Efficiency of the groundwater artificial recharge from dam water release in arid area

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Abstract: This paper describes a methodology to estimate the groundwater artificial recharge efficiency. The water table fluctuation method (WTF), stream-flow (SF) estimation method and Hydrus-1D model are used to estimate the effective water quantity reaching the aquifer. The efficiency of the stream flooding on groundwater level trend was discussed based on groundwater table fluctuation. The comparison between the three methods is found to be valuable for determining the range of plausible recharge amounts and for highlighting the uncertainty of the estimates. SF method yields the largest recharge estimate whereas the WTF method provides actual recharge reaching the aquifer. SF method and Hydrus-1D model show the best fit between estimated recharge volume and water volume released with a coefficient-of-determination ($R^2$) of 0.9 and 0.8, respectively. The combination of the stream flow with water-table fluctuations methods is recommended to increase the constancy of recharge estimates and preliminary assessment.

Keywords: artificial recharge; assessment; stream infiltration; groundwater; water level.

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1 Introduction

In arid and semiarid areas, the recurrence of rain drought combined with groundwater overexploitation has a direct consequence on the water table decline and the critical status of groundwater natural recharge. This situation causes a serious concern in regions with large groundwater demand (Triki et al., 2013). One of the main issues to this fact is the artificial recharge of groundwater to maintain the native water table level (Abdalla and Al-Rawahi, 2012; Al-Assad and Abdulla, 2010; Alderwish, 2010; Jacenkow, 1984; Scanlon et al., 2006; Sharda, 2006). The artificial recharge as a groundwater management
tool intends to provide storage space free of cost, to avoid evaporation losses and to allow the use of stored water in dry seasons (De Vries and Simmers, 2002; Du et al., 2013).

Figure 1 Flowchart for groundwater recharge estimate

The efficiency of any aquifer artificial recharge program depends on the quantity of water reaching the water table which is generally assessed by several methods with different accuracy.

Allison et al. (1994), Scanlon et al. (2002) and Sophocleous (1991) discussed various approaches for estimating recharge in arid and semiarid areas mainly based on physical and chemical methods. The analysis of water table fluctuations method (WTF) is considered a useful tool for determining the magnitude of both short- and long-term changes in groundwater recharge and has been widely applied under arid and semiarid conditions (Healy and Cook, 2002; Maréchal et al., 2006; Takounjou et al., 2011).

The hydrological budget method accounts for all inflow and outflow, as well as storage changes in the unsaturated and saturated zones. Some of the latest reviews of existing approaches and case studies in the field of groundwater recharge simulation have been reported by several researchers (Chien and Fang, 2012; He et al., 2008; Grinevskii
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The Hydrus-1D model was used by many authors for the simulation of water movement in soil (Kanzari et al., 2012; Leterme et al., 2012; Suleiman, 2008). Such a model should describe the location, timing and probable mechanisms of recharge and provide initial estimates of recharge rates based on several factors: climate, topography, land use/cover, soil, geomorphology and hydrogeology, etc.

In this paper, a methodology using a variety of groundwater recharge assessments discussed based on the case of Nadhour-Saouaf artificial recharge site in Tunisia using water release from hill dams. The artificial recharge groundwater in Nadhour-Saouaf aquifer was estimated using the WTF method, stream-flow water balance estimation method (SF) and Richard soil water balance model (Hydrus-1D). Hence the flow chart of the methodology developed in this work is shown in Figure 1.

2 Materials and methods

2.1 Study area

The Nadhour-Saouaf syncline, located in Northern Tunisia, extends over an area of 400 km² between mountains in the North and the Northwest and alluvial ranges in the South (Figure 2). The climate is mostly semiarid, with hot dry summer and wet winter. The mean annual precipitation is 400 mm and the mean annual temperature is 18°C. The evaporation far exceeds the rainfall with a mean annual amount of 1,560 mm. This region has a rather unstable climate with irregular rainfall quantity and highly variable spatial distribution (Ali et al., 2016).

The high relief of the syncline area favoured the development of a relatively dense stream system with a several wadis running across the basin characterised by fluviatile deposits of highly permeable coarse sediments (Kacem, 2008).

