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Application of the SWAT Model to the Hydrological Modeling of the Nfifikh Watershed (Morocco): Study of the Dynamics of Surface and Groundwaters and Their Relationship with Soil Properties

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Abstract: Water resources in semi-arid regions are increasingly affected by climate variability, making hydrological modeling essential for assessing water availability and supporting watershed management. In this study, the Soil and Water Assessment Tool (SWAT) was applied to simulate the hydrological behavior of the Nfifikh watershed in Morocco using climate data from local meteorological stations complemented with gridded datasets, a 30 m digital elevation model, soil maps, and land-use data derived from satellite imagery. Observed streamflow at the watershed outlet was used for model calibration and validation following standard SWAT procedures. Model performance was evaluated using the Nash–Sutcliffe efficiency (NSE), coefficient of determination (R^2), percent bias (PBIAS), and the RMSE–standard deviation ratio (RSR), showing very good agreement between simulated and observed daily flows. Results indicate that about two thirds of annual precipitation are lost through evapotranspiration, while streamflow is generated through surface runoff, lateral flow, and shallow subsurface contributions. Spatial patterns highlight higher runoff and sediment production in steep upland areas and greater flow regulation downstream. The study provides useful insights for water resource management in semi-arid watersheds.

1 INTRODUCTION

Semi-arid watersheds are characterized by strong hydro-climatic variability and irregular rainfall regimes, which exert a dominant control on runoff generation, soil water balance, and sediment transport processes

(Abbaspour et al., 2018; Samimi et al., 2020). Short, high-intensity rainfall events often generate rapid surface runoff and enhanced erosion, while prolonged dry periods limit recharge and increase water stress, posing significant challenges for sustainable water and soil management in data-scarce and heterogeneous environments (Dutta & Sen, 2018; Eini et al., 2023).

Physically based hydrological models have become essential tools for analyzing watershed-scale hydrological processes under complex climatic and physiographic conditions (Gassman et al., 2014). When coupled with Geographic Information Systems (GIS), these models enable the integration of topography, land use, soil properties, and climate data to simulate spatially distributed hydrological responses over long time periods and across heterogeneous landscapes (Arnold et al., 2012). Among the available modeling frameworks, the Soil and Water Assessment Tool (SWAT) has been extensively applied to investigate surface runoff generation, soil water dynamics, subsurface flow response, and sediment transport under a wide range of environmental and climatic settings (Guzman et al., 2015).

Numerous studies have demonstrated that SWAT is capable of reproducing key components of the hydrological cycle when appropriate calibration and validation strategies are applied. In particular, systematic calibration approaches and multi-criteria performance evaluation have been shown to significantly improve model robustness and reliability, even in data-scarce watersheds (Abbaspour et al., 2018; Moriasi et al., 2007). Previous applications have also highlighted the importance of explicitly representing spatial heterogeneity through the definition of Hydrological Response Units (HRUs), which enable the model to account for variations in land use, soil properties, and slope gradients within a watershed (Arnold et al., 1998; Almeida et al., 2018).

Despite its widespread use, SWAT applications remain unevenly distributed across different geographic contexts (Bressiani et al., 2015). While numerous studies have focused on well-instrumented watersheds, relatively few applications have addressed semi-arid basins in North African settings, where hydrological responses are strongly influenced by heterogeneous soils, variable topography, and increasing anthropogenic pressure (Samimi et al., 2020). This imbalance limits the availability of region-specific modeling experience and constrains the transferability of parameterization and calibration schemes developed in more humid or data-rich environments to semi-arid and data-scarce regions (Abbaspour et al., 2018; Sabale et al., 2024).

Addressing this gap requires case studies that explicitly analyze the spatial interactions between surface runoff generation, soil water storage, groundwater contribution, and sediment dynamics, while accounting for land-use patterns and topographic controls at appropriate spatial scales. Previous SWAT-based studies have shown that small to medium-sized watersheds are particularly suitable for such analyses, as they exhibit rapid hydrological responses to climatic variability and land-surface conditions (Meaurio et al., 2015; Sabale et al., 2024).

In this context, the present study applies the SWAT model to the Nfifikh watershed in northwestern Morocco to analyze surface runoff, baseflow contribution, and sediment dynamics in a semi-arid environment characterized by heterogeneous soils and variable topography . Using a calibrated and validated modeling framework, the study provides spatially explicit insights into hydrological functioning at the HRU scale and contributes to the application of SWAT in data-scarce Mediterranean and North African watersheds (Abbaspour et al., 2018; Samimi et al., 2020).

2.MATERIALS AND METHODS

2.1 Study area

The study was conducted in the Nfifikh watershed, (Figure 1) a semi-arid basin located in northwestern Morocco, extending across the regions of Mohammedia, Benslimane, Beni Yakhlef, and Khouribga. The watershed is characterized by pronounced heterogeneity in topography, land use, and soil properties, combined with strong seasonal and interannual rainfall variability typical of Mediterranean semi-arid climates. These characteristics make the basin well suited for hydrological modeling of surface runoff, groundwater contribution, and water balance dynamics under data-limited conditions (Almeida et al., 2018).

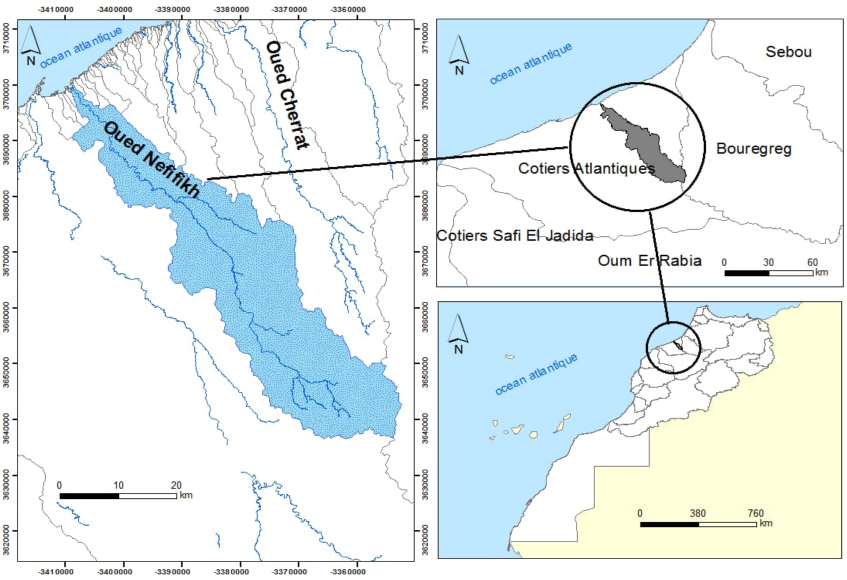

Fig. 1: Study area: Nfifikh watershed.

