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Impact of dam water impoundment on hydrological regimes and downstream alluvial aquifer recharge: A case study in the Wadi El-Hai Basin, Southeastern Algeria

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In arid regions, where water scarcity is a pressing concern, dams are often relied upon to supply water for irrigation, industry, and human consumption. However, these hydraulic structures can have significant negative impacts on downstream hydrological regimes and ecosystems. This research aims to assess the effects of Fountain of Gazelles Dam in southeastern Algeria on the hydrological regime of Wadi El-Hai and the recharge of the Wadi Biskra alluvial aquifer downstream. The study compares historical flow data from Wadi El-Hai before and after the dam's operation, examining the correlation with piezometric fluctuations in the Wadi Biskra alluvial aquifer. A strong positive correlation (0.83) was found between water releases from the dam and rising groundwater levels, indicating that higher releases tend to replenish the aquifer. In contrast, reduced releases lead to a decline in water levels. Groundwater drawdowns of up to 5 meters were observed in the aquifer, reflecting the adverse impact of the dam on recharge. These findings emphasize the critical role of controlled water releases in sustaining groundwater resources. They also highlight the importance of adaptive water management strategies to mitigate the adverse effects on groundwater recharge. By addressing these issues, sustainable water management practices can be implemented to ensure long-term aquifer sustainability in arid regions.

KEY WORDS: dams, hydrological regime, wadis, alluvial aquifer recharge, arid regions, groundwater drawdown

Introduction

Dams have long been considered a practical solution for regulation of surface water intended for irrigation, drinking water supply, and flood control (Bouwer, 2000; Nilsson and Berggren, 2000; Molle et al., 2013; Lee et al., 2018; Zakarya et al., 2023). Indeed, the hydro-climatic conditions of arid regions are characterized by flows often taking the form of violent floods causing inundations, followed by periods of drought (Nanekely, 2020; De Girolamo et al., 2022) (Herizi and Bensefia, 2024). This situation has frequently necessitated the construction of dams to regulate Wadis, prevent flood-related damages, and store water volumes for use during dry (Altinbilek, 2002; Kantoush et al., 2022). However, dam construction in these regions has also presented significant challenges, including evaporation, siltation, salinization, and various downstream impacts (Sallam et al., 2018; Yifru et al., 2021). Consequently, the hydrological regimes of regulated Wadis are significantly affected by dams (Magilligan and Nislow, 2005).

Furthermore, alluvial aquifers have facilitated the development of ancient palm groves and represent a crucial source of drinking water for oasis dwellers in arid regions (Gouskov, 1962; Coelho et al., 2017). However, their recharge primarily depends on flooding events in the Wadis (Sorman and Abdulrazzak, 1993; Abdalla et al., 2014). Today, human activities, particularly regulation of surface water combined with severe drought episodes observed in recent decades (Brouziyne et al., 2024), have strongly disrupted the downstream hydrological regimes of Wadis and the regular recharge of alluvial aquifers (Djuma et al., 2017; Salas et al., 2016; Epting et al., 2021). For centuries, the Oasis of Biskra in southeastern Algeria has developed on a groundwater aquifer interacting with the Wadi, which recharges it during floods (Gouskov, 1962; Morin et al., 2009). Today, regulation of surface water after the commissioning of Fountain of Gazelles Dam in 2000 (Rehamnia et al., 2021) has disrupted water regimes and limited aquifer recharge. Additionally, a new dam commissioned in 2021 on the Wadi Abdi (a left-bank tributary of the Wadi Biskrain) in Bouzina (Bendjerad et al., 2023) will further deprive the aquifer of recharge from this Wadi. The integration of data sources, including satellite observations and ground-based hydrological measurements, is increasingly essential to track hydrological trends and their impacts on water systems, particularly under the strain of climate change (Touati et al., 2025). The impacts of dam construction on hydrology, sediment transport, and groundwater recharge have been extensively studied, offering critical insights into the complex interactions

between dams and water systems. (Petts and Gurnell, 2005) reviewed dams' geomorphological and ecological effects on downstream rivers, highlighting how flow and sediment transport alterations modify channel morphology and drive riparian and ecological changes. Their study emphasized the need to adopt transient-state models at a reach scale to address the long-term impacts of regulated rivers in semi-arid and temperate regions. (Djuma et al., 2017) investigated the functionality of retention dams for groundwater recharge, quantifying their contribution to aquifer recharge and assessing sediment accumulation in semi-arid regions. Their findings indicated that control dams could recharge aquifers with up to 30 % of the flow, highlighting their potential as practical tools for enhancing groundwater resources. Nevertheless, uncertainties regarding recharge rates and sedimentation processes underline the need for improved methodologies to optimize their design and management. (Zhang et al., 2020) studied the hydrological effects of cascading dams under climate variability using a modeling approach, enhancing the understanding of how dam operation interacts with climate variability to influence stream hydrology. In large river systems, (Hwang et al., 2021) analyzed the alteration of natural flow frequencies in the Colorado River basin. Using wavelet analysis, their research illustrated how dams progressively modify dominant frequencies of natural flow and propagate these changes through river networks. Their findings underscore the critical role of dams in altering temporal dynamics of flow variability, impacting ecosystem health and water resource management. Finally, (Jiang et al., 2024) studied the effects of the Lake Poyang hydraulic dam project on groundwater-surface water interactions in a lake-river-aquifer system. Using a three-dimensional numerical model, their study demonstrated that dam regulation could significantly increase regional groundwater storage during dry seasons, mitigating groundwater deficits during extreme drought.

Overall, these studies underscore the multifaceted impacts of dams on hydrological regimes, groundwater recharge, and ecosystem dynamics. The existing research collectively highlights the necessity of adopting integrated management approaches that reconcile sustainable water resource development with preserving hydrological and ecological integrity, particularly in arid and semi-arid regions. This study relies on the historical flow analysis of Wadi El-Hai before and after the dam's commissioning and their correlation with piezometric fluctuations in the Wadi Biskra alluvial aquifer. The goal is to understand better how flow regulation by the dam affects aquifer recharge. The results that were obtained highlight the negative impact of Fountain of Gazelles Dam on the recharge of the Wadi Biskra alluvial aquifer. This study could provide valuable guidance for policymakers to implement necessary measures to mitigate these negative impacts and ensure sustainable water resource management.

Study area

The study area is in southeastern Algeria and comprises two distinct physiographic units. The first unit corresponds to the watershed of Fountain of Gazelles Dam. The second unit is the alluvial aquifer of Wadi Biskra (Ghiglieri et al., 2021).

