Chapter 15
Application of the FEFLOW Groundwater Model in the Zayandeh Rud Catchment

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15.1 Introduction

The groundwater model was build up with the commercial software package FEFLOW (Diersch 2014), which calculates water flow, mass and heat transport in porous media. For a better understanding, the groundwater model will be named FEFLOW Model in the remainder of this paper. The aim of the FEFLOW model was to identify the volumetric amount of seepage water in relation to the groundwater levels nearby the Zayandeh Rud River. The area under investigation has an extension of 22,868 km^2 and covers nine sub-catchments (codes: 4201, 4202, 4203, 4205, 4206, 4207, 4208, 4209 and 4217). Not the entire area under investigation is part of the FEFLOW model; rather, the main focus is the porous aquifer system nearby the Zayandeh Rud River. Therefore, the area for the FEFLOW model was restricted to the aquifer extension. An overview of the aquifer extension, the areas of the FEFLOW, SWAT and the MIKE BASIN model is presented in Fig. 15.1. The FEFLOW model covers an area of 10,446 km^2

15.2 Model Setup

The boundary to the northern part is defined by the aquifer extension in sub-catchment code 4205. In the north-western part, a watershed between sub-catchment codes 4207 and 4214 defines the boundary of the FEFLOW model. The aquifer in sub-catchment code 4204 is already partly dry. Along with the narrow bottleneck connection to the aquifer in the neighboured sub-catchment

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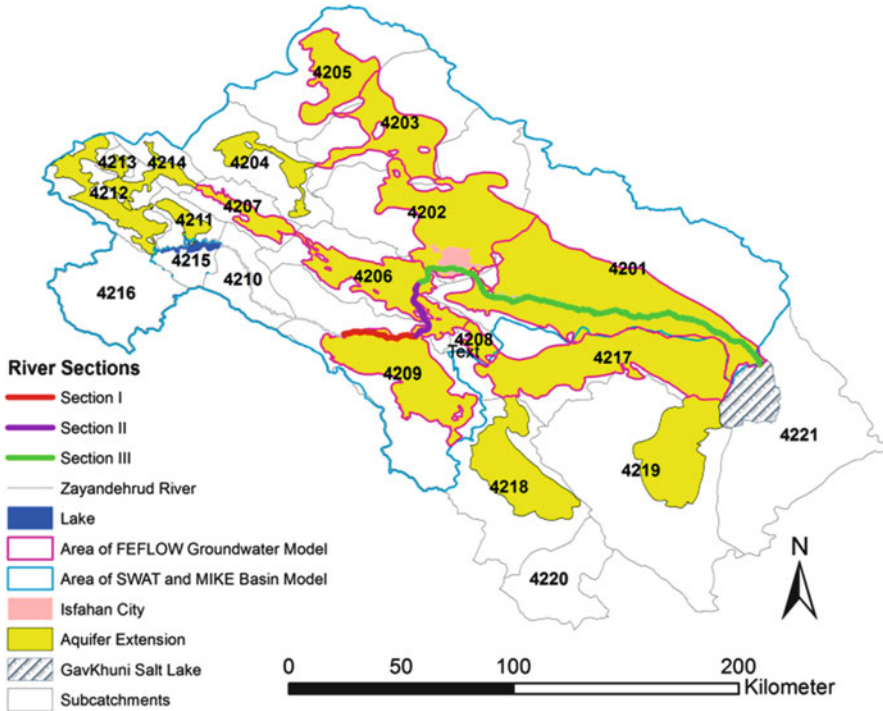
Fig. 15.1 Overview of the extension of the three models, the extent of the aquifer and the division of flow sections for the exchange between the MIKE BASIN and the FEFLOW models (Mohajeri et al. 2016)

code 4203, this led to the assumption that the sub-catchment code 4204 has no influence on the water exchange between Zayandeh Rud River and the nearby aquifer. In the south, the aquifer extensions of sub-catchments 4217 and 4209 were used as boundaries for the FEFLOW model. For the sub-catchments 4218, 4219, 4220 and 4221, the available data was insufficient for a reliable implementation within the FEFLOW model or the water exchange was considered as not relevant for the interaction between the aquifer and the Zayandeh Rud River (DHI-WASY 2014).