The geological outcrops of the syncline structure of Nadhour-Saouaf area include Eocene, Oligocene, Miocene, Pliocene and Quaternary deposits (Figure 3) with a dominance of Mio-Plio-Quaternary ones. The lower part of the Miocene constitutes detrital deposits (intercalation of clay and sandstone). The Oligocene is mainly composed of coarse sandstone and occupies the main aquifer recharge area. The Eocene includes the Souar and Metlaoui formations. The upper Eocene composed of a thick impermeable sequence of clay or marl of the Souar formation constitutes the substratum of the superficial aquifer.

The groundwater aquifer is mainly recharged by runoff infiltration through the wadi bed after heavy rain (Zammouri and Feki, 2005). Therefore, the groundwater exploitation in this district started at the beginning of the Roman period after the first discovery of valuable spring water resource (Hamza, 1990). In the years 2000s, the total number of pumping wells increased rapidly and consequently the total extraction volume reached $5.2 \times 10^6$ m³ in 2007. As a direct impact of increased water abstraction, the groundwater level decline was propagated to the entire aquifer in the study area. Consequently, the groundwater became overexploited as its natural recharge by rainwater cannot maintain a positive hydrological balance. To improve natural recharge regime of the water table artificial groundwater recharge infrastructure was implemented in Nadhour-Saouaf region.
and consists of releasing water from hill dams in the wadi bed. The total length of the artificial recharge river bed is about 11.5 km downstream the Saadine hill dam.

**Figure 2** Location of the study area

**Figure 3** Hydrogeological cross section
2.2 Artificial recharge operation and monitoring

The water release from dams is one of the artificial recharge methods that are used extensively to replenish groundwater, especially in arid regions (Al-Turbak et al., 1989; Sendil et al., 1990). In the study area, surface water runoff is collected by means of a small upland reservoir (the Saadine hill dam) built in 2001 with a storage capacity of $3.6 \times 10^6 \text{ m}^3$. Between 2003 and 2012, eight artificial recharge operations were carried out by the Tunisian water resource authority (DGRE), using water collected at the Saadine hill dam. The artificial recharge consisted of water release from the dam reservoir in the stream bed. The volume released is directly related to rainfall and ranged between $0.4 \times 10^6 \text{ m}^3$/year and $2.5 \times 10^6 \text{ m}^3$/year. During the recharge operation, one to several flood waves per day through the wadi bed are released. The flood duration ranged from 16 h/day to 24 h/day. The total duration of recharge operation ranged between 28 days and 196 days (DGRE, 2003–2012). The control of the flood recharge wave is ensured by many runoff-gauging stations. However, four piezometers were installed for the monthly monitoring of the effect of the artificial recharge on the groundwater level.

2.3 Quantitative estimation of groundwater artificial recharge

The artificial recharge assessment was investigated in the Nadhour-Saouaf area using three methods.

2.3.1 Water-table fluctuation method

The WTF method assumes that a water-level rise of an unconfined aquifer is caused by recharge coming to the water table considered with a constant specific yield. The attractiveness of the WTF method comes from its less data requirement, its simplicity and its ease to use. The WTF method has no assumptions on mechanisms by which water infiltrates through the unsaturated zone; therefore, the presence of preferential flow paths within the unsaturated zone in no way restricts its application. The method works best over short periods for shallow water tables that display sharp water-level rises and declines following recharge events (Scanlon et al., 2002; Yin et al., 2011). The WTF links the change in groundwater storage with resulting WTF through the storage parameter or specific yield in unconfined aquifer (Maréchal et al., 2006). It can also give information on temporal and areal recharge variations (Sophocleous, 1991). The WTF is considered one of the most promising and attractive in humid environment and semiarid areas (Takounjou et al., 2011; Xu and Beekman, 2003).

The recharge estimate by WTF method is calculated using equation (1).

$$ R = S_y \frac{\Delta h}{\Delta t} $$

where $S_y$ is the specific yield and $\Delta h$ is the water-table elevation variation on the time span $\Delta t$.

