

A framework toward developing a groundwater conceptual model

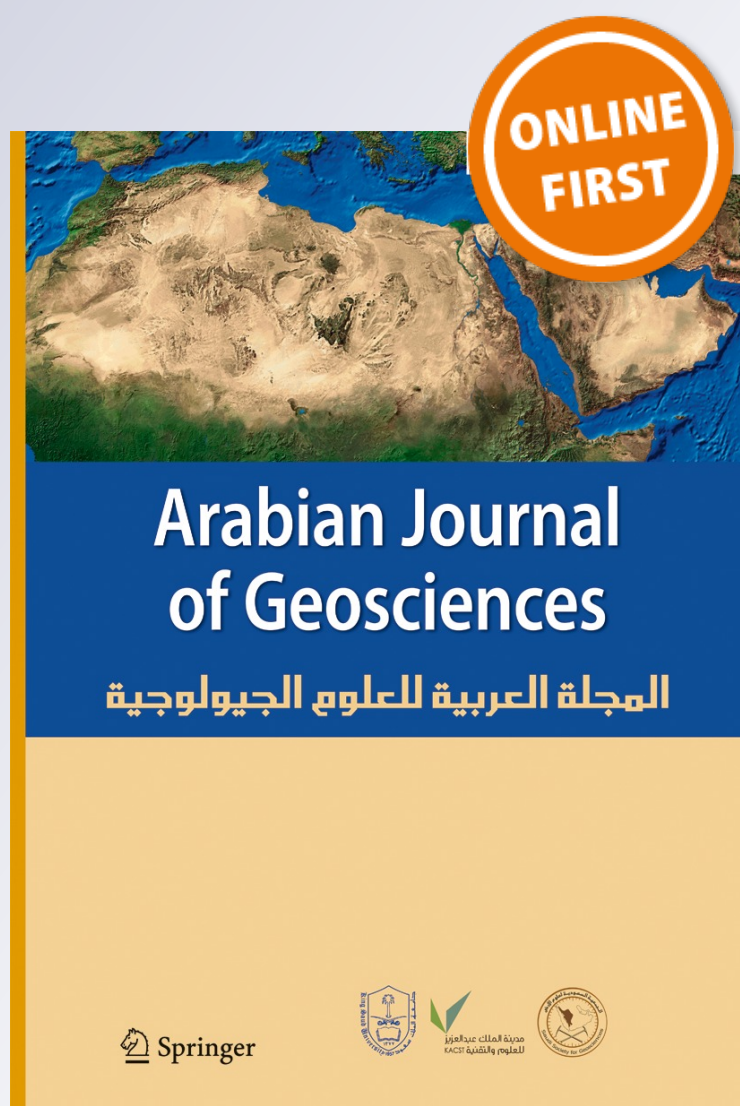
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A framework toward developing a groundwater conceptual model

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Abstract Developing an accurate conceptual model is the most important step in the process of a groundwater numerical modeling. Disorganized and limited available data and information, especially in the developing countries, make the preparation of the conceptual model difficult and sometimes cumbersome. In this research, an integrative and comprehensive method is proposed to develop groundwater conceptual model for an unconfined aquifer. The proposed method consists of six steps. A preliminary step (step 0) is aimed at collecting all the available data and information. The output of the first step as “controlling observations” is conceptual model version 00. This step should be rigorously checked due to its critical role in the controlling of final conceptual model. Step 2 determines the aquifer geometry. The output of this step is conceptual model version 01. Step 3 is responsible to determine hydrodynamic properties and its output develops conceptual model version 02. Step 4 evaluates the surface and subsurface interactions and lateral in/out groundwater flows. The output of this step is conceptual model version 03. Step 5 is to integrate the results from other steps and to deliver the final conceptual model version. The accuracy level of the conceptual model and the annual groundwater balance is also determined at this step. The presented groundwater conceptual model procedure was implemented for the Neishaboor

plain, Iran. Results showed its usefulness and practicality in developing the conceptual model for the study area.

Keywords Conceptual model · Groundwater · Development · Iran

Introduction

Groundwater resources are considered to be significant and economical water resources. The comprehensive recognition and proper utilization of this valuable resource, especially in arid and semi-arid areas, has an important influence on the sustainable development of social and economic activities (Izady et al. 2012). In the last decade, discords have occurred among groundwater users for the rights of the groundwater resource, particularly in highly exploited areas. The lack of knowledge about the groundwater flow and the availability of the resource precluded the formulation of suitable groundwater management plans (Nastev et al. 2005). Therefore, it is necessary to simulate groundwater behavior for a better understanding of the aquifer conditions. A simulation of groundwater behavior that takes into consideration the various parameters and properties of aquifer is only possible through modeling (Bredehoeft and Hall 1995; Gerla and Matheney 1996; Varni and Usunoff 1999; Nastev et al. 2005; Bedekar et al. 2012). In order to develop an appropriate numerical groundwater flow model and a more quantitative representation of the subsurface hydrology, the formation of a conceptual model is critical (Vandenberg 1982; Neuman 1988; Anderson and Woessner 1992; EPA, DOE, NRC 1994; Reilly 2001; Neuman and Wierenga 2003a, b; Palma and Bentley 2007; English et al. 2007; Barazzuoli et al. 2008; Seifert et al. 2008; Jusseret et al. 2009; Gillespie et al. 2012). The purpose of the conceptual model is to simplify the field problem and organize the associated field data so that the system can be analyzed more readily by means of a numerical

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model. A conceptual model is a pictorial representation of the groundwater system in terms of hydrogeologic units, system boundaries including time-varying inputs and outputs, and hydraulic as well as transport properties including their spatial variability (Anderson and Woessner 1992; Meyer and Gee 1999). The conceptual model is the basic idea of how the system or process operates; it forms the basic idea for the model (Bredehoeft 2005). Conceptual models are built on the past experience or previous work in a study area, knowledge of similar hydrogeologic regimes, site-specific data, and even institutional paradigms (Gillespie et al. 2012). In fact, one specific but very important component of the modeling process is the conceptualization of actual groundwater system. Also, it has been suggested that uncertainty in groundwater modeling is largely dominated by uncertainties arising from the definition of groundwater conceptual models (Carrera and Neuman 1986a, b; Neuman and Wierenga 2003a, b; Højberg and Refsgaard 2005; Poeter and Anderson 2005; Refsgaard et al. 2006; Meyer et al. 2007; Ye et al. 2010; Rojas et al. 2008, 2010a, b). In recent years, a number of authors have acknowledged that conceptual model uncertainty which has received less formal attention in groundwater applications than it should (Neuman 2003; Neuman and Wierenga 2003a, b; Bredehoeft 2003, 2005; Carrera et al. 2005; Poeter and Anderson 2005; Refsgaard et al. 2006; Rojas et al. 2008). Moreover, ignoring conceptual model uncertainty may result in biased predictions and/or underestimation of predictive uncertainty (Ye et al. 2010).

Despite the utmost importance of the groundwater conceptual model, not much of detailed instructions or procedures are available to build up such a model; however, some general guidelines have been published (Anderson's book; Anderson and Woessner 1992, USGS reports). Moreover, disorganized and limited available data and information, especially in the developing countries, make the conceptual modeling complicated and tedious. Therefore, in this research a new detailed procedure was presented to develop a groundwater conceptual model for an unconfined aquifer. Additionally, the proposed method has been applied, to confirm and prove the suitability and applicability of the suggested approach, to the Neishaboor plain.

Materials and methods

The study area

Neishaboor watershed is located between 35° 40' N to 36° 39' N latitude and 58° 17' E to 59° 30' E longitude with semi-arid to arid climate, in the northeast of Iran (Fig. 1). The total geographical area is 9,158 km² that consists of 4,241 km² mountainous terrains and about 4,917 km² plain. The maximum elevation is located in the Binalood Mountains (3,300 m

above sea level), and the minimum elevation is at the outlet of the watershed (Hoseinabad) at 1,050 m above sea level. The average daily discharge at Hoseinabad hydrometric station was 0.36 m³ s⁻¹ for the period of 1997–2010, with a minimum value of zero and a maximum value of 89 m³ s⁻¹. The average annual precipitation is 265 mm, but this varies considerably from one year to another (CV=0.13). The mean annual temperatures changes from 13 °C at Bar station (in the mountainous area) to 13.8 °C at Fedisheh station (in the plain area). The annual potential evapotranspiration is about 2,335 mm (Velayati and Tavassloi 1991).

Neishaboor watershed is located between Binalood and Central Iran structural zones, and is separated into two distinct parts from a geological viewpoint (Fig. 1). The mountainous northeast part of the watershed consists of Devonian and Silurian calcareous and dolomitic formations, Jurassic siltstone, and calcareous rocks in the vicinity of Eocene and Neogene clastic sediments. The second part, which is located in southeast, south, and west mountainous parts of the study area, comprise Upper Cretaceous ophiolites (southwest and west) and volcanic rocks. The largest riparian trace is located in Maroosk river approximately 500 m in width. The major alluvium plans of study area are located at south of Kharv (the area is approximately 36 km²). Moreover, there are several alluvium plans located in Mirabad area (north of Neishaboor city) with the whole area of about 27 km². Furthermore, alluvium plains can be seen in the north of the study area (such as Bujan, Grineh, Maroosk, etc.) which the area is about 40 to 50 km². In addition, medium grain size alluviums with fine matrix cover an extensive part of the Neishaboor plain. Limon and argil fine-grain-size alluviums cover the central parts of the study plain. These fine-grained alluviums had become saline near to the plain's outlet due to evaporation from groundwater in the past (Velayati and Tavassloi 1991).

Theoretical background of the proposed procedure

A conceptual model of groundwater flow is an aggregated and qualitative framework upon which data related to subsurface hydrology can be interpreted (Anderson and Woessner 1992; Reilly 2001; Neuman and Wierenga 2003a, b; Palma and Bentley 2007; English et al. 2007; Barazzuoli et al. 2008; Jusseret et al. 2009). Development of the conceptual model requires a rigorous and conscientious incorporation of data, information, and reports pertaining to the aquifer and groundwater flow in the project area. The basic components of a groundwater conceptual model are physical boundaries and appropriate boundary conditions, distribution of hydrodynamic properties, and surface and subsurface interactions. A conceptual model can subsequently be populated with project-specific characteristics, such as groundwater levels, recharge zones, and

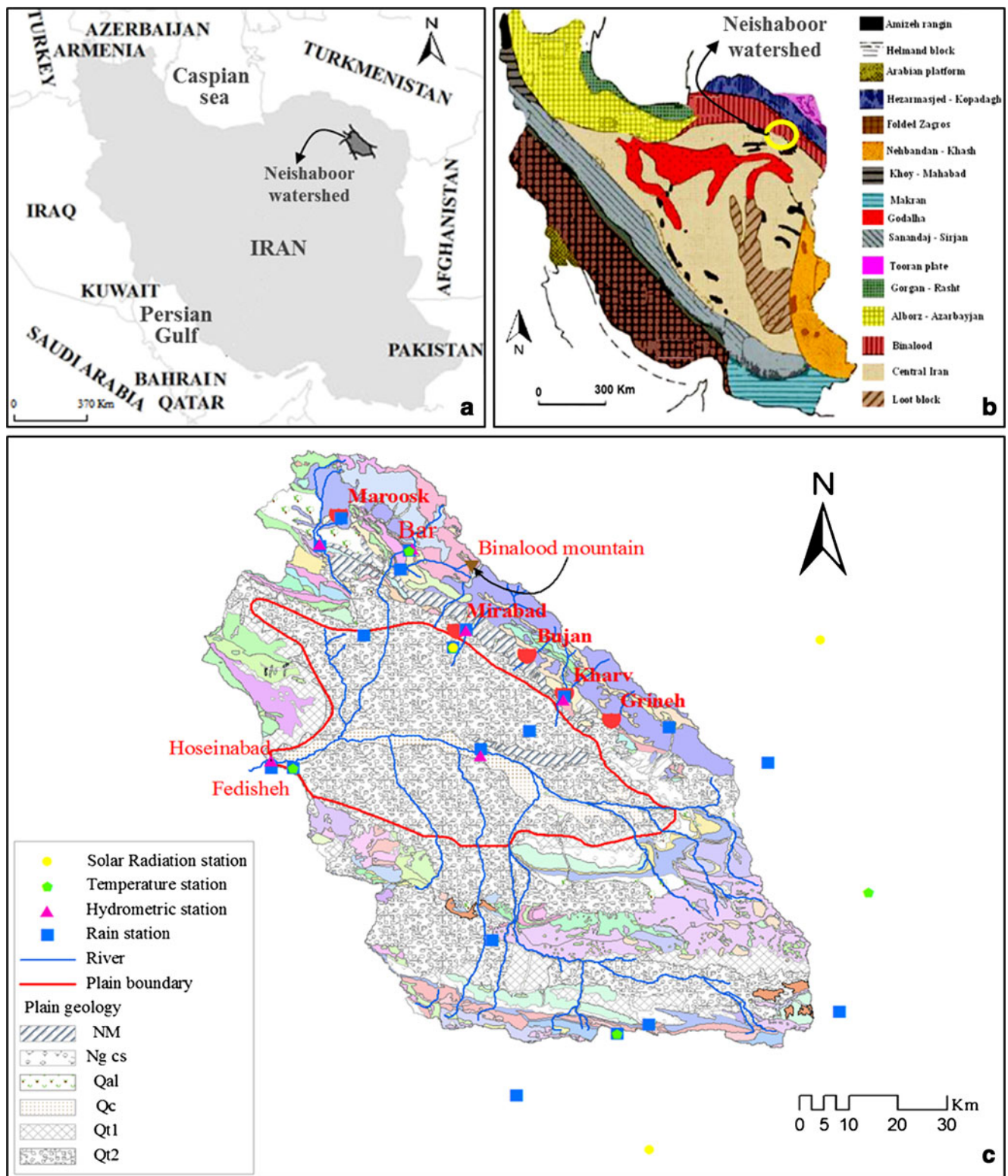


Fig. 1 a Neishaboor watershed location map. b Sedimentary and structural zones of Iran. c Geological map along with main aquifer, meteorological stations, and river network of the Neishaboor watershed. Note that

NM, *Ng cs*, *Qal*, *Qc*, *Qt1*, and *Qt2* are marl, red-brown, and gypsiferous; siltstone; sandstone; conglomerate; recent alluvium; clay flat; older terraces; and younger gravel fans and terraces, respectively

connectivity between withdrawal points and discharge zones, and finally will be used for numerical modeling.

