

Assessment of Artificial Recharge Efficiency Against Groundwater Stress in the El Khairat Aquifer

M. Zammouri, N. Brini and F. Jarraya Horriche

1 Introduction

In semi-arid regions, aquifers are mainly recharged by infiltration of flood water through beds of ephemeral streams (wadis). A good knowledge of aquifer recharge is recommended for the efficient and sustainable groundwater resources.

Today, in Tunisia, most aquifers show signs of stress manifesting by a continuous decline of the water table and a drying up of natural outlets, due to an excessive increase of groundwater extraction. To remedy this, Tunisian manager policy is oriented towards the development of surface water mobilization works (dams, benches etc.). Many upland dams are used for artificial aquifer recharge by releasing the reservoir water. Direct and indirect measurements of artificial aquifer recharge are expensive. Modeling can be a useful tool to assess the artificial groundwater recharge effectiveness.

2 Objectives

The El Khairat aquifer, which is located in the eastern center of Tunisia, is affected by the groundwater extraction. The construction of El Khairat dam upstream of the plain has harmed the aquifer recharge as no artificial recharge operations were carried out during the first three years following the dam construction. Since 2000, many artificial recharge operations were carried out by Tunisian Water Authorities

M. Zammouri (✉) · N. Brini
Faculty of Sciences of Tunis, University of Tunis El Manar, 2092 Tunis, Tunisia
e-mail: z_mounira@yahoo.fr

F. Jarraya Horriche
Georesources Laboratory, Centre of Research and Water Technologies,
Technopole Borj Cedria, BP273, 8020 Soliman, Tunisia

to re-establish the natural recharge. They consisted of releasing water from the El Khairat reservoir to the natural downstream bed of the wadi channel.

This paper aims to assess the efficiency of the artificial groundwater recharge campaigns carried out in the El Khairat alluvial plain. Data from the Tunisian agencies responsible for the management of water resources (DGRE and CRDA of Sousse) have been collected and explored. A conceptual model is used to evaluate the artificial recharge of El Khairat aquifer. The model findings are analyzed to determine the factors and constraints influencing the yield of this technique of artificial recharge and to compare the groundwater recharge corresponding to artificialized regime to the recharge occurring in natural conditions.

3 Materials and Methods

3.1 Study Area Description

The El Khairat plain, extending over an area of about 63 km² (Fig. 1), is characterized by a semiarid climate with an aridity index of 11.5 mm/°C, a yearly potential evapotranspiration reaching 1,730 mm and erratic annual rainfall ranging from 39 to 744 mm over the period 1972–2015. The plain contains an alluvial aquifer which is important for the economic activity of the region. The geology of the alluvial plain is dominated by tertiary and quaternary deposits. The alluvial deposits are constituted by pebbles, gravel, sand and clayey sand. The alluvial thickness is variable and can exceed 100 m in the centre of the plain. The bedrock of the alluvial deposits consists of late Eocene marls or Mio-Pliocene clays.

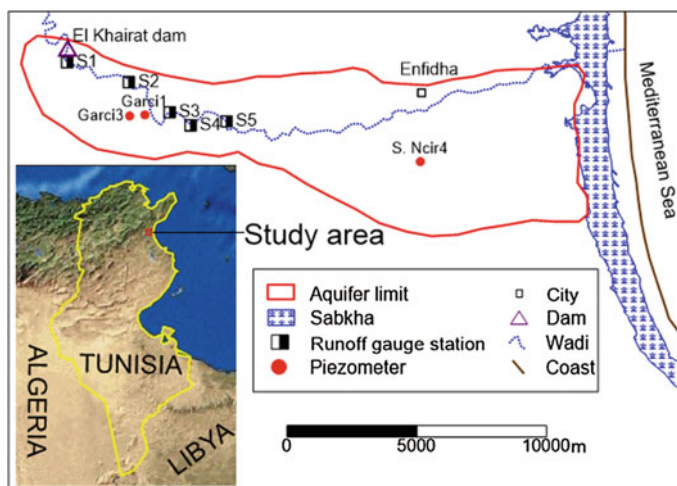


Fig. 1 Location and overview of the El Khairat plain

The aquifer is recharged mainly by infiltration of water from flood events. The El Khairat wadi is the most important stream. In 1999, El Khairat wadi was dammed upstream of the plain in order to protect the Enfidha town against flooding. Between 2002 and 2015, part of the stored reservoir water was released to the natural downstream bed of the wadi channel for artificial aquifer recharge.

3.2 Conceptual Modelling of the Groundwater Recharge

The groundwater recharge is one of the most hard water balance terms to assess, often poorly known. It involves open-channel flow, infiltration into the unsaturated zone and saturated groundwater flow. Using direct or indirect measurements to assess the groundwater recharge (Dassi et al. 2005; Sophocleous 1991; Xi et al. 2008) are expensive and difficult to implement at the regional level.

