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DEVELOPMENT OF GROUNDWATER MODEL FOR THE ARID AND SEMIARID AREA：THE WADI KAFREIN CATCHMENT/JORDAN

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Summary. In this work, a high precision groundwater flow model integrating all important geological features of the hydrogeological system is developed to investigate the hydrological processes in the Wadi Kafrein area. The object-oriented software OpenGeoSys (OGS) is applied and then updated in order to meet the challenges of complex geological features of the study area. The comparisons between the simulation results and the observation data show that the flow model is capable of reproducing historical groundwater level changes to a satisfactory degree. Since the Wadi Kafrein area is one of the arid and semiarid regions in the Lower Jordan Valley, the models developed in this study can be a useful tool for analyzing the hydrological processes and improving groundwater management practices elsewhere affected by similar geological and hydrogeological conditions.

1 INTRODUCTION

The groundwater resources in Jordan are limited due to semi-arid to arid climatic conditions. In the Wadi Kafrein area, groundwater resources are the major reliable source of water supply for domestic and agricultural purposes. In order to achieve a sustainable exploitation of groundwater resources and to quantify the impact of climate change on water resources, a proper understanding of the behavior of the groundwater system and assessment of the groundwater resources is an important prerequisite.

Wadi Kafrein is one of the three major wadis (i.e. Wadi Shueib, Wadi Kafrein and Wadi Hisban), which incise deeply into the Western Slopes of the East Bank in the northeast of the Dead Sea (Figure 1). The study area (the subsurface catchment of Wadi Kafrein), lies on the western margin of the Asian continent and belongs geographically to the Eastern Mediterranean Basin, and it is located in the lower Jordan Valley. The centre of the study area is located at WGS84 coordinates 31° 55’ N and 35° 46’ E with a total area of about 189 km^2.

The coordinates in this work are based on the Palestine Grid coordinate system which uses the meter as its standard unit. The maximum extension of the study area is 19 km in east- west and around 24 km in north- south direction. The highest point in the study area is located on the eastern border with an elevation of +1,096 m msl. The lowest point is located next to a large surface water reservoir (Wadi Kafrein Dam) with an elevation of -190 m msl[1].

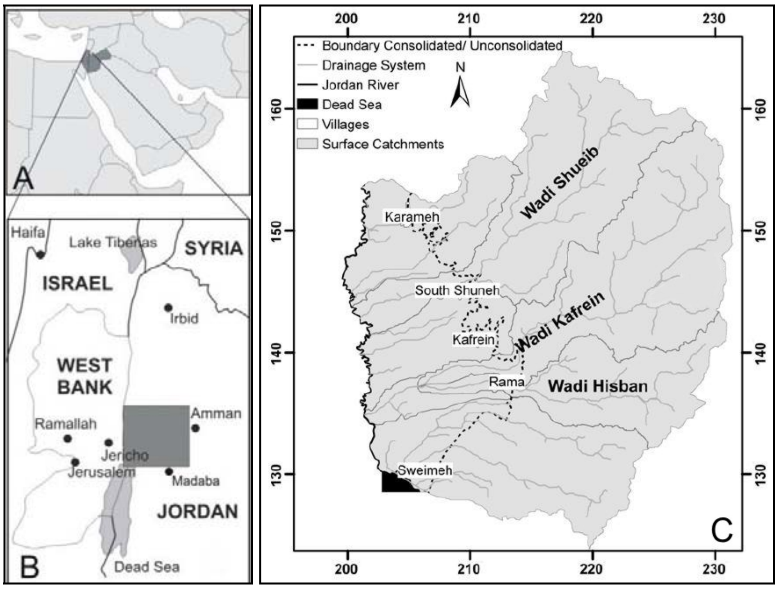

Figure 1: Location of the study area. A: The Middle East; B: Study area in the regional context; C: Study area with its neighbouring catchments. (compiled from Toll et al.[1])