2.2 Data sources and preprocessing

Hydrological model setup was supported by multiple spatial and climatic datasets obtained from national and international sources. A 30-m resolution Digital Elevation Model (DEM) was used to delineate the watershed, extract the drainage network, and derive slope and flow direction, following standard ArcSWAT procedures (Neitsch et al., 2011; Abbaspour et al., 2018).

Meteorological inputs, including daily precipitation, minimum and maximum temperature, relative humidity, wind speed, and solar radiation, were obtained from stations located in Mohammedia, Beni Yakhlef, Benslimane, and Khouribga. To address data gaps, station records were complemented with CHIRPS precipitation and CHIRTS temperature datasets, a common approach in semi-arid regions (Almeida et al., 2018).

Soil data were derived from national soil maps and supplemented with soil physical properties (texture, permeability, and available water capacity) obtained from the FAO database, which are commonly used for SWAT soil parameterization in data-scarce regions (Neitsch et al., 2005; Arnold et al., 2012). Land-use and land-cover (LULC) maps were generated from Landsat-8 imagery using supervised classification in ArcGIS 10.1 and used as a key input for hydrological response unit definition, following standard GIS-based SWAT applications (Bressiani et al., 2015; Abbaspour et al., 2018).

The land-use and land-cover (LULC) map derived from Landsat-8 imagery was evaluated using independent reference data and a confusion matrix approach. The classification achieved an overall accuracy above 85% with a Kappa coefficient greater than 0.80, which is consistent with accuracy levels reported in comparable SWAT-based applications in semi-arid environments and is considered adequate for HRU parameterization (Bressiani et al., 2015; Abbaspour et al., 2018). Remaining uncertainties are mainly associated with transitional agricultural and peri-urban areas, a common limitation in medium-resolution satellite-based land-use classifications.

2.3 Hydrological model description and setup

Hydrological simulations were performed using the Soil and Water Assessment Tool (SWAT) implemented through the ArcSWAT interface in the ArcGIS environment. SWAT is a semi-distributed, process-based, continuous-time model operating at a daily time step and designed to simulate the effects of land use, soil characteristics, and climate variability on watershed-scale hydrological processes (Arnold et al., 1998).

After watershed delineation, the basin outlet was defined and the watershed was subdivided into sub-basins. Hydrological Response Units (HRUs) were generated by intersecting land-use classes, soil types, and slope categories to represent landscape heterogeneity and its influence on hydrological processes (Almeida et al., 2018).

2.4 Model calibration and validation

Model calibration and validation were conducted following widely adopted SWAT-CUP application protocols to ensure transparency, reproducibility, and physical consistency of the simulated hydrological processes. In order to reduce the influence of unknown initial conditions related to soil moisture and shallow aquifer storage, a warm-up period of two years was applied prior to calibration, as commonly recommended in SWAT-based hydrological studies (Abbaspour et al., 2018; Almeida et al., 2018).

Calibration was initially performed at the monthly time step for the period 1993-1998 to capture the dominant seasonal hydrological signal of the semi-arid Mediterranean climate, while minimizing the influence of short-term variability and observational noise (Moriasi et al., 2007). Model validation was subsequently carried out using an independent daily discharge dataset for the period 2008-2012, allowing the assessment of model performance under contrasting hydro-climatic conditions and evaluating its capacity to reproduce both peak flows and baseflow dynamics (Meaurio et al., 2015; Sabale et al., 2024).

Calibration and uncertainty analysis were implemented using the SWAT-CUP software with the SUFI-2 algorithm. A parsimonious calibration strategy was adopted by focusing on a limited set of hydrologically sensitive parameters controlling surface runoff generation, soil water storage, groundwater response, evapotranspiration, and channel routing, in line with sensitivity analyses reported in comparable ArcSWAT applications in semi-arid and data-scarce basins (Abbaspour et al., 2018; Almeida et al., 2018). The main calibrated parameters included the Curve Number (CN2), soil saturated hydraulic conductivity (SOL-K), available water capacity (SOL-AWC), baseflow recession factor (ALPHA-BF), groundwater delay time (GW-DELAY), threshold water depth in the shallow aquifer (GWQMN), soil evaporation compensation factor (ESCO), and channel Manning's roughness coefficient (CH-N2).

Within the SWAT-CUP framework, parameters were adjusted either as relative changes (r) or as absolute values (v), following standard SUFI-2 calibration practice. Parameter ranges were defined based on physically plausible limits reported in the literature and previous SWAT applications, while all remaining parameters were retained at their default values derived from soil and land-use databases. This approach minimizes the risk of over-parameterization and enhances the robustness and transferability of the model (Abbaspour et al., 2018; Moriasi et al., 2007).

Model performance was evaluated using multiple statistical indicators, including the Nash-Sutcliffe Efficiency (NSE), coefficient of determination (R^2), percent bias (PBIAS), and the RMSE-standard deviation ratio (RSR), in accordance with established hydrological model evaluation criteria (Moriasi et al., 2007). The high performance values obtained during both calibration and validation periods are attributed to the strong seasonal rainfall control and coherent spatial structure of the Nfifikh watershed, rather than to over-calibration, a behavior frequently reported in well-calibrated SWAT applications at the basin scale (Meaurio et al., 2015; Almeida et al., 2018).

It should be noted that groundwater-related outputs in SWAT represent conceptual shallow aquifer storage and exchange processes rather than a fully physically based groundwater flow system. Consequently, simulated recharge and baseflow components are interpreted as indicative hydrological fluxes within the SWAT conceptual framework, consistent with previous ArcSWAT calibration studies (Abbaspour et al., 2018). The main parameters considered during calibration, their SWAT-CUP adjustment type, and the physically plausible parameter ranges are summarized in Table 1.