The Wadi El-Hai watershed is the largest basin on the southern flank of the Aurès mountains, covering an area of 1728 km² (Benamor et al., 2024). It is characterized by mountain ranges oriented northeast-southwest, which decrease in elevation from north to south, such as the Belezma mountains in the north, reaching a maximum altitude of 2161 m (Boultif et al., 2024). Consequently, most sub-basin comprises foothills with a northwest exposure (Bensekhria and Bouhata, 2022). Nevertheless, two distinct morphological units can be identified: the first (plain) as shown in Fig. 1, lies between Batna and Ain Touta, at altitudes ranging from 900 m to 1100 m, covering 25% of the sub-basin area, approximately 36 km long and 6 to 8 km wide. The second (glacis) is located southwest and extends from El Kantara to Fountain of Gazelles Dam site, running alongside Wadi El-Hai. Wadi El-Hai is formed by the confluence of two watercourses: Wadi Chaaba or Télattou, which originates on the eastern flank of the Belezma mountains (2161 m) and passes through the marl-clay formations of the Ain Touta plain, and Wadi Beni Fedhala, originating on the southwest flank of the Larbaa mountains (Ich Ali, 1815 m) (Athmani, 2018). The study area is characterized by a semi-arid (upstream) to arid (downstream) climate under Mediterranean influence (Chafaa et al., 2013). Analysis of average annual precipitation data reveals a rapid decrease towards the south. Indeed, the Châbat Ouled Chelih station, located on the southern flank of the Belezma mountains at an altitude of 1200 m, receives an average annual rainfall of 413 mm. Further south, the Loutaya station, situated on the southern foothills of the Aurès mountains at an altitude of 270 m, receives an average of 262.49 mm annually. The Biskra rainfall station, located in the Ziban plain at an altitude of 112 m, receives an average annual rainfall of 133.91 mm. Similar to other basins on the southern flank of the Aurès mountains, the Wadi El-Hai basin is characterized by alternating anticlines (Jurassic outcrops) and synclines (Miocene fillings) oriented northeast-southwest (Laffitte, 1939).

There are few hydrogeological studies on the alluvial aquifer of Wadi Biskra, apart from some very old works and an analog (electrical) model study conducted by the Central Society for the Equipment of the Territory (SCET-COOP, 1967). The aquifer begins downstream of the confluence of Wadis El-Hai and Abdi and extends to the gorge at Elalia. The reservoir covers an area of 5 km², has an average depth of 40 meters, and has an estimated alluvial volume of 100 x 10^6 m³. It is almost divided into two distinct parts. Upstream, a sizeable spreading area is linked to the confluence of the two Wadis. This zone is wide, has high transmissivity, and represents the most significant part of the reservoir (approximately twothirds). It extends continuously up to the upstream gorges, just after the confluence of the El-Hai and Abdi wadis, and continues to the limestone gorge of the Biskra wadi. As the Wadi flows downstream, the riverbed narrows, forming the least known part of the reservoir,

particularly at the Miocene gorge (Fig. 1b). The impermeable Miocene clays form the bedrock of the alluvial formations and the eastern and western banks of the main bed of Wadi Biskra. This geological setting facilitates water accumulation, contributing to the formation of the phreatic aquifer (Arras et al., 2014).

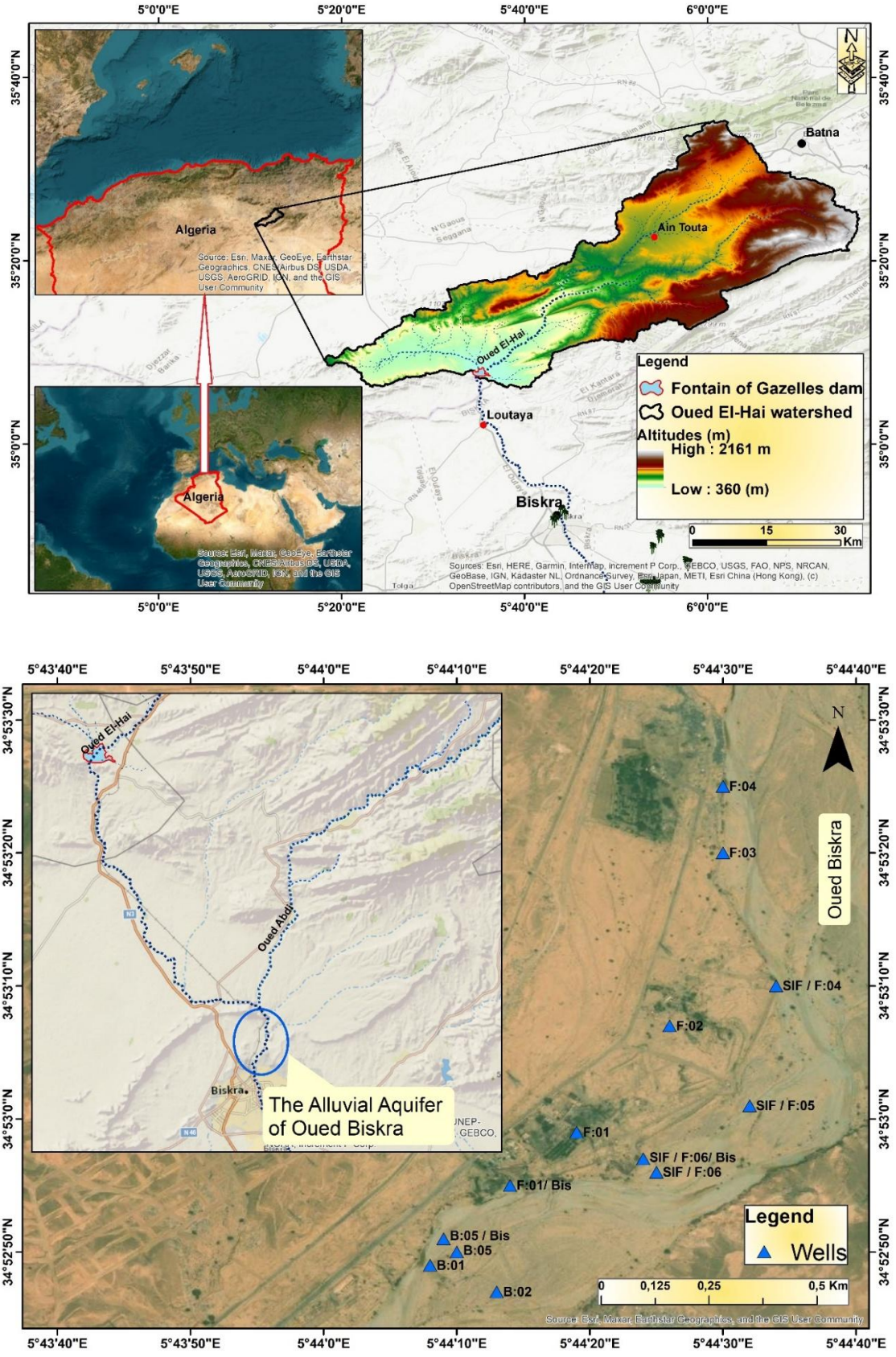


Fig. 1. a) The Wadi El-Hai Watershed. b) The Alluvial Aquifer of Wadi Biskra.

The total porosity of the 100 x 10^6 m³ of alluvium determines the amount of water stored within it. In France, coarse and sandy alluvium values range from 10 to 15%. American researchers (Branch and Todd, 1957) generally use much higher values, ranging from 25 to 35% and up to 45%. The value retained for the entire reservoir is approximately 30%, which, for an alluvial volume of 100 x 10^6 m³, results in an estimated 30x10^6 m³ of exploitable stored water (SCET-COOP, 1967).