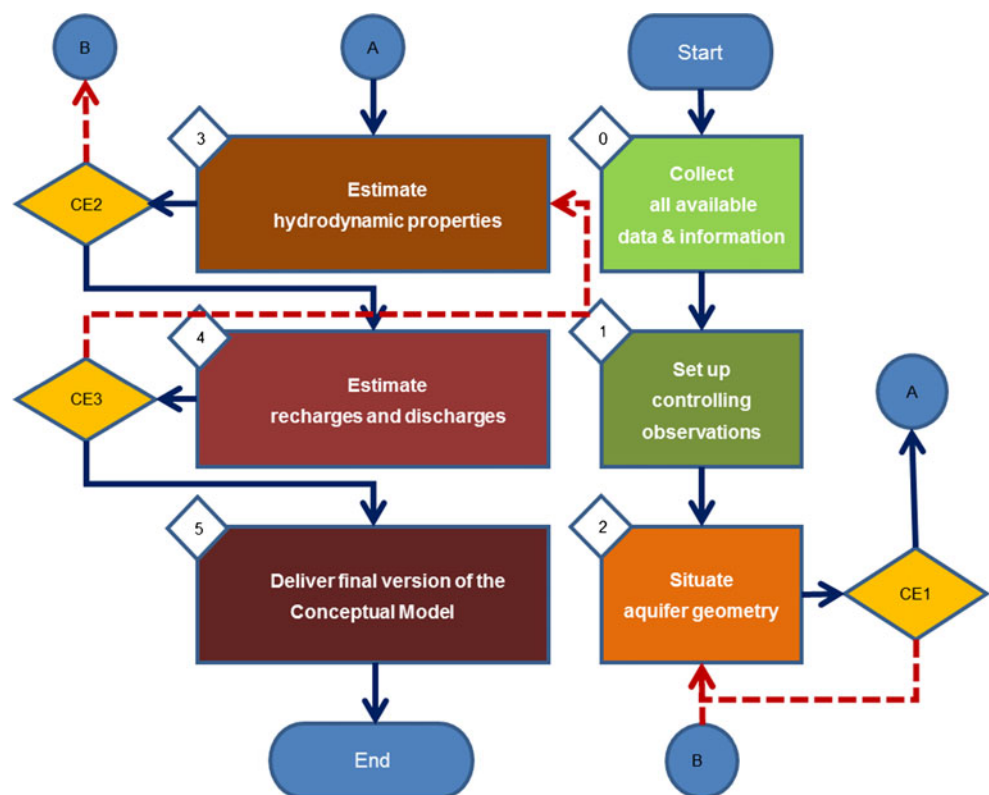
The conceptual model also allows the general conclusions regarding the impacts of hydrologic conditions on groundwater

flow. Moreover, conceptualization is useful to explore hidden facts and to fill data gaps for a better understanding of the groundwater system. Undoubtedly, accuracy level of the numerical model inversely depends on the depth of these gaps (data uncertainty, data scarcity, etc.). Therefore, a conceptual model evolves forever and conceptualization is an endless process. Figure 2 shows an overall schematic diagram of the suggested “conceptual model development” procedure.

Figure 2 shows a six-step procedure (0 to 5) for developing a groundwater conceptual model. The preliminary step is aimed at collection of all available quantitative and qualitative data and information. Step 1 is the very basic step that controls other steps. In fact, information from observation wells, hydrometric stations, and withdrawal wells’ discharges are chosen as “controlling observations”. However, to make sure these data are adequately confident and flawless, they are double-checked against each other and any other factual data rigorously. Any remaining persistent conflicting data/information is omitted from the controlling data set. Step 2 is to determine the aquifer geometry. One of the influential data for this step is digital elevation model (DEM). The bedrock position, aquifer physical boundary, and stratigraphy of the aquifer are determined at this stage. Before entering the next step, a consistency evaluation (CE) in regards to controlling observations has to be done. If any inconsistency (or conflict) is found, then step 2 is reconsidered to resolve the conflicts. Step 3 is responsible

to determine the hydrodynamic properties of the aquifer. Again a CE has to be done, but these time outputs of step 2 are added to the controlling data set. If any inconsistency (or conflict) is found, then steps 2 and 3 are reconsidered to resolve the conflict. Step 4 is aimed at evaluation of the interaction between surface water and groundwater bodies. Also, this step determines any incoming/outgoing groundwater flows between the aquifer and its surroundings. At this stage, CE is also necessary. If any inconsistency (or conflict) is found, then steps 3 and 4 are reconsidered to resolve the conflict. The last step, step 5, is to integrate the results from other steps to deliver the overall conceptual model and estimate the annual groundwater balance components. At this stage, based on the adequacy/accuracy of the available data/information, the accuracy level of the conceptual model is determined. This is done for each parameter separately via scoring spatial availability of measured or estimated data and the robustness of estimated data. Moreover, adequacy of conceptual model is elaborated to serve a numerical model. Upon the results of the last step, a list of further studies/tests has to be recommended to fill the gaps and promote the model accuracy that enhances the aquifer conceptualization. If development of a satisfactory numerical model is required, the list should contain minimum prerequisites of the numerical model. However, a comprehensive list would be generated with respect to the conceptual model accuracy level.

Fig. 2 Schematic diagram of the development procedure for the groundwater conceptual model. CE is the acronym for consistency evaluation. It means that if any inconsistency (or conflict) is found among the specified steps, those are re-considered to resolve the conflict with regards to controlling observations



Worth to be mentioned is the hierarchy of reference to the information. We considered available data/information in three levels: quantitative observed data, qualitative observed data, and local expert experiences. In each step, main data/information (quantitative and qualitative observed data) is to be conferred firstly. Next, if the spatial distribution (abundance/scarcity) is not satisfactory, then one has to refer to the third-level data. Keep in mind that usage of the third-level data must be minimized due to their inherent ambiguity and uncertainty. This has concluded to a “*satisfied with ...*” check *within* steps, as shown in steps flowcharts. Note that minimum usage of the third-level data is limited to enhancement of spatial distribution of data, while in the case of conceptual model conflicts (conflict *between* steps) all available data must be used.

Pre-step (step 0): Collect all available data and information

At the pre-step, all available data and information (quantitative or qualitative) are summed up. It is strongly recommended to collect all data and information from all available sources. Particularly, in the developing countries which suffer from disorganized data sources, more attempts should be made. The local expert knowledge is a crucial qualitative source of information in such circumstances.

Step 1: Set up controlling observations

Step 1 is a basic step that controls other steps (Fig. 3). The information and data from piezometers, hydrometric stations, and discharges from withdrawal wells are chosen as “controlling observations”. In fact, these precious data and information have an important role to develop a conceptual model. Therefore, these should be cross-checked against each other and any other factual data to make sure that the data is adequately confident and flawless. For example, groundwater level in piezometers

is investigated whether it represents a deep or a perched aquifer water table. For this reason, the comparison of mentioned groundwater level with depth of groundwater in other surrounding wells would be useful. Also, hydrometric data is used to approximate groundwater contribution (baseflow) to surface flows. If there was any persistent conflicting data/information, they should be omitted from the controlling data set due to its great importance in other steps of developing groundwater conceptual model. However, it is sturdily advised to keep all available data. The output of this step is conceptual model version (ver.) 00 as both maps and time series tables.

Step 2: Situate aquifer geometry

Step 2 determines the aquifer geometry. The first output of this step is ground surface DEM and aquifer physical boundary; bedrock and stratigraphy of the aquifer are then defined at this stage. Figure 4 shows a schematic diagram of step 2 and its output.

Surface topography validation

Basic topographic attributes extracted from DEM are entered to the groundwater models. The alluvium and saturated layer thicknesses are directly affected by the accuracy of the selected DEM. Thus, it is strongly recommended that the accuracy of available DEMs be examined before being approved. The terrain elevation data are accessible from several major sources with low to high spatial resolutions. These are mainly local topographic maps, Shuttle Radar Topography Mission (SRTM) (<http://srtm.csi.cgiar.org/SELECTION/inputCoord.asp>) and Advanced Space-borne Thermal Emission and Reflection

Fig. 3 Schematic diagram of step 1 and its output

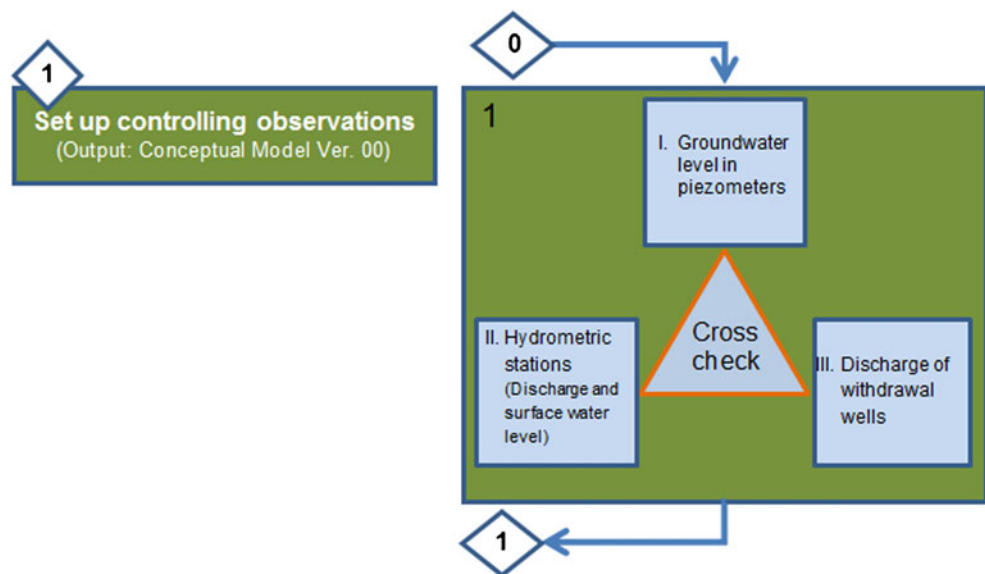
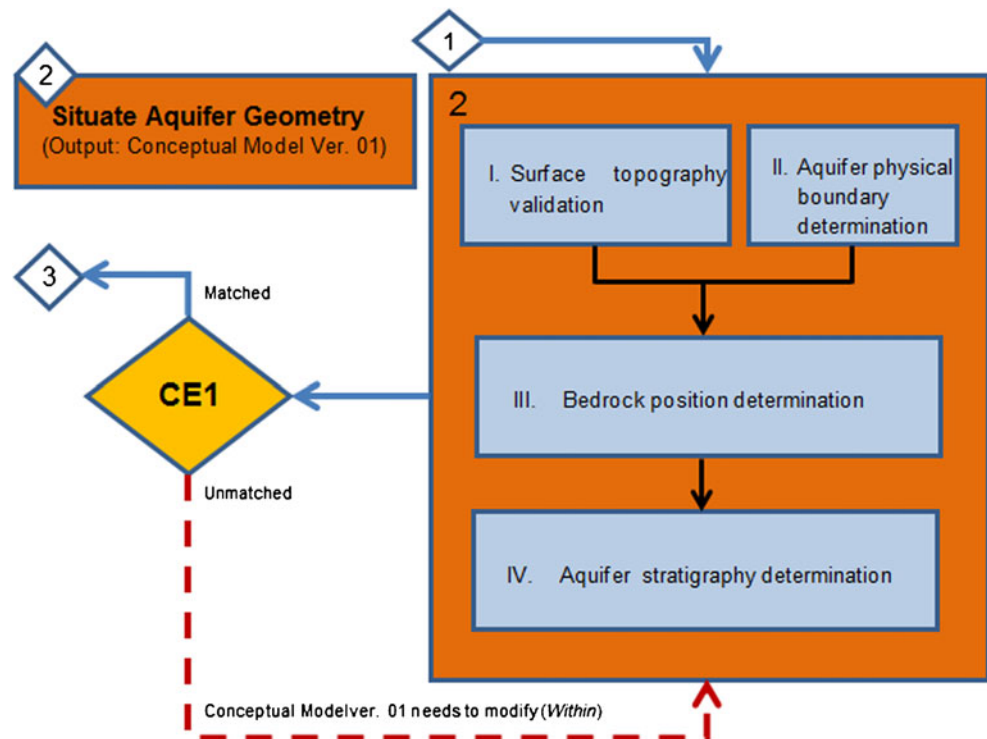


Fig. 4 Schematic diagram of step 2 and its output



Radiometer (ASTER) (<http://www.gdem.aster.ersdac.or.jp/search.jsp>). The ground surface level at the piezometer locations can be used as a benchmark to check the accuracy of the available DEMs. Field measurements with differential GPS technique is also recommended for checking these DEMs against each other and for conflicting points.

