application de l'eau, ce qui améliore la concordance entre l'évapotranspiration réelle et l'évapotranspiration potentielle et réduit les pertes. Bien que l'efficacité de l'irrigation de surface puisse être améliorée en réduisant les lames appliquées et en optimisant l'aménagement des parcelles, de telles configurations nécessitent des durées d'irrigation très courtes et des interventions fréquentes. À l'échelle de la parcelle, cela implique une grande complexité opérationnelle, qui rend ces solutions peu pratiques dans les petites exploitations gérées manuellement. L'étude montre que les performances de l'irrigation sont déterminées non seulement par les processus hydrauliques, mais aussi par la faisabilité opérationnelle. Sur la base de ces résultats, une approche de conception par étapes est proposée, combinant une distribution initiale par rotation et le maintien d'une flexibilité hydraulique afin de permettre une transition vers un fonctionnement à la demande. Cette approche favorise l'adoption progressive de systèmes d'irrigation plus efficaces tout en garantissant leur exploitabilité initiale. Plus largement, les résultats soulignent l'importance de concevoir les infrastructures d'irrigation comme des systèmes adaptatifs capables de s'accommoder de pratiques évolutives dans un contexte d'incertitude climatique et institutionnelle.

Mots clés : Irrigation goutte à goutte; Besoins en eau des cultures; Forte capacité d'infiltration; Flexibilité hydraulique; Infrastructures d'irrigation.

INTRODUCTION

The design of irrigation systems in climate-exposed and data-scarce regions presents a fundamental challenge: infrastructure must often be defined in the absence of reliable demand data, consolidated irrigation practices, and well-established operational rules. This challenge is particularly relevant in regions undergoing transition from rainfed to irrigated agriculture, where future water use is shaped not only by climatic variability but also by socio-technical uncertainty related to farmers' experience, irrigation method adoption, and plot-level management (Nikolaou *et al.*, 2020).

In southern Madagascar, these uncertainties are amplified by strong interannual rainfall variability, increasing evaporative demand, and fragile soil systems characterised by low water retention capacity and high infiltration rates. At the same time, irrigation practices remain largely undeveloped, and farmers have limited experience with water management at plot level. As a result, irrigation system design must anticipate a range of possible operational pathways rather than rely on stabilised demand patterns or predefined irrigation methods.

A key tension arises from the likely preference for gravity irrigation during the initial stages of implementation. This preference reflects its perceived simplicity, low investment requirements, and compatibility with manual labour. However, under local soil conditions, gravity irrigation may be poorly suited to efficient water management, particularly where high infiltration rates and low soil water storage capacity increase the risk of deep percolation losses. Conversely, localised irrigation systems, such as drip irrigation, offer greater control over water application and higher potential efficiency, but may face technical, economic, and organisational barriers to immediate adoption (Falkenmark, 1979; Nikkels *et al.*, 2019).

The central design challenge is therefore not simply the selection of a single irrigation method, but the development of an irrigation network capable of supporting a transition over time (Nikkels *et al.*, 2019). In particular, secondary networks must be able to operate initially under gravity-based rotational delivery while preserving the hydraulic flexibility required for a progressive shift towards on-demand and more efficient irrigation systems.

This study addresses this challenge using the Havelo–Mandrare project in southern Madagascar as a case study. The analysis focuses on the interaction between soil hydraulic behaviour, irrigation method, field geometry, and operational constraints. A modelling framework combining ISAREG, WinSRFR, and RZWQM is used to evaluate irrigation performance under contrasting scenarios, linking crop water requirements, field application performance, and root-zone soil water response.

The objective is not only to compare irrigation methods, but to inform the design of irrigation systems capable of operating under uncertainty and evolving over time. In this context, the study proposes a staged and flexible design approach that supports short-term feasibility while maintaining the conditions required for long-term resilience and improved water-use efficiency.