Table 1. Key SWAT parameters used for SWAT-CUP (SUFI-2) calibration and validation in the Nfifikh watershed**.**

Parameter	Hydrological process represented	SWAT-CUP change type	Calibration range
CN2 (Curve Number)	Surface runoff generation	r	-0.20 to +0.20
SOL-K	Saturated hydraulic conductivity	r	-0.50 to +0.50
SOL-AWC	Available water capacity	r	-0.30 to +0.30
ALPHA-BF	Baseflow recession factor	v	0.01 to 1.00
GW-DELAY (days)	Groundwater delay time	v	0 to 300
GWQMN (mm)	Threshold water depth in shallow aquifer	v	0 to 5000
ESCO	Soil evaporation compensation factor	v	0.10 to 1.00
CH-N2	Manning’s roughness coefficient for main channel	v	0.01 to 0.15

Note: In SWAT-CUP (SUFI-2), parameters were adjusted either as relative changes (r) or absolute values (v), following standard calibration practice.

2.5 Spatial analysis of model outputs

Simulated outputs were analyzed spatially and temporally within a GIS environment to assess spatial variability in water balance components across the watershed. Spatial patterns of surface runoff, groundwater contribution, evapotranspiration, and sediment dynamics were interpreted in relation to soil properties, topographic gradients, and land-use distribution, providing a spatially explicit understanding of hydrological functioning in semi-arid environments (Zhao et al., 2024).

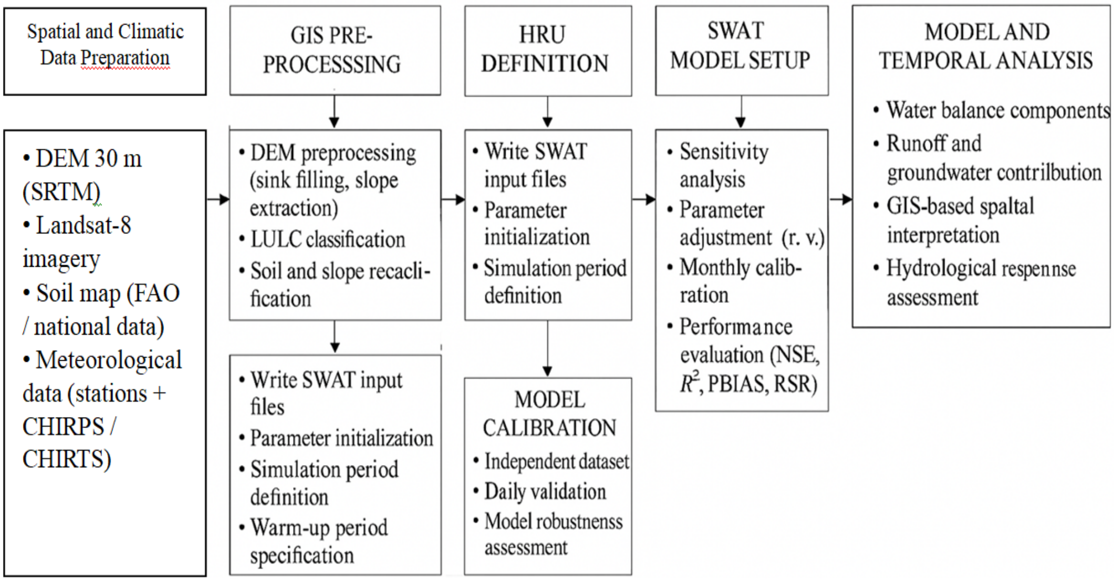

Fig. 2: Methodological framework of SWAT modeling, calibration, and validation applied to the Nfifikh watershed.

3. RESULTS

3.1 Spatial hydro-geomorphological setting of the Nfifikh watershed and implications for SWAT simulations

The spatial configuration of the Nfifikh watershed exerts a fundamental control on the distribution of hydrological processes simulated by the SWAT model. The basin is characterized by a pronounced longitudinal topographic gradient extending from the southeastern uplands toward the northwestern outlet, as illustrated by the Digital Elevation Model (Fig. 3). Elevations range from approximately 2 m in the downstream valley bottoms to more than 800 m in the upstream sectors, generating marked contrasts in slope steepness and drainage density across the watershed.

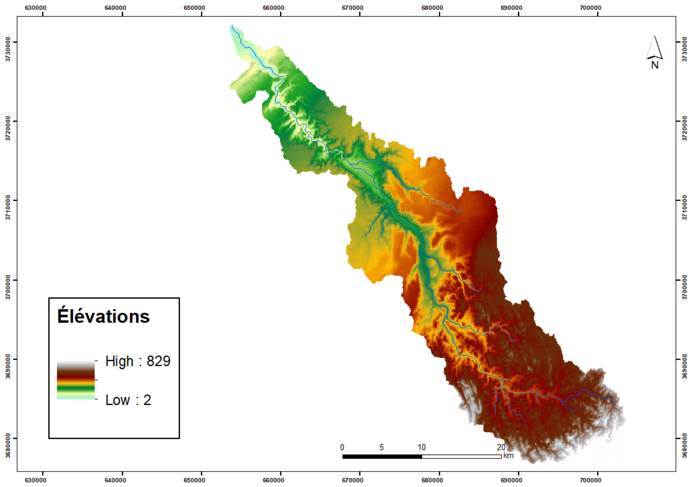

Fig. 3: Digital Elevation Model (DEM) of the Nfifikh.

This geomorphological structure gives rise to a well-developed dendritic drainage network, with steep upstream tributaries converging toward progressively gentler downstream reaches. Similar configurations have been shown to strongly influence surface runoff generation, sediment mobilization, and baseflow contribution in SWAT-based studies, particularly in semi-arid and Mediterranean environments (Arnold et al., 1998; Meaurio et al., 2015). In the Nfifikh watershed, steep upstream slopes are associated with faster flow concentration and shorter response times, whereas downstream foothills and valley-bottom zones favor flow attenuation and sustained subsurface contributions.

The spatial distribution of slope classes derived from the DEM plays a key role in structuring Hydrological Response Units (HRUs) and differentiating hydrological behavior across the basin. Slopes exceeding 15% are primarily concentrated in the eastern and southeastern sectors, while gentle slopes (0–5%) dominate the downstream areas. This slope-based stratification enhances the model's capacity to represent spatial variability in runoff potential and erosion sensitivity, as widely recommended in SWAT applications (Arnold et al., 1998; Neitsch et al., 2011).