Conceptual modelling is a good alternative approach to model the recharge mechanism (Hernandez 2000; Hughes 1995; Zammouri and Feki 2005). This approach is used in modelling of artificial groundwater recharge by water releases from the El Khairat reservoir. The wadi bed is divided into several serial reaches. Each reach considered to be an entity with homogeneous characteristics flows into the downstream one. The model input consists of the daily water volume released from the dam. For each reach, the production function is represented by a soil storage zone and four transfer reservoirs (Fig. 2). The conceptual model structure was described in details in a previous paper (Zammouri and Feki 2005).

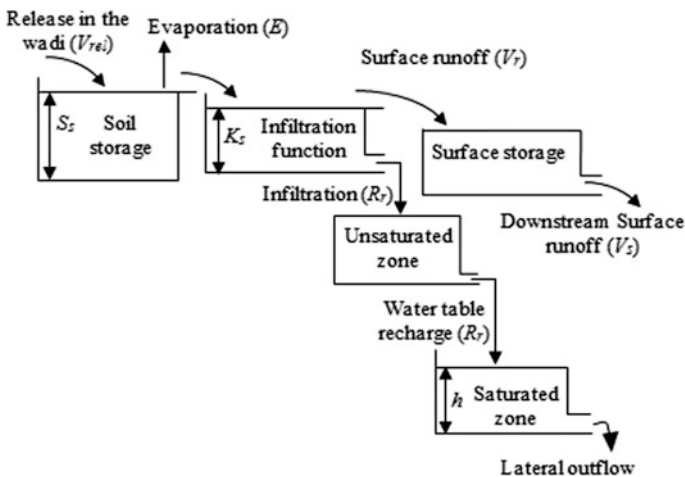


Fig. 2 Structure of the conceptual model showing the linkage between the different reservoirs

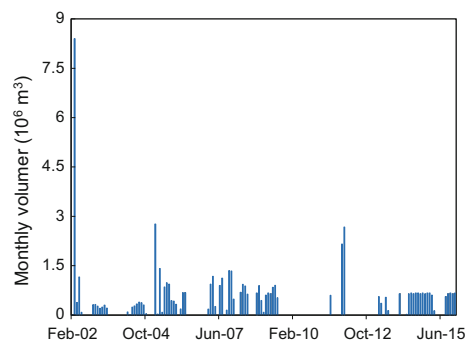
Daily released water (V_{rel}) from the El Khairat reservoir enters the soil storage zone, which retains all moisture until the storage (S_s) is full. The storage is emptied by evapotranspiration (E). Actual evapotranspiration occurs at the potential rate. The first transfer reservoir having a finite capacity (K_s) controls the amount of moisture that infiltrates into the soil (R_r). Overflow from this reservoir constitutes the surface runoff (V_r). The second transfer reservoir is a surface storage zone. It is aimed to the runoff routing through the wadi course according to an exponential depletion and allows calculating the effective runoff (V_e). The third transfer reservoir represents the unsaturated zone. It allows defining the infiltration function delay. The fourth transfer reservoir represents the saturated zone. It is characterized by the water table level (h), which is calculated by applying the water balance for the groundwater reservoir under unsteady conditions.

Since 2002 onwards, several artificial recharge operations were carried out by CRDA of Sousse. The annual released water ranged from $1.2 \times 10^6 \text{ m}^3$ in 2003 to $10.7 \times 10^6 \text{ m}^3$ in 2002, with daily volume varying between 4000 and 79,500 m^3 . The recharge operation may last from one month to one year. For the dry years such as 2010, there was no artificial recharge operation (Fig. 3).

Measurements of the surface runoff are available only for the first recharge campaign carried out over the period 2/28/2002–6/8/2002. During this campaign, flood routing was controlled by five runoff gauging stations (Fig. 1). Accordingly, the El Khairat wadi bed was divided into four reaches, in relation to the runoff gauging location, with a total length of 9.7 km, downstream the El Khairat reservoir.

The calibration of the model consists of reproducing the daily surface runoff volume observed at the runoff gauging stations as well as the water table level observed at the piezometers located in close proximity of the wadi course. The reference period for the calibration of the surface runoff is 2/28/2002–4/18/2002 while the validation is carried out over the period 4/19/2002–6/8/2002. For the groundwater flow, calibration is carried out over the period 2/28/2002–11/20/2003.

