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Transient Fluid Flow Modeling in Fractured Aquifer of Sechahoon Iron Mine Using Finite Element Method

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Abstract

Considering the fact that a large volume of iron reserve in the Sechahoon Iron Mine in Yazd Province has located under the water table, it is necessary to conduct a comprehensive study on water flow within the pit and its surroundings. The conceptual model of the aquifer was created using the surface and underground geological information compared with water table data of the area of interest. In the data preparation stages, in order to create the numerical model, Logan and Lufran tests were carried out to determine the hydrodynamic coefficients of the layers. The precipitation and evaporation, as well as the fractures and faults of the region, as a medium for flow channels in the hard formation, were also studied. The model was created in a transient state between 2000 and 2014. To validate its results, the water table was measured 4 times in the last 4 months of 2014. Considering the complexities in the heterogeneous fractured aquifer of the study area, numerical modeling results for the basin in a transient state present 90 percent correlation with field studies. Having investigated the water balance in the region, the boundary condition of the model was determined as the input water from the eastern south and the runoff water in the western north of the region. Since the general trend of faults in the area is north-south, the water table variation is slight on north-south and intense on the east-west direction. On the other hand, due to the fact that the maximum flow is along the faults and fractures, the water table contour lines in different locations over the region are closed.

Keywords: *Sechahoon Iron Mine, Numerical Modelling, Fractured Formation, Finite Element Method, Feflow.*

1. Introduction

One of the most common problems in open pit mining is penetration of water into the pit. It has also other negative impacts on rocks geotechnical properties, the stability of walls slope, loading and transportation, drilling and blasting, equipment and facilities and their maintenance, humidity in ore minerals, wastes and ecosystem. Therefore, designing a suitable water control system has an important role in creating a dry and safe mining front, reducing the usage of slurry blasting materials, and so on. The most important stage after collecting and completing the information information collection and completion is modelling the underground water flow and determining the direction of fluid current to design the drainage system. One of the most important advantages of numerical modelling of aquifers is the ability to investigate different scenarios for determining the most efficient approach before its implementation [1].

In recent years, the growing depth of mining in underground bedrock reserves demanded the application of hydrogeological studies to inquire detailed information from underground heterogeneous formations. In other words, as the depth increases from surficial alluvium to the bedrock, the complexities increase by variation in the formation type through increasing the depth from surficial alluvium to the bedrock. In such a situation, the fluid does not anymore flow anymore all over the region and is confined to the fractured and faulted media. Therefore, at first, it is necessary to detect disconformities, and then, to investigate the way the fluids fluid flow in this heterogeneous environment [2-6]. Due to water penetration in northern and southern pits in the Sechahoon iron mine, we have tried to investigate the hydrogeological situation of the region and model the fluid's flow in the invaded mining place.