The distribution of slope classes and their hydrological relevance within the Nfifikh watershed are summarized in Table 2.

Table 2. Distribution of slope classes and their hydrological relevance in the Nfifikh watershed.

Slope class (%)	**Share of watershed area (%)**	**Mean slope (%)**	**Dominant HRU hydrological behavior**
0–5	40–45	3	High infiltration potential, enhanced groundwater contribution, delayed runoff response
5–15	35–40	9	Moderate runoff generation, mixed surface–subsurface response
>15	15–25	>20	Rapid surface runoff generation, high erosion sensitivity, short hydrological response time

Soil characteristics further modulate these topographic controls. The soil map (Fig. 4) reveals a clear spatial correspondence between soil classes and the basin's geomorphological gradient. Fine-textured and moderately developed soils dominate the upland areas, while deeper and more permeable soils are prevalent in the downstream plains and valley corridors. In SWAT simulations, such contrasts translate into spatial differences in key hydrological parameters, including curve number (CN2), soil saturated hydraulic conductivity (SOL_K), and available water capacity (SOL_AWC), which collectively govern runoff generation, infiltration, and subsurface flow processes (Neitsch et al., 2011; Moriasi et al., 2015).

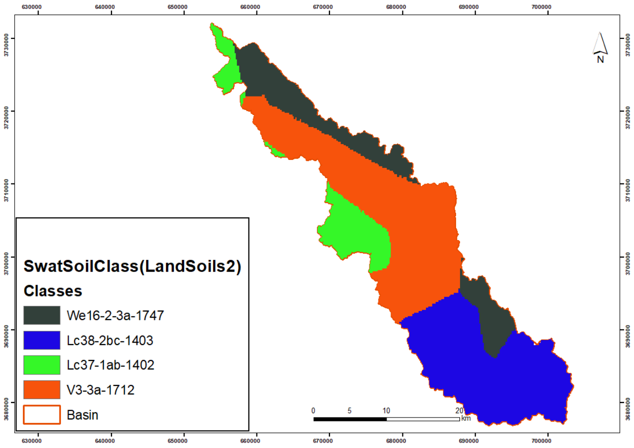

Fig. 4: Soil classes (SWATSoilClass) in the Nfifikh watershed.

Land-use patterns exhibit a similar spatial organization (Fig. 5), closely aligned with topography and soil distribution. Rainfed agriculture and fallow land dominate the steeper upland sectors, whereas pasturelands, riparian zones, and localized forest patches are mainly distributed across the lower slopes and valley bottoms. Previous SWAT-based studies have shown that such land-use contrasts strongly influence hydrological response by modifying surface roughness, soil disturbance, and vegetation cover, thereby affecting both runoff and sediment dynamics (Abbaspour et al., 2018; Almeida et al., 2018).

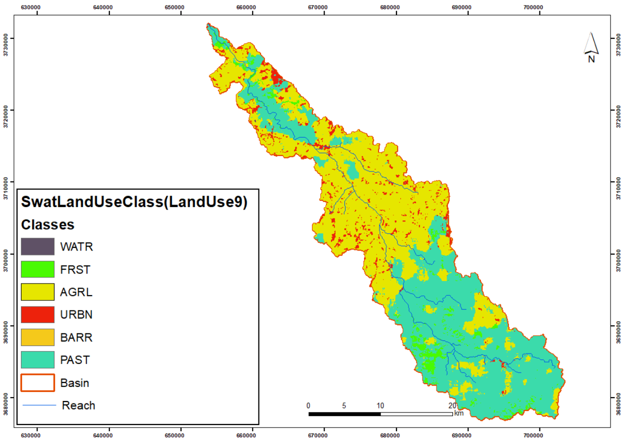

Fig. 5: Land cover and use class (SWATLandUseClass) map of the Nfifikh watershed.

The main land-use categories and their associated hydrological response characteristics as represented in the SWAT model are summarized in Table 3.

Table 3: Land-Use Classes and Associated Hydrological Response Parameters (CN2, SOL-K, and Sediment Yield) in Nfifikh.

Land-use class	Description	CN2 (Curve Number)	SOL-K (mm/h) Hydraulic Conductivity	Sediment Yield Tendency (SED)	Hydrological Behavior

Rainfed agriculture (cropland)	Cultivated fields, seasonal crops	78 - 88	2 - 15	Medium to high	Moderate infiltration, moderate-high runoff, soil disturbance increases erosion
Fallow / Bare land	Exposed or minimally vegetated soil	85 - 92	1 - 8	High	High runoff, low retention, strong susceptibility to erosion
Pasture / Grassland	Natural/managed grazing areas	65 - 80	8 - 30	Low to medium	Higher infiltration, moderate runoff, moderate soil protection
Shrubland / Rangeland	Bushy and semi-woody vegetation	70 - 82	5 - 20	Medium	Moderate infiltration, reduced erosion compared to bare land
Forest patches	Localized wooded areas	55 - 70	20 - 50	Very low	High infiltration, excellent soil protection, recharge zones
Urban / Built-up	Residential, roads, infrastructure	90 - 95	0 (impervious)	Very low (sediment trapped), but high runoff concentration	Very low infiltration, fast runoff response, peak flow increase
River / Valley bottoms	Channel and riparian zones	Variable (lower)	High	Very low	Groundwater discharge - baseflow areas

This table summarizes the key land-use types in the Nfifikh basin and their associated hydrological behaviors as represented in the SWAT model, highlighting contrasts in runoff generation, soil infiltration, and sediment response across the watershed

The combined effect of topography, soil properties, and land use is reflected in the spatial organization of the drainage network and sub-basin structure (Fig. 6). Multiple tributaries converge toward the main channel, promoting localized amplification of flow and sediment transport in upstream confluences, followed by progressive flow attenuation downstream. This longitudinal organization provides a coherent physical framework for interpreting the spatial variability of SWAT-simulated surface runoff, baseflow contribution, and sediment yield across the watershed, without invoking assumptions beyond the model's conceptual structure (Arnold et al., 1998; Meaurio et al., 2015).