Despite its simplicity and the abundance of available data (Healy and Cook, 2002), the accuracy related to this method depends on the assumption that water-table fluctuations are caused by recharge and not by other factors such as evapotranspiration,
changes in atmospheric pressure, the presence of entrapped air ahead of a wetting front, extraction of water by pumping and temperature effects (Healy and Cook, 2002; Yin et al., 2011). Additionally, careful examination of water-level records in conjunction with rainfall data is necessary in order to correctly identify water-level rises that can be attributed to artificial recharge events. Hence, the selected monitoring wells for groundwater artificial recharge estimate (Pz1, Pz3 and Pz9) are not affected by pumping and located near the wadi bed.

2.3.2 SF estimation method

The SF method uses the water budget concept to estimate the groundwater recharge from water released in the stream bed. The equation of the water budget may be written as follows

\[ R = Qin - Qout - E - \Delta S \]  

where \( R \) is the recharge from stream infiltration [L\(^3\)/T], \( Qin \) is the upper inflow [L\(^3\)/T] and \( Qout \) is the lower outflow [L\(^3\)/T] measured in the runoff gauging stations respectively. \( E \) is the evaporation from surface water [L\(^3\)/T] and \( \Delta S \) is the change in the unsaturated zone water storage.

2.3.3 Hydrus-1D model

Hydrus-1D (Simunek et al., 2008) simulates one dimensional water flow in variably saturated media in various time steps. For the simulation of water flux, induced by artificial recharge, the Hydrus-1D model Version 4.14 is used. The input parameters used in the model were precipitation (cm/day), daily evaporation (cm/day) and daily water volume released from the hill dam. The variable pressure head/flux type was used as the top water flow boundary condition and the constant pressure head type was selected as the bottom water flow boundary condition.

Unsaturated zone lithology and the depth to the groundwater describe the model set up layer. The depth to groundwater at Saadine zone ranges from 30 to 38 m and composed of unconsolidated fluvial deposits. Based on available boreholes data, beneath the top soil, the lithology composition is almost entirely sandy with minor amount of clay. However, layer with a mixture of gravelly sand is observed between depths of 2 m and 21 m. For depths from 21 to 27 m, the textural layer is identified as clay loam. The sediment composition of the bottom substrate is of clayey sand type. Before the running experiments, Van Genuchten hydrodynamic parameters \( \theta_r \) (residual water content), \( \theta_s \) (saturated water content), \( K_s \) (saturated hydraulic conductivity) and empirical shape factors \( \alpha \), \( n \) and \( m \) were determined from the Hydrus-1D catalogue and the literature for each layer (Table 1).

<table>
<thead>
<tr>
<th>Layer (cm)</th>
<th>( \theta_r ) (cm(^{-1}))</th>
<th>( \theta_s ) (cm(^{-1}))</th>
<th>( K_s ) (cm/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–2,000</td>
<td>0.0450</td>
<td>0.1452</td>
<td>6.8712.8</td>
</tr>
<tr>
<td>200–21,000</td>
<td>0.010.390</td>
<td>0.4531000</td>
<td></td>
</tr>
<tr>
<td>2,100–27,000</td>
<td>0.0950,0410,0191,316.24</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2,700–38,000</td>
<td>0.10.380,0.271,232.88</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
3 Results and discussion

3.1 Water-table fluctuation method

In the study area, groundwater levels were monthly recorded in three piezometers (Pz1, Pz3 and Pz9) for artificial recharge monitoring (Figure 2). For the WTF method application, the required specific yield was obtained from pumping tests. Aquifer tests conducted over a period of hours are used to obtain Sy and integrated over large areas. In the study area, groundwater is mined from the Oligocene and Miocene sandstone, which has a narrow variation in specific yield. The synthetic value used is 0.25.

The water level fluctuation (Δh) for each recharge operation is calculated as the difference between the peak of the rise and the low point of the extrapolated antecedent recession curve at the time of the peak. To estimate the amount of apparent recharge reaching the aquifer from the water released in the stream bed, the WTF method was applied based on the equation (1) for the time period 2003–2012. The recharge rates range from 0.7 to 8.2 mm/day (Table 2) and seem to be strongly related to the water volume released.

