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Impacts of climate change on water resources and inter-basin water transfer: The Loukkos basin, Morocco

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Abstract: Climate change poses a major challenge for water-resources management in arid and semi-arid regions, particularly in the Mediterranean basin, where declining precipitation and increasing hydrological variability threaten water security. This study evaluates the impacts of climate change on water availability in the Loukkos River basin (Northern Morocco) and assesses the feasibility of inter-basin water transfer (IBWT) as an adaptation strategy under future climatic conditions. The analysis is based on a comprehensive methodological framework combining statistical analysis of long-term hydrological records (1945–2022), stochastic modelling for projected inflow scenarios, and reservoir system simulation using the River Basin Simulation Model (RIBASIM), incorporating climate scenarios to reflect uncertainty in precipitation patterns. Results revealed a significant hydrological regime shift around 1979, followed by a decline in water availability. Mean annual inflows decreased by approximately 41 and 31% in the Oued El Makhazine–Tfer and Dar Khrofa dams, respectively. Reservoir simulations illustrate the basin's capacity to satisfy local water demands while maintaining inter-basin transfer potential. Under baseline conditions, transferable volumes reach approximately 193 $Mm^3 \cdot yr^{-1}$ increasing to 271 $Mm^3 \cdot yr^{-1}$ by 2050, with the construction of the Tfer dam. Climate change projections indicate that transferable volumes exhibit high interannual variability and may decline to zero in certain years. The findings highlight the critical role of strategic infrastructure development, particularly enhanced storage capacity, in mitigating climate change impacts. Inter-basin water transfer remains viable, but its long-term reliability under climate uncertainty depends on flexible allocation rules and adaptive management.

Keywords: AutoRegressive Integrated Moving Average (ARIMA), climate change, inter-basin water transfer, Loukkos basin, modelling, River Basin Simulation Model (RIBASIM), water management

INTRODUCTION

Water resources are among the first systems directly affected by climate change, especially in arid and semi-arid regions where they are highly vulnerable (Döll and Romero-Lankao, 2017; IPCC, 2021). The Mediterranean basin, known as a climate change hotspot, is facing accelerated challenges including reduced precipitation, increased evapotranspiration, and amplified hydrological variability with warming rates approximately 20% above the global average (Cramer *et al.*, 2018; Lionello and Scarascia, 2018; Zemzami, Habib and Haida, 2026). Over 5 billion people around the world could be affected by water scarcity by 2050. Countries of the Mediterranean basin will be facing the most severe impacts. Morocco exemplifies these regional challenges, which have led to a rapid intensification of water stress over the past few decades. The country's water resources have dropped from 2,560 m^3 per capita per year in 1960 to the absolute water scarcity threshold of 500 m^3 per capita per year (MEMEE, 2016). This raises a fundamental question: how can water-rich northern regions support southern regions facing stressed water conditions in a climate that is becoming more unpredictable?

Observed climatic trends highlight the urgency of this issue. Since the 1980s, winter precipitation in Morocco has decreased by 15–30%, while reference evapotranspiration is projected to increase (from +7 to +19%), and actual evapotranspiration decreases in response to reduced precipitation, ultimately leading to reduced water availability in all North African dam catchments (Tramblay *et al.*, 2017).

In addition, the irregular spatial and temporal distribution of precipitation in Morocco is challenging for optimal water management. The northern parts of the country, such as the Rif, Middle Atlas, Gharb, and Loukkos, receive relatively abundant and more regular rainfall, especially in the winter, whereas large parts of the country experience highly irregular and limited precipitation patterns (Driouech *et al.*, 2020). The Sebou and Loukkos basins in the north hold 51% of the country's water resources, while representing only 7% of the national territory, whereas the remaining basins support about 92% of national water demand (MEE, 2023).

The National Meteorological Directorate predicts precipitation may potentially decrease by 50% by 2070–2099 compared to the 1961–2000 average (ABHL, 2023). Some recent studies show that Morocco could experience 25–40% reduction in its renewable water resources by 2050 if no adaptation measures are undertaken. The northern regions may experience severe changes (Driouech *et al.*, 2020). In response, Morocco's National Water Plan 2020–2050 (MEE, 2023) emphasises large-scale hydraulic infrastructure and adaptive strategies to address growing regional imbalances in water availability.

Inter-basin water transfer (IBWT) is an innovative adaptation strategy for addressing regional disparities in water access, particularly under climate change conditions (Gupta and Zaag van der, 2008; Zhuang, 2016). Experiences from around the world demonstrate both opportunities and challenges related to large-scale water transfer projects. Spain's Tajo-Segura transfer system, operational since 1979, can transfer up to 33 $m^3 \cdot s^{-1}$ of water over 230 km (Morote, Olcina and Rico, 2017). Tunisia's interconnected reservoir system, on the other hand, transfers water over 500 km from the northwest to the east, which helps to balance out regional water shortages (Besbes, Chahed and Hamdane, 2019).

However, transfer projects also present important technical, environmental, and socioeconomic challenges. Infrastructure costs, energy needs, environmental effects, and institutional coordination complexities require careful evaluation (Besbes, Chahed and Hamdane, 2019). Climate change complicates transfer planning because of uncertainties regarding future water availability in donor basins.

This research addresses fundamental questions regarding inter-basin transfer viability under climate change conditions through comprehensive analysis of the Loukkos basin in northern Morocco.

The Loukkos basin is an ideal case study due to its considerable water resource potential, its existing infrastructure, and strategic importance for regional water security. The basin experiences substantial water losses to the sea through spillage, averaging 240 Mm^3 annually (1983–2023). At the same time, southern regions face water-stress conditions (MEE, 2023). The present study aims to assess the impacts of climate change on water availability in the Loukkos basin and to critically evaluate the feasibility and robustness of inter-basin water transfer under multiple climate and demand scenarios. By integrating long-term hydrological analysis, stochastic modelling, and reservoir system simulation, this research provides decision-relevant insights to support sustainable water resources management in both donor and recipient basins under increasing climatic uncertainty.