Aquifer physical boundary

The physical limits of the study region must be determined to develop any groundwater conceptual model. Figure 5 shows a schematic diagram of the required steps for this process.

Topography and geology maps are used to make a first draft of the aquifer physical boundary. This boundary is then amended using intersection points of current groundwater level and bedrock maps to produce a preliminary physical boundary map. At this stage, many boundary points need to be modified due to an ambiguity of the groundwater table near boundary. For this reason, bedrock and groundwater level raster layers are subtracted from each other. In the obtained raster layer, wherever the bedrock located above the groundwater level, the boundary should be manually corrected. This is done based on local expert knowledge, and depth and discharge of withdrawal wells.

Bedrock position

The bedrock is known as a lower boundary of an aquifer. Figure 6 shows a schematic diagram of required steps for determination of the bedrock.

Usually, borehole logs together with geo-electric sounding measurements (interpreted using general geological and hydrogeological information) are used to determine the position of the bedrock. However, this information is not sufficient in many locations and still there are ambiguities with the bedrock positioning. Therefore, other information such as logs from any fully penetrated withdrawal wells, is useful to clarify the bedrock position. Many more cross-checks should be made between these results and other information such as local expert knowledge and even experiences/observations of well-drillers teams.

Aquifer stratigraphy

Aquifers can be generally categorized to unconfined, semi-confined, and confined. The aquifer type is often derived from geo-electric soundings results, pumping tests, drilling logs, and local expert knowledge. This process is commonly called stratigraphy which specifies the aquifer heterogeneity and anisotropy. In general, the details of this process follow the same paths as the process of bedrock determination.

CEI Before entering step 3, findings of this step have to be checked with “controlling observations” step (step 1). Specifically, elevations of bedrock and withdrawal wells bottoms are to be checked against each other. If any withdrawal well has penetrated through the bedrock, this is then considered as a potential conflict that has to be resolved.

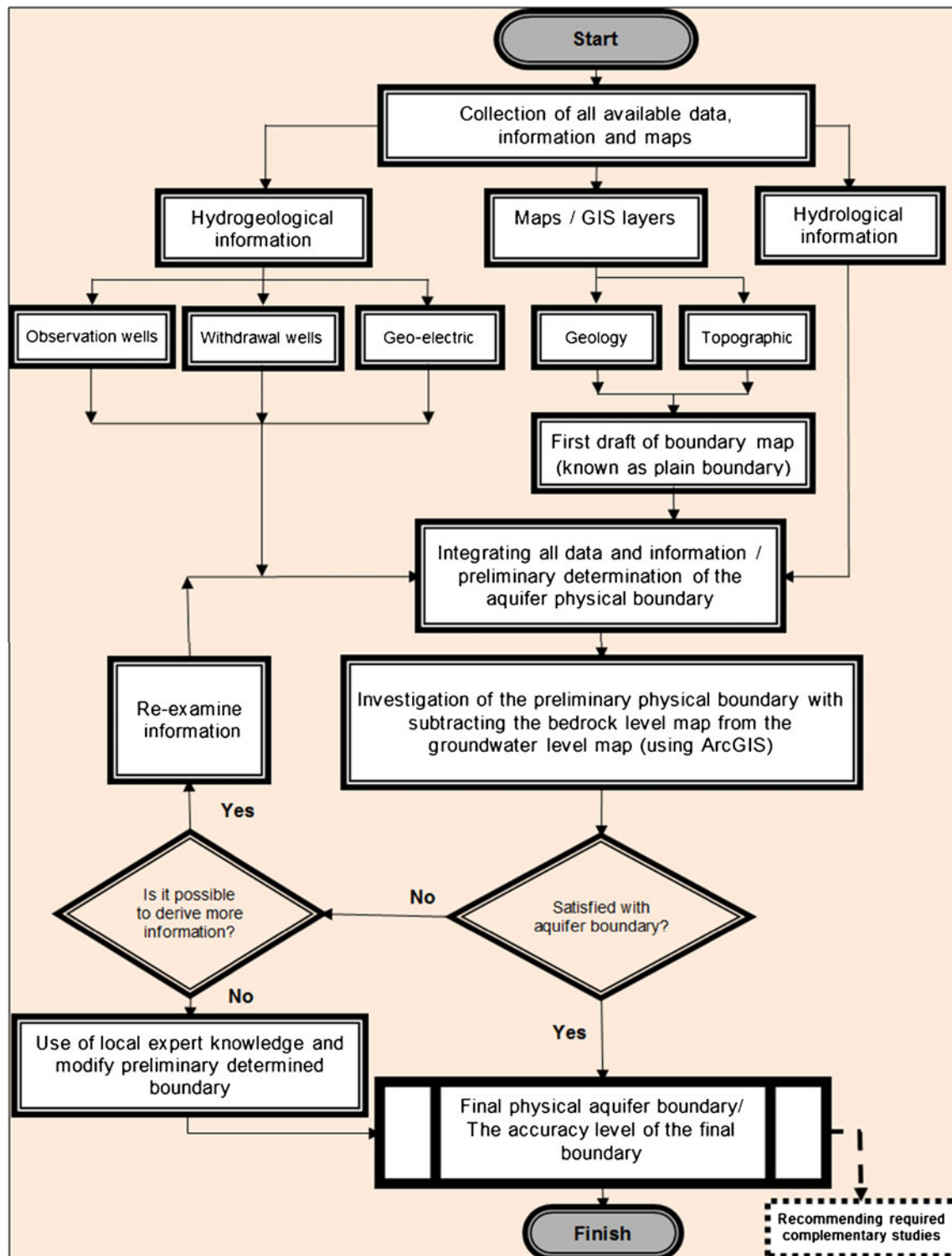


Fig. 5 Schematic diagram of required steps for determination of the physical boundary

Step 3: Estimation of hydrodynamic properties

In this step, the spatial distribution of the aquifer hydrodynamic properties are estimated (Fig. 7).

Hydraulic conductivity

The spatial distribution of the hydraulic conductivity is one of the most challenging aspects of hydrogeology modeling.

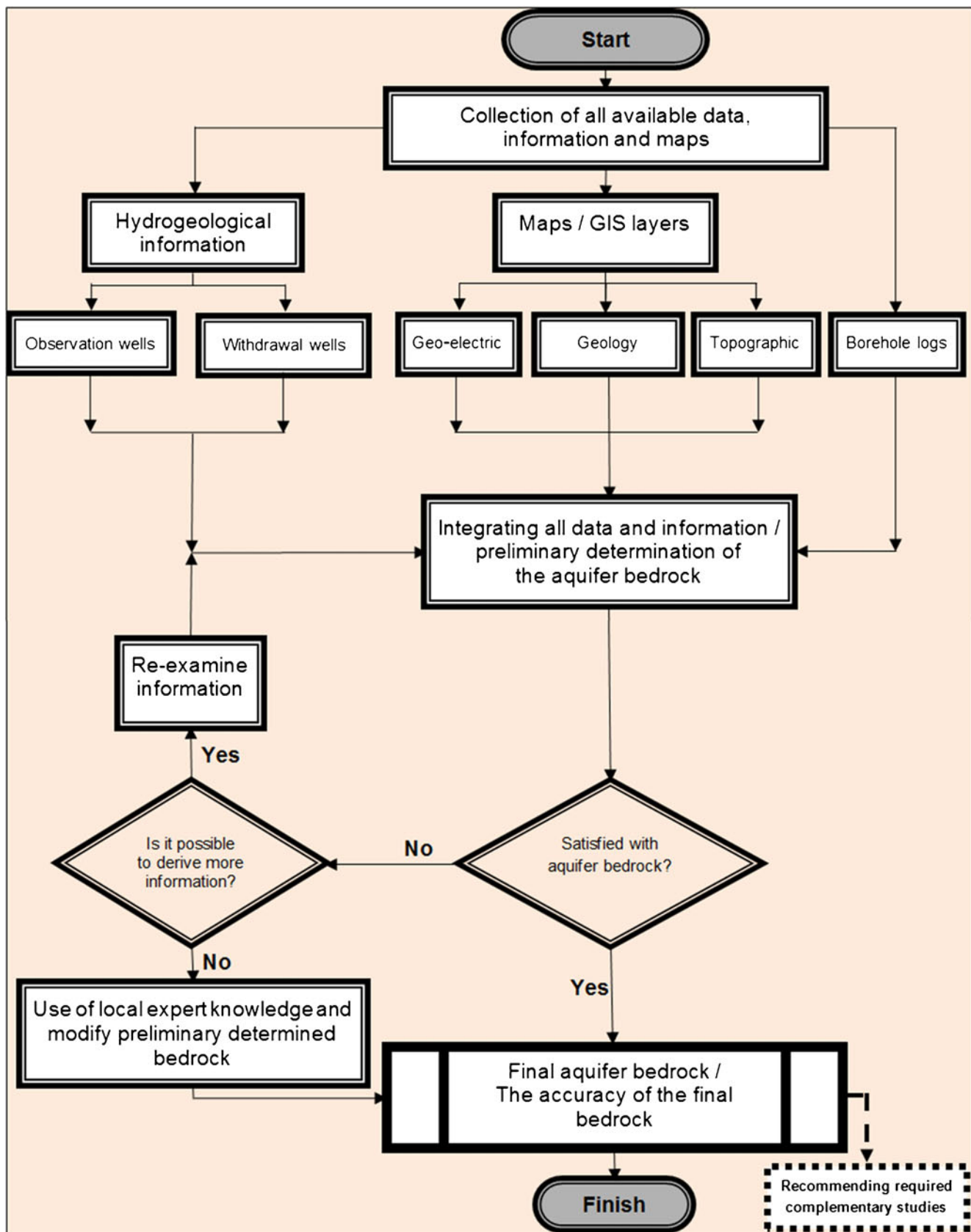


Fig. 6 Schematic diagram of required steps for determination of the bedrock

The aquifer heterogeneity not only influences the groundwater flow but also has the greatest impacts on the movement of contaminants. It has been shown that the spatial distribution of hydraulic conductivity forms a large source of uncertainty in groundwater modeling (Freeze 1975; Gelhar 1986; Moore and Doherty 2005; Rojas et al. 2010a, b). Usually, the spatial distribution of the measured hydraulic conductivities is not sufficient for the groundwater model calibration. Therefore, appropriate estimation of the hydraulic conductivity has an undeniable role in groundwater modeling. Figure 8 shows a schematic diagram of required steps for determination of the hydraulic conductivity.

There are direct and indirect methods to estimate saturated hydraulic conductivity (K_s). The direct methods (e.g., pumping test, tracer test, etc.) are based on field measurements of saturated hydraulic conductivity or transmissivity to generate realizations of the K_s or T (Hill et al. 1998; Moore and Doherty 2005). However, the measurement of K_s in the field is costly, time consuming, and cumbersome.