STUDY AREA AND PROJECT CONTEXT

The Havelo–Mandrare project is located in southern Madagascar, within the Anosy and Androy regions, more specifically in the districts of Amboasary-Sud and Ambovombe-Androy, as shown in Figure 1. The intervention area forms part of the Malagasy Grand Sud, one of the most climate-vulnerable regions of the country.

This region is characterized by a hot and dry climate, broadly corresponding to a semi-arid climate (BSh), according to Köppen-Geiger classification. Annual rainfall is generally very low, often below 500 mm, and is marked by strong interannual variability. Together with high evaporative demand, these conditions result in a pronounced hydrological deficit. Such climatic constraints severely limit rainfed agricultural production and contribute to recurrent food insecurity, prolonged lean periods, and strong dependence on external support.

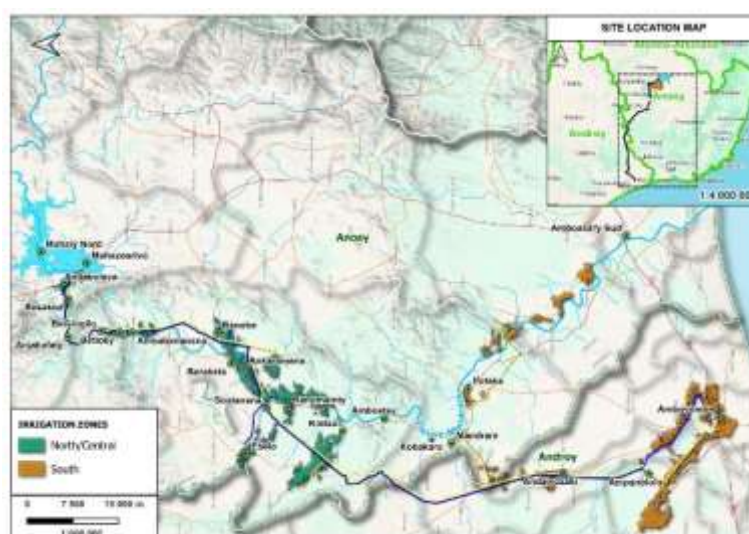


Figure 1. Location of the Havelo–Mandrare project in southern Madagascar.

Soils in the project area show strong variability in depth, texture and irrigation suitability, although many units are characterized by limited water retention and high infiltration rates. These properties are critical for irrigation performance, particularly under gravity-fed systems.

The population in the project area is predominantly rural and relies mainly on subsistence agriculture and traditional livestock systems. Water access remains highly constrained, both for domestic use and for agricultural production. Irrigation development aims to improve water security and agricultural productivity under these conditions, although irrigation practices are not yet well established and farmer experience remains limited.

The Havelo–Mandrare irrigation scheme is based on a hierarchical water conveyance and distribution system. The primary conveyance system consists of a gravity-fed network of large-diameter pipelines (2 × DN 2000) extending over approximately 150 km. Given the spatial distribution of the irrigated areas (approximately 18,000 ha), intermediate regulating reservoirs are incorporated along the primary network. The secondary irrigation networks are supplied either from the conveyance pipes or from the reservoirs, and are designed to deliver water at plot level through hydrants. The design incorporates hydraulic flexibility, allowing different operation modes, including rotational delivery and potential future on-demand supply. This configuration supports a staged operational approach, ensuring initial system functionality under simple management conditions while preserving the capacity to adapt to evolving irrigation practices.

For analysis and design purposes, the project area was divided into two main regions: a North/Central zone and a South zone. This subdivision reflects differences in climatic conditions, soil characteristics, irrigation suitability, and existing agricultural practices, and was used consistently throughout the modelling framework and the definition of irrigation scenarios.

The cropping systems considered in the project include staple crops, intercropping systems, and seasonal rotations representative of local agricultural practices. Their distribution varies between the North/Central and South zones reflecting differences in agro-climatic conditions, soil characteristics, water availability, and farming objectives (Figure 2).