Data collection and methodology

To study and monitor the effect of the Water Impoundment of Fountain of Gazelles Dam on the recharge of the Wadi Biskra alluvial aquifer, we adopted an approach combining qualitative and quantitative methods (Fig. 2). The operational data of Fountain of Gazelles Dam, obtained from the National Agency for Dams and Transfers, covers 21 years (2000–2021). This data includes the volumes of released water (in hm³) and the frequency, duration, and dates of the releases. A quality control check was conducted to identify and correct potential gaps or outliers. This analysis enabled the examination of interannual and seasonal variations in water releases, which are essential for assessing their role in aquifer recharge (Seif et al., 2024).

Piezometric level measurements were carried out by the Water Resources Directorate of the Wilaya of Biskra on boreholes tapping the Wadi Biskra alluvial aquifer, all of which are currently in operation and extracting groundwater from this aquifer (Fig. 1b). Representative boreholes distributed across different aquifer areas were selected to ensure adequate spatial coverage. The collected data was then chronologically organized, allowing for monitoring water level evolution throughout the study period and identifying spatiotemporal variations (Anand et al., 2020). However, gaps were identified in some time series due to interruptions in measurements (Mammadova and Negri, 2024). The linear regression method was applied to address these gaps. This method estimates missing values based on the linear relationships between the available data (El Mezouary et al., 2024). A detailed study was conducted to analyze the general trends between the water releases from Fountain of Gazelles Dam and the piezometric variations observed in the Wadi Biskra alluvial aquifer.

The objective was to understand better the hydrodynamic interactions between the releases and aquifer recharge and to characterize the direct or indirect influence of the dam's commissioning on groundwater resources (Pokhrel et al., 2018). Additionally, statistical methods were applied to evaluate the correlations between the volumes of water released from Fountain of Gazelles Dam and the piezometric variations in the Wadi Biskra alluvial aquifer. This approach allowed for the identification of general trends and potential patterns or anomalies in the aquifer's response to the water releases (Ramah et al., 2024).

The modeling of drawdowns in the Wadi Biskra alluvial aquifer was carried out using numerical simulations and Inverse Distance Weighting (IDW) spatial interpolation (Aziz et al., 2024). This interpolation method estimates

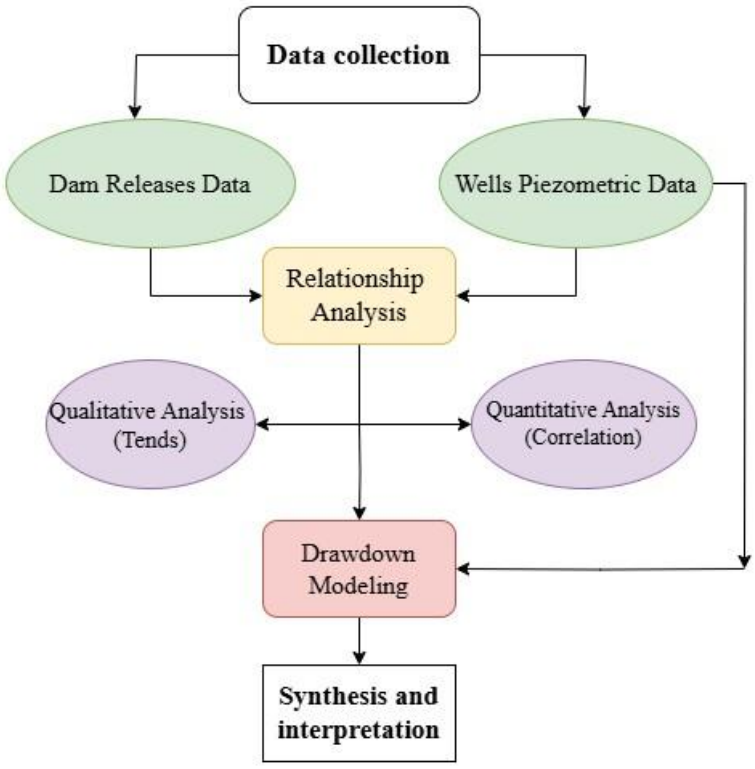


Fig. 2. Adopted Methodology.

unknown values based on an inverse-weighted distance from measured points and provides a simple and effective way to reflect the spatial variability of piezometric levels (Salehi et al., 2024). By applying IDW, the impact of water releases from Fountain of Gazelles Dam on piezometric levels could be assessed. This approach contributed to a better understanding of the recharge and drawdown mechanisms while also providing a basis for predicting future impacts of water releases on aquifer dynamics in the context of sustainable water resource management.

Results

Dam assessment and water releases

The construction of the Fontaine des Gazelles dam, with a capacity of 55 hm^3, played a major role in improving the agricultural land in the Loutaya plain, which previously suffered from poor groundwater quality. However, annual inflows vary yearly due to alternating dry and wet years. The latter often occurs as intense floods, rarely lasting more than a few days per year. This irregularity necessitates management strategies to ensure the safety of downstream settlements and the dam itself (Hachemi et al., 2025). Such variability makes it essential for water release strategies to be adaptable to different hydrological conditions, balancing flood control with water storage for future use. The volumes discharged and water released through the bottom outlet during floods were recorded over four years (2004, 2005, 2006, and 2009). The first discharge occurred in 2004, following exceptional floods in October, April, and May, with a discharged volume of 32 hm^3 and a total volume released through the bottom outlet of 8.7 hm^3. In 2009, a maximum discharged volume of 58 hm^3 was recorded due to an exceptional flood in April, with 3.76 hm^3 released through the bottom outlet. These large discharge events highlight the significant impact of intense seasonal floods on the dam's operation and the need for precise flood management strategies.

However, no further releases have been recorded since that year. The absence of further releases post-2009 indicates a potential shift in water management strategy or reduced flood events, leading to insufficient water recharge for the downstream alluvial aquifer. It is important to note that floods occurring during the high-water season contributed to the recharge of the Wadi Biskra alluvial aquifer (Fig. 3). The relationship between water releases and aquifer recharge suggests that managing floodwaters could improve groundwater replenishment, especially during dry years.

Flood events and their impact on the Wadi Biskra alluvial aquifer

Before the commissioning of Fountain of Gazelles Dam (in the year 2000), Wadi El-Hai experienced several flood events, the most significant of which occurred in September 1979, with an absolute peak discharge estimated at 467 m^3/s. During this flood, a water volume of 40.34 hm^3 was discharged (Table 1). These inflows played a crucial role in recharging the Wadi Biskra alluvial aquifer, ensuring the replenishment of the annually extracted volumes (7 x 10^6 m^3/year), a value provided by the Water Resources Directorate of the Wilaya of Biskra, as their total volumes exceeded the aquifer's storage capacity of 30 hm^3.