Additionally, the aquifer heterogeneity implies a large number of field measurements to characterize the horizontal and vertical hydraulic conductivity of the study area (Jabro 1992). Accurate estimation of K_s in the field is limited by the lack of precise knowledge of the aquifer heterogeneity (Uma et al. 1989). Therefore, it is necessary to apply simplified empirical methods to estimate the saturated hydraulic conductivity based on easily measurable aquifer properties. Particularly, hydrogeologists have attempted to relate hydraulic conductivity to grain size (Egboka and Uma 1986; Uma et al. 1989; Pinder and Celia 2006). The relationship between specific yield and hydraulic conductivity can also be used to estimate these parameters based on which one is available (Theis et al. 1963; Lohman 1972; Ahuja et al. 1989; Razack and Huntley 1991; Hamm et al. 2005). In other words, the specific yield data

obtained from well development reports and other resources can provide useful estimates of hydraulic conductivity. The geo-electric method is also used to estimate hydraulic conductivity based on transverse resistance (Griffith 1976; Kelly 1977; Louis et al. 2004).

Keeping in mind that estimated hydraulic conductivity should be amended with other geological facts such as formation types and saturated and alluvium thickness, especially where a falling water table exists, old measured K values have to be revised.

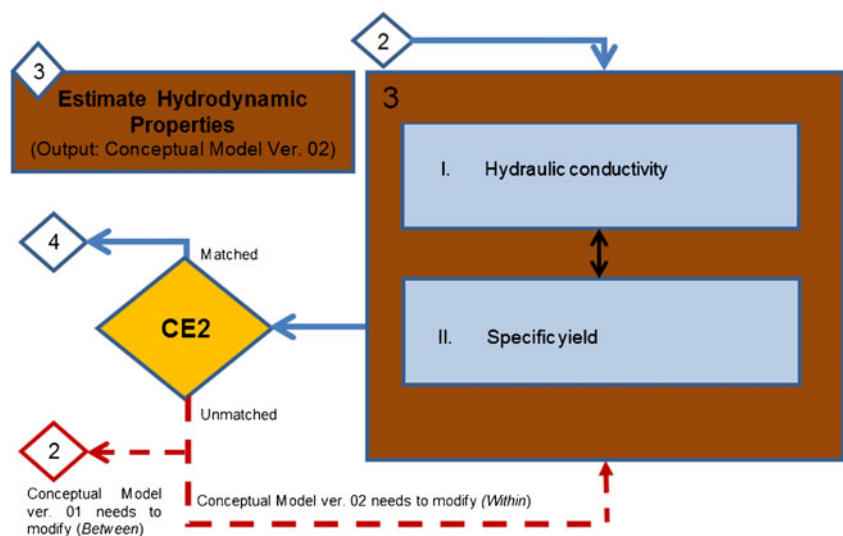
Specific yield

Beside to hydraulic conductivity, the specific yield has a crucial effect on the accuracy of groundwater modeling. Existence of reliable specific yield estimations facilitates the model calibration. Figure 9 illustrates the required steps for estimating the specific yield.

There are direct and indirect methods to estimate specific yield. Most of the details of this process follow same paths as the process of hydraulic conductivity estimation; therefore, the granulation method is only reported here (Johnson 1967). In this method, the texture of the excavated materials from different depths are determined, and based on their texture, the specific yield of the materials are estimated from the typical tables such as Table 1. The weighted average of the estimated specific yields can be designated as the specific yield of the aquifer in the spot of excavation. In the presence of a falling water table, old measured specific yields should be corrected.

CE2 Before entering step 4, findings of this step have to be checked with those of steps 1 and 2. Specifically, estimated K_s and S_y values have to be consistent with wells' saturated depths and discharges.

Fig. 7 Schematic diagram of step 3 and its output



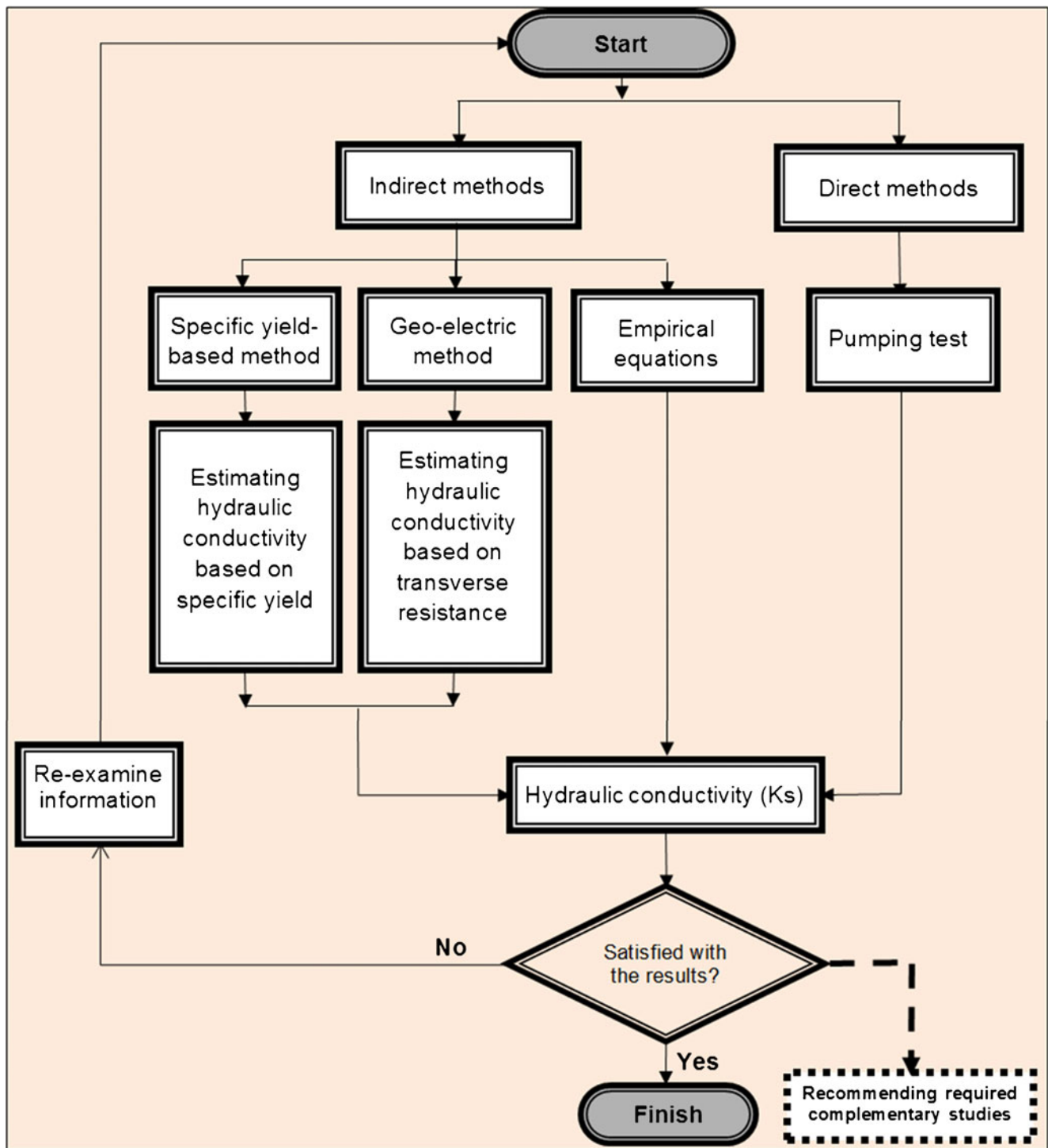


Fig. 8 Schematic diagram of required steps for determination of the hydraulic conductivity

Step 4: Identification of aquifer recharge and discharge

In this step, interaction of surface and subsurface water bodies is evaluated. This step also determines any regional flows between the aquifer and its surroundings (Fig. 10).

Spatial and temporal variation of discharge and recharge

It is necessary to determine spatial and temporal variation of discharge from aquifer due to its substantial role in the groundwater modeling especially in arid and semi-arid areas.

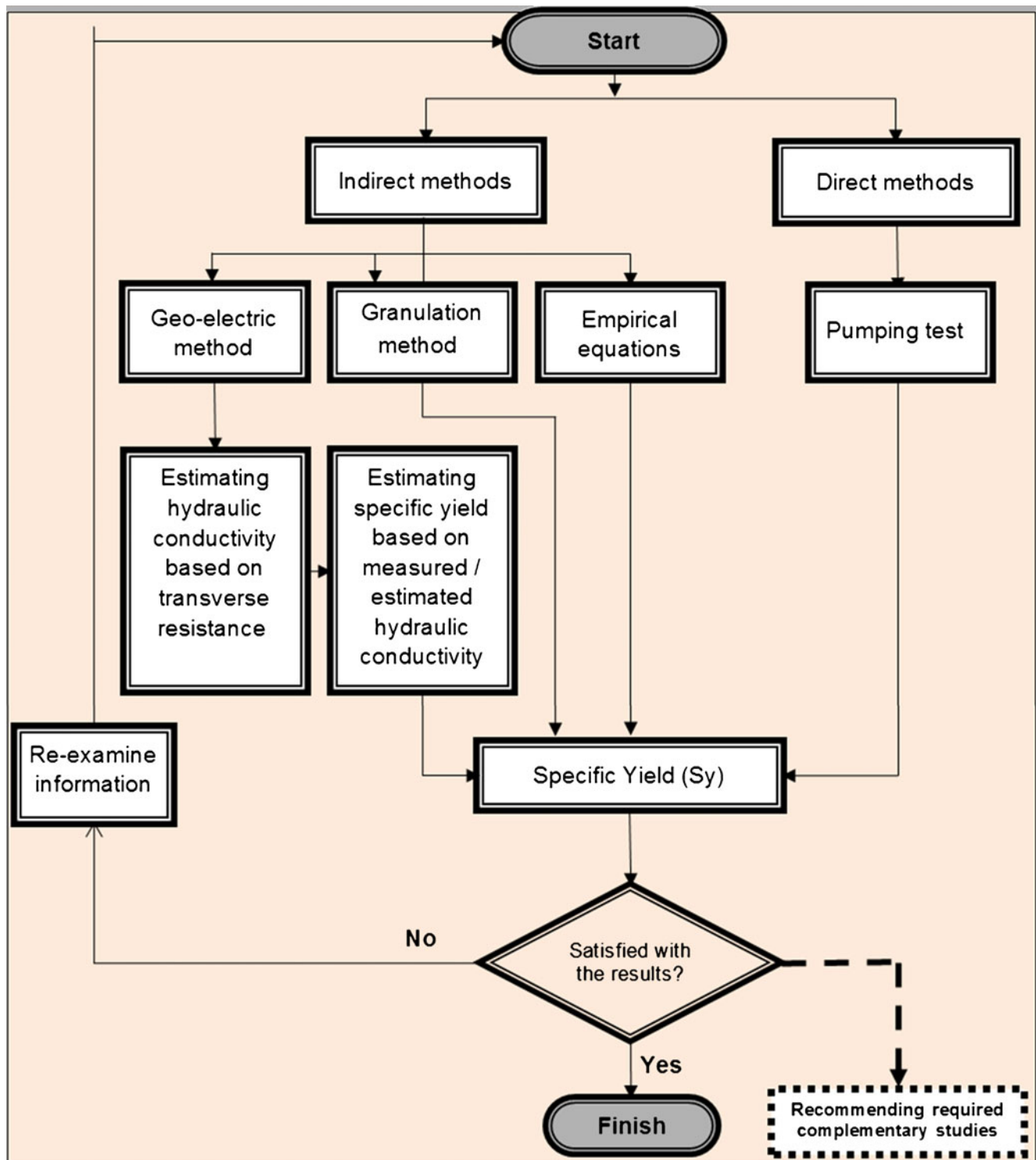


Fig. 9 Schematic diagram of required steps for determination of specific yield

The discharge temporal variation of each withdrawal well should be specified. Discharge data in many developing countries are usually measured every few years (i.e., sampling interval, say 5-year). Care has to be given not to mismatch withdrawal wells records from one sampling to another.

Knowing discharges of each withdrawal well, for two consecutive discharge sampling years, a linear variation is considered to define the discharge trend.

It seems that the quantification of groundwater recharge is a major problem in many water-resource investigations.