Tanigouchi and Fillion (1996) and Berthoud and Kohel (2003) modeled the underground water flow through defining a so-called 'Fracture Plates Model. They used a triangular mesh which was defined by quadrangle shapes to create a network with hexagonal shapes. This method needs the simultaneous production of 2D and 3D shapes for fractures and rocks matrixes, respectively. They considered rock's matrix as a continuous medium and solved the problem only using the triangle mesh and Finite Element Method (FEM) [7-8]. Molinero (2001) tested and validated the numerical modelling of the underground water flow in transportation of contaminations and chemical reactions in fractured granites [8]. Later in 2003, Molinero et al. modeled the underground water flow in fractured media using the TRANMEF-3 code in the Aspo, Sweden [10]. Kolditz and Bauer (2004) and Kolditz et al. (2008) created a 2.5-dimensional rock network with 3D planar surfaces and then investigated it using triangular mesh on the GeoCAD software. They considered the rock's matrix as a continuous medium and solved the problem using the triangle mesh and Finite Element Method (FEM) [11-12]. After the development of the HydroGeoSphere numerical model by Blessent et al. (2009), quadrangle shapes were also used in meshing. Geometrical characteristics, spatial expansion, and dimension and location of each fracture in 3D space was shown using the average dispersion of fractures [13]. Numerical models are based on the continuity of water table and the density on the fracture/rock's matrix separation surface, which is related to the instantaneous balance between these two domains. This method is also called 'common node method' (Therrien et al., 2007 and Sudicky, 1996) which is an array of the porosity matrix. Therefore, the nodes in fractured places are called 'common nodes' which are affected by both factors of rock's matrix and fractures plates [14-15]. Donglin Dong et al. (2012) used MODFLOW numerical method to optimize the amount of pumped water in a coal mine. The weakness of application of this code in defining the geometry of the aquifer is that it has developed for porous media; on the other hand, considering facing the heterogeneous rocks through increasing the depth and crossing from the alluvium environment, the modelling has to consider its complexities [16]. Krčmář (2014), as well, used this code to model the underground water in a mine [17]. Álvarez et al. (2015) modeled groundwater flow in an open pit located in limestones using the same code [18]. Like other models created by numerical models of MODFLOW, this model can also consider only the role of faults on the movement of formations with various permeability coefficients, and does not deal with faults as a fluid flow media. In this research, we have tried to develop a heterogeneous numerical model of the basin, and to determine the value and direction of the flow through taking into account the faults and fractures as the main media.

2. Research Principals and Methodology

2.1. Input Water Sources in Open Mines

In order to accurately predict the value of the input water in open mines and design the drainage network, it is necessary to determine various sources of waters and the runoff locations in the model [19-22]. The input waters enter into the pit from two important sources:

1. Rainfall and surficial streams;
2. Underground vertical and horizontal flows from aquifers, alluviums and bedrocks.

2.2. Rainfall and surficial streams

Surficial waters from rainfall can directly, and streams and sudden floods can indirectly enter into an open mine. Although rainfalls and surficial streams have small components with respect to the input underground waters, they should not be disregarded in modelling the input waters, the water level recovery, and the quality of water [19, 22-24]. In modelling the quality of pit water, surficial water flow consists of two parts:

- The surficial water in the upper levels of the pit has a high concentration of metals which have been washed out from the oxidized rocks and geological formations of the pit walls. This part of the surficial water is usually considered as 50 to 100 percent of the precipitation [19, 25-29].
- The surficial water originating from other parts of the watershed basin. This water has less solved metals in and is considered as 10 to 20 percent of the precipitation.

The precipitation can be directly measured or indirectly estimated from regional flow data or surficial fluid flow models [19, 25-29].

2.3. Underground Input Waters

The volume of underground water flowing from aquifers into the open mines is more than other water sources. This has an effective influence on the correct calculation of the volume of input water and is necessary to be correctly predicted. The water volume entering from water table into the mining areas is composed of the following components:

- The water resulted from loss or initial potentiometric level drop that is resulted from evaporation or mine drainage [19,30].
- Inactive component of underground water flow that is resulted from the initial hydraulic gradient of the water table or piezometric level [19,30].

2.4. Flow in a Single Fracture

Let the hydraulic flow in a fracture be the same as the flow between two parallel plates. The flow equation between two parallel plates for an incompressible Newtonian fluid is computed from the fundamental Navier-Stockes equation as follows [31]:

$$\rho(\frac{\delta U_i}{\delta t} + \sum_{\lambda=x,y,z} U_\lambda \frac{\delta U_i}{\delta \lambda}) = \mu \sum_{\lambda=x,y,z} \frac{\delta^2 U_i}{\delta \lambda} - \frac{\delta P}{\delta i} + \rho g_i \quad (1)$$

Where ρ_i is the fluid's density, Ui is the scalar component of the velocity vector along the current, Pi is fluid's pressure, and gi is the scalar component of gravity acceleration in direction i. The flow equation between two parallel plates (e.g. a joint, supposing it is a planer plate with constant aperture) resulted from the Navier-Stockes equation namely 'cubic law' as follows:

$$q = \frac{ga3}{12v} \nabla H \quad (2)$$

Where g is the gravity acceleration of the Earth, *a* is an effective aperture, ν is cinematic viscosity, H is the hydraulic slope, and q the crossing flow from the surface unit. The above equation can be written as:

$$q = C \,.\, \Delta H \quad (3)$$

$$C = \frac{ga3}{12vl} \quad (4)$$

Where C is conductivity value and l is the joint's length [31].