It is worth noting that peak flood inflows are often recorded during spring and autumn. Maximum monthly inflows are primarily observed in April and May. The volume discharged during floods was recorded over four years (2004, 2005, 2006, and 2009). After the commissioning of Fountain of Gazelles Dam, peak

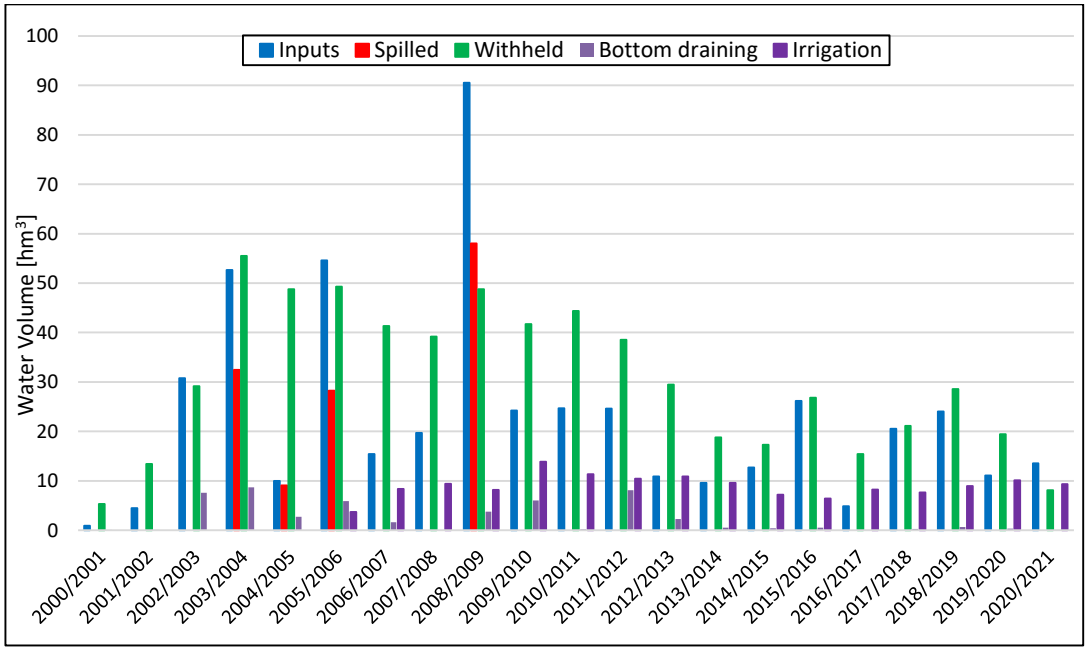
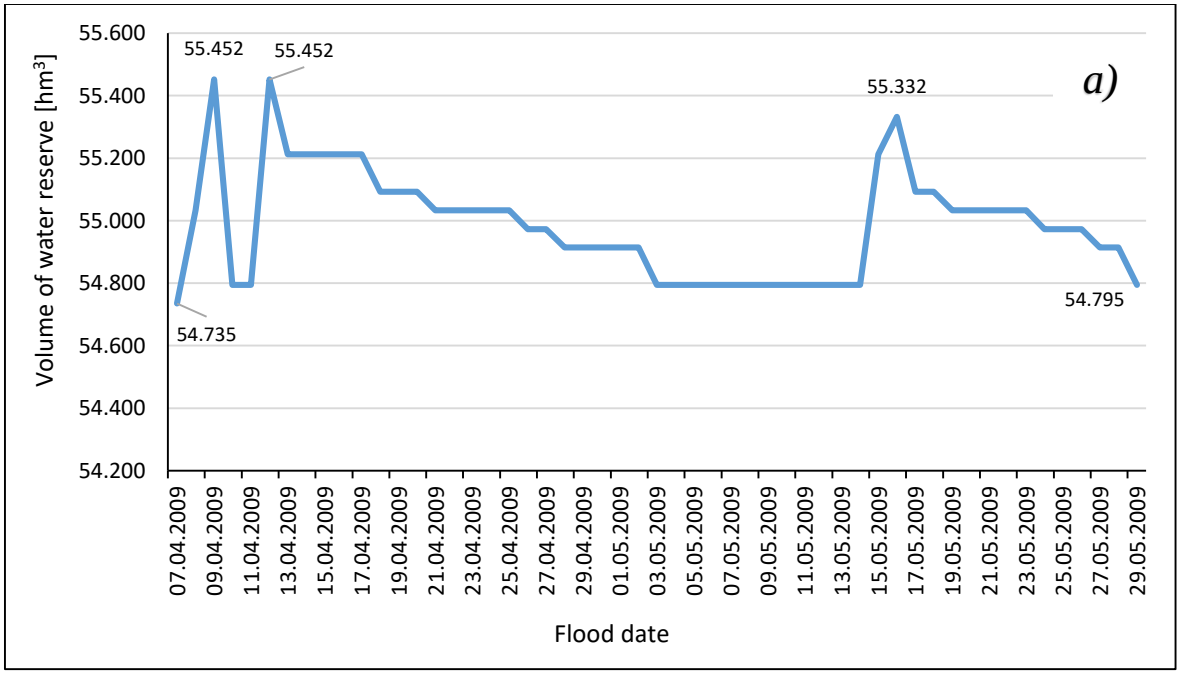


Fig. 3. Water balance of fountain of Gazelles Dam.

flood inflows continued to occur, particularly during these months. Fig. 4a shows the water reserve volume at Fountain of Gazelles Dam during the April and May 2009 floods. The graph highlights how the dam's water reserve rapidly increased, with a peak of 55.452 hm³ recorded on April 11, 2009, followed by a gradual decrease to 54.795 hm³ by May 29, 2009. These fluctuations in water reserve volume reflect the rapid inflow of water from the flood and the subsequent releases from the dam as it managed the excess water. Without such intense flood events, the dam would not have reached its maximum storage capacity, emphasizing the crucial role of peak flood inflows in replenishing the dam's capacity. Fig. 4b illustrates the volume of water flowing into Fountain of Gazelles Dam during the April and May 2009 floods. The sharp spike in water flow, with a peak of 3.897 hm³ on April 7, 2009, marks the onset of the flood. This intense inflow indicates the high volume of water entering the dam within a short period, directly impacting the dam's storage and water release strategy. As the inflow diminished over time, the volume gradually decreased, with 3.086 hm³ recorded by May 26, 2009. Fig. 4c shows the water spilled from the dam during the same period. The graph reveals substantial releases, with 3.240 hm³ spilled on April 7, 2009, followed by 2.549 hm³ released on May 22, 2009. These releases were essential in managing the floodwaters, preventing downstream flooding while also supporting the recharge of the Wadi Biskra alluvial aquifer. The large water spills during peak flood events highlight the importance of managing such releases to prevent excess water accumulation and ensure the proper functioning of the dam. However, the absence of further releases after 2009 indicates a decline in the dam's ability to support aquifer recharge. This reduction in releases signals a need for more strategic planning regarding water management. Without controlled, periodic releases, the recharge of the Wadi Biskra aquifer is jeopardized, risking long-term depletion. This underscores the importance of revisiting water release strategies to ensure the region's sustainable management of groundwater resources.