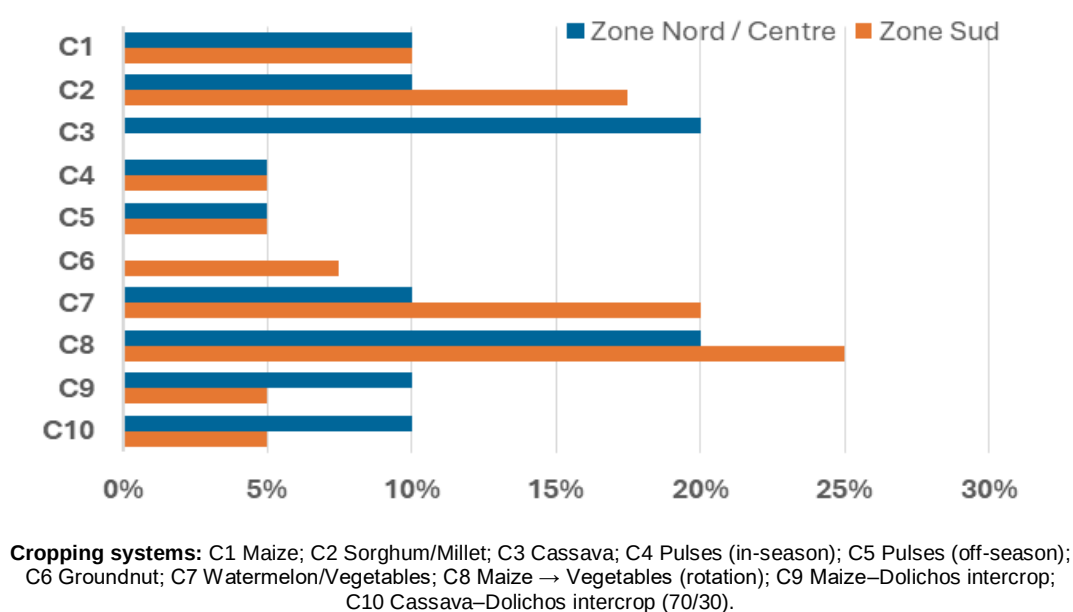


Figure 2. Cropping system distribution in the North/Central and South zones.

Staple crops and intercropping systems are generally compatible with simple gravity-based irrigation methods, particularly under conditions of limited capital availability and technical capacity. In contrast, localized irrigation systems, especially drip irrigation, provide greater control over water application, allowing better adaptation to crop water requirements and soil conditions. These systems are particularly relevant for dry-season production and higher-value crops, such as vegetables, for which water use efficiency and application uniformity becomes critical.

These selected cropping systems were therefore used to define representative irrigation requirements and scheduling scenarios, which provided the basis for the subsequent modelling of irrigation performance under alternative water delivery and field application strategies.

METHODOLOGICAL FRAMEWORK

Soil characterization and clustering

Soil characterization was based on field surveys and laboratory analyses, allowing the identification of two main soil layers: a topsoil layer (TS, approximately 0–20 cm) and an underlying subsoil layer (SS). This two-layer representation was consistently adopted throughout the clustering analysis and soil–water simulations.

K-means clustering (MacQueen, 1967) was used to group soils with similar hydraulic and physical properties, reducing spatial complexity while preserving the main patterns relevant for irrigation performance assessment. The analysis was carried out separately for the North/Central and South zones using saturated hydraulic conductivity (Ks), water retention capacity (CU), and soil depth as key variables.

For soil-water modelling, Ks values were estimated using the Rosetta pedotransfer approach (Zhang and Schaap, 2017). These estimates should therefore be interpreted as relative indicators of Ks rather than absolute measurements. Within the modelling framework, Ks values were used consistently with soil water retention characteristics to represent infiltration, redistribution, and drainage processes.