Little is known about the geological layering of the alluvium aquifer in the study area, given that no interpreted geological cross sections were available. Only the existence of one approximately 10-metre-thick clay layer in sub-catchment code 4201 is widely accepted by the Esfahan Regional Water Board. This clay layer separates the upper unconfined from the lower aquifer, for which it is assumed to have confined conditions. The top, bottom and extension of the clay layer were defined by data from the Iranian partners. The sedimentary lithofacies show imbedded coarse gravel/sandy deposits of proximal to muddy, fine-grained deposits of distal areas of Quaternary dry land alluvial megafans (Arzani 2012). Little usable data for a stratified and layered geological model was available. Excluding the clay
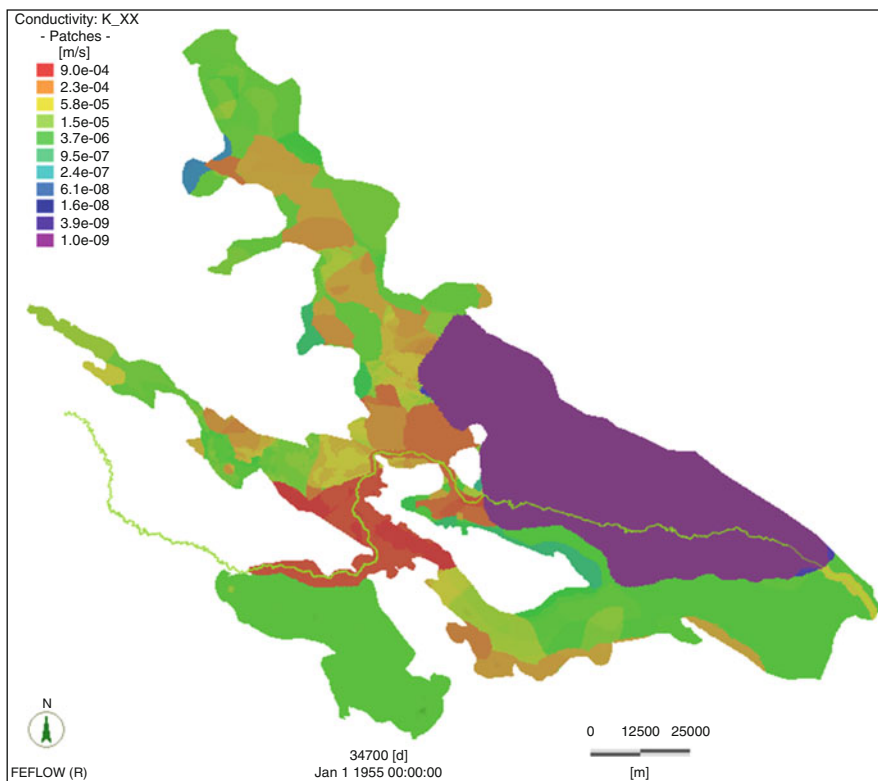
Fig. 15.2 Extension of the clay layer together with the distribution of hydraulic conductivity (DHI-WASY 2014)

layer, the rest of the model was assumed to comprise a vertically homogeneous geology. The extension of the clay layer is illustrated in Fig. 15.2.

In the study area, three major groundwater extraction methods are applied, namely springs, wells and qanats. Springs are natural sites where groundwater comes out of the sub-surface and becomes surface water. A comparison between the location of springs and geological fault structures indicates a clear correlation between these two. Wells are all kinds of man-made structures where groundwater is lifted by electric pumps or other mechanical lifting methods. Qanats are traditional artificial systems for extracting groundwater at topographic slopes by horizontal shafts burrowed into the groundwater. A detailed description of the functionality of qanats is provided by Wulff (1968). In the FEFLOW model, the extraction of more than 1300 springs, almost 1000 qanats and approximately 38,500 wells was considered. While the extraction of springs and qanats mostly depends on natural processes, the extraction of wells can be managed by the operators. The average groundwater extraction by wells in the model for the period from 1999 to 2012 was 2482 million m^3/year. Considering that the average qanat and spring