Table 1. Flood events of Wadi El-Hai before the Dam's water impoundment (Belagoune, 2012)

Flood date	Maximum daily discharge [m³ s⁻¹]	Flow volume during the flood [hm³]
1-Oct-69	294	25.4
29-Sep-70	137.1	11.84
27-Nov-71	130.6	11.28
01-July-76	294	25.4
18-May-77	272.6	23.55
2-Sep-79	467	40.34
30-Sep-86	147	12.7



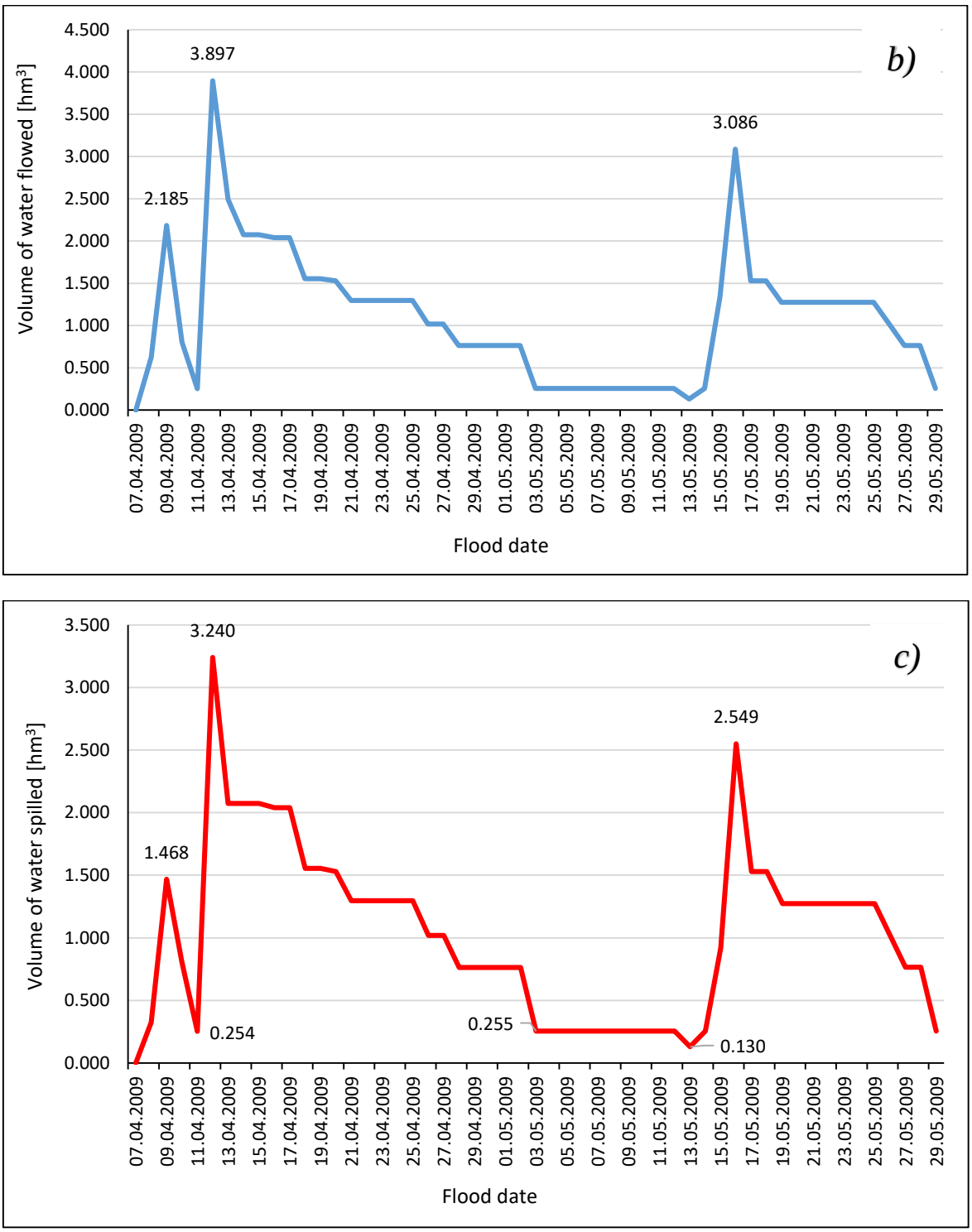


Fig. 4. Water dynamics at fountain of Gazelles Dam during the April and May 2009 floods: a) Storage volume, b) Discharge volume, and c) Water release.

Water levels of the Wadi Biskra alluvial aquifer

The curves in Fig. 5 below represent the evolution of water levels in the Wadi Biskra alluvial aquifer, measured between 1994 and 2020. These data highlight the spatiotemporal variations in water levels across several boreholes before and after the commissioning of Fountain of Gazelles Dam.

The graph in Fig. 5 shows the water levels at various wells in the Wadi Biskra alluvial aquifer from 1994 to 2020. The general trends reveal significant fluctuations in water levels, influenced by both natural events and human interventions. In 1994, before the commissioning of Fountain of Gazelles Dam, the water levels (represented in light blue) were generally higher compared to subsequent years. This suggests that the aquifer was relatively stable, with natural flood contributions likely maintaining the water levels.

The absence of controlled releases from the dam during this period, combined with natural recharge processes, likely resulted in the higher initial water levels observed in 1994. However, by 2006 (represented in green), a noticeable decline in water levels occurred across several wells, particularly around *SIF F:04* and F:01 Bis. This decline is attributed to reduced natural flood contributions and the absence of regulated water releases from Fountain of Gazelles Dam. The reduction in recharge and increasing groundwater extraction likely contributed to this decrease in water levels. This decline can be linked to the significant water storage fluctuations and releases in 2009, as seen in Fig. 4a, where the dam's storage volume increased during the peak flood events. However, without regular releases, the aquifer's water levels remained low. In 2009 (represented in dark blue), there was a slight recovery in water levels, especially in wells influenced by exceptional flood events and water releases from the dam. These releases, shown in Fig. 4b, temporarily replenished the aquifer and provided a brief respite from the ongoing decline in water levels. However, even after this recovery, the water levels in 2009 were still lower than in 1994, indicating that the aquifer's long-term recharge was insufficient to keep pace with the increasing extraction and climatic impacts. From 2012 (represented in purple) to 2020 (represented in red), the water levels show a degree of stabilization, although fluctuations remain evident. This stabilization is likely the result of local authorities implementing new water extraction fields to supply drinking water to Biskra City. As a result, the pressure on the aquifer may have been reduced, which helped mitigate the impact of over-extraction. Despite these interventions, the overall trend reveals a progressive decline in water levels from 1994 to 2020. Although specific periods, such as 2009, exhibited a temporary recovery due to floods and increased water releases, the overall water levels remain consistently lower than in 1994. This suggests that the natural recharge from floods, as demonstrated in Fig. 4c, has been insufficient to compensate for the increasing withdrawals and climatic impacts over time. The analysis of Fig. 8 reveals that, despite temporary recoveries, the long-term decline in water levels indicates that the natural recharge mechanisms, including flood contributions, have been unable to keep up with the growing water demand. This trend emphasizes the need to revisit water management strategies, as discussed in Figs 5, 6, and 7, to ensure the sustainability of the Wadi Biskra alluvial aquifer. It should be noted that the similarity observed among certain trends (e.g., 1994, 2006, and 2009, as well as between 2012 and 2020) can be explained by the fact that the wells draw from the same alluvial aquifer and are geographically close to one another, which exposes them to similar hydrogeological and operational conditions.