Irrigation system configurations

To evaluate the performance of alternative irrigation strategies under the prevailing agro-climatic and soil conditions, two main irrigation system configurations were considered: surface irrigation and drip irrigation. These configurations were selected to represent both the practices likely to be adopted in the short-term and the targeted medium-term transition towards more efficient systems within the project area.

In the southern region, very small basins, typically around 5 m × 5 m, are already used by farmers as an adaptive response to local soil conditions, since smaller basins reduce irrigation duration and help limit deep percolation losses. In northern areas, where rice irrigation is practiced, field layouts tend to be less fragmented and more elongated, reflecting different hydraulic management conditions associated with ponding irrigation.

Based on these observed conditions, surface irrigation was analysed using simplified basin layouts representative of smallholder farming systems. Three field configurations were considered: small basins (5 m × 5 m), intermediate layouts (5 m × 20 m), and elongated plots (5 m × 50 m). These configurations allowed the sensitivity of irrigation performance to basin length and irrigated area to be assessed under contrasting soil and management conditions.

Localized irrigation scenarios were represented by drip systems, which allow controlled water application directly to the crop root zone. This configuration enables irrigation volumes and timing to be adjusted more precisely to crop water requirements, reducing non-beneficial water losses.

Modelling approach

The modelling approach was designed to assess the flexibility of the secondary irrigation network under contrasting operational pathways. A sequential modelling framework was adopted, combining irrigation scheduling, surface irrigation hydraulics, and root-zone water balance analysis. ISAREG (Teixeira and Pereira, 1992) was used to estimate crop water requirements and define irrigation schedules compatible with rotational water delivery. WinSRFR (Bautista et al., 2009) was then applied to assess the hydraulic feasibility of surface irrigation, including advance, infiltration distribution and potential application efficiency under different basin lengths and inflow rates. Finally, RZWQM (Ahuja et al., 2000) was used to simulate root-zone water dynamics, drainage, and crop water uptake under drip and gravity irrigation scenarios.

Together, these models link irrigation demand, field application performance and soil-water response, supporting an integrated assessment of the proposed secondary irrigation network. In particular, the framework was used to evaluate whether the network can initially operate under gravity-based rotational delivery while maintaining the technical conditions required for a future transition towards on-demand drip irrigation. Simulations were conducted for maize during the rainy season, representing a dominant and water-demanding cropping condition within the project area.

RESULTS AND DISCUSSION

Soil water properties

In the southern, the limited variability in soil properties, together with the relatively small number of observations, led to the definition of two representative clusters. By contrast, the greater heterogeneity of soil properties in the North/Central zone supported the identification of three distinct clusters.

Across most soil groups, Ks tended to decrease from the topsoil to the subsoil, reflecting higher bulk density, reduced macroporosity, and greater horizon differentiation with depth. This pattern is consistent with the observed increase in water retention in subsoil layers, suggesting that deeper horizons may store more water but transmit it more slowly. These hydraulic characteristics reveal two distinct patterns (Table 1). Clusters N1 and N2, dominated by clay loam and sandy clay textures, exhibit lower Ks values and higher water-retention capacity, indicating a more moderate infiltration response and greater soil water storage. By contrast, N3, S1 and S2 clusters are dominated by sandy textures, with higher Ks values and lower CU, reflecting faster infiltration and a higher susceptibility to deep percolation losses.

Table 1. Representative soil hydraulic properties by cluster and soil layer

Cluster	Zone	Dominant texture	Ks for TS / SS (mm/h)	CU for TS / SS (m/m)	Soil depth (m)
N1	North/Central	Clay-loam	≈ 4.7 / 3.1	0.18 / 0.17	0.9
N2	North/Central	Clay-sandy	≈ 6.7 / 4.9	0.13 / 0.13	1.0
N3	North/Central	Sandy	≈ 15.7 / 8.7	0.11 / 0.12	1.5
S1	South	Sandy	≈ 14.9 / 10.0	0.11 / 0.10	0.6
S2	South	Sandy	≈ 18.2 / 13.1	0.10 / 0.10	1.2

Ks is the saturated soil hydraulic conductivity, TS is the top soil layer SS is the sub soil layer, CU is the water retention capacity.