MATERIALS AND METHODS

STUDY AREA

The Loukkos River basin covers an area of 3,740 km^2 and includes several important agricultural zones in Morocco, contributing to the national economy. Oued Loukkos and Oued El Makhazine are the two main rivers that make up the basin's hydrographic network. These rivers exhibit typical Mediterranean flow patterns, with high flows in the winter and spring and low flows in the summer and autumn. Historical records show inter-annual variability, with maximum annual inflows exceeding 3,000 $Mm^3 \cdot yr^{-1}$ during wet years and minimum flows below 50 $Mm^3 \cdot yr^{-1}$ during drought periods (ABHL, 2023). The region presents a Mediterranean climate with Atlantic influence, which confers substantial water-resource potential. Precipitation is concentrated between October and April, and the annual average ranges between 700–800 mm.

Water resource development in the Loukkos basin has been strategically designed to support agricultural production, flood control, domestic water supply, and energy generation. The Oued El Makhazine dam, with 672.9 Mm^3 storage capacity, provides water for domestic supply, irrigation, and energy production while contributing to flood protection. The Dar Khrofa dam, with a capacity of 480 Mm^3, supplements the system's storage while serving dedicated irrigation areas. A third major infrastructure, the planned Tfer dam, is designed to significantly enhance storage capacity, with a projected volume of approximately 900 Mm^3, thereby increasing water storage capacity and system resilience, particularly under future climatic variability. The agricultural perimeters in the Loukkos basin covers approximately 47,210 ha and represents one of Morocco's important agricultural development areas (MEE, 2023). Figure 1 shows the concept model of the Loukkos water system.

The current water demands reflect the basin's multi-sectoral importance. According to Loukkos Water Basin Agency (Fr.: Agence du Bassin Hydraulique du Loukkos – ABHL), domestic water-supply requirements are 27 $Mm^3 \cdot yr^{-1}$ (2020), serving urban centres including Larache, Ksar El Kebir, and Ouazzane, as well as rural communities. This demand is expected to reach roughly 41 $Mm^3 \cdot yr^{-1}$ by 2050, representing a 52% increase driven by population growth and improved service coverage. The agricultural water demand is more dominant, estimated at approximately 300 $Mm^3 \cdot yr^{-1}$ under the current situation. Future projections suggest significant demand growth, reaching 465 $Mm^3 \cdot yr^{-1}$ by 2050 due to planned irrigation expansions and intensification programmes.

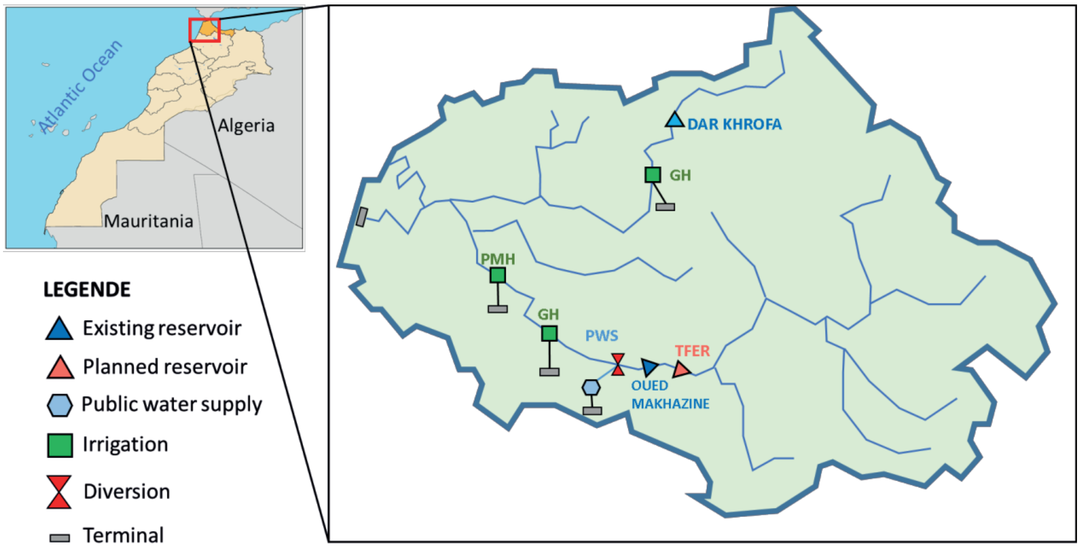


Fig. 1. Conceptual model of the Loukkos water system; PWS = public water supply; GH = large scale irrigation; PMH = small and medium scale irrigation; source: own elaboration

METHODS

This research uses a comprehensive three-phase methodological framework to assess the effects of climate change on water availability and to evaluate the feasibility of inter-basin water-transfer potential under multiple future scenarios. The approach combines statistical analysis of long-term hydrological records, stochastic modelling of future inflows, and reservoir system simulation. Stage 1 involves the analysis of historical hydrological data using multiple statistical tests to identify changes in the hydrological regime; stage 2 applies stochastic modelling based on AutoRegressive Integrated Moving Average (ARIMA) models to generate future inflow scenarios, incorporating climate change adjustments ranging from a 30% decrease to a 10% increase in precipitation; stage 3 integrates these scenarios into RIBASIM simulations to evaluate system performance under different infrastructure configurations and demand conditions. This integrated approach allows a robust assessment of inter-basin water transfer feasibility under climate uncertainty (Fig. 2).