According to Köppen[2], the study area can be classified as a GROUP B, Dry (arid and semiarid) climates, because precipitation is less than the potential evapotranspiration. Since morphology has the largest influence on the prevailing climate, the area can be classified into three different climatic zones as the highlands area, the Western Slopes of the East Bank, and the Jordan Valley[1]. The climate in the highlands is of Mediterranean type. It is characterized by long, hot, dry summers and short, cool, rainy winters. Towards the west, the climate undergoes a rapid change to semi-arid and arid climate in the Jordan Valley. The western slopes act as a transition zone between the Mediterranean climate along the highlands in the east and the arid climate in the Jordan Valley in the west. As the other wadis, Wadi Kafrein does not show perennial flow evidence. Rainfall takes place only during the winter months. During and after the rainy events, floodwater drains down to the Jordan Valley.

In this work, a three-dimensional groundwater model is developed for a selected typical arid and semiarid area, the Wadi Kafrein area. The most challenging of this work is how to apply a groundwater flow model to a steep and complex geometry of the multi-aquifer system. Since the study area is close to the active plate boundary, its geology is rather complex. Moreover, the study suffers from a serious lack of reliable and geographically spread data and information. The basic idea of this paper was to develop and to apply a methodology in order to handle the complexity in the modeling of the study area. The present model could be transferred to the other regions with the similar geological and hydrological conditions.

2 MODEL DEVELOPMENT AND IMPLEMENTATION

A literature survey of groundwater research in the Jordan Valley revealed that different groundwater flow models have been developed and applied to resolve different groundwater flow problems. In particular, groundwater flow and transport model of the neighbouring area have been successfully developed, such as the northern Jordan Valley[3], the Jericho area[4], the Zarqa River basin[5,6] and Amman-Zarqa basin[7]. However, the numerical model developed for the Wadi Kafrein area has to meet the challenges of data scarcity and the complex geometry of subsurface strata. For this purpose, the numerical model is implemented in the framework of the scientific modeling software OpenGeoSys (OGS) [8,9], in which new functionalities are added. The main concept of OGS is to encapsulate the geometry, the mesh and physical data, and the corresponding methods into different objects. More important, the object-oriented programming allows an easy extension of the code to more complex applications. The capability of OGS in groundwater flow and transport simulations has been verified against a large number of benchmarks, e.g. the classical seawater intrusion problem of Henry, the free convection problem by Elder and the salt dome problem[8].

2.1 Conceptual flow model

The study area is a multi-aquifer system that includes regional aquifers which are located in the mountainous area and downstream. From the geological perspective, three unconsolidated groups exist in the study area. Above the early Cretaceous transgressive unconformity, the Lower Cretaceous Kurnub Group follows along the margins of the rift valley. The most important regional aquifer in the highlands is located in the lower Ajlun Group. Because of the presence of the Fuheis and the Shueib marls and claystones, the lower Ajlun Group forms a multilayered aquitard (locally even an aquiclude) with embedded aquifers, such as the massive limestones of the upper Na’ur and of the Hummar Formations. Contrastingly, the overlying Wadi as-Sir Formation consists in the area mainly of well bedded and massive limestone of a prograding and agrading carbonate platform. It forms the important Upper Aquifer together with the basal Belqa Group[1].

The predominant elements governing the geological structure and flow regime are the NNE-trending Kafrein normal fault and associated fault bounding the Kafrein syncline to the West, and the Kafrein asymmetric syncline[10]. Wadi Kafrein follows synclines and flows down the western slopes of the Transjordanian Mountains toward the Jordan Valley depression. Therefore, groundwater flow in the study area is structurally determined. It flows from the northeast down to the Jordan Valley in the southwest. However, in the vicinity of the drainage areas, groundwater is redirected toward the wadis.