Table 1 Specific yield in percent for different soil textures and materials (after Johnson 1967)

Material	Specific yield (%)		
	Maximum	Minimum	Average
Clay	5	0	2
Sandy clay	12	3	7
Silt	19	3	18
Fine sand	28	10	21
Medium sand	32	15	26
Coarse sand	35	20	27
Gravelly sand	35	20	25
Fine gravel	35	21	25
Medium gravel	26	13	23
Coarse gravel	26	12	22

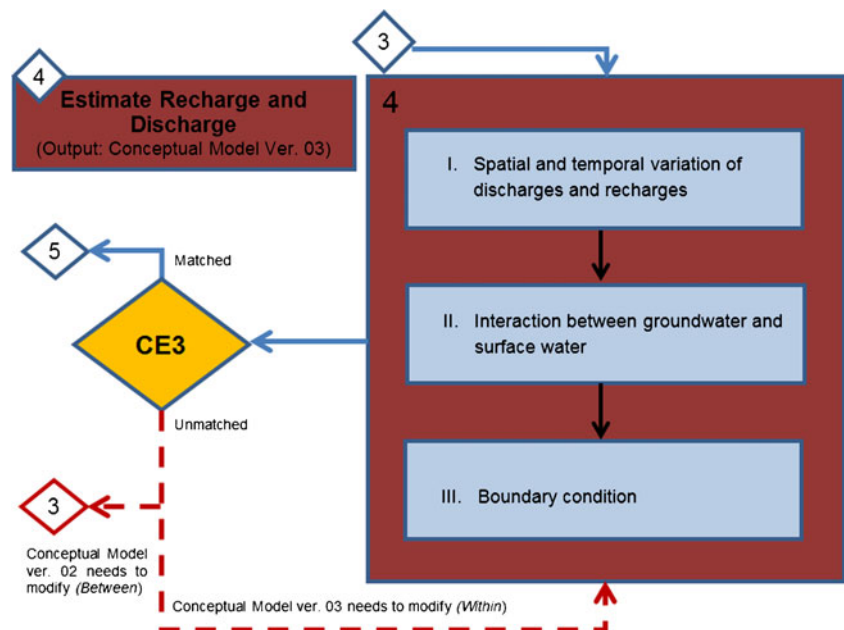
This is particularly intensified in arid and semi-arid areas, with very small recharge quantities, where small groundwater recharges are likely to be lost in the uncertainty of the dominant larger inputs and outputs (Allison et al. 1984; Gieske 1992; Wheeler 2010). It is believed that recharge takes place through four pathways: through fractured rocks in the mountain block with subsequent flow to aquifers, in alluvial fans at the base of the mountains, within streambeds, and direct infiltration in the plain.

Mountain block recharge is difficult to assess due to its inherent uncertainty. Mountain front recharge can be assessed using traditional methods based on piezometers, if available. Recharge from alluvial fan is the most important recharge component in arid and semi-arid areas. Piezometers are also used to measure the recharge from alluvial fans. In the absence

of such data, the boundary of aquifer has to be shifted inward to the first available piezometer. Then, the recharge from alluvial fan becomes a regional /lateral recharge. Streambed recharge is discussed in the next section.

A wide variety of methods is available to estimate direct infiltration from plain. Determining which of these techniques is likely to provide reliable recharge estimates is often difficult. Various factors need to be considered when choosing a method of quantifying recharge (precipitation, evapotranspiration, soil, land use, and crop management). A thorough understanding of the attributes of the different techniques is critical. Literature review shows that among all methods for estimating recharge, models play a very useful role in the recharge estimation process (Scanlon et al. 2002). They are used to determine sensitivity of recharge estimates to various parameters and to predict how future changes in climate and land use may affect recharge rates. The water balance methods such as WTF (water table fluctuation) (Meinzer 1923; Meinzer and Stearns 1929), CRD (cumulative rainfall departure) (Bredenkamp et al. 1995), and RIB (rainfall infiltration breakthrough) (Xu and Beekman 2003) can also be used, provided that reliable water table data is available. However, to develop the conceptual model a simple and applicable method with acceptable accuracy is to estimate recharge according to groundwater transmissivity (Gieske 1992; Dewandel et al. 2008; Wheeler 2010). In this method, aquifer is divided into several zones based on its transmissivity. The recharge was then estimated as a percentage of effective precipitation (Gieske 1992; Wheeler 2010) and groundwater extraction (Dewandel et al. 2008) for different zones. Additionally, a percentage of potential evaporation is considered as groundwater evaporation from the water table, if the depth of groundwater is less than 5 m. Figure 11

Fig. 10 Schematic diagram of step 4 and its output



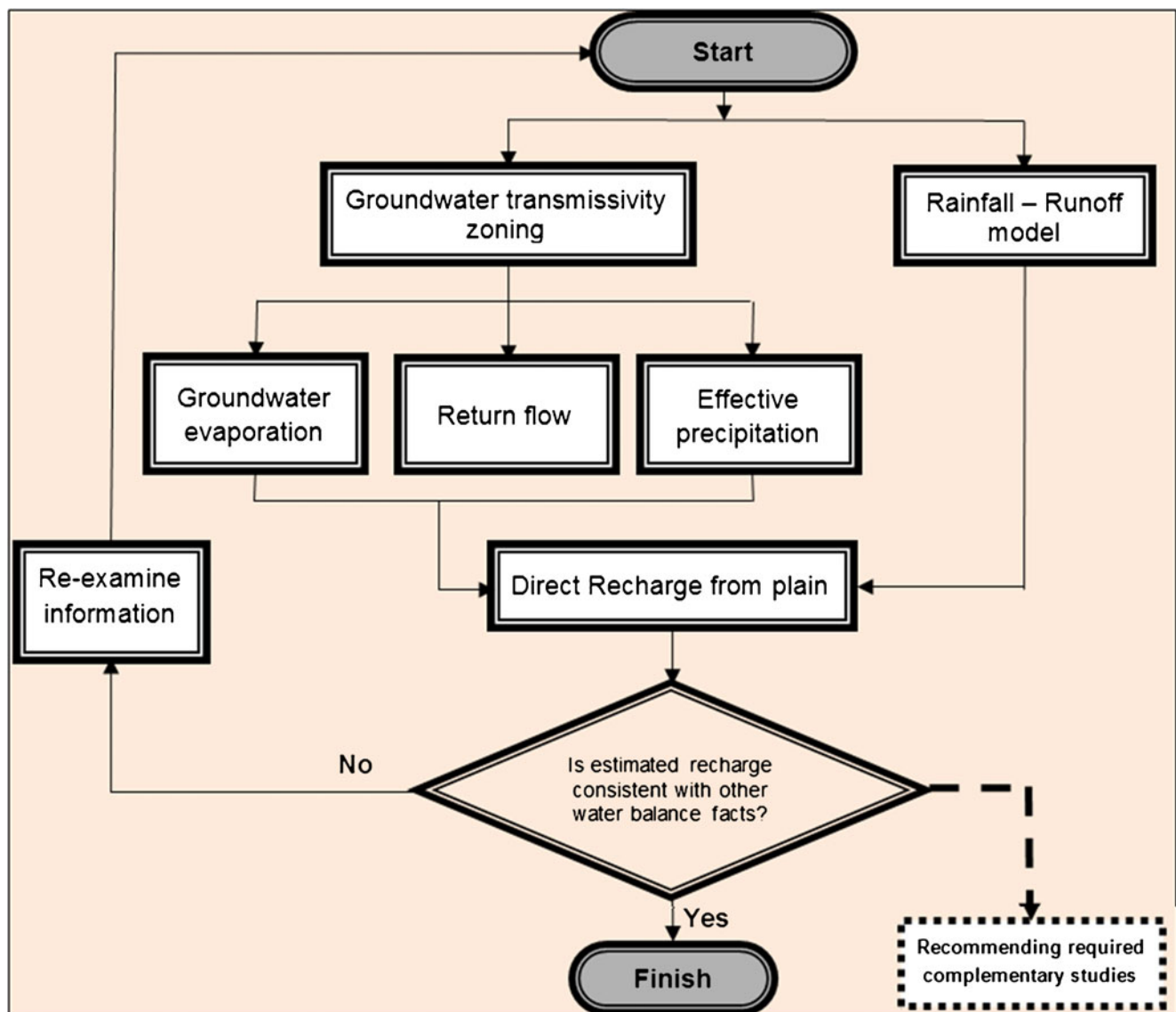


Fig. 11 Schematic diagram of required steps for direct recharge estimation based on transmissivity

shows a schematic diagram of required steps for estimation of direct recharge from plain based on transmissivity.

Interaction between groundwater and surface water

Accurate representation of groundwater–surface water interactions is crucial for groundwater modeling in the arid and semi-arid areas. In fact, groundwater and surface water are not isolated components of the hydrologic system but instead interact in a variety of aspects. Therefore, an understanding of the basic principles of interactions between groundwater and surface water is needed for effective management of groundwater resources. A more detailed description of the groundwater–surface water interactions is given by Sophocleous (2002). In many arid/semi-arid areas with a thick vadose zone, the interaction is mostly a recharge from streams to aquifer. Streambed

recharge can be estimated using the water balance model. Although it is relatively simple to estimate, streambed recharge is still poorly characterized. The easiest approach to measuring streambed recharge is through measurement of channel losses through channel path. This requires that the flow be measured at several locations along a stream within the flow period. Excluding withdrawals, any downstream decrease in flow is attributed to recharge through the bed between the measurements locations. While conceptually simple and requiring minimal instrumentation, this approach needs hydrometric stations; otherwise, it is costly and time consuming.

Boundary condition

Groundwater flow models typically have upper, lateral, and lower boundaries. The upper boundary is often taken to be

the groundwater levels. Piezometer water levels are usually given as initial condition. The lower boundary of a model is often considered to be the bedrock (explained in the “[The Bedrock](#)” section). The lateral boundaries are often the most difficult to be defined for hydrologic analysis. These boundaries are characterized as one of three types. For the first type, the groundwater level at the boundary is defined as a function of time. For the second type, the flux of water across the boundary is defined as a function of time. For the third boundary type, a no-flow boundary is assigned. The groundwater levels along with geo-electric measurements in the boundaries are analyzed with flownet technique to determine the boundary types (Anderson and Woessner 1992). Local expert knowledge is undoubtedly useful for enhancement of the conceptual model.

CE3 Before entering step 5, findings of this step have to be checked *within* and *between*. The *within* check is to make sure that the results are rational due to the aquifer annual water balance. The *between* check is made of many folds. The recharge amounts and seasonalities have to be consistent with the aquifer thickness, water-table elevations and its seasonalities, and also land use. The lateral boundary conditions have to be consistent with surrounding geological features, as well as with granulation and groundwater gradients.

Step 5: Deliver final version of the conceptual model

Step 5 is to integrate the results from other steps and to determine spatial accuracy level of the conceptual model components. Main outputs of this step are declaration of mathematical modeling feasibility and the annual groundwater balance (Fig. 12).

To visualize the accuracy of the developed conceptual model, a grid with proper cell size (compared to the plain area) is overlaid on the aquifer map. Then, the spatial accuracy level for each component of the conceptual model is specified for all grid cells, in five different classes, as explained in Table 2.

The ultimate score of each grid cell is summed up based on the score of the conceptual model components. The overall accuracy of the conceptual model is then summarized via average cells' scores. At this stage and based on determined accuracy level, feasibility of aquifer mathematical modeling should be assessed. Surely, this is relevant to desired accuracy and is judgmental. Another issue at this stage is to determine the minimum required gap filling complementary studies. This is to enhance the conceptual model accuracy to a satisfactory level for mathematical modeling. The final conceptual model is only

revisited when sufficient up-to-date data have been collected, which often may take several years, or when new information and/or scientific evidence challenge the original conceptualization. It is worthy to be reminded that the conceptual model is not only a prerequisite for modeling but is also the base of any managerial decision making.

Application of proposed method in the Neishaboor plain

Results of the developed conceptual model for the Neishaboor aquifer are presented in the following sections.

Hydraulic heads (controlling observations)

The groundwater elevations from piezometers were checked for their veracity in this step. The interpolated potentiometric surface, based on groundwater level measurements, is shown in Fig. 13. The regional groundwater flow originates primarily from the east, northeast, and south, and discharges to the southwest of the study area.

Aquifer geometry

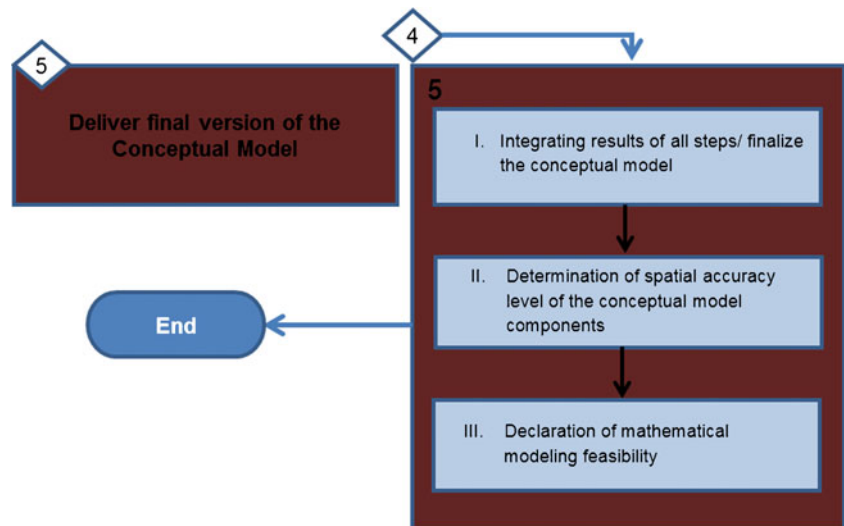
The terrain surface

Among available topographic maps, two with 1/50,000 and 1/25,000 scales were selected. Moreover, SRTM and ASTER DEMs were downloaded. These were cross-checked against each other and for conflicting points a field measurement of the piezometer coordinates and the ground surface elevation at these points with differential GPS technique was performed. The piezometers (official elevations) were considered as benchmark points. The investigation shows these benchmarks are best matched with SRTM DEM (RMSE was 8.82, 5.12, 4.33, and 9.44 m for 1/50,000, 1/25,000, SRTM, and ASTER DEMs, respectively). Finally, SRTM DEM was selected as the base elevation model.