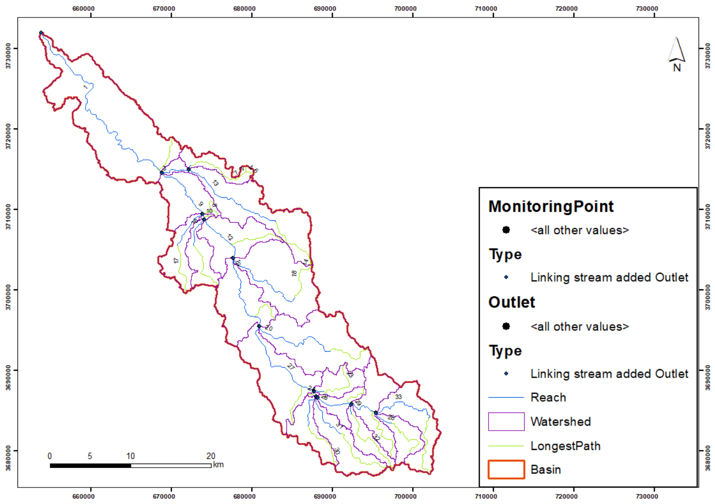

Fig. 6: Drainage network, watershed boundary, sub-basins, and longest flow path (LongestPath) of the Nfifikh watershed.

Overall, this spatial hydro-geomorphological setting establishes the physical context within which subsequent quantitative results on runoff, groundwater contribution, and sediment dynamics are interpreted. Rather than serving as a descriptive background, it provides an analytical basis for linking mapped patterns to the spatial distribution of SWAT outputs at the HRU and sub-basin scales.

2.3 Surface and groundwater flow dynamics in the Nfifikh watershed using the SWAT model

Figure 7 synthesizes the main components of the annual water balance simulated by the SWAT model for the Nfifikh watershed. The results depict a hydrological regime typical of semi-arid Mediterranean basins, characterized by strong evaporative demand and limited effective rainfall. Mean annual precipitation is approximately 420 mm, whereas potential evapotranspiration exceeds 1300 mm, indicating that water availability is primarily constrained by atmospheric demand rather than precipitation input. Similar hydro-climatic imbalances have been widely reported in semi-arid watersheds modeled using SWAT (Arnold et al., 1998; Moriasi et al., 2007).

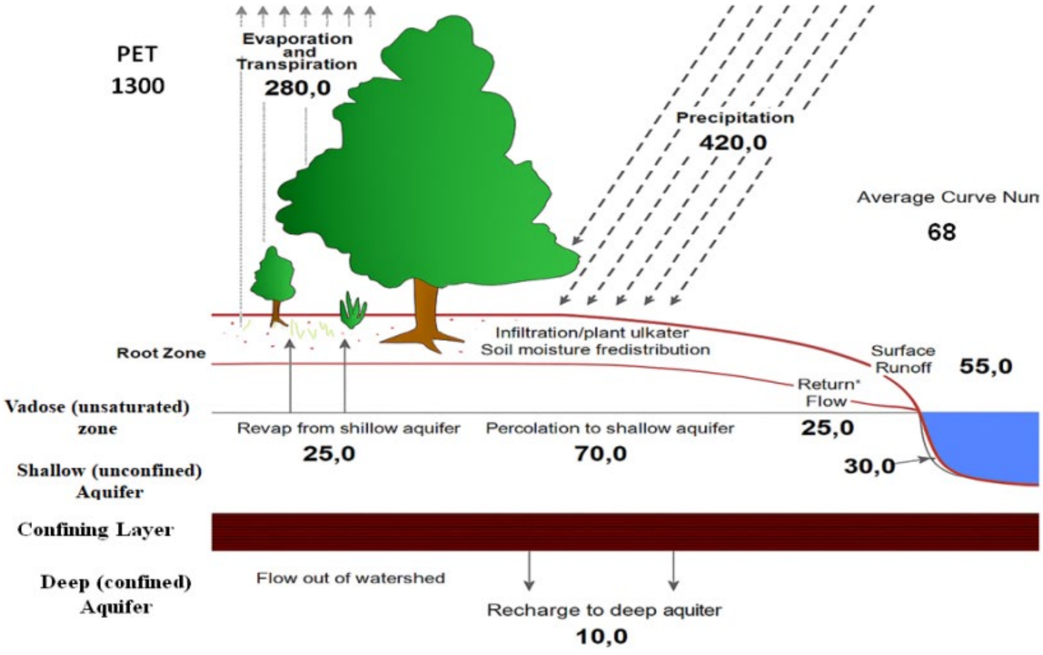

Fig. 7: Annual water balance of the Nfifikh watershed – Results of the SWAT model.

Quantitative partitioning of rainfall reveals that evapotranspiration represents the dominant loss term, accounting for about 67% (280 mm) of annual precipitation (Table 4). This confirms that vegetation water use and soil evaporation are the primary controls of the basin water balance, as commonly observed in water-limited environments (Oki et al., 2001). Approximately 26% of precipitation (110 mm) contributes to streamflow generation, which is further partitioned into surface runoff (55 mm), lateral subsurface flow (25 mm), and baseflow contribution from the shallow aquifer (30 mm).

Table 4. Annual water balance components simulated by SWAT for the Nfifikh watershed.

Water balance component	**Depth (mm/year)**	**Share of precipitation (%)**
Precipitation	420	100
Actual evapotranspiration	280	67
Surface runoff (SURQ)	55	13
Lateral flow (LATQ)	25	6
Baseflow (GW_Q)	30	7
Shallow aquifer recharge (RECHRG)	70	17
Deep aquifer recharge	10	2

The simulated recharge of approximately 70 mm/year represents percolation to the shallow aquifer storage conceptualized within SWAT. It is important to emphasize that this component does not represent physically explicit groundwater flow, but rather a simplified reservoir controlling delayed contributions to streamflow (Neitsch et al., 2005; Arnold et al., 2012). Similar conceptual interpretations of groundwater recharge have been adopted in semi-arid SWAT applications to avoid overestimation of subsurface processes (Abdalla, 2009; Baalousha, 2016).

Seasonal dynamics further highlight the basin's rapid hydrological response to intense rainfall events following prolonged dry periods. During autumn and winter storms, soils often exhibit reduced infiltration capacity due to antecedent moisture deficits and surface sealing, leading to a dominance of surface runoff on steep slopes. This mechanism produces short-lived but sharp flood peaks and promotes enhanced sediment mobilization, a behavior consistent with SWAT-based analyses in arid and semi-arid catchments (Dutta & Sen, 2018; Prabhanjan et al., 2015).