Statistical analysis of hydrological series and trend detection

The assessment of climate change impacts is based on historical inflow data covering the period from September 1945 to August 2022, corresponding to 78 hydrological years. The data were obtained from the Loukkos Water Basin Agency (ABHL) and the General Directorate of Hydraulics (DGH–DRPE). Monthly inflow series were aggregated into annual values for trend analysis, while the monthly data were retained for the analysis of seasonal variability. Three statistical tests were applied to detect potential structural breaks in the hydrological time series: the Pettitt test (Pettitt, 1979), the Buishand test (Buishand, 1982), and the standard normal homogeneity test (Alexandersson, 1986). Trend analysis was conducted using the Mann–Kendall test (Mann, 1945; Kendall, 1975) together with Sen's slope estimator (Sen, 1968). For autocorrelated series, the modified Mann–Kendall test incorporating the correction proposed by Hamed and Rao (1998) was applied to ensure reliable significance testing. All statistical analyses were performed at a significance level of 5%, with 95% confidence intervals.

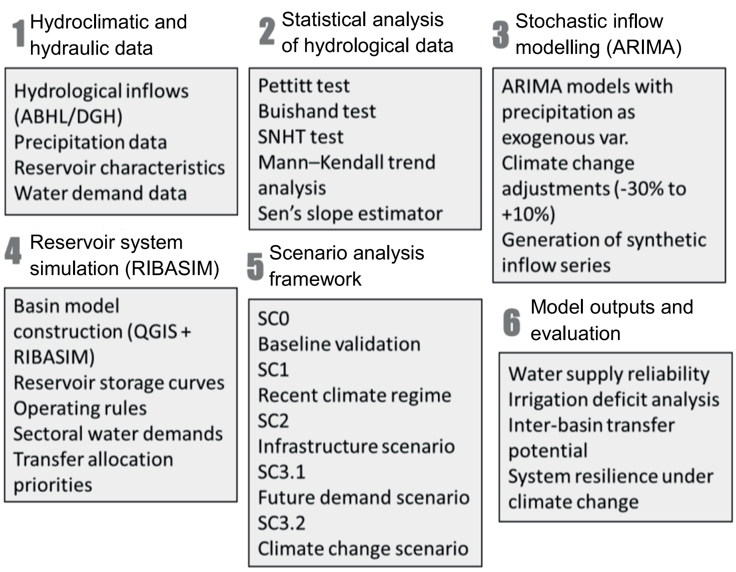


Fig. 2. Methodological framework for assessing climate change impacts and IBWT potential; ABHL = Loukkos Water Basin Agency, DGH = General Directorate of Hydraulics, SNHT = standard normal homogeneity test, ARIMA = AutoRegressive Integrated Moving Average, RIBASIM = River Basin Simulation Model, SC = scenario; source: own elaboration

Stochastic inflow modelling and climate change integration

Future inflow series were generated using ARIMA models. To improve model realism and predictive capability, precipitation was incorporated as an exogenous variable. Climate change effects were integrated by adjusting the generated time series according to regional projections derived from global and regional climate models. The Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2021) indicates that North Africa, including Morocco, is very likely to experience a warmer and drier climate during the 21st century. Under intermediate and high-emission scenarios (SSP2-4.5 and SSP5-8.5), average annual precipitation is projected to decline by approximately 10 to 50% by the mid-to-late 21st century (IPCC, 2021). These projections are consistent with regional analyses derived from CMIP6 model ensembles (Lee *et al.*, 2021; Douville *et al.*, 2022). At the national scale, Morocco's National Water Plan adopts a set of precipitation reduction scenarios (−10%, −15%, −20%, −25% and −30%) for water resources planning and hydraulic infrastructure design (ABHL, 2023; MEE, 2023). However, some global climate models (GCMs) indicate the possibility of localised or seasonal increases in precipitation over limited regions and periods (Giorgi and Lionello, 2008; Hoerling *et al.*, 2012; Spinoni *et al.*, 2018).

To account for this uncertainty, a stochastic ARIMA model was implemented to generate inflows series representing both decreasing and increasing precipitation conditions within a plausible range of –30% to +10% relative to the historical baseline. The 10 projected inflow series constitute equiprobable stochastic ensemble members generated from the same calibrated ARIMA framework. They share the same model structure, calibrated parameters and climate change assumptions, and differ only through the stochastic sampling of the model residuals used to reproduce the variability of future inflow sequences. Consequently, the ensemble does not represent 10 distinct climate scenarios, but 10 plausible realisations of future inflow variability under the precipitation change assumptions adopted in Morocco's National Water Plan (MEE, 2023). This approach allows the projected inflow regime to reflect both the imposed climate change signal and the intrinsic interannual variability of basin runoff. The upper bound of +10% was selected to represent the upper envelope of precipitation increases suggested by CMIP6 projections for the Western Mediterranean. Most multi-model ensemble assessments indicate a dominant drying trend across the Mediterranean basin, particularly under high-emission scenarios such as SSP5-8.5, characterised by declining mean annual precipitation and increased drought frequency (Tarin-Carrasco, 2024). For northern Morocco, several regional studies suggest that rainfall reductions could approach 30% by the end of the century under high-emission scenarios. Although a limited number of GCMs simulate localised or seasonal increases in precipitation, these outcomes remain relatively rare within the ensemble and are associated with substantial uncertainty (Giorgi and Lionello, 2008; Lionello and Scarascia, 2018). Consequently, the +10% upper bound was retained as a conservative representation of the plausible range of precipitation increases. This assumption is also consistent with the precautionary approach adopted in Morocco's National Water Plan (MEE, 2023) and the Integrated water resources management plan for Loukkos, Tangier and Mediterranean coastal basins (ABHL, 2023), both of which emphasise planning strategies based primarily on the central and dry ranges of projected climate trajectories.