The data on groundwater level fluctuation and the estimated recharge against the water volumes released are plotted in Figure 4(a). A linear correlation is observed for the high and low release values which are being associated to the high and low values of groundwater-level fluctuation with a coefficient-of-determination ($R^2$) of 0.8. However, the relationship between the recharge rate and the release volume shows a quite moderate coefficient-of-determination ($R^2$) of 0.6.

3.2 Hydrus-1D simulation

The results of simulations contribute to quantitatively evaluate the effect of water release on the groundwater recharge. On the other hand, the total amount of recharge calculated using the Hydrus-1D flux shows a wide range of values from 0.11 to 1.19 million cubic metres representing 37 to 92% with an average of 58% of the total water volume released (Table 2). This estimated value is in line with Nazoumou and Besbes (2001) who estimated the amount of recharge to 65% of water released volume. For all recharge operations cumulating a water release of $1.5 \times 10^6$ m$^3$ or more, the estimated aquifer recharge is quite steady and not sensitive to the total volume released [Figure 4(b)] but it is positively affected by higher floods duration. The estimated recharge and released volumes show a proportional linear behaviour [bold line in Figure 4(b)] with a coefficient-of-determination ($R^2$) of 0.8 indicating a well interdependent volumes.

3.3 SF estimation method

In order to estimate the stream infiltration, the flow data of the recharge wave over the Saadine stream bed were collected from 2003 to 2012. Meteorological data needed by SF method to estimate evaporated volume from surface water released in the wadi bed was daily evaporation. In this study, data were collected from the Mogranmeteo-station in the Zaghouan city. During the entire period of study, the calculated evaporated water volume varied from $5.9 \times 10^3$ to $128.7 \times 10^3$ m$^3$ for 2009 and 2007 respectively. For the
evaluation of the unsaturated water storage ($\Delta S$) the mass balance of Hydrus-1D was used. The considered ($\Delta S$) volume was estimated to $0.25 \times 10^6$ m$^3$.

Using the SF method, the stream infiltration amount is found between 31 mm/day and 102 mm/day. The coefficient-of-determination ($R^2$) of estimated recharge as a function of the water volume released is of 0.9 indicating a high linear trend. As indicated in Table 2, the total amount of the estimated recharge volume using the SF method ranges between 0.25 and $2.06 \times 10^6$ m$^3$. This corresponds to 81 to 95% of the released water volume and an average of 87%. The high efficiency of artificial recharge via releasing water from hill dam in the stream bedwas reported by Zammouri and Feki (2005) to reach an average volume of recharge of 96% of the released water volume.

3.4 Discussion of the three estimation methods

The summary of the results of groundwater calculation by various methods is shown in Table 2. For all recharge periods, the largest recharge estimates were determined using the SF water budget model and the unsaturated water flux model using Hydrus-1D reflecting potential recharge rate in the stream bed. This is expressed by a mean recharge rate of 3 mm/day reaching the aquifer estimated by the WTF method. However, the SF method and the Hydrus-1D small difference comes from the fact that Hydrus-1D uses an amount of released water for vadose zone saturation. The correlation between the results of SF method and the Hydrus-1D shows a positive relationship with a coefficient-of-determination ($R^2$) of 0.9.

Hence, the estimate using unsaturated water flux concept with Hydrus-1D may be considered as a preliminary result. The SF method yields reasonable estimates and this method is considered as useful and promising for variable climate conditions (Misstear et al., 2009; Yin et al., 2011).

3.5 Effect of artificial recharge on groundwater level

In order to determine the effect of artificial recharge on groundwater level trends, the changes in the water-table over a nine years period, based on groundwater table measurements, the recharge operations and the monthly rainfall variations are plotted (Figure 5). From 2001 to 2003, the groundwater level declines due to continuous groundwater overdraft and rainfall scarcity. By increasing the monthly rainfall in 2007, an increase in the groundwater level in piezometers Pz1, Pz3 and Pz9 was observed. The rainfall increase between 2004 and 2007 induced a great water volume stored in the dam reservoir used for artificial recharge operations. Subsequently, a maximal groundwater level increase of 1.3 and 1.03 m is respectively observed in piezometers Pz1 and Pz9. In the piezometer Pz4, the artificial recharge was not able to show an effective increase and stopped the level decrease between 2004 and 2006. For the period from 2007 till 2009, the groundwater level declined about 4.3 m, corresponding to an average of 1.4 m/year.
Table 2
Estimated groundwater artificial recharge from streambed filtration