Fig. 3 Historical released water in the artificial campaigns carried out over the period 2002–2015



4 Results and Discussion

The calibration process indicates the high model sensitivity to the infiltration capacity (K_s) and the depletion parameter of the superficial storage reservoir, which describe the runoff routing technique. The calibration results are of good to medium quality. The correlation coefficient varies between 0.5 and 0.93 and the coefficient of efficiency ranges from 0.21 to 0.8. Figure 4 shows model calibration results at the runoff gauging station S2 as well as the observation well Garcí3.

The simulated water balance of the artificial groundwater recharge operations over the period 2/28/2002–11/20/2003 indicates an infiltration coefficient ranging between 40 and 80% of the released water. Evaporation losses are insignificant, in general lower than 1%. Losses by surface runoff beyond the permeable part of the wadi course can be important. They are strongly related to the releases discharge rate, which varied on average between 0.25 and 0.5 m³/s. High discharge rates of flood waves reaching sometimes 0.9 m³/s involved significant losses by runoff of up to 30%.

The calibrated model is used to simulate the artificial recharge operations carried out over the period 2002–2015. The yearly groundwater artificial recharge over this period varied between 10⁶ m³ and 5.3 × 10⁶ m³ (Fig. 5), with an average value of

Fig. 4 Model calibration and validation results: **a** comparison between the observed and simulated streamflow volumes; **b** temporal reproduction of water table level

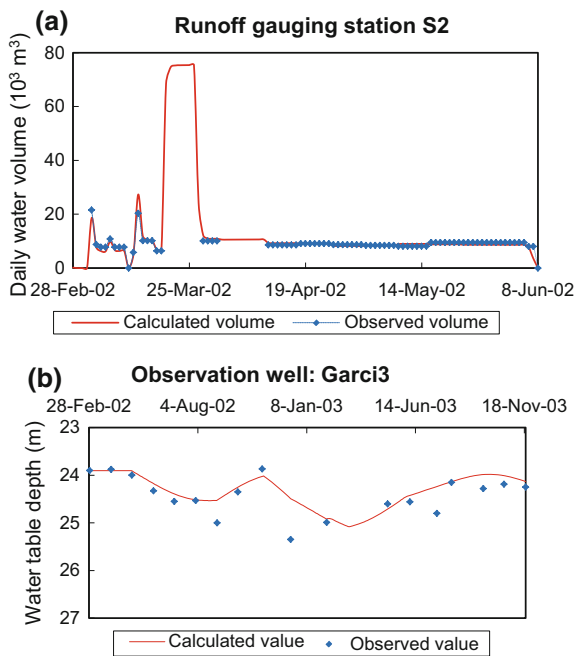
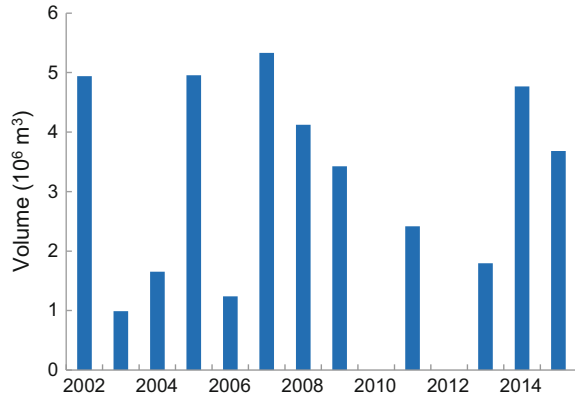


Fig. 5 Calculated artificial groundwater recharge



$2.8 \times 10^6 \text{ m}^3/\text{year}$. It was null in the years 2010 and 2012 because of the absence of recharge operations. These values are still below the mean natural recharge rate estimated between 6×10^6 and $10.5 \times 10^6 \text{ m}^3/\text{year}$ (Manaa et al. 1996; Brini and Zammouri 2016).

The important deficit in recharge is due to the absence of artificial recharge operation in 2010 and 2012 and to low released water in several years. The analysis of the historical artificial recharge operations carried out over the period 2002–2015 indicate a total released water of $59.4 \times 10^6 \text{ m}^3$, with a mean yearly value of $4.2 \times 10^6 \text{ m}^3$ and a standard variation of $3.2 \times 10^6 \text{ m}^3$. This is inconsistent with one of the objectives of El Khairat wadi damming that consists of mobilizing large flood waters for groundwater artificial recharge. The maximum released volume of $10.7 \times 10^6 \text{ m}^3$ in 2002 doesn't reach the capacity storage of the El Khairat reservoir equal to $13 \times 10^6 \text{ m}^3$.

The released water quantities seem to be insufficient to compensate the groundwater recharge in natural conditions. However, as shown in Fig. 6, the piezometric level at piezometers located in close proximity of the potential recharge area such as Garci1 shows rather a rising trend while piezometers located far from the recharge area such as S. Ncir4 show, in general, a groundwater level decreasing (Brini and Zammouri 2016). On the other hand, the analysis of the impact of artificial groundwater recharge on the groundwater quality showed a slight decrease of the salinity in the zone located near the recharge site (Ketata et al. 2011). This confirms the high rate infiltration in the vicinity of the wadi.