Relationship between dam releases and aquifer water levels

Fig. 6 illustrates the relationship between the volumes of water released from Fountain of Gazelles Dam (spillways and bottom outlet discharges) and the water levels of the Wadi Biskra alluvial aquifer between 1994 and 2020. A strong positive correlation of 0.83 is observed, which indicates that as the volume of water released from the dam increases, the water levels in the aquifer tend to rise. Conversely, reducing water releases is associated with declining water levels in the aquifer. Between 1994 and 2009, both the water releases and aquifer water levels exhibited a slight upward fluctuation, with water releases

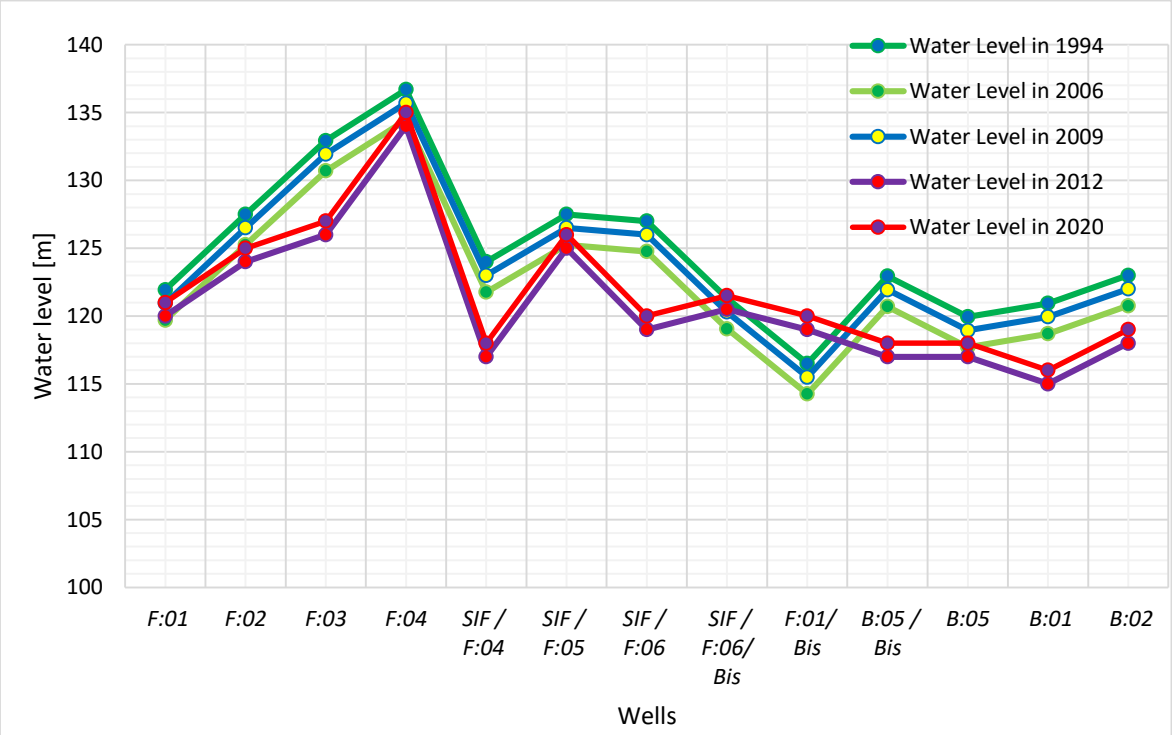


Fig. 5. Water Levels of the Wadi Biskra Alluvial Aquifer (1994–2020).

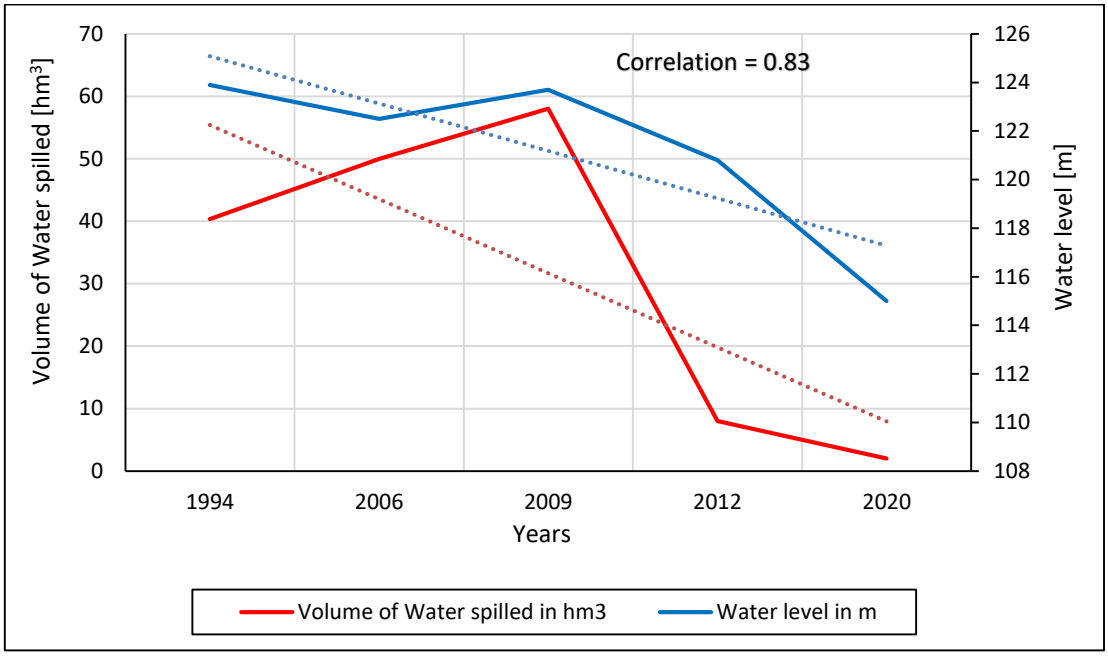


Fig. 6. Relationship between dam releases and average aquifer water levels.

peaking at around 60 hm³ in 2009 and the aquifer water level reaching approximately 124 m. This period reflects the significant recharge of the aquifer due to substantial water releases and exceptional flood events, as discussed earlier in the results. However, after 2009, a drastic reduction in water releases is observed, with the volume dropping to less than 10 hm³ by 2020. This release decrease corresponds to a significant decline in aquifer water levels, which fell to around 110 m by 2020. The marked decline in water levels during this period highlights the crucial role that regular water releases from the dam play in replenishing the Wadi Biskra alluvial aquifer. The positive correlation of 0.83 suggests that Wadi El-Hai inflows, influenced by Fountain of Gazelles Dam's releases, play a vital role in maintaining aquifer water levels. The reduction in water releases since 2009 has had a noticeable impact on the aquifer's recharge, underscoring the importance of sustainable water management practices to preserve groundwater resources in the region.