Reservoir system simulation

The Loukkos basin reservoir system was simulated using the RIBASIM model developed by Deltares, which enables integrated representation of the basin's hydroclimatic data and water system infrastructure (reservoirs, water demands, operation rules, etc.) (Krogt van der, 2011). The conceptual scheme of the Loukkos basin was constructed from spatial datasets processed in QGIS (version 3.34.5 LTR). The main hydrological and infrastructural components were systematically integrated into the model (Fig. 3),

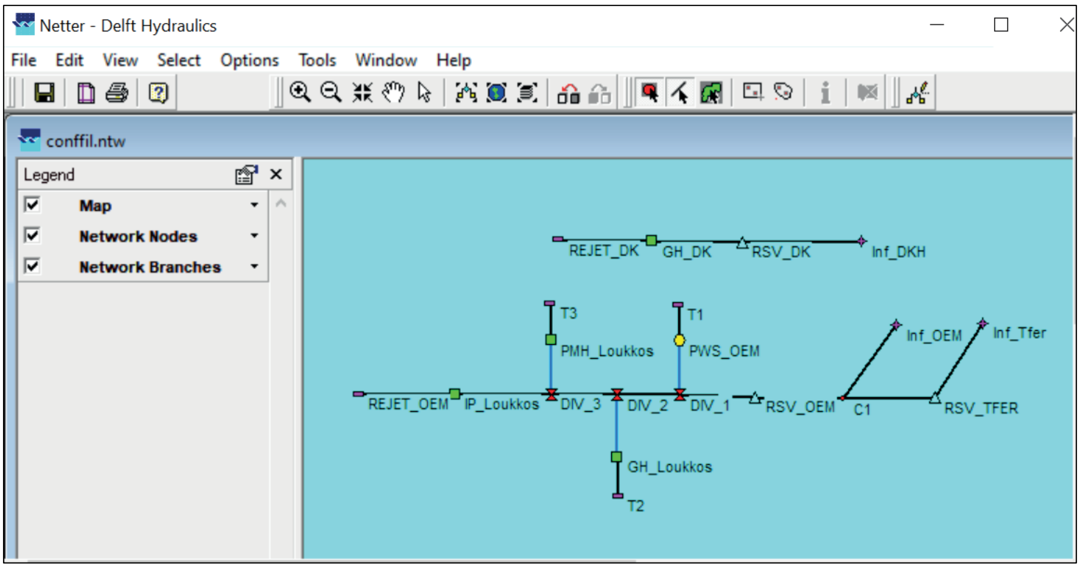


Fig. 3. RIBASIM scheme illustrating the main components of the Loukkos basin system; REJET_DK = spillway of Dar Khrofa dam (DK), GH_DK = large scale irrigation of DK, RSV_DK = Dar Khrofa dam, Inf_DKH = Dar Khrofa inflow, REJET_OEM = spillway of Oued El Makhazine dam (OEM), IP = private irrigation, DIV = diversion, RSV_OEM = Oued El Makhazine dam, PHM = small and medium scale irrigation, PWS = public water supply, GH = large scale irrigation, T1, T2, T3 = terminals, C1 = confluence, Inf_OEM = OEM inflow, Inf_Tfer = Tfer inflow, RSV_TFER = Tfer dam; source: own elaboration

including reservoir height-surface-volume relationships, operational storage levels, design discharge rates, and evaporation losses.

Model simulations were performed to evaluate water availability and system performance under current (2022) and future (2050) conditions. Water supply reliability thresholds were defined according to the flexibility of different water uses (Tab. 1).

Table 1. Supply reliability criteria by sector

Sector	Deficit threshold (%)	Maximum annual deficit (%)	Failure frequency (year/decade)	Priority level
PWS	0	0	0	1
GH	15	50	2	2
PMH and IP	15	50	2	3
IBWT	variable	variable	variable	4

Explanations: PWS = public water supply; GH = large scale irrigation; PMH = small and medium scale irrigation; IP = private irrigation.
Source: own study.

Scenario design and comparative framework

The modelling framework comprises 10 scenarios (SC0–SC3.2) designed to evaluate reservoir system performance under present conditions, recent hydroclimatic variability, future demand and infrastructure development, and climate change uncertainty.

SC0 – Baseline scenario (model validation). Used to validate the model under present-day conditions using observed historical inflows, current water demands (2022), existing reservoirs with sedimentation losses up to 2022, and standard operating rules with no drought restrictions unless storage falls below 40% of total capacity.

SC1 – Assessment under recent climate variability. System performance is evaluated using the post-breakpoint hydrological series (1979–2022; 44 years) while maintaining current demand levels (2022), existing infrastructure with sedimentation losses up to 2022, and standard operating rules with drought restrictions triggered when storage falls below 40% of reservoir capacity.

SC2 – Infrastructure benefit assessment. This scenario quantifies the benefits of planned infrastructure under an optimistic climate scenario using the complete historical inflow record (1945–2022; 78 years), combined with projected water demands for 2050, planned infrastructure including sediment accumulation up to 2050, and optimised operating policies incorporating water transfer coordination and drought alert thresholds.

SC3.1 – Future scenario without additional climate change evaluation. Evaluates the effects of increasing demand and infrastructure development while maintaining historical hydrological conditions. It uses the post-breakpoint inflow series (1979–2022), projected water demands for 2050, planned infrastructure with sediment accumulation up to 2050, and optimised operating rules including inter-basin water transfer coordination and a 40% drought alert threshold.