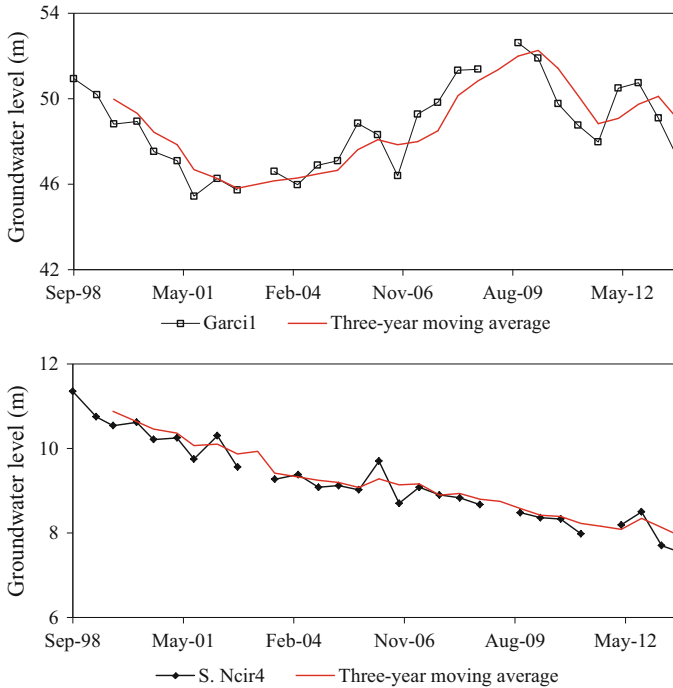


Fig. 6 Observed groundwater level (above sea level) at selected observation wells

5 Conclusion

The results of the artificial groundwater recharge modelling indicated high infiltration rates and insignificant evaporation losses. Losses by surface runoff beyond the permeable part of El Khairat wadi were large when the releases discharge rates were high. To avoid this, releasing water at discharge rate lower than $0.3 \text{ m}^3/\text{s}$ is recommended. The calculated mean groundwater artificial recharge over the period 2002–2015 is $2.8 \times 10^6 \text{ m}^3/\text{year}$. It is low compared to the mean value corresponding to the groundwater recharge in natural conditions. At present, the El Khairat reservoir is used for artificial recharge and cereal irrigation. The artificial recharge yield can be improved if the reservoir will be exclusively used for the groundwater artificial recharge. The artificial recharge effect is mainly located along the permeable course El Khairat wadi, in the upstream of the plain. It is advisable to extend the technique of artificial groundwater recharge in remote areas affected by groundwater extraction activity in the aquifer.

References

- Brini N, Zammouri M (2016) Groundwater recharge modelling in semi-arid regions; a case study of El Khairat alluvial plain (Tunisia). *QJEGH* 49(3):229–236. doi:[10.1144/qjegg2015-084](https://doi.org/10.1144/qjegg2015-084)
- Dassi L, Zouari K, Faye S (2005) Identifying sources of groundwater recharge in the Merguellil basin (Tunisia) using isotopic methods: implication of dam reservoir water accounting. *Environ Geol* 49:114–123
- Hernandez M (2000) Modeling runoff response to land cover and rainfall spatial variability in semi-arid watersheds. *Environ Monitor Assess* 64:285–298
- Hughes DA (1995) Monthly rainfall–runoff models applied to arid and semi arid catchments for water resource estimation purposes. *Hydrol Sci J* 40(6):751–769
- Ketata M, Gueddari M, Bouhlila R (2011) Hydrodynamic and hydrochemical evolution of groundwaters during artificial recharge: a case study of El Khairat aquifer system in Enfidha (Tunisian Sahel). *J Appl Sci Res* 7(3):286–293
- Manaa M, Chaieb H, Amri R (1996) Etude par modèle hydrogéologique de la nappe alluviale de l’oued El Khairat. DGRE, Ministry of Agriculture, Tunisia
- Sophocleous MA (1991) Combining the soil water balance and water-level fluctuation methods to estimate natural groundwater recharge: practical aspects. *J Hydrol* 124:229–241
- Xi C, Zhang Z, Zhang X, Chen Y, Qian M, Peng S (2008) Estimation of groundwater recharge from precipitation and evapotranspiration by lysimeter measurement and soil moisture model. *J Hydrol Eng* 13(50):333–340
- Zammouri M, Feki H (2005) Managing releases from small upland reservoirs for downstream recharge in semi-arid basins (Northeast of Tunisia). *J Hydrol* 314:125–138