In contrast, subsurface components play a regulatory role during dry periods. Baseflow contributions of approximately 30 mm/year persist throughout summer months, sustained by gradual release from the shallow aquifer reservoir. The simulated upward capillary flux (25 mm/year) represents a conceptual soil–aquifer interaction within SWAT, whereby moisture is redistributed toward the root zone under high evaporative demand. This process should be interpreted as an internal soil–water balance adjustment rather than an explicit groundwater rise, as emphasized in previous modeling studies (Guzman et al., 2015).

Spatial aggregation of SWAT outputs reveals clear contrasts in flow pathways across the watershed (Table 5). Steep upland areas generate a disproportionate share of surface runoff, whereas downstream zones with gentler slopes and more permeable soils favor infiltration and baseflow contribution. Such differentiation reflects the combined influence of slope gradient, soil hydraulic properties, and land-use patterns on hydrological partitioning, consistent with conceptual frameworks underlying distributed watershed models (Arnold et al., 1998; Kaleris & Langousis, 2017).

Table 5. Dominant flow pathways across major physiographic zones of the Nfifikh watershed**.**

Physiographic zone	**Dominant slope class**	**Dominant flow component**	**Hydrological implication**
Eastern and southeastern uplands	>15%	Surface runoff (SURQ)	Rapid response, high erosion sensitivity
Central sub-basins	5–15%	Mixed runoff and lateral flow	Transitional hydrological behavior
Northwestern lowlands and valleys	0–5%	Infiltration and baseflow	Flow attenuation, sustained discharge

Overall, the simulated surface and subsurface flow dynamics reflect a system dominated by fast runoff generation during episodic rainfall events, coupled with limited but persistent subsurface storage that sustains low-magnitude baseflow during dry periods. This dual behavior is characteristic of semi-arid Mediterranean watersheds and supports the interpretation of SWAT outputs as indicators of hydrological functioning rather than exact representations of physical groundwater processes (Abdalla, 2009).

3.3 Sediment Budget and Surface Runoff Dynamics in the Nfifikh Watershed

The sediment budget simulated by the SWAT model provides a quantitative framework for analyzing the interaction between surface runoff generation and soil erosion processes within the Nfifikh watershed. In semi-arid basins, sediment dynamics are primarily driven by short-duration, high-intensity rainfall events that generate rapid surface runoff on steep and sparsely vegetated slopes (Dutta & Sen, 2018; Prabhanjan et al., 2015). This behavior is clearly reflected in the spatial distribution of sediment yield and runoff components shown in Figure 8.

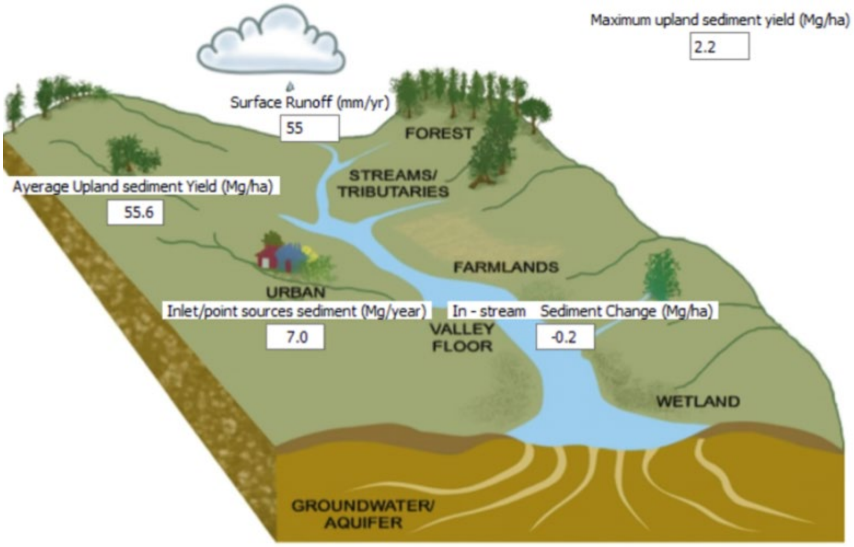

Fig. 8: Sediment balance and spatial distribution of surface runoff in the Nfifikh watershed - SWAT model results.

At the watershed scale, the mean annual surface runoff is approximately 55 mm, consistent with the runoff contribution identified in the overall water balance. Sediment yield values simulated by SWAT represent average HRU-level outputs aggregated to sub-basin and watershed scales, rather than point-scale erosion measurements. When expressed in standard SWAT units (t/ha/year), the highest erosion-prone HRUs in the upland sectors exhibit low-to-moderate sediment yields typical of semi-arid Mediterranean catchments, where limited rainfall frequency constrains total annual soil loss despite intense episodic events (Kumar et al., 2015; Dutta & Sen, 2018).

To complement the spatial patterns depicted in Figure 8, sediment and runoff outputs were quantitatively aggregated according to dominant land-use categories (Table 6) . This aggregation allows a clearer distinction between sediment source areas and zones of reduced transport capacity, and facilitates direct comparison of hydrological responses across different land-use types. By summarizing HRU-level outputs at the land-use scale, the analysis strengthens the link between spatially explicit model results and their underlying controlling factors.

Table 6. Mean sediment yield and runoff characteristics by major land-use type in the Nfifikh watershed.

Land-use category	Dominant slope class	Mean surface runoff (mm/year)	Relative sediment yield (t/ha/year)	Sediment response
Rainfed cropland	5-15% / >15%	High	Moderate to high	Primary sediment source
Fallow / bare land	>15%	Very high	High	Strong erosion hotspot
Pasture / grassland	0-5% / 5-15%	Moderate	Low to moderate	Partial sediment retention
Forest patches	0-5%	Low	Very low	Effective erosion control
Valley floor / channel	0-5%	Low	Negative or near zero	Net sediment deposition

Spatial analysis of Figure 8 highlights a clear differentiation between sediment source areas and sediment storage zones. The eastern and southeastern uplands emerge as the dominant sediment-generating regions, where steep slopes, fine-textured soils, and intensive agricultural land use promote rapid runoff concentration and soil detachment. Similar spatial patterns have been documented in SWAT-based erosion studies conducted in arid and semi-arid environments, where slope gradient and land-cover disturbance jointly control sediment mobilization (Kumar et al., 2015; Dutta & Sen, 2018).