<table>
<thead>
<tr>
<th>Year</th>
<th>Water volume released 10⁶ m³</th>
<th>Recharge time (day)</th>
<th>Estimated groundwater recharge in mm/day</th>
<th>Estimated recharge volume in 10⁶ m³</th>
<th>Estimated recharge volume (percent water volume released)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>WTF method</td>
<td>SF ID</td>
<td>Hydrus-method</td>
<td>SF ID</td>
</tr>
<tr>
<td>2003</td>
<td>0.44</td>
<td>103</td>
<td>-</td>
<td>312</td>
<td>34</td>
</tr>
<tr>
<td>2004</td>
<td>1.61</td>
<td>196</td>
<td>4.1</td>
<td>682</td>
<td>52.8</td>
</tr>
<tr>
<td>2005</td>
<td>2.54</td>
<td>175</td>
<td>8.2</td>
<td>102.2</td>
<td>50.2</td>
</tr>
<tr>
<td>2006</td>
<td>1.67</td>
<td>167</td>
<td>1.3</td>
<td>79.7</td>
<td>49.1</td>
</tr>
<tr>
<td>2007</td>
<td>1.79</td>
<td>166</td>
<td>2.2</td>
<td>79.9</td>
<td>50.6</td>
</tr>
<tr>
<td>2008</td>
<td>0.29</td>
<td>55</td>
<td>0.7</td>
<td>40.2</td>
<td>28.2</td>
</tr>
<tr>
<td>2009</td>
<td>0.45</td>
<td>28</td>
<td>1.6</td>
<td>78.1</td>
<td>35.9</td>
</tr>
<tr>
<td>2012</td>
<td>1.86</td>
<td>170</td>
<td>-</td>
<td>80.3</td>
<td>49.4</td>
</tr>
<tr>
<td>Total</td>
<td>10.65</td>
<td>1,060</td>
<td>-</td>
<td>-</td>
<td>49.4</td>
</tr>
<tr>
<td>Mean</td>
<td>1.3</td>
<td>132.5</td>
<td>3.0</td>
<td>70</td>
<td>43.8</td>
</tr>
</tbody>
</table>
Figure 4  Correlation of estimated recharge and released volume, (a) from WTF method (b) from SF method and Hydrus-1D model

Figure 5  Groundwater level, artificial recharge and rain fall variation in the study area from 2001 to 2009
Generally, the important effect of artificial recharge on groundwater level changes is expressed by two aspects: the rise of the groundwater mound on the aquifer in response to infiltration from the released water, and also the reduction in the rate of the decline of the groundwater after recharge.

4 Conclusions

The efficiency of any aquifer artificial recharge program depends on the quantity of water reaching the water table which is generally assessed by several methods of various accuracies. These methods are mostly based on groundwater level evolution considering the recharge operation. Many of these methods failed to estimate the water volume reaching groundwater body particularly in heavy exploited aquifers. Hence, this work describes a simple procedure to assess the artificial recharge of aquifers using the WTF method, the SF method and the Hydrus-1D model.

The WTF method produces the actual recharge estimates reaching the aquifer from the released water whereas the SF method and the Hydrus-1D yield the infiltration rate in the stream bed. Largest recharge volume estimated by SF method ranges from 81 to 95% of the water volume released. The Hydrus-1D simulation shows a recharge volume varying from 37 to 92% of the total water released from the hill dam. The recharge volume using the SF method was higher than that of Hydrus-1D. In fact, even this model is relatively well appropriated for flow in the unsaturated zone; it cannot consider the effect of preferential flow channels and consequently underestimate the recharge.

In order to overcome the uncertainties in estimating the artificial recharge, we recommend the use of complementary methods: the SF method could be combined with the WTF method to increase the reliability of recharge estimates. The Hydrus-1D model is especially recommended for previsions and may provides values more consistent using results of previous methods for calibration.

References


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