The bedrock

To determine the position of the bedrock, the geo-electric sounding results from 1965 and 1966 (in 21 cross-sections, with 232 sounding points) were used. The distribution of these geo-electric soundings was satisfactory. Through the recent years, much new valuable information has been added. To achieve maximum possible clarity for the bedrock, a combination of old and new information was considered. New information consisted of withdrawal well logs, scattered geo-electric soundings (49 case, for other applications), and new borehole logs. Besides, local experts and/or drillers were

Fig. 12 Schematic diagram of step 5 and its output



consulted in many cases to resolve conflicts or uncertainties. Of 1,638 well logs, 329 were located on the geophysical cross-sections or their adjacent, and only 52 of these were drilled to the bedrock. Moreover, 85 agricultural wells which had encountered (based on well-drillers' sayings) with the specified bedrock were picked. In addition, valuable information extracted from five exploratory wells was used. Not only was this information compared with each other but also its quality was evaluated by other useful data such as depth and discharge of the adjacent withdrawals wells, regional geological formation, and local expert knowledge. The bedrock position became almost clear everywhere within the plain (Fig. 14). The bedrock depth varies from 0 to 260 m in the different parts of the plain. A Neogene and Marne rocks outcrop is seen in the southeast of the plain which was considered as impermeable boundaries to the groundwater flow system. The alluvial fans in the east of the plain formed the deepest part of the bedrock, ranging from 180 to 260 m. This thick alluvial near to the mountains

probably pertains to paleo-rivers in the past when hydrological conditions were different.

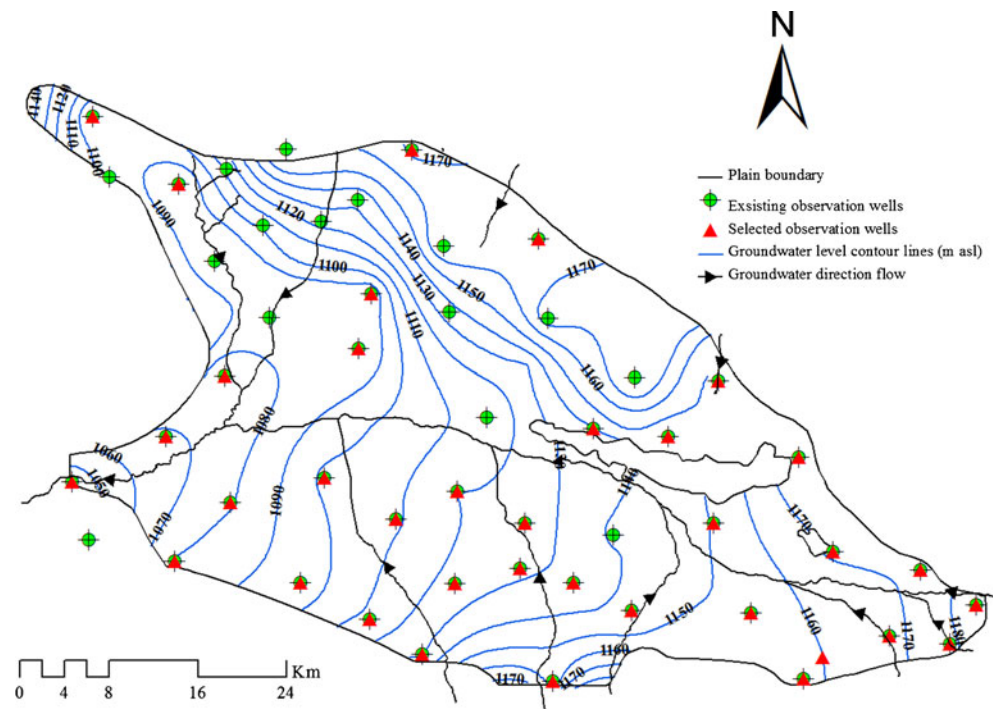
The physical aquifer boundary

The physical aquifer boundary is investigated in terms of physical limits and hydrological boundary types. To determine the initial physical limits of the plain, the topography and geology maps were used. Afterward, the plain boundary was improved using the intersection points of the groundwater level and descending and ascending limbs of the geo-electric cross-section. Since the geo-electric cross sections belonged to 1965 and 1966, considering the current groundwater level that has changed substantially from that time led us to modify the physical aquifer boundaries. For this reason, the bedrock raster was subtracted from the groundwater level to construct the saturated layer. In the obtained raster layer, everywhere the bedrock was located above the groundwater level; the boundary was modified manually and via local expert knowledge.

Table 2 Different classes for determination of the spatial accuracy level of the conceptual model components

Class	Definition	Description	Color	Score
A	Excellent	- Based on at least one "measured value" in the cell - No non-resolved conflicts against the measured value	White	4
B	Good	- Using interpolation methods based on sufficient neighboring measurements - Using empirical equations based on confident and adequate measured input parameters - No non-resolved conflicts against the estimated value	Light gray	3
C	Acceptable	- Using interpolation methods based on limited neighboring measurements - Using empirical equations based on limited measured input parameters - No non-resolved conflicts against the estimated value	Gray	2
D	Poor	- Using empirical equations based on estimated input parameters - Some non-resolved conflicts might persist against the estimated value	Dark gray	1
F	Non-acceptable	- No data in the cell - Persistent impasse conflicts among data or facts	Black	0

Fig. 13 Groundwater level contour lines for the Neishaboar aquifer (October 2010) along with general groundwater flow direction

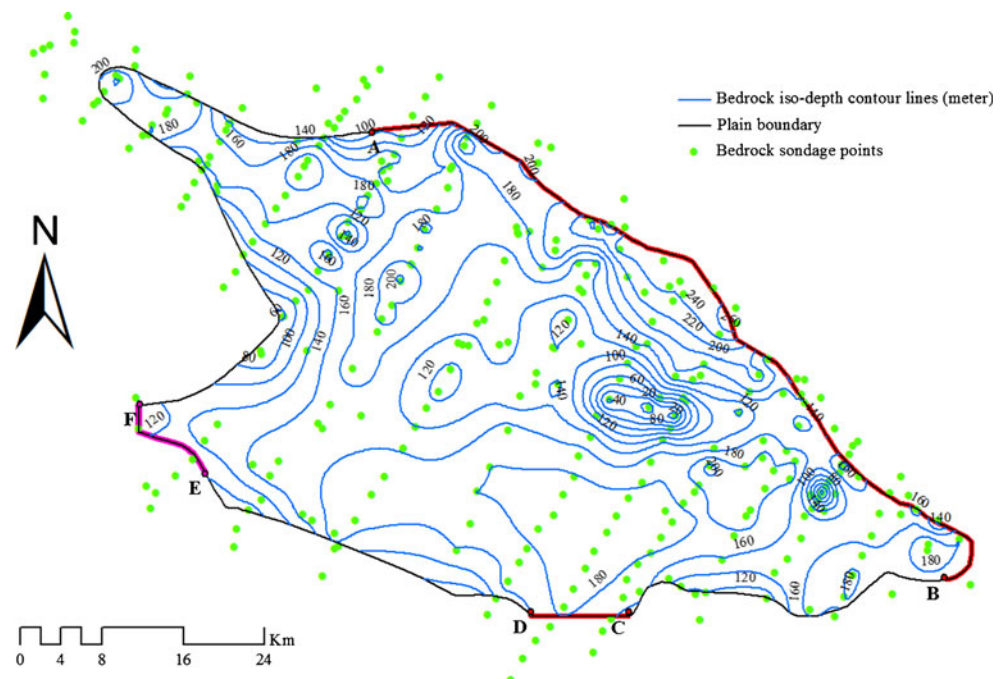


The hydrological boundary types

Based on 1956 and 1966 reports, the southeast and east boundaries of the aquifer associated with a groundwater inflow path. The southeast flow path represents the general direction of flow from the Rokh plain to the Neishaboar plain. The east boundary of study area is bounded by the Binalood Mountainous with small-permeability sedimentary rocks, and Marne and Neogene stones materials. However,

intervening tributary drainage basins provide a source of groundwater inflow to the study area. These two parts of the boundary were defined as specified head (transient water table elevation at the boundary). The south boundary represents a no-flow condition because of low permeability of its composing material. The southwest boundary of the study area was characterized as an outflow path and a specified head boundary condition was considered (Fig. 14).

Fig. 14 Bedrock depth contour lines for the Neishaboar aquifer, spatial distribution of sounding points, and boundary conditions, Red (A–B; C–D) and pink (E–F) lines are inflow and outflow boundary conditions, respectively



Despite the fact that the aquifer is vertically heterogeneous, the geo-electric survey of 1965 and 1966, drilling logs, geology maps, and local consultants showed that Neishaboor aquifer can be considered as an unconfined aquifer. However, further study is being performed in order to assess the stratigraphy of the Neishaboor plain thoroughly and accurately.

Hydrodynamic properties

The spatially distributed hydrodynamics properties were estimated using different methods. In the report of 1970 from Khorasan-e-Razavi Regional Water Authority, at 45 points, the specific yield was estimated using the granulation method. The hydraulic conductivity was calculated from estimated specific yield and suggested experimental equation in the literature. Two different experimental equations were used. The first is as follows:

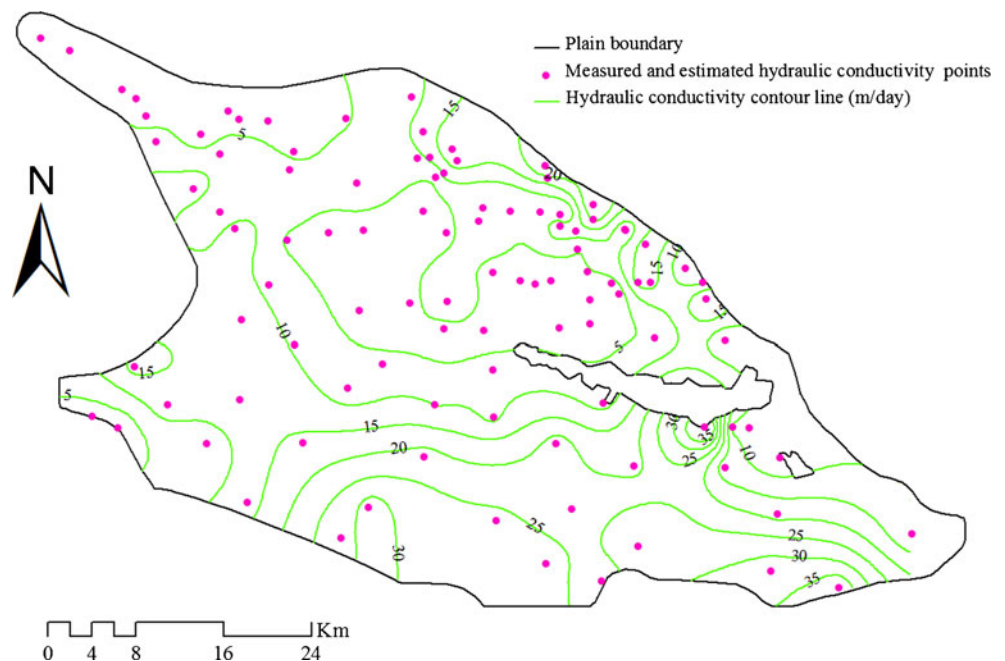
$$S_y = \sqrt{K} \quad (1)$$

where S_y is specific yield (%) and K is hydraulic conductivity (cm/day). The second relation (Ahuja et al. 1989) is as follows:

$$K = 0.2561e^{0.231 \times S_y} \quad (2)$$

where S_y is specific yield (%) and K is hydraulic conductivity (cm/h). Also, some other point measures of the specific yield and hydraulic conductivity were in the literature for particular purpose (dam construction, steel manufacturer, etc.). Estimated hydraulic conductivity values ranged from 0.12 to 56 m/day. The greatest values are observed in the east, south, and south-west of the plain, and near the plain outlet the conductivity decreases due to fine-grained alluviums (Fig. 15).

Fig. 15 Hydraulic conductivity contour lines and spatial distribution of measured and estimated points



The specific yield also has the same variation as hydraulic conductivity. The north and south of the plain has the greatest specific yield value (0.17), while the east and west of the plain is associated with the smallest value (0.05) (Fig. 16).