In contrast, mid-basin sectors characterized by gentler slopes and increased vegetation cover exhibit reduced sediment production and enhanced infiltration. These areas function as transitional zones where a portion of the eroded material is temporarily stored or redeposited before reaching the main channel. Forested and pasture-dominated HRUs act as effective sediment buffers, reducing transport capacity and limiting downstream sediment transfer, consistent with findings reported in distributed watershed modeling studies (Prabhanjan et al., 2015; Moriasi et al., 2007).

Channel and valley-floor environments represent the terminal component of the sediment budget. Slightly negative sediment balances simulated within the main channel reflect net deposition rather than active erosion, indicating that a substantial fraction of the sediment mobilized from upland areas is retained within alluvial reaches and riparian zones. This depositional behavior is a common feature of semi-arid drainage networks, where declining slope gradients and reduced flow energy favor sediment storage downstream (Kumar et al., 2015).

In order to further clarify the spatial organization of sediment processes across the watershed, sub-basin scale sediment balances were grouped into major physiographic zones. This zonal classification (Table 7) highlights the transition from sediment-producing upland areas to downstream deposition zones, and provides a simplified yet robust framework for interpreting sediment routing and storage within the drainage network.

Table 7. Spatial differentiation of sediment source and sink zones in the Nfifikh watershed.

Basin sector	Dominant process	Sediment balance	Geomorphic implication
Upland slopes (E-SE)	Detachment and transport	Positive	Primary sediment source
Mid-basin reaches	Partial deposition	Near neutral	Temporary storage and buffering
Valley floor and channel	Deposition	Negative	Long-term sediment retention

Overall, the sediment budget analysis confirms a strong spatial gradient in erosion and deposition processes across the Nfifikh watershed. Surface runoff generated on steep upland slopes acts as the primary driver of sediment mobilization, while downstream zones progressively attenuate sediment transport through deposition and storage. These results underscore the necessity of spatially differentiated management strategies, prioritizing erosion control and runoff reduction in upland agricultural areas, while preserving and enhancing natural sediment retention functions in downstream valleys. Such an approach aligns with best practices derived from SWAT-based sediment management studies in semi-arid watersheds (Dutta & Sen, 2018; Prabhanjan et al., 2015).

4.3 Daily Flow Dynamics and Model Performance in the Nfifikh Watershed

Daily streamflow simulations were evaluated against observed discharge records to assess the ability of the SWAT model to reproduce short-term hydrological variability in the Nfifikh watershed. The analysis covered the 2008–2012 period and explicitly distinguished between calibration and validation phases in order to test the temporal robustness of the model under contrasting hydro-climatic conditions. Model performance was assessed using complementary statistical indicators, including the Nash–Sutcliffe efficiency (NSE), coefficient of determination (R^2), percent bias (PBIAS), and the RMSE–standard deviation ratio (RSR), following established evaluation guidelines for watershed-scale models (Moriasi et al., 2007).

Figure 9 compares observed and simulated daily discharge together with corresponding precipitation inputs. The hydrograph reveals a typical semi-arid flow regime characterized by sharp discharge peaks in response to intense autumn and winter rainfall events, followed by extended low-flow periods during summer. The SWAT model satisfactorily reproduces the timing and magnitude of most peak flows, as well as the recession behavior following storm events. Minor discrepancies are mainly associated with a limited number of high-flow events, during which simulated peaks tend to be slightly underestimated, a behavior commonly reported in distributed hydrological models applied to semi-arid basins.

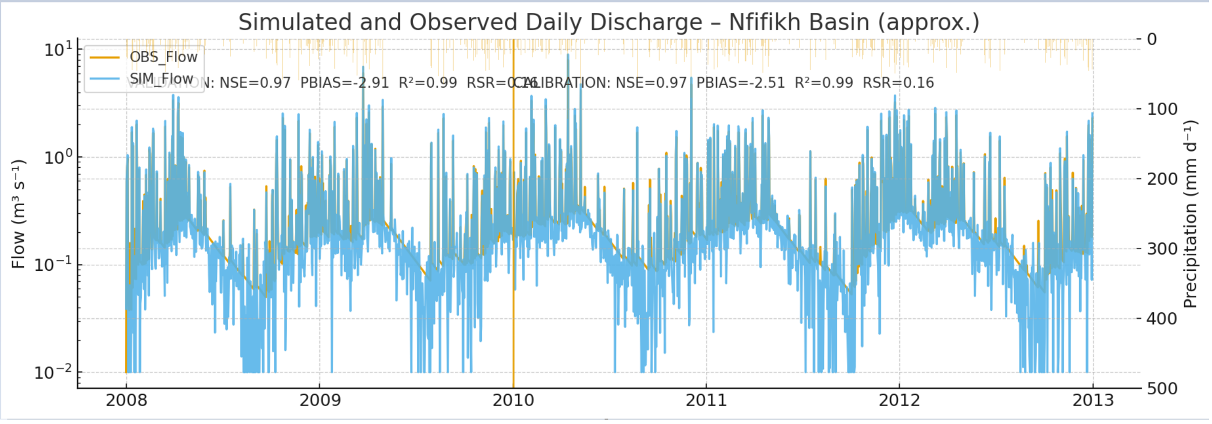

Fig. 9: Observed and simulated daily flow as a function of precipitation in the Nfifikh watershed (2008-2012; calibration and validation periods).

Beyond peak-flow simulation, the model captures the persistence of low but continuous discharge during dry periods, reflecting delayed contributions from shallow subsurface storage conceptualized within the SWAT framework. This representation supports a realistic simulation of baseflow recession without explicitly modeling physically based groundwater flow, in line with the conceptual structure of the model (Arnold et al., 1998; Neitsch et al., 2005).

Quantitative performance statistics for daily streamflow simulation are summarized in Table 8. During the calibration period, the model achieved very high performance, with NSE and R^2 values of 0.97 and 0.99, respectively, indicating excellent agreement between observed and simulated discharge. Validation results remain robust, with NSE = 0.91 and $R^2 = 0.94$, demonstrating that the model retains predictive skill under independent conditions. PBIAS values of −3.5% for calibration and −6.8% for validation indicate a slight tendency toward underestimation of streamflow volumes, while RSR values below 0.5 confirm low residual variance relative to observed variability.

Table 8. Performance statistics for daily streamflow simulation during calibration and validation periods.