2.5. Flow Modelling in Discrete Features in Feflow Software Package

Feflow is one of the most useful software in hydrogeological modeling. In this software, fractures and faults are considered as discrete features. The important parameters of these features are cross section area, hydraulic aperture, and specific storage. Given the two parameters of cross section area and hydraulic aperture, one can consider a fracture as a dike to be a fluid flow medium. Note, however, that the two first parameters are used in the calculation of Reynolds's number, as well. Having given these parameters to the software, it will automatically calculate Reynolds's number for laminar and turbulent flows to be used in solving the equations. Generally, in this software, there are three equivalent equations for fractures:

- Darcy Law
- Hagen-poiseuille law
- Manning-Strickler law

Note that Darcy law is a general law of fluid flow, but Hagen-poiseuille law and Manning-Strickler law respectively consider the pipe and canal as discrete features to solve flow's equations. Manning-Strickler law, however, can be considered for canals with any cross section area. For example, similar to Hagen-poiseuille law, it can consider a pipe with a circular cross-section, but not a saturated pipe, and in fact, supposes that part of the circular cross section is considered as the environment of calculating the Reynolds's number. In these theories, the flow is based on the pressure difference between the fracture's input and output. This pressure difference can be shown as the difference in hydraulic head. Equation 1 shows Hagen-poiseuille law for a 2D flow. Figure 1 illustrated an imaginary cylinder of this law.

$$\Delta P = \frac{8\mu LQ}{\pi r4} \quad (5)$$

Where P is pressure, µ is fluid viscosity, L is cylinder length, Q is fluid discharge, and r is cylinder's radius [32].

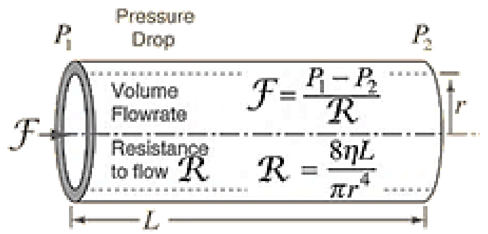

Figure 1. Considered cylinder for fractures flow modeling

3. Introduction of the Study Area

3.1. Geographical location

The Sechahoon ore deposit has located in 47 km northeast of Bafgh and 35 km from Choghart Iron Mine, on the highland of Sechahoon at the height of 1700 over the see level. Bafgh in Yazd Province has located in 115 km due east of Yazd City, with road and railway accesses. The rainfall in this region is low with an average rainfall of 75 mm per year. The average annual evaporation and Potential Perspiration over the mine area is 799 mm per year. As an effective parameter on region's evaporation and climate, Saturation is 34.3 percent. However, regarding that the mine area has located on an arid desert land, it is not legal to dug any wells or use the water from Qanats, springs, etc [33].