extraction equals 214 million m^3/year, the total groundwater extraction in the model area is approximately 2696 million m^3/year.
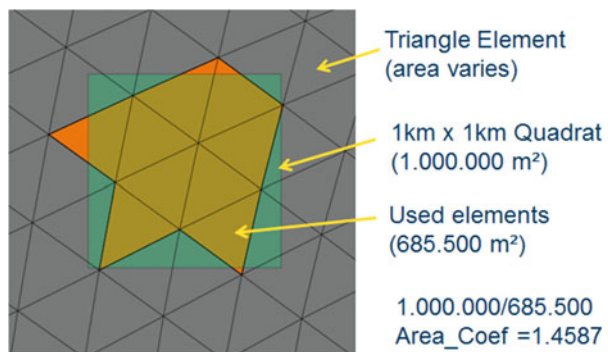
The groundwater extraction was established in the FEFLOW model by using the two parameters "In/Outflow on Top/ Bottom" and "Source/Sink". Two different parameters were used to separate between deep and shallow wells. Deep wells have a depth of more than 50 m, while shallow wells extract at depths below 50 m. The Esfahan Regional Water Board (ERWB) provided yearly values of groundwater extraction for the overall river basin (Gavkhuni Basin) for the period from 2007 to 2010 (Iranian calendar year 1385 to 1388). From this data, a percentage-based depth coefficient ("*Depth_coef*") was calculated by considering the average extraction rates of all 3 years. The coefficient defines the extraction per sub-catchments in proportions of deep and shallow extraction. Yearly data of groundwater extractions was only available on a sub-catchment scale. However, for the FEFOW model, the spatial distribution of groundwater extraction is an important issue. Therefore, the average extraction capacities of all wells were summarised on a 1000*1000 m raster. In the following step, the percentage distribution of the average extraction capacity per sub-catchment was calculated. The resulting coefficient ("*Perc_coef*") represents the proportion of the summed extraction in one square kilometre in relation to the total extraction per sub-catchment.

FEFLOW calculates on a triangular mesh, while the coefficient *Perc_coef* was calculated on a square basis. Therefore, it was necessary to implement a coefficient that takes different areas of the square and the selected triangles into account. This coefficient was named "*Area_coef*" and its calculation is shown by means of an example in Fig. 15.3.

As a result, three dimensionless coefficients were generated. By multiplication with the observed extraction rate (for every time step in the available time series), a correct representation of the groundwater extraction rate for the FEFLOW model could be calculated. The following equation was used:

$$GW_{ext} = Perc_{coef} * Area_{Coef} * Depth_{Coef} * time\ series$$

Fig. 15.3 Example for the calculation of the coefficient Area_coef (DHI-WASY 2014)

Triangle Element (area varies)

1km x 1km Quadrat (1.000.000 m²)

Used elements (685.500 m²)

1.000.000/685.500 Area_Coef =1.4587

The groundwater extraction and the so-called groundwater return flow are closely connected processes. The groundwater return flow denotes a process where irrigated water percolates through the unsaturated zone and recharges the aquifer. This artificial recharge depends on several processes and parameters. Respective data to gain more insights into these processes was not available. Therefore, a simplified approach for the groundwater return flow was implemented. The groundwater return flow was assumed as product of the groundwater extraction (groundwater extraction by wells, springs and qanats) and a spatial variable coefficient, which represents the amount of surface water being used for agriculture irrigation. The implementation of the groundwater return flow in the FEFLOW model was performed by using the parameter "Source/Sink" in the first layer. The groundwater return flow was automatically linked to the groundwater extraction. Groundwater extraction and groundwater return flow only take place as long as the aquifer is not dry. In case no water is available, the groundwater extraction and the groundwater return flow are automatically switched off. The mean artificial groundwater recharge by irrigation implemented in the FEFLOW model amounts to 161 mm/a. In arid environments, in which irrigation is predominantly applied as flood irrigation, Global Water Partnership (2012) reported values between 70 and 300 mm/a. Based upon data from Consulting Engineers Water and Sustainable Development (2010), the artificial recharge in the area under investigation amounts to approximately 179 mm/a, which fits well to the amount implemented in the FEFLOW model.