Discharge and recharge

To determine the temporal discharge variations, the discharge sampling of all withdrawal wells in 1999 and 2009 for the case study was accomplished (Fig. 17). The number of wells was reported as 1,767 and 4,003 in 1999 and 2009 where 1,612 of them were common between these two years. Other wells were added to the well list based on their drilling year. It was found that extraction for common wells in the 1999 and 2009 was 768 and 667 Mm^3 , respectively. Total extraction for all wells in 1999 and 2009 was 768 and 681 Mm^3 , respectively. It can be seen that there was a diminishing discharge trend for the common wells (13 %). However, 1.7 % of decreased extraction was compensated by increased number of wells. A linear variation was considered for determining discharge along two consecutive discharge sampling years. The withdrawal for industrial purposes was not taken into consideration since it is not significant in the investigated area.

The areal recharge rate was estimated according to transmissivity variations on a monthly scale. Therefore, the aquifer was divided into several zones based on its transmissivity. The recharge was then estimated as a percentage of precipitation and groundwater extraction based on transmissivity in each zone. In other words, 0 to 5 % of rainfall (Gieske 1992; Wheater 2010) and 10 to 24 % of groundwater extraction (Dewandel et al. 2008) was considered as an aquifer recharge.

Fig. 16 Specific yield contour lines and spatial distribution of measured and estimated points

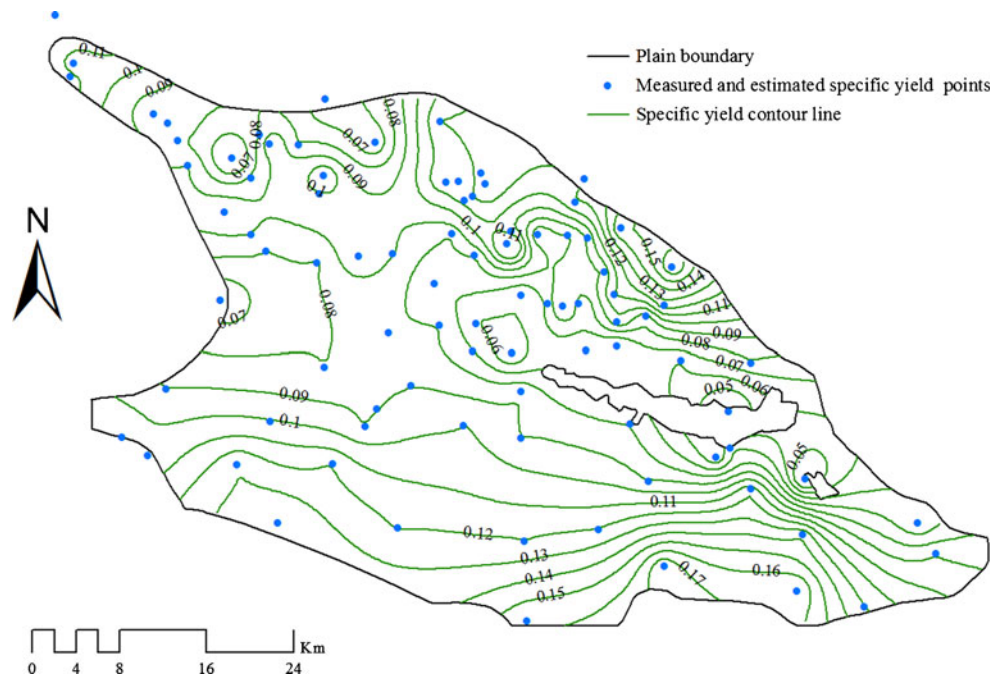


Figure 18 shows the considered recharge zone based on transmissivity.

The accuracy level of conceptual model components

The score of all conceptual model components was firstly determined and then summed up in each grid cell. Figure 19 shows overall accuracy level of each grid cell based on proposed method in “Step 5”.

In regards to Fig. 19, most cells have “good” conditions. The satisfactory condition is observed near the boundaries. The white cells are well distributed along the aquifer. It can

be concluded that overall accuracy level of developed conceptual model for the Neishaboer plain has “good” to “fair” condition. Therefore, the numerical modeling could be done based on the developed conceptual model. Nevertheless, it is strongly recommended to revisit developed groundwater conceptual model when sufficient data were collected; however, gathering new data may take several years.

Annual groundwater balance

The mean annual groundwater balance was calculated from October 2000 to September 2010 in a “water year” (period

Fig. 17 Spatial distribution of agricultural wells (October 2009)

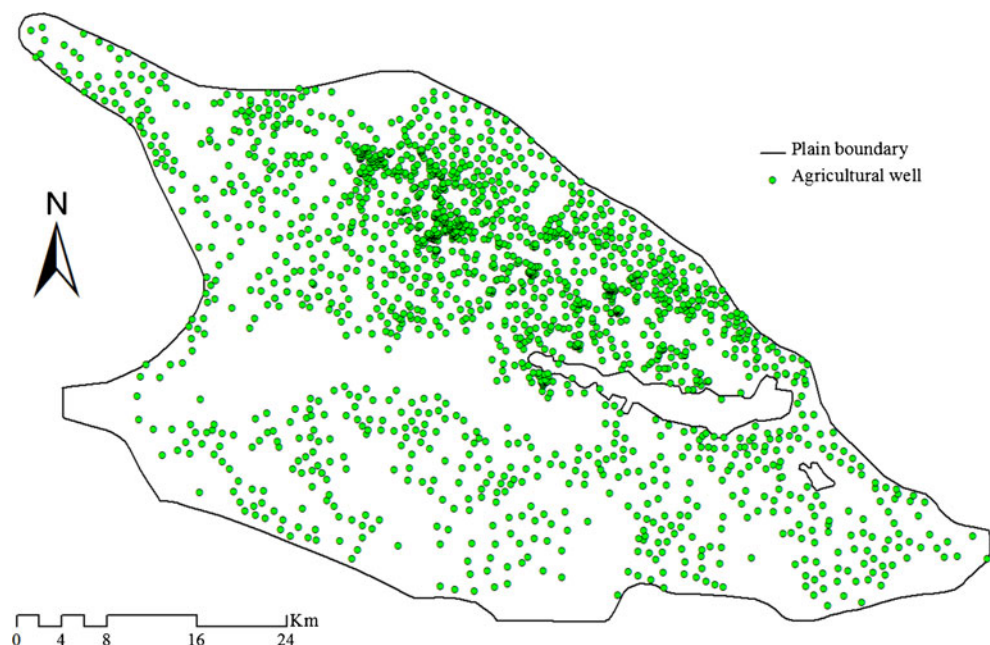
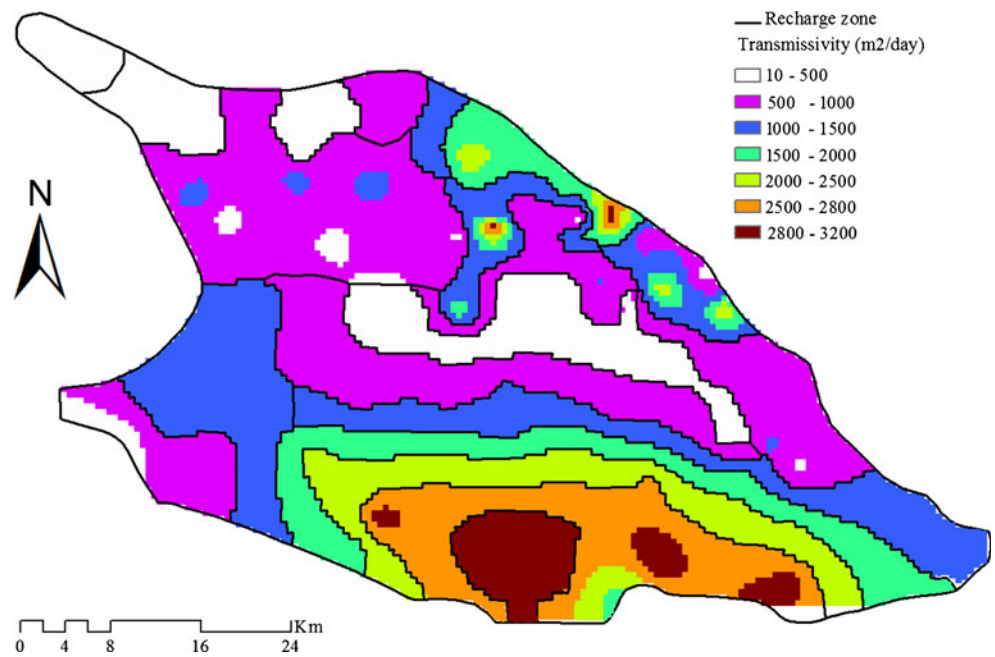


Fig. 18 Recharge zoning with respect to the transmissivity

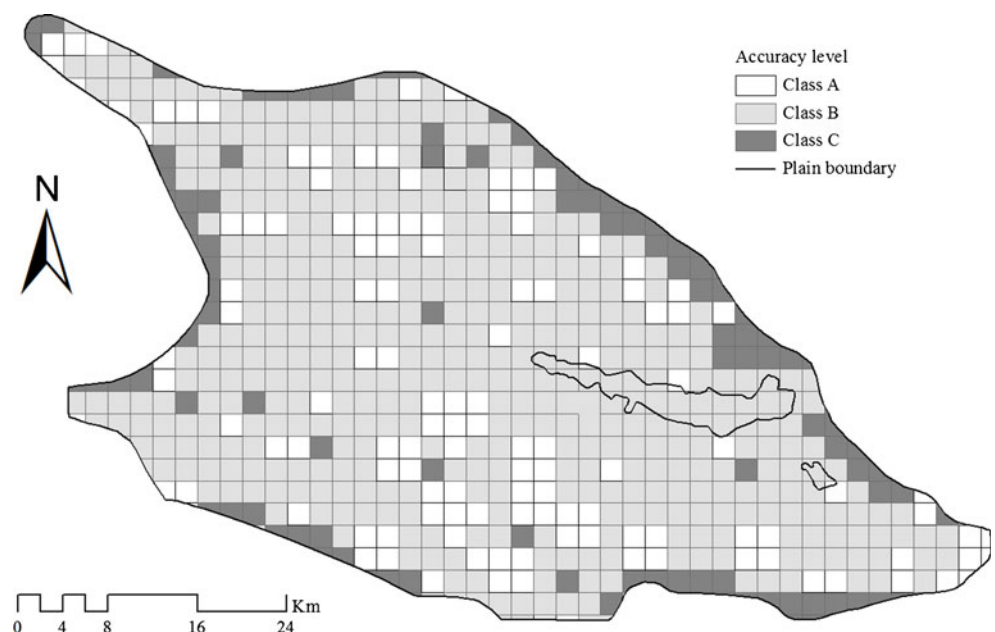


between October 1st of one year and September 30th of the next one) scale. Areal recharge provides the bulk of the water, with 212 Mm³/year. The inflow from the Binalood (east) mountainous and Rokh (south) plain provides 109 Mm³/year. The lateral groundwater outflow from the study area through the drainage basin is 11 Mm³/year. Groundwater withdrawal is equivalent to 598 Mm³/year with important effect on the annual groundwater balance in the study area. The study aquifer shows a mean annual negative balance (net extraction) of 287 million cubic meters due to extensive extraction for agricultural purpose. Regarding significant negative groundwater balance, it is necessary to consider appropriate scenarios for better management of the plain.

Summary and conclusion

Formation of a conceptual model is critical to develop an appropriate numerical groundwater flow model. In this study, performance of a new detailed proposed procedure was investigated to develop the groundwater conceptual model in the Neishaboor plain. It is worth noting that many researches tried several times to formulate a quantitative numerical model in the study area. Unfortunately, they could not construct a numerical groundwater model because of lacking suitable groundwater conceptual model. Therefore, it was decided to propose a procedure to develop a suitable groundwater conceptual model before constructing any numerical model. The

Fig. 19 Spatial accuracy level of each grid for the developed groundwater conceptual model



suggested method was useful and efficient for developing a conceptual model in the study area. However, there is still room for improving the proposed method using further applications in the different unconfined aquifers in the future.

The proposed method consists of six steps. The pre-step is aimed at the collection of all available data and information. The output of the first step as “controlling observations” is conceptual model ver. 00. This step should be double-checked rigorously because of its critical role in controlling the final conceptual model. The second step is to determine the aquifer geometry. The output of this step is conceptual model ver. 01. Before leaving this step, a consistency evaluation (CE), with regard to controlling observations, has to be done. The third step is responsible to determine the hydrodynamic properties, and its output is conceptual model ver. 02. Again make sure that the CE has to be done if any inconsistency (or conflict) is found. The fourth step is aimed at evaluation of the interaction between surface water and groundwater bodies and lateral in/out groundwater flow. The output of this step is conceptual model ver. 03. Again, CE has to be done. The fifth step is to integrate the results from other steps and to deliver the final conceptual model version. Also, spatial accuracy level of conceptual model is determined at this step. At last, annual groundwater balance is estimated.