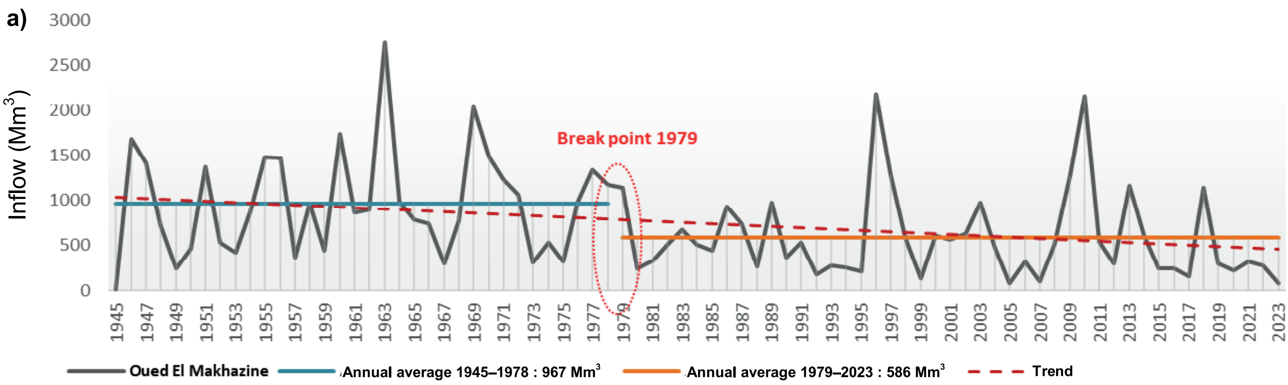
SC3.2 – Future scenario incorporating climate change. Climate uncertainty is represented through stochastic inflow sequences generated with ARIMA models for 2021–2050 (30 years), producing 10 realisations to capture hydrological variability. Simulations include projected water demands for 2050, planned infrastructure with sediment accumulation up to 2050, and optimised operating policies integrating water transfer coordination and drought management thresholds.

Results from SC0, SC1, SC2, SC3.1, and SC3.2 were compared to evaluate system robustness and quantify the influence of climate change on future water availability and inter-basin transfer capacity.

RESULTS AND DISCUSSION

STATISTICAL ANALYSIS AND CLIMATE CHANGE IMPACTS ON WATER RESOURCES

The statistical analysis reveals a clear shift in the hydrological regime of the Loukkos basin around 1979, marking the onset of a sustained decline in water availability. This structural break is consistently identified by all applied change-point detection tests, confirming a significant alteration in the basin's hydrological behaviour. Before 1979, mean annual inflows at the Oued El Makhazine–Tfer system averaged 966.71 $Mm^3 \cdot yr^{-1}$, decreasing to 567.84 $Mm^3 \cdot yr^{-1}$ in the post-1979 period, which corresponds to a reduction of approximately 41%. Similarly, the Dar Khrofa system experienced a decline from 232.08 $Mm^3 \cdot yr^{-1}$ to 158.73 $Mm^3 \cdot yr^{-1}$, representing a 31% decrease (Fig. 4 and Tab. 2). These results indicate a substantial and persistent reduction in surface water availability across the basin.



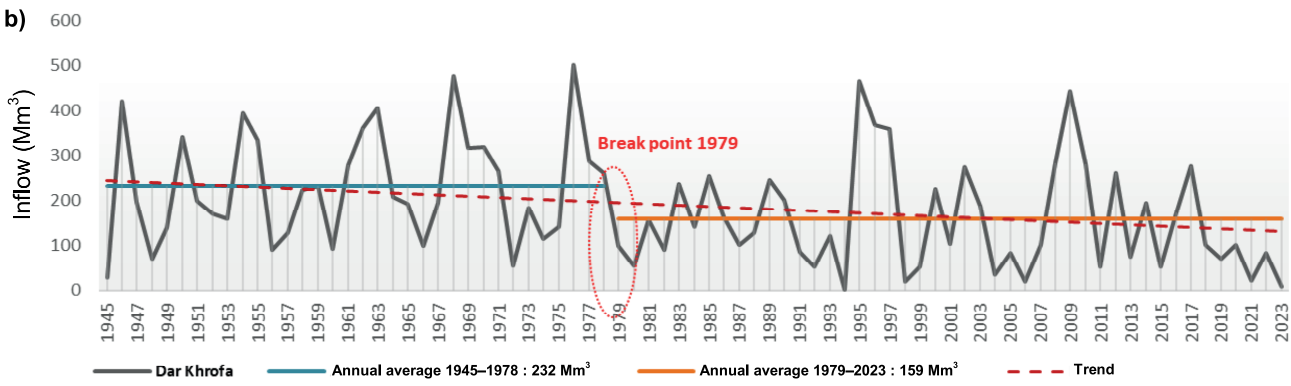


Fig. 4. Time series inflow characterisation (1945–2022): a) Oued El Makhazine dam, b) Dar Khrofa dam; source: own study

Table 2. Statistical analysis results

System	Pre-1979 average (Mm^3)	Post-1979 average (Mm^3)	Trends (%)	Mann–Kendall *p*-value	Sen's slope ($Mm^3 \cdot yr^{-1}$)
Oued El Makhazine-Tfer	966.71	567.84	–41.2	0.0003	–7.68
Dar Khrofa	232.08	158.73	–31.6	0.0020	–1.45

Source: own study.

The Mann–Kendall trend analysis substantiates highly significant declining trends ($p < 0.01$) throughout the entire observation period. Sen's slope estimates reveal annual decreases of 7.68 $Mm^3 \cdot yr^{-1}$ for the Oued El Makhazine and 1.45 $Mm^3 \cdot yr^{-1}$ for Dar Khrofa. These results are consistent with broader Mediterranean climate trends, which have shown a 10–30% drop in precipitation since the 1970s (Hoerling *et al.*, 2012). The convergence of statistical evidence underscores the strong influence of climate change on long-term water resource availability in the Loukkos basin.

FUTURE PROJECTIONS AND INFLOW GENERATION

Following detection of the 1979 break point, ARIMA models were used to generate future hydrological scenarios based on the 44 years after 1979, which are representative of the current climatic regime. Model development employed automatic selection with precipitation as an exogenous variable. The final models exhibited strong diagnostic performance, including satisfactory residual whiteness ($p > 0.20$) and preservation of observed seasonal patterns (Tab. 3). To further assess model performance on the test set, root mean square error (*RMSE*) and Nash–Sutcliffe efficiency (*NSE*) were computed. The results show satisfactory to good performance for both stations (Tab. 3). The moderate *NSE* value at Oued El Makhazine–Tfer is consistent with the known tendency of ARIMA models to smooth extreme peaks. These results, combined with the Ljung-Box residual whiteness test, confirm the overall adequacy of the selected models for generating future inflow scenarios.