Irrigation performance and operational constraints

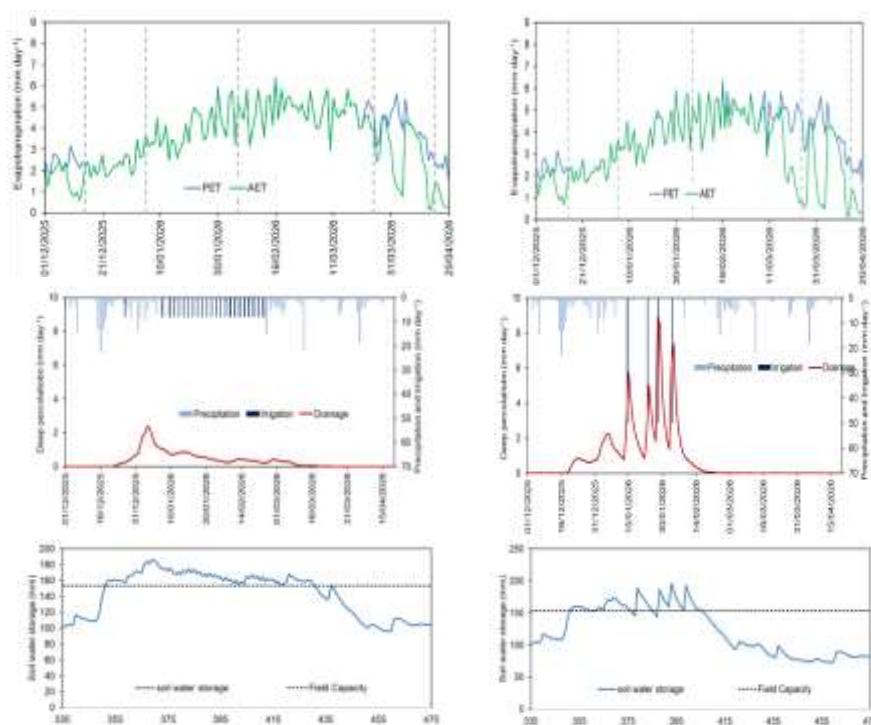
The soil characterization highlights a dominant hydraulic behaviour across the study area, characterized by high infiltration capacity and limited water retention capacity. These conditions strongly constrain irrigation performance, particularly under surface irrigation, where rapid infiltration increases the risk of deep percolation losses.

Figure 3 illustrates the simulated soil–water dynamics for a representative cluster in the southern zone, comparing drip and basin irrigation under identical climatic conditions. Table 2 summarizes the main RZWQM simulation results and presents the overall water-balance efficiency (E_{WB}) during the irrigation period, accounting for precipitation, irrigation, variation in the soil water storage (ΔS) and deep percolation losses. The irrigation depths and scheduling assumptions used in the RZWQM simulations were supported by ISAREG modelling, which was used to define crop water requirements and irrigation calendars under the constraints imposed the rotation method operation.

Table 2. Summary of RZWQM results

Scenario	Total Prec. (mm)	Prec. during irrigation period (mm)	Irrigation (mm)	Total Drainage (mm)	Drainage during irrigation period (mm)	AET (mm)	ΔS (mm)	E_{WB} (%)
Cluster N1 / Drip	361	133	200	128	117	424	9	~ 64%
Cluster N1 / Gravity	361	133	200	132	107	426	3	~ 68%
Cluster N3 / Gravity	361	133	200	125	114	411	25	~ 65%
Cluster S1 / Drip	350	95	184	67	42	484	-17	~ 85%
Cluster S1 / Gravity	350	95	200	121	117	446	-17	~ 60%
Cluster S2 / Drip	350	95	184	66	55	487	-19	~ 80%
Cluster S2 / Gravity	350	95	200	127	120	443	-20	~ 59%

Prec. = precipitation; ΔS = soil water storage variation; E_{WB} = overall water-balance efficiency.