Discussion

The analysis of the isopieze contours in Fig. 7 clearly shows that the Water Impoundment of Fountain of Gazelles Dam has had a significant impact on the piezometric levels of the Wadi Biskra alluvial aquifer. Before 2000, water levels in the aquifer were relatively stable, with values recorded at 121 m in *F:01*, 123 m in *F:02*, and 117 m in *B:01*. These water levels, depicted in Fig. 8 (light blue), reflect the natural state of the aquifer before the dam's intervention. The stability in water levels before the dam's Water Impoundment suggests that natural recharge from flood events, which occurred frequently, was sufficient to maintain the aquifer's levels. However, after the Water Impoundment of the dam, a decline in water levels was observed, particularly by 2006, as shown in Fig. 5 (green). Notably, wells such as *F:01* and *F:06* experienced decreased water levels, *F:01* dropping from 121 m to 120 m, *F:06* from 121 m to 120 m, and *B:01* from 117 m to 116 m. This decline is attributed to reduced natural flood contributions due to the dam's operation and increased groundwater extraction. As seen in the study of the Tamanrasset alluvial aquifer in the South of Algeria, similar dynamics were observed, where natural flood events significantly impacted the recharge process of alluvial aquifers, and intensive groundwater extraction reduced the effectiveness of natural recharge mechanisms (Hadj-Said et al., 2024). The significant impact of flood events on water levels is evident from the 2009 flood event, which temporarily recharged the aquifer, as reflected in the increase in water levels in *F:02* and *F:06* (from 122 m to 124 m and 120 m to 123 m, respectively) as shown in Fig. 7. These fluctuations align with the volume of water stored in the dam during the flood period, depicted in Fig. 4a, which demonstrates how the dam filled rapidly, peaking at 55.5 hm³. Similar dynamics are reported in the case of the Complexe Terminal aquifer in central Algerian Sahara, where the flood-induced recharge from seasonal floods played a crucial role in replenishing aquifers. However, the recharge capacity remained limited under increased withdrawal pressure (Guendouz et al., 2003). Nevertheless, the cessation of releases after 2009 led to a continuous decline in water levels, bringing them to lower elevations than those recorded in 1994. For example, by 2020, the water levels at *F:01* had dropped to 119 m and *B:01* to 116 m, as shown in Fig. 5 (red). This shows that, despite the temporary recovery from the 2009 floods, the long-term impact of reduced releases has led to persistent aquifer depletion. The pattern observed in Fig. 4 highlights the relationship between flood events, water releases, and aquifer recharge, demonstrating that regular water releases from the dam

are crucial for maintaining groundwater levels in the Wadi Biskra aquifer.

Further analysis of water level changes between 1994 and 2020, as shown in Fig. 8, reveals that several boreholes, particularly F-03, SIF-F04, and SIF-F06, have experienced a drawdown exceeding 5 meters, with other boreholes showing less pronounced declines. These drawdowns, particularly in the western and northern parts of the aquifer, suggest that the reduced availability of floodwater recharge and the increased extraction for local needs have compounded the issue of aquifer depletion. As seen in the groundwater recharge dams in Oman, controlled releases are crucial for mitigating depletion and ensuring adequate recharge in arid regions (Abdalla and Al-Rawahi, 2013). Despite some localized recovery observed in SIF-F06-Bis and F01-Bis, where water levels have increased slightly due to a reduction or temporary cessation of extraction, the overall water level decline persists.

The analysis in Fig. 9 further supports these findings. It becomes clear that despite the annual extraction volume of 7.2 hm³, which represents only one-third of the annual inflow from Wadi El-Hai (23.27 hm³), the aquifer has still not been able to recover due to the impact of Fountain of Gazelles Dam. This suggests that while there is some compensation from the average inflow from Wadi Abdi (10 hm³), it is insufficient to offset the impacts of reduced floodwater recharge. The correlation between water releases and aquifer levels, as shown in Fig. 6, further underscores the importance of regular water releases. The strong positive correlation of 0.83 between the volume of water released and aquifer water levels indicates that aquifer levels tend to rise as water releases increase, and vice versa. Between 1994 and 2009, water levels fluctuated with releases, reaching a peak in 2009, aligning with the high discharge recorded in that year. However, since 2009, the sharp decline in releases has been mirrored by a steady drop in water levels, highlighting the critical role of controlled water releases play in replenishing groundwater reserves. This pattern is consistent with findings from other recharge studies, where artificial recharge methods significantly contributed to replenishing aquifers in arid areas (Abdalla and Al-Rawahi, 2013). The Discussion reveals that Fountain of Gazelles Dam's operation, especially its water release strategies, has profoundly impacted the recharge of the Wadi Biskra alluvial aquifer. While natural recharge mechanisms like floods temporarily assist in replenishing the aquifer, sustainable water release practices are necessary to ensure long-term

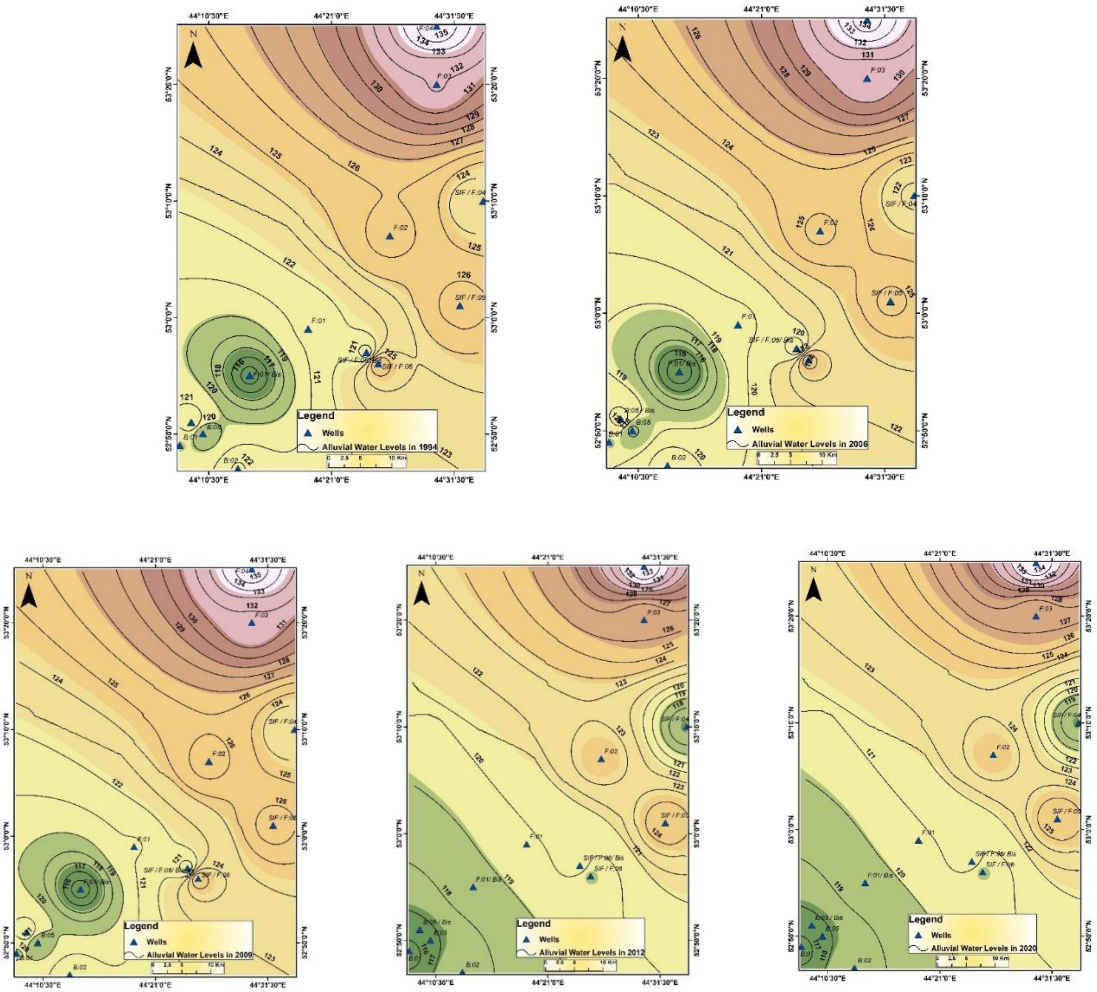


Fig. 7. Isopieze contours of the Wadi Biskra alluvial aquifer (1994–2020).