The natural groundwater recharge was calculated by a separate SWAT model (Faramarzi and Besalatpour 2014). An average natural groundwater recharge of 0–2 mm/a (around 1% of the yearly precipitation) is common for arid environments. In semi-arid to arid environments, groundwater recharge rates of 8 mm/a are suggested by Gräbe (2012). Nikouei et al. (2012) analysed several sub-catchments in the Zayandeh Rud basin and differentiated between an average groundwater recharge of 13 and 2 mm/a (the latter represents groundwater recharge during drought periods). Due to the low percolation to the sub-surface and the high surface water run-off at hard rock mountains, Gieske and Miranzadeh (2000) described a relatively high groundwater recharge near the mountains. For the FEFLOW model, two natural types of groundwater recharge were defined. Recharge occurs on flat land when precipitation percolates down to the sub-surface and finally reaches the groundwater ("*GWR_A*"). At the borders of the aquifer, the alluvial aquifer is fed by additional mountain front recharge ("*GWR_M*"). A schematic model concept and vertical discretisation of the 3D-FEFLOW model is shown in Fig. 15.4.

The elevation of slice 1 was defined by the available digital elevation model. The top and bottom of the clay layer (slice 4 and slice 5) were defined by data from the Esfahan Regional Water Board. The bottom of the FEFLOW model was defined by the aquifer base, which was also provided by the Iranian partners.

The Zayandeh Rud River was defined with a vertical 3rd kind (Cauchy) boundary condition on slice 1 and slice 2. The exchange occurs at both sites of the vertical area represented by these boundary conditions. As the thickness of the first layer equals approximately 25 m, a good representation of the average river infiltration width of 50 m could be guaranteed with this method. Measurements of surface
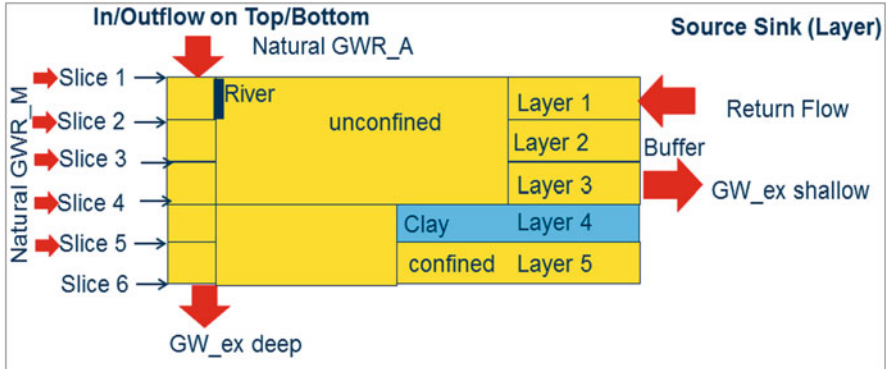
Fig. 15.4 Schematic model concept and vertical discretisation of the 3D-FEFLOW model (DHI-WASY 2014)

water heads were available at four stations, namely Pole-Kalleh, Dizicheh, Lenj and Moursian. While the four stations cover around 60 km of the total river length, for the majority of the river length (150 km) no surface water measurements were available. For these areas, surface water levels were derived by means of topography data as well as free satellite images.