The generated inflow series for the 2024–2054 period reflect a wide range of possible future hydrological conditions. Mean annual inflows vary from increases of up to 27% to decreases of as much as 57% relative to the reference period, indicating substantial uncertainty in future water availability (Tab. 4). While overall variability decreases by approximately 26%, the generated series exhibit pronounced interannual fluctuations, with maximum annual flows ranging from –65% to +58% compared to observed values (Tab. 4).

Seasonal patterns remain largely preserved, with winter and spring peak flows maintained across scenarios. However, the increased frequency of extreme conditions characterised by short-duration floods and prolonged droughts highlights the growing instability of the hydrological regime. These results emphasise that climate change is likely to reduce average water availability while simultaneously increasing uncertainty and the occurrence of extreme events.

Table 3. AutoRegressive Integrated Moving Average (ARIMA) model performance

System	Selected model	AIC	Ljung-Box *p*-value	*RMSE* (Mm^3)	*NSE*
Oued El Makhazine-Tfer	ARIMA(1,0,2)(2,0,1)[12]	3968.86	0.22	70.31	9.79
Dar Khrofa	ARIMA(0,0,1)(0,0,2)[12]	2913.38	0.29	0.565	0.803

Explanations: AIC = Akaike information criterion, p = significance, *RMSE* = root mean square error, *NSE* = Nash–Sutcliffe efficiency.
Source: own study.

Table 4. Generated series characteristics (2024–2054) compared to observed (1979–2022)

Impact parameter	Loukkos basin inflows	Implication
Mean flow change	from +27% to −57%	reduced water availability
Variability change	−26.1%	more predictable but lower flows
Maximum flow change	from −65% to +58%	large range of interannual variability; extreme events are more frequent: flash floods and prolonged droughts
Seasonal pattern	preserved	maintained winter-spring peaks

Source: own study.

RESERVOIR BASIN SIMULATIONS

Reservoir system simulations were conducted using RIBASIM to evaluate water-system performance in the Loukkos basin under current (2022) and future (2050) conditions across 10 different scenarios, incorporating different hydrological inputs, infrastructure configurations and demand projections. The simulations provide insights into system resilience, allocation priorities, and inter-basin transfer potential under climate uncertainty.

Under the reference scenario (SC0), despite the observed decline in inflows, the Loukkos basin remains capable of meeting local water demands. Only 34% of available inflows are allocated to domestic and agricultural uses, while an average of 562.7 $Mm^3 \cdot yr^{-1}$ is lost to the sea through spillage. This highlights the basin's substantial untapped transfer potential under current conditions.

Future scenarios account for both water demand growth and infrastructure development. The planned Tfer dam construction will increase the total storage capacity by 78%, significantly enhancing drought resilience and reducing spillage losses. Under moderate climate scenarios for 2050 (SC2, SC3.1), the system satisfies 100% of domestic water demand and 80% of irrigation demand, even with a 55% increase in total water requirements. Transferable volumes reach 271 $Mm^3 \cdot yr^{-1}$ under baseline conditions (SC2) and 156 $Mm^3 \cdot yr^{-1}$ under moderate climate stress (SC3.1).

In contrast, the pessimistic climate change scenario (SC3.2) reveals substantial interannual variability in inter-basin transfer potential, ranging from 0 to over 300 $Mm^3 \cdot yr^{-1}$, with a mean value of 89 $Mm^3 \cdot yr^{-1}$. In several simulated years, transfer capacity drops to zero, reflecting the combined effects of reduced inflows and increased demand. Nevertheless, all simulations respect predefined sectoral priority and reliability criteria (Tab. 1), ensuring full reliability for domestic supply (Tab. 5). The simulated scenarios are those defined in the section Scenario design and comparative framework.

Table 5. Reservoir simulation results

Performance indicator	SC0	SC1	SC2	SC3.1	SC3.2
Scenario configuration					
Time horizon	2020	2020	2050	2050	2050
Hydrological series	1945–2022	1979–2022	1945–2022	1979–2022	10 generated inflow series
Infrastructure	existing	existing	+ Tfer dam	+ Tfer dam	+ Tfer dam
Climate impact level	reference	moderate	baseline	moderate	moderate severe
Water resource availability					
Average annual inflows ($Mm^3 \cdot yr^{-1}$)	950.2	726.7	950.2	726.7	from 322.8 to 996.7
Inflow reduction / reference situation (%)	–	−23.5	–	−23.5	from −57 to +27
System storage capacity (Mm^3)	1,153	1,153	2,053	2,053	2,053
Domestic water supply performance					
Annual demand (Mm^3)	27	27	41	41	41
Annual supply (Mm^3)	27	27	41	41	41
Supply reliability (%)	100	100	100	100	100
Deficit frequency (%)	0	0	0	0	0
Agricultural irrigation performance					
Total annual demand (Mm^3)	300.0	300.0	465.0	465.0	465.0
Total annual supply (Mm^3)	299.8	294.3	463.8	462.7	462.5

cont. Tab. 5

Performance indicator	SC0	SC1	SC2	SC3.1	SC3.2
Supply reliability (%)	100	98	80	80	80
Maximum annual deficit (%)	30	33	50	50	50
Water balance components					
Total system supplies (Mm^3)	326.8	321.3	504.8	503.7	503.5
Spillage to sea (Mm^3)	562.7	345.5	121.1	66.8	from 43 to 394
Spillage reduction / SC0 (%)	–	–38.6	–78.3	–88	from –30 to –92
Evaporation losses (Mm^3)	65.1	62.4	71.0	63.2	47.6
Inter-basin transfer potential					
Annual transfer volume (Mm^3)	193.4	134.9	271.3	156.4	from 0 to 301.6 mean: 89
Impact of capacity storage enhancement on IBWT / SC0/SC1 (%)	–	–	+40 (SC0)	+16 (SC1)	–
Impact of climate change on IBWT / SC0/ SC2 (%)	–	–30 (SC0)	–	–42 (SC2)	from –100 to +11 (SC2)
Transfer reliability (%)	83	55	48	76	73
Minimum annual transfer (Mm^3)	6.8	0	0	0	0

Explanations: SC = scenario, IBWT = inter-basin water transfer.
Source: own study.