Drip irrigation – Irrigation depth 8 mm

Gravity irrigation – Irrigation depth 50 mm

Figure 3. RZWQM simulation results for cluster S1 (South zone): comparison between drip (8 mm) and gravity (50 mm) irrigation.

Drip irrigation results show a close alignment between actual evapotranspiration (AET) and potential evapotranspiration (PET), reflecting improved control of water application within the root zone. Under these conditions, soil moisture remains comparatively stable and deep percolation losses are reduced, particularly in the southern clusters, where irrigation represents the dominant water input during the simulation period. By contrast, basin irrigation is characterized by larger application depths and lower control over infiltration dynamics, resulting in higher drainage losses and greater variability in soil

water storage. These effects are particularly evident under high-Ks conditions, where excess water rapidly percolates below the root zone following irrigation events.

However, the simulations also show that drainage behaviour cannot be interpreted independently of the broader climatic and hydrological context. In the North/Central clusters, drainage volumes remain relatively high under both irrigation methods. This behaviour is associated with the combined effect of higher precipitation inputs and lower atmospheric demand during the simulation period, which reduces the relative influence of irrigation method on total drainage. For this reason, comparisons between irrigation methods should be interpreted primarily within each pedoclimatic context rather than directly between regions. In both cases, the results indicate that irrigation performance depends strongly on the ability to control application depth and irrigation frequency.

The quantitative comparison confirms that drip irrigation generally achieves similar or higher AET, while reducing drainage losses and improving overall water-balance efficiency. Nevertheless, the results also highlight that efficient irrigation under the prevailing soil conditions depends not only on the irrigation method itself, but also on irrigation scheduling and operational management. This aspect becomes particularly important under future on-demand operation, where irrigation timing and application depth will depend increasingly on farmers' decisions. In this context, the gradual accumulation of irrigation management experience becomes a key factor for improving water-use efficiency and strengthening the long-term resilience of the irrigation scheme under increasing climatic variability.

The performance of gravity irrigation under the prevailing soil conditions is constrained not only by hydraulic factors, but also by operational feasibility at field level. Although SRFR simulations show that application efficiency can be improved by reducing irrigation depth and optimizing inflow rates, such improvements require strict control of both field layout and irrigation timing.

The selection of field level inflow rates was supported by SRFR simulations, allowing the identification of configurations that minimize application losses under the prevailing soil conditions. Figure 4 illustrates the variation in potential application efficiency as a function of basin length and inflow rate for the highly permeable soil groups.