2.2 Three-Dimensional structural model

The finite element method is employed to simulate the groundwater flow in the study area. In order to gain accurate simulation results, a high resolution finite element mesh is required to represent the complex geometry of subsurface strata. In this study, all required GIS data such as the subsurface catchment, the Digital Elevation Model (DEM) and the geological features of layers for the study domain for modelling, are converted into the appropriate formats for numerical modeling by using the commercial ArcGIS 9.3 software package (ESRI Inc.). The geological formations are divided into eight hydrological units and most of them have the outcrop areas. All layers are mapped onto the corresponding elevation. As a result, a hybrid mesh of 24,115 elements (3,772 tetrahedral elements and 20,343 prismatic elements) with 13,390 nodes is generated based on the newly developed approach for elements removal and adjustment. Mapping results and material groups (vertically shifted) of the whole domain are depicted in Figure 2. It can be seen that the current structural model incorporates all important geological features, such as channels, folds and thickness variations of the different geological strata. The new mapping approach enables the complex structural details of the geological formations to be accurately reproduced in the numerical model domain, i.e. the finite element mesh.

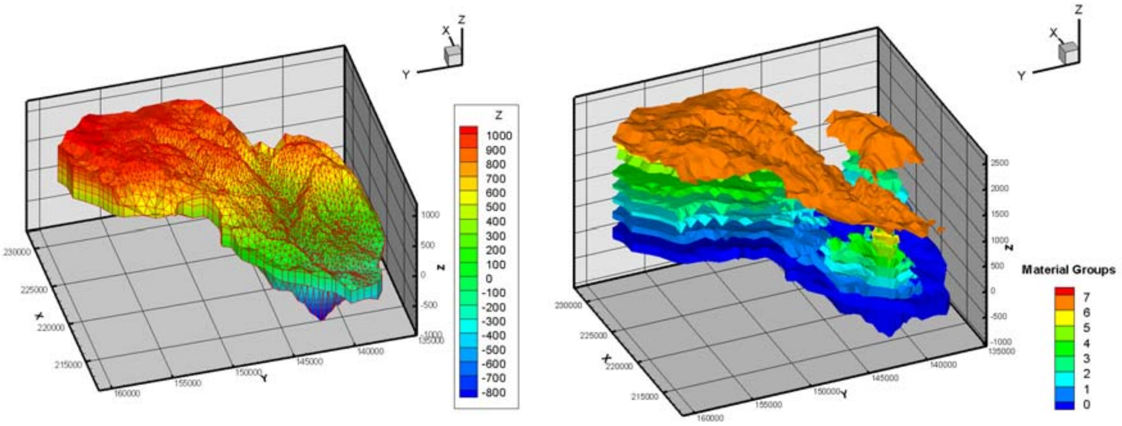

Figure 2: Mapping result (left) and material groups (right) of the whole domain

2.3 Three-dimensional groundwater flow model

The governing equations for three-dimensional groundwater flow are based on water mass balance and Darcy's law[11]. According to the hydrogeological background, the following boundary conditions are set in the steady state model. Constant head boundary conditions are applied to the northeast boundary and the southwest boundary, while no-flow boundary conditions are set to other part of the catchment borders. The adjustment for the values of the constant head boundary conditions is performed during the model calibration procedure in order to achieve a best agreement between the calculated and the observed groundwater levels at the observation wells. For the transient model, the variant hydraulic heads are assigned to the southwest boundary due to the lack of the real quantities of the outflow flux from there. Based on the head gradient at the nearest Observation Well 1, all nodes on the surface vertically extended from the southwest boundary are defined as constants during any given time step, but vary for every time step. Different from the steady-state, no-flow boundary conditions are prescribed on the northeast boundary.

From the view point of water budget, the source/sink terms of the hydrological system are defined by the recharge from infiltration and discharge (i.e. wells and springs as previously stated) to or from the study area. In the study area, the major inflow source is the vertical recharge from precipitation on the outcrops in the eastern highlands and the major outflow sources are pumping abstraction, springs discharge and lateral discharge across the southwest boundary. Since available rainfall stations are sparsely distributed in the study area, it is a complementary measure to use secondary attributes that are more densely sampled. Considering elevation is the most widely used additional information in the geostatistical analysis of precipitation distribution[12], the multivariate geostatistical method External Drift Kriging (EDK) is applied to interpolate the rainfall distributions in this study and the elevation are used as a covariate[13]. Furthermore, it is complicated to establish a precise regional distribution of the recharge rates because the related data are scarce and incomplete. As an alternative, the recharge to the aquifers by infiltration of surface water is modeled as an estimated recharge rate of the rainfall for all surface nodes. For the transient model, the abstraction rates of the production of the wells and discharge of the springs are assigned to the corresponding mesh nodes.