15.3 Calibration

The FEFLOW model was build up as an unsaturated model because even during the 1995–2009 period several parts of the aquifer became dry. For the unsaturated flow, porosity data from Consulting Engineers Water and Sustainable Development (2010) and Safavi and Bahreini (2009) was used. The model was build up as a transient model with constant boundary conditions. The model was calibrated for the 1995–2009 period mainly by manual variation of the parameters hydraulic conductivity and the return flow coefficient. From the total number of 311 observation wells, 55 are in a range of 5 km around the river. Accordingly, these 55 observation wells were classified as relevant and considered during the calibration process. The scatter plot for the relevant 55 observation wells is presented in Fig. 15.5, showing that the entire GWM has an acceptable quality, although observed and calculated heads can differ by several meters in some parts of the model. The root-mean-square deviation for these wells equals 10.6 m. To facilitate the comparison between datasets or models with different scales, usually this RMS value is normalised with respect to the range of observed values within the model domain. In this case, the groundwater levels vary between 1470 and 1860 m, resulting in a normalised NRMS value of less than 3%, which is good for such a large-scale model (DVGW 2014).
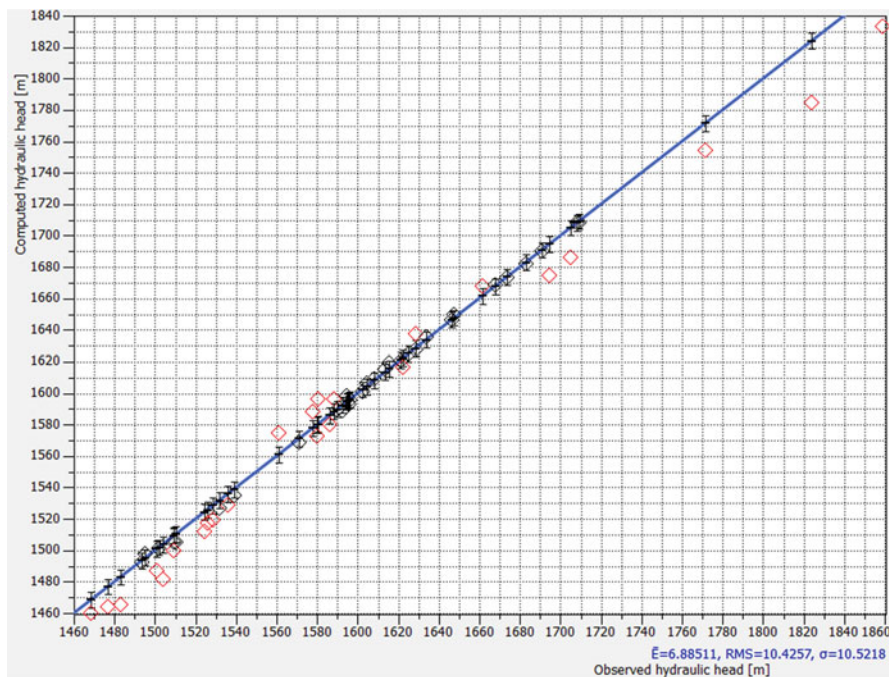
**Fig. 15.5** Scatter plot the 55 relevant observation wells

To demonstrate the quality of the transient model calibration with respect to the change of groundwater levels within the simulation period, a cross-section view through sub-catchment 4206 (Najafabad) is shown in Fig. 15.6.

The cross-section view shows a good correlation between the observed and calculated heads at the selected section for the end of 2009. Furthermore, it shows the strong drawdown of more than 60 metres in the centre in only 15 years. The river leakage causes a strong inflow into the FEFLOW model and causes a significant smaller drawdown in the area near the river.

15.4   Groundwater and Surface Water Interaction

Regarding the groundwater resources, the extensive over-use of groundwater can be clearly illustrated by the groundwater levels, which have been decreased locally by more than 50 m during the last 15 years. Downstream of Pol Kale, the Zayandeh Rud River is losing water to the groundwater, in a process commonly known as river leakage.

As long as the river can be sufficiently recharged by releases from the main dam to avoid dryness in the river bed and as long as the groundwater levels are not
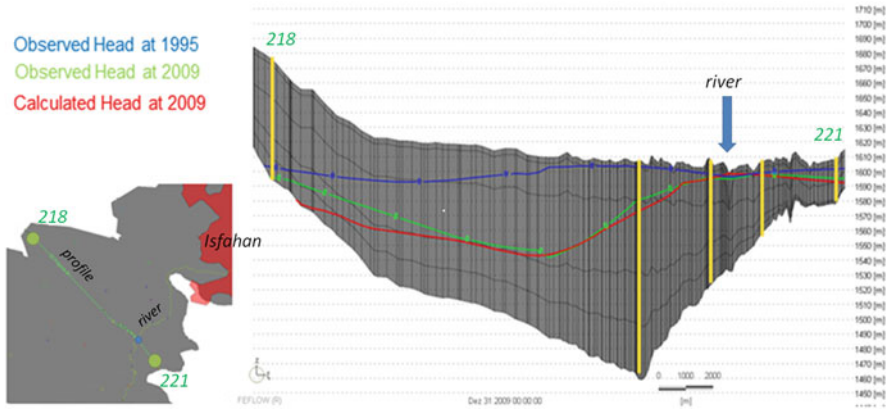
Fig. 15.6 Cross-section views through sub-catchment 4206 (Najafabad) with observed heads at 1995 and 2009 and calculated heads in 2009 (Mohajeri et al. 2016)