The inflow time series generated using the ARIMA model were simulated to estimate projected annual water transfer volumes under climate uncertainty across stochastic scenarios from model 1 to model 10 (Fig. 5). The findings indicate significant interannual and inter-model variability in transfer potential, with annual volumes varying from zero to over 600 Mm^3 across different climate scenarios. The wide envelope of projections (0–650 Mm^3) highlights the significant uncertainty associated with long-term water resource planning under climate change conditions.

It is important to underscore that meeting the water requirements of the donor basin, especially for drinking water

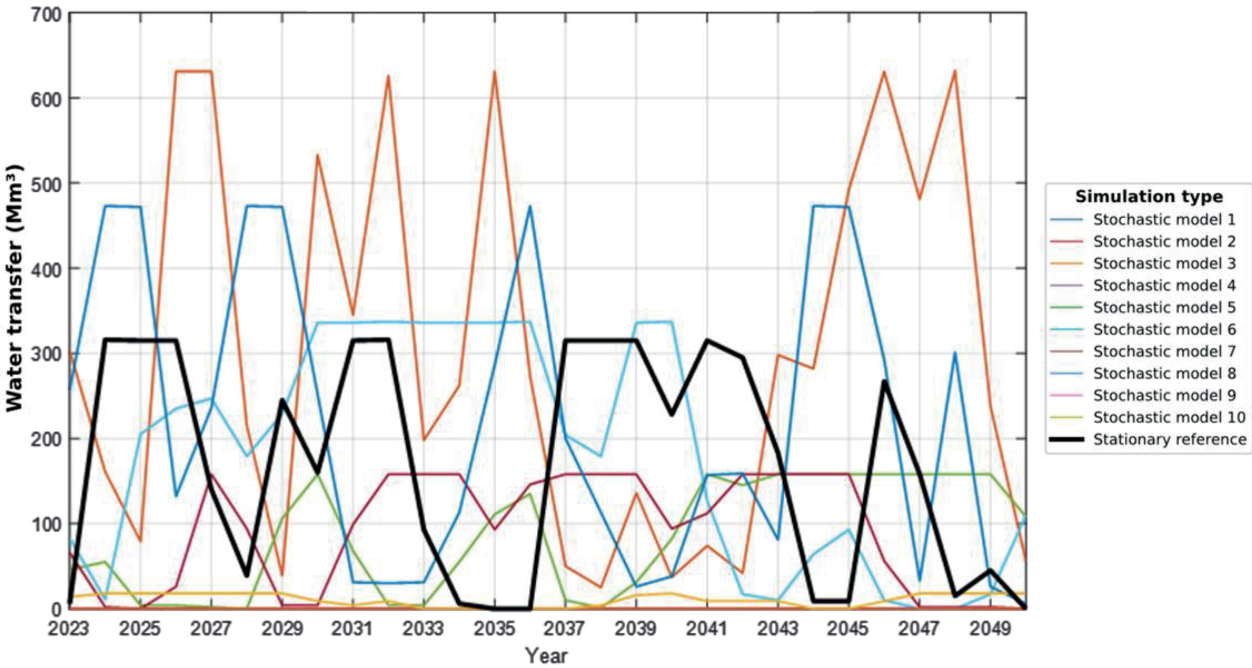


Fig. 5. Projected annual water transfer volumes (2023–2050) for the 10 equiprobable stochastic inflow realisations generated by the ARIMA model under scenario SC3.2; the 10 realisations share the same climate change assumptions (precipitation adjustment envelope from –30% to +10% relative to the 1979–2022 baseline) and differ only through random sampling of the model innovations; they are intended to be interpreted collectively as an ensemble representing hydrological uncertainty rather than individual climate scenarios; the bold line indicates the stationary reference scenario; source: own study

supply and irrigation, remains an overriding priority that cannot be compromised by transfer objectives. In the modelling framework adopted in this study, inter-basin transfers are considered only after local demands have been fully satisfied. This reflects a fundamental principle in water resources management: the redistribution of water between basins should never occur at the expense of the security of the originating basin. Such an approach is particularly relevant under conditions of growing hydroclimatic uncertainty, where the risk of shifting water shortages from one region to another must be carefully avoided. Accordingly, the transfer potential identified for the Loukkos basin should be understood not as a fixed allocation, but as a conditional surplus that may be mobilised only when local water needs are fully secured. Ensuring that this principle remains embedded in planning and operational rules is essential for maintaining both the sustainability of the donor basin and the long-term credibility of inter-basin transfer strategies.

Three critical patterns emerge from this analysis. First, a strong inter-model divergence is observed between optimistic and pessimistic climate scenarios. Under favourable hydroclimatic conditions, transfer volumes can exceed 300 Mm^3 in wet years, indicating a substantial surplus capacity in the donor basin. In contrast, pessimistic scenarios are characterised by markedly reduced inflows, leading to limited or absent transfer potential during dry years. Second, the frequency of zero-transfer years increases significantly under severe climate conditions, occurring in approximately 20–30% of the simulated years. These zero-transfer events are associated with prolonged drought sequences, during which available water resources are fully allocated to priority local uses, leaving no surplus for inter-basin transfer. This highlights the vulnerability of fixed-volume transfer commitments in the context of increasing hydrological extremes. Third, projected transfer volumes exhibit substantially higher inter-annual variability and volatility (0–650 $Mm^3 \cdot yr^{-1}$) compared to the stationary reference scenario (150–350 $Mm^3 \cdot yr^{-1}$), in which transfer volumes remain within a narrower and more predictable range. Climate change not only reduces mean transfer potential but also amplifies uncertainty, increasing the likelihood of extreme low-transfer years.