For simulations, material properties have to be specified for fluids, solids and the porous medium (i.e. the aquifers and aquitards), respectively. The specific storage values of the porous medium are assumed based on the storativity coefficient from hydrogeological units and layers thickness. As for the hydraulic conductivity, limited pumping test data are available for the study area. Therefore, the available data do not allow to obtain a detailed resolution of different conductivity zones. In the current model, the hydrogeologic units and their characteristics are compiled from Margane et al. [14].

3. RESULTS AND DISCUSSIONS

The objective of the calibration is to obtain an optimal fit between the calculated and the measured data, which is also an important measure for the reliability of the present groundwater model. The calibration of the current model includes two sequential steps. Firstly, the steady-state model representing the pre-developed aquifer system was calibrated using the measured water level data from four observation wells, in order to understand the trend of groundwater level in the whole domain. Then the transient model calibration was accomplished by simulating ground water level changes in response to the variations of the natural recharge quantities due to the rainfall fluctuations, wells abstraction and springs discharge from 1996 to 2008, based on the preliminary hydrogeological properties obtained from the steady-state calibration.

3.1 The steady-state model

To obtain the best match between the calculated and the observed groundwater levels at the observation wells, the necessary adjustment of the boundary conditions is performed during the model calibration procedure. Meanwhile, the annual averaged rainfall distributions are applied to the top surface and the recharge rate to the groundwater is assumed as 20 % of the rainfall. Four observation wells are distributed in different part of the study area. Figure 3 (left) shows a scatter diagram of the observed versus calculated water level in monitoring wells. Obviously, the obtained water levels of the observation wells are very close with their measured values. The simulation results of the hydraulic heads under steady-state conditions are shown in Figure 3 (right). It can be seen that the general groundwater flow pattern is clearly represented, i.e. from the highlands area to the Jordan Valley. Therefore, it can be concluded from the comparisons presented here that the steady-state model provided a fair simulation of the pre-developed groundwater flow in the Wadi Kafrein area.

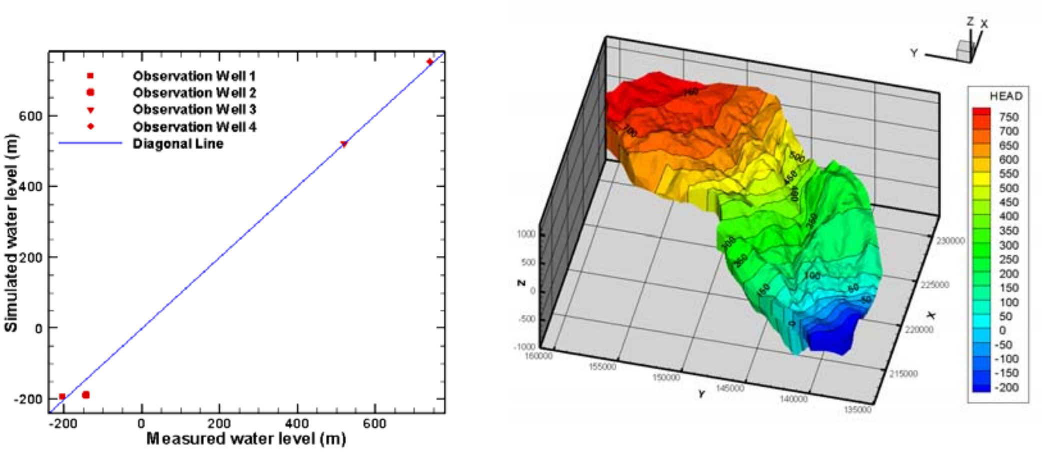

Figure 3: Left: Observed versus calculated hydrographs at four specific observation wells; Right: the contour map of the calculated hydraulic head in the whole domain.