Application of proposed method in the Neishaboor aquifer showed that the presented procedure can offer reliable framework for developing groundwater conceptual model. However, introduction of such procedure needs further investigations. It is hoped that with further applications by more researchers in the future, we should be able to find patterns about the successful cases and failure cases with the mentioned procedure.

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References

- Ahuja LR, Cassel DK, Bruce RR, Barnes BB (1989) Evaluation of spatial distribution of hydraulic conductivity using effective porosity data. *Soil Sci* 148:404–411
- Allison GB, Barnes CJ, Hughes MW, Leany IWJ (1984) Effects of climate and vegetation on oxygen-18 and deuterium profiles in soils. In: *Isotope hydrology*. International Atomic Energy Agency, Vienna, pp 105–123
- Anderson MP, Woessner WW (1992) *Applied groundwater modeling, simulation of flow and advective transport*. Academic, San Diego
- Barazzuoli P, Nocchi M, Rigati R, Salleolini M (2008) A conceptual and numerical model for groundwater management: a case study on a coastal aquifer in southern Tuscany, Italy. *Hydrogeol J* 16:1557–1576. doi:10.1007/s10040-008-0324-z
- Bedekar V, Niswonger RG, Kipp K, Panday S, Tonkin M (2012) Approaches to the simulation of unconfined flow and perched groundwater flow in MODFLOW. *Ground Water* 187–198
- Bredehoeft J (2003) From models performance assessment: the conceptualization problem. *Ground Water* 41(5):571–577. doi:10.1111/j.1745-6584.2003.tb02395.x
- Bredehoeft J (2005) The conceptualization model problem—surprise. *Hydrogeol J* 13(1):37–46. doi:10.1007/s10040-004-0430-5
- Bredehoeft J, Hall P (1995) Ground-water models. *Ground Water* 33:530–531
- Bredenkamp DB, Botha LJ, Van Tonder GJ, Van Rensburg HJ (1995) Manual on quantitative estimation of groundwater recharge and aquifer storativity. WRC Report No TT 73/95
- Carrera J, Neuman SP (1986a) Estimation of aquifer parameters under transient and steady state conditions: 1. Maximum likelihood method incorporating prior information. *Water Resour Res* 22(2):199–210. doi:10.1029/WR022i002p00199
- Carrera J, Neuman SP (1986b) Estimation of aquifer parameters under transient and steady state conditions: 2. Uniqueness, stability, and solution algorithms. *Water Resour Res* 22(2):211–227. doi:10.1029/WR022i002p00211
- Carrera J, Alcolea A, Medina A, Hidalgo J, Slooten L (2005) Inverse problem in hydrogeology. *Hydrogeol J* 13(1):206–222. doi:10.1007/s10040-004-0404-7
- Dewandel B, Gandolfi JM, de Condappa D, Ahmed S (2008) An efficient methodology for estimating irrigation return flow coefficients of irrigated crops at watershed and seasonal scale. *Hydrol Process* 22:1700–1712
- Egboka BCE, Uma KO (1986) Comparative analysis of transmissivity and hydraulic conductivity values from the Ajali aquifer system of Nigeria. *J Hydrol* 83:185–196
- English PM, Lewis SJ, Dyal A, Sandow J, Coram JE (2007) 3D groundwater conceptual model pilot project. Feasibility report for the condamine alliance. Geoscience Australia, Queensland
- EPA, DOE, NRC, (1994) A technical guide to ground-water model selection at sites contaminated with radioactive substances, EPA 402-R-94-012, Washington, DC
- Freeze R (1975) A stochastic-conceptual analysis of one-dimensional groundwater flow in non-uniform, homogeneous media. *Water Resour Res* 11(5):725–741
- Gelhar LW (1986) Stochastic subsurface hydrology from theory to applications. *Water Resour Res* 22(9):135S–145S
- Gerla PJ, Matheney RK (1996) Seasonal variability and simulation of groundwater flow in a Prairie Wetland. *Hydrol Processes* 10:903–920
- Gieske ASM (1992) Dynamics of groundwater recharge: a case study in semi-arid eastern Botswana. PhD thesis, Vrije Universiteit, Amsterdam, 289 pp
- Gillespie J, Nelson ST, Mayo AL, Tingey DG (2012) Why conceptual groundwater flow models matter: a trans-boundary example from the arid Great Basin, western USA. *Hydrogeology Journal* DOI 10.1007/s10040-012-0848-0
- Griffith DH (1976) Application of electrical resistivity measurements for the determination of porosity and permeability in sandstones. *Geoexploration* 14(3–4):207–213
- Hamm SY, Cheong JY, Jang S, Jung CY, Kim BS (2005) Relationship between transmissivity and specific capacity in the volcanic aquifers of Jeju Island, Korea. *J Hydrology* 310:111–121
- Hill M, Cooley R, Pollock D (1998) A controlled experiment in ground water flow model calibration. *Ground Water* 36(3):520–535. doi:10.1111/j.1745-6584.1998.tb02824.x
- Højberg A, Refsgaard J (2005) Model uncertainty—parameter uncertainty versus conceptual models. *Water Sci Technol* 52(6):177–186
- Izady A, Davari k, Ghahraman B, Alizadeh A, Sadeghi M, Moghaddamnia A (2012) Application of panel-data modeling to predict groundwater levels in the Neishaboor Plain, Iran. *Hydrogeol J* 20(3):435–447. doi:10.1007/s10040-011-0814-2
- Jabro JD (1992) Estimation of saturated hydraulic conductivity of soils from particle size distribution and bulk density data. *Trans ASAE* 35:557–560

- Johnson AI (1967) Specific yield-compilation of specific yields for various materials. U.S. Geological Survey, Water Supply Paper 1662-D, 74 p.
- Jusseret S, Tam VT, Dassargues A (2009) Groundwater flow modelling in the central zone of Hanoi, Vietnam. *Hydrogeol J* 17:915–934. doi:10.1007/s10040-008-0423-x
- Kelly WE (1977) Geoelectric sounding for estimating aquifer hydraulic conductivity. *Ground Water* 15(6):420–425
- Lohman SW (1972) Ground-water hydraulics. US Geol Surv Prof Paper 708:45–46
- Louis I, Karantonis G, Voulgaris N, Louis F (2004) Geophysical methods in the determination of aquifer parameters: the case of Mornos river delta, Greece. *Res J Chem Environ* 18(4):41–49
- Meinzer OE (1923) The occurrence of groundwater in the United States with a discussion of principles. US Geol Surv Water-Supply Pap 489, 321 pp
- Meinzer OE, Stearns ND (1929) A study of groundwater in the Pomperaug Basin, Conn. with special reference to intake and discharge. US Geol Surv Water-Supply Pap 597B:73–146
- Meyer PD, Gee GW (1999) Groundwater conceptual models of dose assessment codes. Presented at U.S. NRC Workshop on Ground-Water Modeling Related to Dose Assessment, Rockville, Maryland
- Meyer P, Ye M, Rockhold M, Neuman S, Cantrell K. (2007) Combined estimation of hydrogeologic conceptual model parameter and scenario uncertainty with application to uranium transport at the Hanford site 300 area, Rep. NUREG/CR-6940 PNNL-16396, U.S. Nucl. Regul. Comm., Washington, D. C.
- Moore C, Doherty J (2005) Role of the calibration process in reducing model predictive error. *Water Resour Res* 41, W05020, doi:10.1029/2004WR003501
- Nastev M, Rivera A, Lefebvre R, Martel R, Savard M (2005) Numerical simulation of groundwater flow in regional rock aquifers, southwestern Quebec, Canada. *Hydrogeol J* 13:835–848. doi:10.1007/s10040-005-0445-6
- Neuman SP (1988) A proposed conceptual framework and methodology for investigating flow and transport in Swedish crystalline rocks. SKB Swedish Nuclear Fuel and Waste Management Co., Stockholm, September, Arbetsrapport 88-37, 39 pp
- Neuman S (2003) Maximum likelihood Bayesian averaging of uncertain model predictions. *Stoch Environ Res Risk Assess* 17(5):291–305. doi:10.1007/s00477-003-0151-7
- Neuman S, Wierenga P. (2003) A comprehensive strategy of hydrogeologic modeling and uncertainty analysis for nuclear facilities and sites, Rep. NUREG/CR-6805, U.S. Nucl. Regul. Comm., Washington, DC
- Neuman SP, Wierenga PJ (2003) A comprehensive strategy of hydrogeologic modeling and uncertainty analysis for nuclear facilities and sites. NUREG/CR-6805, prepared for US Nuclear Regulatory Commission, Washington, DC
- Palma HC, Bentley LR (2007) A regional-scale groundwater flow model for the Leon–Chinandega aquifer, Nicaragua. *Hydrogeol J* 15:1457–1472. doi:10.1007/s10040-007-0197-6
- Pinder GF, Celia MA (2006) Subsurface hydrology. Wiley, Hoboken
- Poeter E, Anderson D (2005) Multimodel ranking and inference in ground water modeling. *Ground Water* 43(4):597–605. doi:10.1111/j.1745-6584.2005.0061.x
- Razack M, Huntley D (1991) Assessing transmissivity from specific capacity in a large and heterogeneous alluvial aquifer. *Ground Water* 29(6):856–861
- Refsgaard J, Van der Sluijs J, Brown J, Van der Keur P (2006) A framework for dealing with uncertainty due to model structure error. *Adv Water Resour* 29(11):1586–1597. doi:10.1016/j.advwatres.2005.11.013
- Reilly TE, (2001) System and boundary conceptualization in groundwater flow simulation. Techniques of water-resources investigations of the U.S. Geological Survey, Book 3, Applications of Hydraulics, Chapter B8, Reston, Virginia
- Rojas R, Feyen L, Dassargues A (2008) Conceptual model uncertainty in groundwater modeling: combining generalized likelihood uncertainty estimation and Bayesian model averaging. *Water Resour Res* 44, W12418, doi:10.1029/2008WR006908
- Rojas R, Feyen L, Batelaan O, Dassargues A (2010) On the value of conditioning data to reduce conceptual model uncertainty in groundwater modeling. *Water Resour Res*, 46, W08520, doi:10.1029/2009WR008822
- Rojas R, Kahunde S, Peeters L, Okke B, Feyen L, Dassargues A (2010b) Application of a multimodel approach to account for conceptual model and scenario uncertainties in groundwater modeling. *J Hydrol* 394:416–435
- Scanlon BR, Healy RW, Cook PG (2002) Choosing appropriate techniques for quantifying groundwater recharge. *Hydrogeol J* 10:18–39. doi:10.1007/s10040-0010176-2
- Seifert D, Sonnenberg T, Scharling P, Hinsby K (2008) Use of alternative conceptual models to assess the impact of a buried valley on groundwater vulnerability. *Hydrogeol J* 16(4):659–674. doi:10.1007/s10040-007-0252-3
- Sophocleous M (2002) Interactions between groundwater and surface water: the state of the science. *Hydrogeology Journal* 10:52–67. doi:10.1007/s10040-001-0170-8
- Theis CV, Brown RH, Meyer RR (1963) Estimating the transmissivity of aquifers from the specific capacity of wells. In: R. Bental (ed) Methods of determining permeability, transmissivity, and drawdown. U.S. Geol. Surv. Water Supply Paper 1536-1, pp. 331–340.
- Uma KO, Egboka BCE, Onuoha KM (1989) New statistical grain-size method for evaluating the hydraulic conductivity of sandy aquifers. *J Hydrol* 108:367–386
- Vandenberg A (1982) An alternative conceptual model of groundwater flow. *J Hydrol* 57:187–201
- Varni MR, Usunoff EJ (1999) Simulation of regional-scale groundwater flow in the Azul River basin, Buenos Aires Province, Argentina. *Hydrogeol J* 7:180–187
- Velayati S, Tavassloi S (1991) Resources and problems of water in Khorasan province. Astan Ghods Razavi, Mashhad (In Persian)
- Wheater, H. S. 2010. Hydrological processes, groundwater recharge and surface–water/groundwater interactions in arid and semi-arid areas. In: Wheeler HS, Mathias SA, Li X (eds) Groundwater modeling in arid and semi-arid areas, 1st ed. Cambridge University Press, Cambridge, pp. 5–37
- Xu Y, Beekman HE (2003) Groundwater recharge estimation in Southern Africa. UNESCO IHP Series No. 64, UNESCO Paris. ISBN 92-9220-000-3
- Ye M, Karl FP, Jenny BC, Greg MP, Donald MR (2010) A model-averaging method for assessing groundwater conceptual model uncertainty. *Ground Water* 48(5):716–728