The broad range of projected transfer volumes (0–650 Mm^3) highlights the significant uncertainty associated with long-term water resource planning under climate change conditions. This high level of variability carries several important implications. First, fixed-volume transfer commitments are inherently risky, as some years may experience zero transferable flows. Second, adaptive management frameworks incorporating flexible and dynamic allocation rules are essential to respond to fluctuating hydrological conditions. Third, recipient basins cannot depend exclusively on inter-basin transfers and must develop complementary and diversified water supply sources. In addition, the stationary reference scenario shows a gradual decline in transferable volumes, from approximately 300 Mm^3 to about 50 Mm^3, reflecting the combined effects of increasing water demand and baseline climate trends in the absence of additional climatic variability.

IMPLICATIONS OF TRANSFER UNCERTAINTY FOR ADAPTIVE WATER MANAGEMENT

The large spread in simulated inter-basin transfer volumes (0–300 $Mm^3 \cdot yr^{-1}$) highlights the profound uncertainty associated with long-term hydroclimatic projections and its implications for water infrastructure planning. Such variability suggests that future water availability in the donor basin cannot be adequately represented by a single forecast. Instead, planning should explicitly accommodate uncertainty by adopting robust and adaptive decision-making approaches (Ranger *et al.*, 2010; Walker *et al.*, 2013). These frameworks prioritise strategies that remain effective across a wide range of possible future conditions rather than those optimised for a single projected scenario. In practical terms, this means favouring phased infrastructure development, flexible operating rules, and periodic reassessment of transfer capacities as new climatic and hydrological information becomes available. For large hydraulic systems such as inter-basin transfers, this approach helps limit the risk of maladaptation, particularly the construction of oversized infrastructure that could become underutilised under severe drying scenarios, while maintaining the possibility of expanding transfer capacity if future water availability proves more favourable. Integrating such adaptive planning principles into national water management strategies would therefore strengthen the resilience of inter-basin transfer schemes under conditions of deep climate uncertainty.

CONCLUSIONS

This study provides a comprehensive assessment of climate change impacts on water availability and inter-basin water transfer (IBWT) potential in the Loukkos basin, offering insights for water management in Mediterranean regions facing increasing hydroclimatic uncertainty. Three main findings emerge.

First, the 1979 hydrological regime shift represents a persistent structural change in basin hydrology, with mean annual inflows declining by 41% at Oued El Makhazine–Tfer and 31% at Dar Khrofa, confirming a long-term reduction in water availability.

Second, despite this decline, the Loukkos basin retains a conditional capacity to support IBWT while meeting local demands. Under current conditions, transferable volumes reach approximately 193 $Mm^3 \cdot yr^{-1}$, but simulations indicate that this potential could decrease to near zero under severe drying scenarios, highlighting the deep uncertainty associated with future hydroclimatic conditions.

Third, the planned Tfer dam significantly strengthens system resilience by expanding storage capacity and reducing spill losses, thereby preserving both local supply reliability and transfer potential under moderate climate scenarios.

These findings carry several operational implications for IBWT planning in Morocco. Infrastructure development remains a key adaptation measure, particularly the completion of the Tfer dam by 2030, which increases basin storage capacity by nearly 80% and substantially improves drought buffering capacity. However, infrastructure alone cannot guarantee long-term transfer reliability under climate uncertainty.

To ensure sustainable implementation of IBWT, governance arrangements must incorporate explicit operational rules. In particular:

– annual transfer allocations should be reviewed each hydrological year using pre-season inflow forecasts (October–November). Transfer volumes should be authorised only when projected end-of-season reservoir storage in the donor basin exceeds predefined security thresholds for domestic supply and irrigation.

– compensation mechanisms for the Loukkos donor basin should be institutionalised and linked to co-investment in local water efficiency programmes, particularly irrigation modernisation. A portion of the economic benefits generated in recipient basins should be reinvested in water-saving technologies within the donor basin to partially offset transferred volumes.
– minimum environmental flow requirements in the Loukkos River should be legally defined prior to transfer authorisation, ensuring that ecological flow thresholds downstream of the Oued El Makhazine system are maintained even during dry years.

A fundamental principle underpinning any transfer scheme is the absolute priority of local water security. In all simulations, public water supply was assigned a zero-deficit constraint, ensuring that transfers occur only when water availability exceeds local needs across all demand horizons and climate scenarios, in accordance with Moroccan water law.

More broadly, the large uncertainty in projected transfer volumes (0–300 $Mm^3 \cdot yr^{-1}$) highlights the limits of static planning approaches. Instead, IBWT strategies should be embedded within adaptive and robust decision-making frameworks, where infrastructure development, operating rules, and transfer volumes are periodically reassessed as new hydrological and climatic information becomes available.

Finally, this study contributes to the broader debate on large-scale inter-basin transfers, which remain associated with important socio-ecological challenges, including donor basin vulnerability, regional equity concerns, and infrastructure lock-in risks. By explicitly integrating priority allocation rules, adaptive governance mechanisms, and conditional transfer criteria, the framework proposed here offers a replicable approach for designing climate-resilient IBWT systems in water-scarce Mediterranean regions.

ABBREVIATIONS

ABHL = Loukkos River Basin Agency
ARIMA = AutoRegressive Integrated Moving Average
DGH = General Directorate of Hydraulics
DRPE = Directorate of Water Research and Planning
GCM = global climate model
GH = large scale irrigation
IBWT = inter-basin water transfer
IP = private irrigation
PMH = small and medium scale irrigation
PWS = public water supply
RIBASIM = River Basin Simulation Model
SNHT = standard normal homogeneity test
SSP = shared socioeconomic pathway

INSTITUTIONAL REVIEW BOARD STATEMENT

Informed consent was obtained from all individual participants included in the study.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

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