Period	NSE	R^2	PBIAS (%)	RSR
Calibration	0.97	0.99	-3.5	0.28
Validation	0.91	0.94	-6.8	0.41

According to the performance classification proposed by Moriasi et al. (2007), these statistics correspond to very good model performance at the daily time scale for both calibration and validation periods. Nevertheless, the exceptionally high efficiency values should be interpreted with caution. In small to medium-sized semi-arid watersheds, strong seasonality and a limited number of dominant runoff events can lead to high performance metrics without implying perfect representation of all internal hydrological processes. This behavior is consistent with the concept of equifinality, whereby different parameter combinations may yield similarly good model performance. Monthly calibration results (not shown) were consistent with the daily-scale performance presented here, indicating that the calibrated parameter set remains robust across temporal aggregation levels.

Overall, the daily flow evaluation confirms that the SWAT model provides a reliable representation of streamflow variability at the watershed outlet. When interpreted within its conceptual framework and associated uncertainties, the model outputs offer a sound basis for subsequent analyses of runoff generation, sediment dynamics, and management scenarios in the Nfifikh watershed.

4. DISCUSION

The hydrological behavior simulated for the Nfifikh watershed reflects the fundamental functioning of semi-arid Mediterranean basins, where limited and irregular precipitation is strongly constrained by high evaporative demand. The dominance of evapotranspiration over runoff and recharge confirms that water availability is primarily controlled by atmospheric demand rather than rainfall input, a pattern widely reported in SWAT-based studies conducted in arid and semi-arid environments (Arnold et al., 1998; Oki et al., 2001). Within this context, the spatial differentiation between rapid runoff generation on steep upland slopes and delayed subsurface contributions in lower valley areas provides a coherent explanation for the observed flow regime at the basin outlet.

The partitioning of streamflow into surface runoff, lateral flow, and baseflow highlights the dual nature of hydrological response in the basin. Short-duration, high-intensity rainfall events generate rapid surface runoff on sloping and sparsely vegetated areas, while shallow subsurface storage sustains low but persistent baseflow during dry periods. This coexistence of fast and slow flow pathways is consistent with conceptual representations of watershed processes in distributed hydrological models, where shallow aquifer storage acts as a buffering reservoir rather than a physically explicit groundwater system (Neitsch et al., 2005; Arnold et al., 2012). Similar interpretations have been emphasized in semi-arid applications to avoid overestimation of groundwater dynamics derived from conceptual recharge terms (Abdalla, 2009; Baalousha, 2016).

Sediment dynamics further reinforce the strong coupling between runoff generation, slope gradient, and land-use distribution. The identification of upland agricultural and bare-soil areas as primary sediment source zones, contrasted with downstream deposition and retention in valley floors and channels, aligns with findings from SWAT-based erosion studies in data-scarce and semi-arid catchments (Prabhanjan et al., 2015; Kumar et al., 2015; Dutta & Sen, 2018). The spatial separation between sediment-producing and sediment-storing zones suggests that a substantial fraction of eroded material is internally redistributed within the basin, rather than exported downstream, a behavior commonly observed in Mediterranean drainage systems with pronounced relief and episodic runoff.

The very good model performance achieved at both daily and aggregated temporal scales supports the reliability of the simulated hydrological patterns. Nevertheless, the exceptionally high efficiency values should be interpreted cautiously. In small to medium-sized watersheds characterized by strong seasonality and a limited number of dominant runoff events, high NSE and R^2 values may arise even under parameter uncertainty. This phenomenon is consistent with the concept of equifinality, whereby multiple parameter sets can yield similar model performance without uniquely identifying internal process representations (Moriasi et al., 2007). Consequently, the results should be interpreted as robust indicators of basin-scale behavior rather than exact representations of all internal hydrological fluxes.

Several sources of uncertainty remain inherent to the modeling framework. The integration of station-based observations with gridded climate products introduces potential bias during extreme rainfall events that disproportionately influence runoff and sediment generation. Likewise, the use of a 30-m DEM may smooth micro-topographic features that locally control flow concentration and erosion pathways. Uncertainties related to soil and land-use classification, particularly in transitional agricultural and peri-urban areas, further affect HRU parameterization and sediment estimates. These limitations are common to distributed watershed modeling and have been widely documented in SWAT applications (Cibin et al., 2010; Muleta & Nicklow, 2005).

From a management perspective, the results emphasize the need for spatially differentiated interventions rather than uniform basin-wide measures. Upland areas identified as runoff and sediment source zones represent priority targets for soil conservation practices, such as erosion control, improved land management, and vegetation restoration, which have been shown to effectively reduce sediment yields in similar SWAT-based studies (Kumar et al., 2015; Dutta & Sen, 2018). Conversely, downstream valley floors and riparian corridors should be preserved as natural retention and buffering zones, as their degradation could substantially increase sediment export and flood risk.

Overall, this study demonstrates the value of distributed hydrological modeling for disentangling the spatial organization of runoff, sediment transport, and subsurface storage in semi-arid watersheds. While the SWAT model remains a conceptual representation of complex hydrological processes, its application to the Nfifikh watershed provides a coherent and policy-relevant framework for understanding hydrological functioning and supporting land and water management strategies. Future research should prioritize higher-resolution topographic data, improved soil and land-use characterization, and the coupling of SWAT with physically based groundwater or sediment transport models to further refine surface–subsurface interaction analysis in similar Moroccan basins (Guzman et al., 2015; Sabale et al., 2024).

5. CONCLUSIONS

This study implemented the SWAT model to provide a spatially explicit assessment of runoff, subsurface flow, and sediment dynamics in the Nfifikh watershed. By integrating topographic, soil, land-use, and climate data, the modeling framework successfully characterized the main hydrological components governing water and sediment redistribution at the watershed scale.

The results deliver a consistent depiction of hydrological functioning under semi-arid conditions and identify priority zones controlling runoff production, sediment generation, and subsurface contribution. These spatial insights offer a practical basis for supporting watershed management, particularly in targeting erosion-prone areas and safeguarding zones that contribute to flow regulation and storage.

Beyond the specific case study, this work demonstrates the applicability of distributed hydrological modeling as a decision-support tool in data-scarce semi-arid basins. Future developments should focus on enhancing data resolution and model coupling to further strengthen predictive capability and support long-term land and water planning.

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