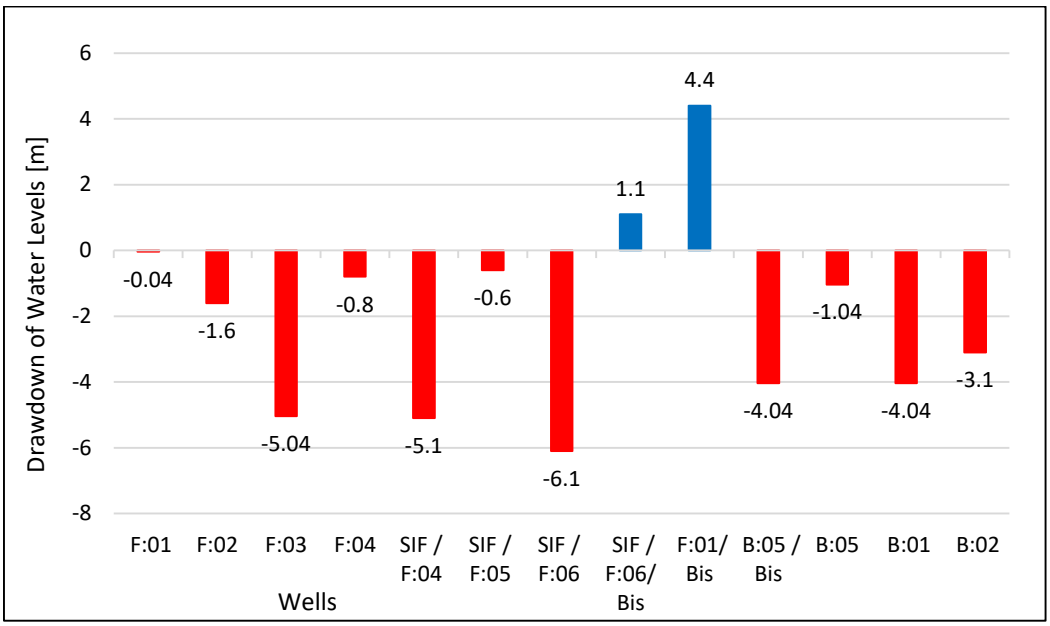


Fig. 8. Drawdown of water levels in wells extracting from the Wadi Biskra alluvial aquifer (1994–2020).

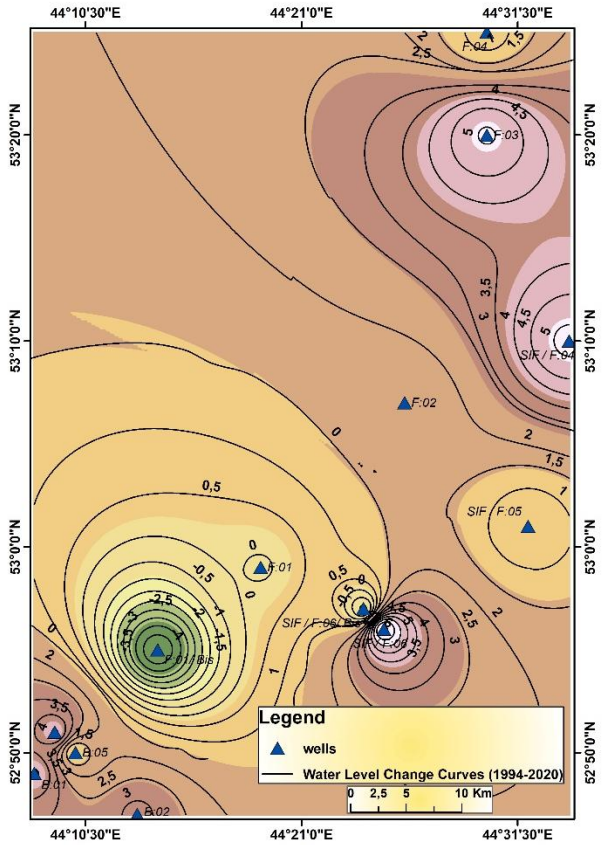


Fig. 9. Drawdown curves of water levels in the Wadi Biskra alluvial aquifer (1994–2020).

groundwater sustainability. Without controlled releases, the Wadi Biskra aquifer will continue to face depletion, highlighting the need for comprehensive and strategic water management. Furthermore, the observed increase in the piezometric level in wells F:01/Bis and SIF/F:06/Bis can be explained by local recharge effects and hydraulic connections with nearby surface water or less exploited areas. These wells are located in areas where the aquifer is more confined and closer to recharge zones, which can lead to a temporary rise in the water level, particularly after periods of rain or a reduction in pumping activity in adjacent wells.

Conclusion

The construction of Fountain of Gazelles Dam has significantly contributed to enhancing agricultural land in the Loutaya plain, an area previously struggling with poor groundwater quality. However, the sustainability of these hydraulic developments is now at risk due to increasing challenges such as evaporation, siltation, and pollution. These challenges are exacerbated by the dam's regulation of inflows from Wadi El-Hai, which has severely disrupted the natural recharge of the Wadi Biskra alluvial aquifer, traditionally replenished by seasonal floodwaters. This disruption has led to significant drawdowns in water levels, especially in boreholes extracting from the aquifer, with some wells showing a decrease in water levels by up to 5 meters. Notably, the static water level in well F-01, for example, dropped from 121 m to 119 m by 2020, a decrease directly linked to reduced floodwater contributions and altered water release strategies. The analysis of isopieze contours and the correlation between water releases from Fountain of Gazelles Dam and piezometric levels demonstrate that the water releases significantly contribute to aquifer recharge. However, since 2009, the cessation of regular water releases has led to a decline in water levels, which have only stabilized at significantly lower elevations than those observed before the dam's Water Impoundment. These fluctuations underscore the importance of consistent and adaptive water management strategies, particularly in arid and semi-arid regions, to mitigate the long-term impacts of such drawdowns. Furthermore, the study's findings align with similar studies in other regions, such as Tamanrasset, Algeria, where controlled releases had a crucial role in aquifer recharge (Hadj-Said et al., 2024). Despite limitations in data availability, this study provides a crucial foundation for understanding the relationship between dam operations and aquifer dynamics. For instance, the negative impact on the Wadi Biskra aquifer is visible, with significant drawdowns recorded between 1994 and 2020. Future research incorporating more comprehensive datasets or advanced analytical techniques, such as continuous monitoring or more refined spatial modeling, could further refine these findings. Such studies would deepen our understanding of regional hydrological dynamics and inform more sustainable water management practices to ensure the long-term viability of groundwater resources in the region.

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