3.2 The transient model

The transient model calibration is accomplished by simulating hydraulic head changes in response to changes in recharge and discharge. For the transient simulations, the basic geometric set-up and material parameters of the aquifer is the same as that used for the steady-state simulations. The resulted flow field of the steady-state is used as the initial condition for the subsequent transient simulations of the flow system. In addition, time and space dependent source terms are imposed on the top surface, such as the monthly rainfall interpolated using External Drift Kriging over the simulation period, the production of the wells and discharge of the springs. The most important numerical step is to create the relations between the functions of time-dependent source terms and their corresponding nodes numbers. To do this, the element nodes on the top surface have to be found taking account of the complexity in the geometry.

With regard to the time series data of water level, only two wells (i.e. Observation Well 1 and Observation Well 3) have records which cover part of the simulation period. The comparison of calculated versus measured groundwater levels of the two wells, together with their corresponding rainfall curves are shown in Figure 4. The left figure shows that there is a good agreement between the calculated and the observed groundwater levels in Observation Well 1. The measured data of this well also indicates that the water level continuously declines over the recorded period. As for Observation Well 3, continuous water level is available for less than two years. Compared with Observation Well 1, Observation Well 3 is located in the recharge area and has higher average precipitation. The measured groundwater level suggests that it fluctuates seasonally as a direct response to precipitation and flood flows, within a range of around 2 m during the recorded time (see the right figure). The calculated water levels rise during and after the rainy season and drop gradually during summer and autumn. Although the calculated results do not show the frequently fluctuations as the observation data, they both present similar varying range.

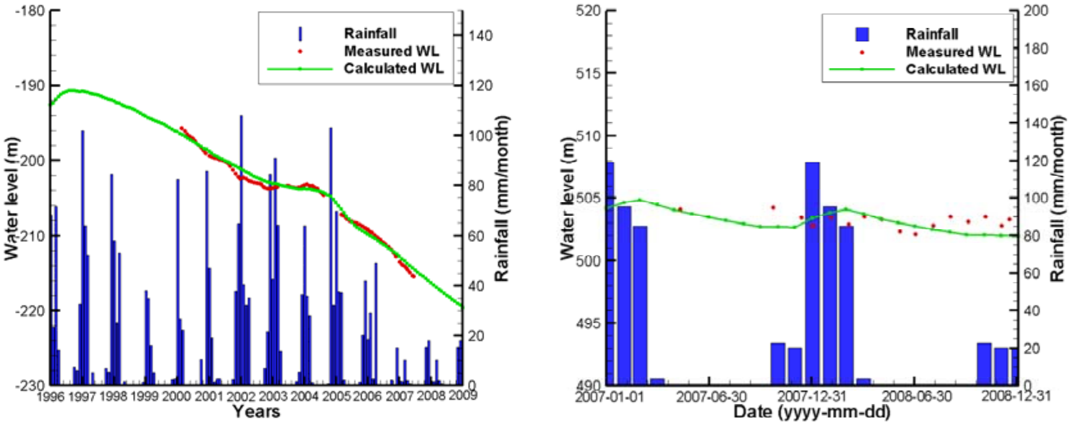

Figure 4: Calculated versus measured water levels of Observation Well 1 (left) and Observation Well 3 (right)

4. CONCLUSIONS

The major conclusions of this work are summarized as follows.

- Using the newly developed mapping approach, the translation of the highly detailed geological formations to an unstructured finite element grid, which consists of tetrahedral elements and prismatic elements, can be realized with a high precision.
- Although the calibration is carried out based on a few available measured wells, the simulation results show that the present flow model is capable of reproducing historical groundwater level changes to a satisfactory degree.
- Slight difference between the simulated and measured water levels still exists in Observation Well 3, because some factors such as return flows from irrigation and the groundwater inflow from the adjacent aquifers are not taken into account so far.
- Since the Wadi Kafrein area is one of the arid and semiarid regions in the Lower Jordan Valley, the models and conclusions from this study are of general interest.

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