completely decoupled from the river, the leakage rate increases linear with falling groundwater levels. For the exchange between the Water Management Tool and the FEFLOW model, three exchange sections were defined: the first section is located between Pole-Kalleh and Diziche (33 km), the second between Diziche and Pole-Choum (64 km) and the third between Pole-Choum and the eastern border of the FEFLOW model (116 km). The sections are illustrated in Fig. 15.7 and the calculated surface water leakage for the three sections is presented in Fig. 15.8.

Because no seasonal dry parts of the river were considered in the FEFLOW model, the exchange rates increased with decreasing groundwater levels. During the first three years, the surface water leakage strongly increases to reach saturated conditions in the relevant parts of the model. After this time, the model becomes stable and calculates a nearly linear increase for the surface water leakage. The river leakage in Sect. 15.1 did not show major changes from 1998 to December 2009, which can be explained with relatively constant groundwater levels in the adjacent aquifer during the simulation time in that section. Section 15.2 passes though sub-catchment code 4206 (Najafabad), where intensive agriculture activities with high groundwater extraction rates cause strong groundwater level decreases. The ongoing decrease of the groundwater level causes an increase in surface water leakage, whereby the same process took place in Sect. 15.3.

For Sect. 15.1, the exchange rate was quantified with approximately 32 million m^3/a. For Sects. 15.2 and 15.3, the exchange rates were quantified with 185 and 268 million m^3/a, respectively, as a weighted average over the simulation time.

The FEFLOW model calculates a total net exchange between surface water and groundwater of 484 million m^3/a. For the FEFLOW model, this positive net exchange results in water gains and thus this number represents an overall surface water flow to groundwater. The calculated net exchange is strongly comparable with the data from Consulting Engineers Water and Sustainable Development (2010), which presented a surface water to groundwater exchange of 525 million m^3/a. Safavi et al. (2015) presented yearly data of groundwater recharge from the
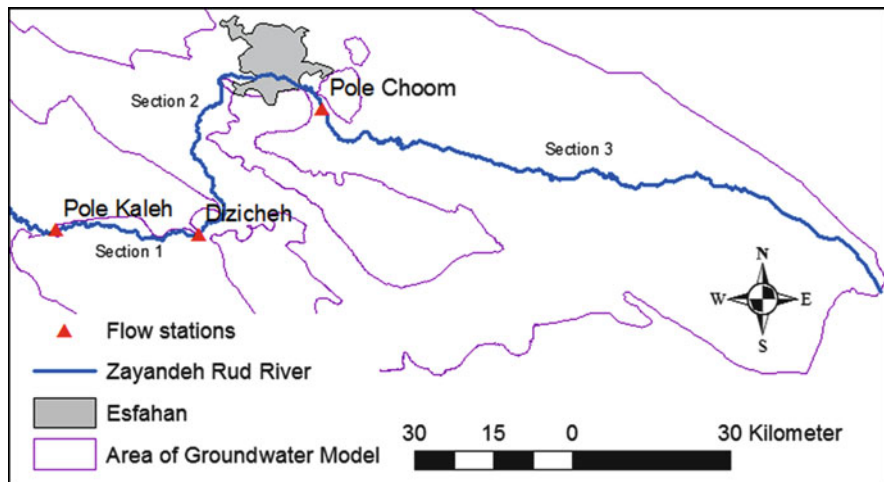
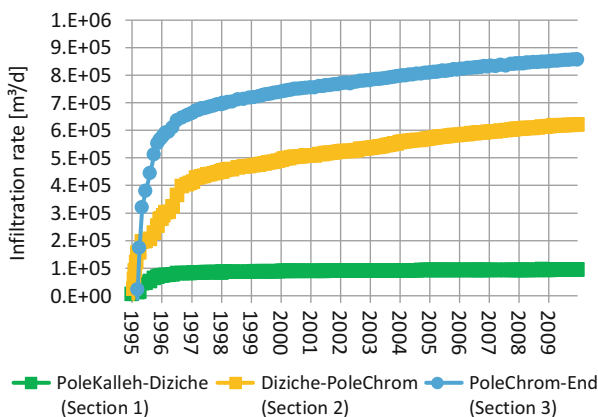**Fig. 15.7** River sections for evaluating surface water and groundwater exchange (DHI-WASY 2014)

Fig. 15.8 Surface water leakage at different sections (DHI-WASY 2014)

Zayandeh Rud River to the adjacent aquifers of approximately 400 million m^3/a for the period from 1991 to 2011. Based upon the river length of 213 km and the average river width of 50 m, the calculated exchange rate is 0.13 m^3/m^2*d.