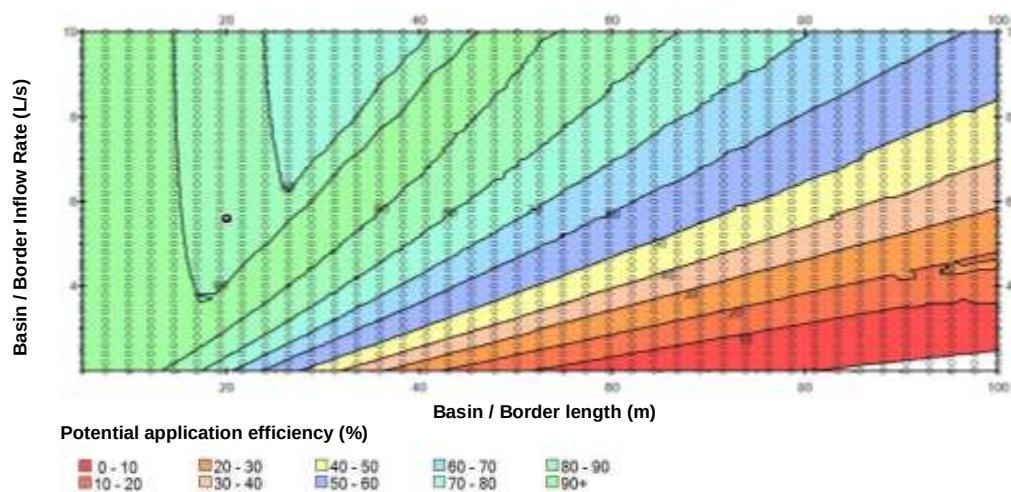


Figure 4. Potential application efficiency as a function of basin length and inflow rate for the high-infiltration soil groups (N3, S1 and S2; infiltration family 1.5), derived from SRFR simulations.

SRFR simulations supported the validation of the inflow rates assigned at hydrant level. For the highly permeable groups represented by infiltration family 1.5 (N3, S1, and S2), high application efficiencies require short basin lengths and well-controlled inflow rates. These requirements become operationally prohibitive when applied at field scale. A 5 m × 5 m layout for a typical 5 ha irrigation unit would result

in approximately 1,184 basins and an irrigation interval of about two days, requiring a level of labour organization or automation that is incompatible with the anticipated smallholder farming systems. Longer basins are still hydraulically feasible for the less permeable N1 and N2 groups, which are represented by infiltration family 0.5. However, controlling the inflow rate, irrigation duration, and application depth continue to be critical to irrigation performance.

DESIGN IMPLICATIONS FOR CLIMATE RESILIENCE

The case study shows that irrigation infrastructure should incorporate climate resilience as an adaptive capacity from the outset. In data-scarce contexts, where irrigation practices are not yet established, infrastructure should not be designed for a single fixed operational mode. Rather, it should enable a gradual transition from straight forward and robust initial operation to more efficient and controlled irrigation systems.

In the Havelo–Mandrare project, this principle is reflected in the combination of rotational delivery during the initial phase and hydraulic flexibility for future on-demand operation. This approach reduces the risk of underuse or operational failure during early implementation, while preserving the possibility of technological and agronomic improvement as farmers gain experience and institutional capacity increases.

The progressive transition from gravity to drip irrigation represents a key pathway for improving irrigation efficiency and climate resilience, by enhancing control over water application and supporting more stable soil moisture conditions under increasing climatic variability. More broadly, the proposed framework shows that irrigation networks in climate-exposed and data-scarce regions should be conceived as adaptive systems. Their resilience depends not only on their capacity to deliver design flows, but also on their ability to support changes in farming practices, irrigation technologies and water management rules over time.

CONCLUSIONS

This study addressed the challenge of designing irrigation systems under conditions of climatic variability, limited data availability, and uncertain future irrigation practices, using the Havelo–Mandrare project in southern Madagascar as a case study.

The results show that under the prevailing soil conditions characterized by high infiltration capacity and limited water retention, gravity irrigation leads to substantial inefficiencies. Although it can meet crop water requirements, it does so at the cost of significant deep percolation losses and limited control over water application. In contrast, drip irrigation enables a closer alignment between water application and soil–crop demand, resulting in improved water use efficiency. The analysis further demonstrates that improving the efficiency of gravity irrigation through reduced application depths and optimized field layouts is technically feasible but operationally impractical. Achieving such performance requires very small basins, short irrigation durations, and high-frequency interventions, which are not compatible with the expected smallholder farming conditions.

These findings highlight that the main limitation of gravity irrigation in this context is not hydraulic but operational. This has direct implications for irrigation system design, which cannot rely on a single predefined mode of operation. Instead, the study proposes a staged design approach combining initial rotational delivery with preserved hydraulic flexibility for future on-demand operation. This allows the system to function under current constraints while enabling a progressive transition towards more efficient irrigation practices, including localized irrigation systems. More broadly, the results support the concept of irrigation infrastructure as an adaptive system. In climate-exposed and data-scarce regions, resilience depends not only on hydraulic performance, but also on the capacity to accommodate evolving farming practices, technologies, and management strategies over time.

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