The general principle of surface water-groundwater interaction is shown in Fig. 15.9. In many systems, natural conditions involve groundwater levels being higher than the surface water level and thus the surface water discharge being increased by groundwater inflow. Along the Zayandeh Rud River, these conditions are currently hardly present. As a result, a constant leakage from surface water to the aquifers is observed. Without a significant decrease of groundwater extraction,
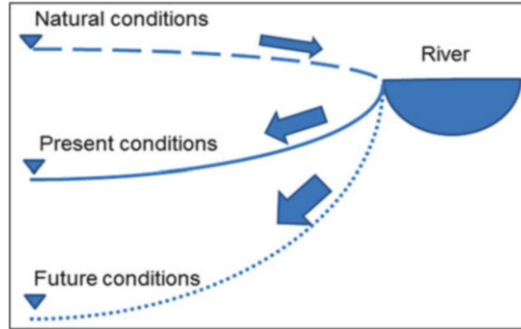
Fig. 15.9 Schematic illustration of the surface water—groundwater interaction
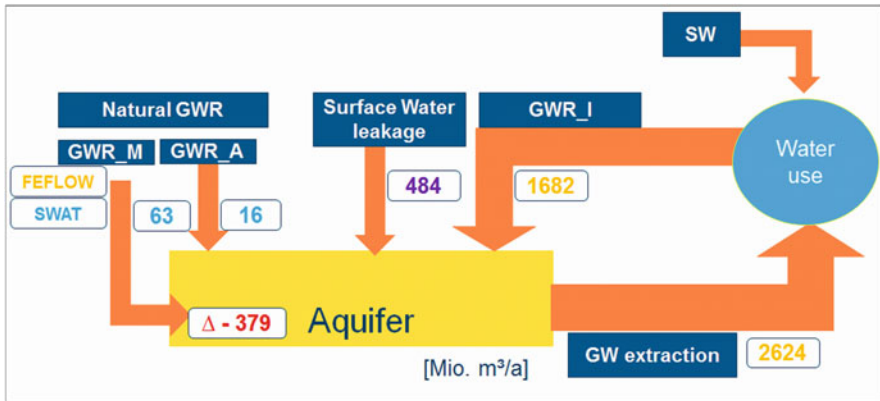

Fig. 15.10 Budget of the FEFLOW model for the 1995–2009 period (DHI-WASY 2014)

the decrease of the groundwater level will continue, which also results in an increasing surface water leakage. The problem of partly and seasonal dry river beds along the Zayandeh Rud River is thus likely to increase as long as no adequate counteracting measures are found.

15.5   Model Budget

To calculate the model budget, all in- and outflows of the model were considered, whereby the budget for the FEFLOW model is illustrated in Fig. 15.10. In this balance, the SWAT results represent those areas that cause an inflow into the FEFLOW model, separated into two components representing the inflows at the plane (GWR_A) and the mountain (GWR_M) areas. Overall, the natural

groundwater recharge for the FEFLOW model is around 79 million m^3/a, while the total groundwater extraction in the FEFLOW model over the model period equals 2624 million m^3/a. This amount marginally differs from the input extraction rate (2696 million m^3/a), showing that at some parts of the model the aquifer became dry and pumping was automatically stopped. Based upon this groundwater extraction, the return flow (groundwater recharge by irrigation, GWR_I) provided the major inflow to the FEFLOW model with 1682 million m^3/a. At this point, it has to be noted that there is significant use of surface water for irrigation, which cannot be explicitly quantified in the actual groundwater budget. The main modelling output for this stage of the overall project–namely the inflow from surface water to groundwater (surface water leakage)–is calculated at 484 million m^3/a.

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