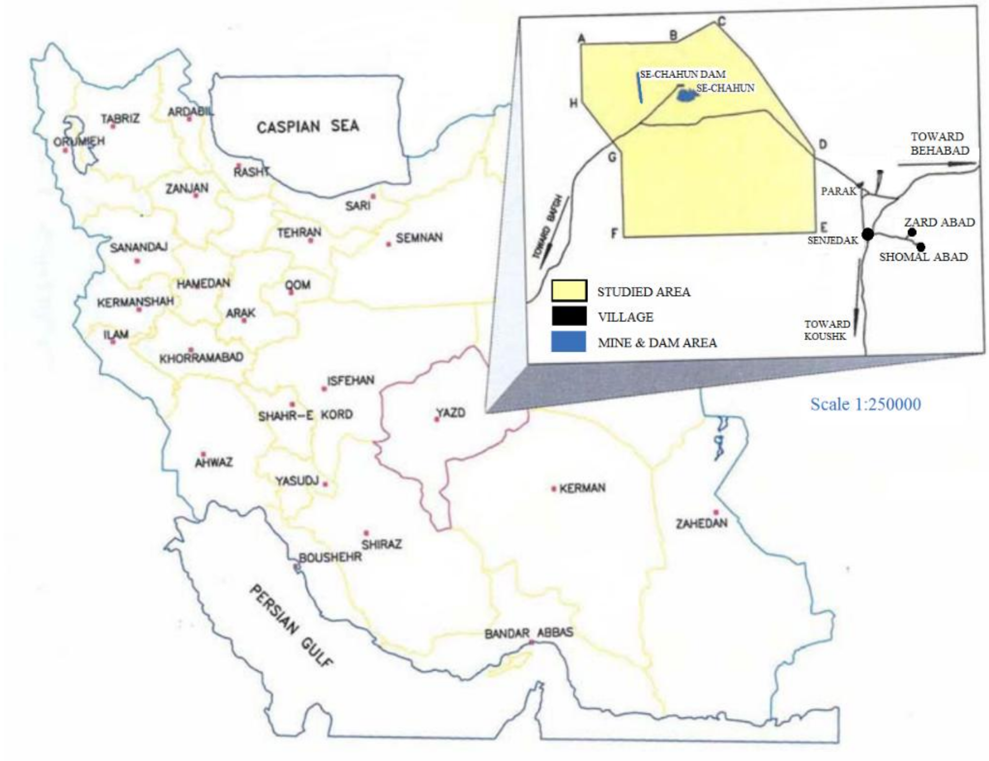

Figure 2. location of the study area.

The Sechahoon mine has two iron anomalies of X and XI. Geographical coordinates of the center for anomaly X are 31° 53' N and 55° 40' E, and for anomaly XI is 31° 55' N and 55° 41' E. The only access road to the region is the asphalted road of Bafgh-Bahabad. The proven reserves of this deposit is 216 million tones. The average iron grade is 41.57 percent, with 0.08% Sulfur, and 0.4% Phosphorus, and the deposit is considered as a Phosphorus-bearing iron mine [33].

3.2. Geology of the Region

Russian geologists have reported that the Sechahoon rocks belong to the Precambrian-Infracambrian Rizoo series. According to these studies and based on the lithological differences, metamorphism degree, and alterations, the rocks in the region are divided into three series:

- The lower series has been composed of a sequence of quartz-feldspar sandstone, siltstone, Schist, and marble. The thickness is more than 400 meters outcropping in southern part of the mine. These rocks have almost an east-west trend with a dip of 20 – 45 degree towards North [33].
- The middle series hosts the iron ore and has formed from volcano-sedimentary rocks covering most of the region. The rocks in this series, especially the ore bearing parts, have suffered from metamorphism [33].
- The upper series is made of sandstone, argillaceous rocks, with intercalations of

limestone, with a total thickness of 300 meters. The upper limit of this series has been covered in some locations by Extrusive rocks [33].

Intrusive rocks are mainly diorite, with granite and grano-syenite in northern-east margins. Dikes are also fine-grained diorite, diabase and porphyritic diabases. These dikes have suffered from alterations with different degrees and have a general east-west trend with high dips (75-80°) and an apparent thickness varying between 0.2 and 24 meters. Based on recrystallization in the vicinity of ore-bearing and host rocks and being coarse-grained in contact with dioritic rocks, the intrusive rocks seem to be younger than the other rocks. The alluviums, as well, have covered the lowland plain that rarely exceed 30 meters [33]. Brief geological studies show that the alluvium have a thickness of less than 30 m which overlies the hard rock formation.

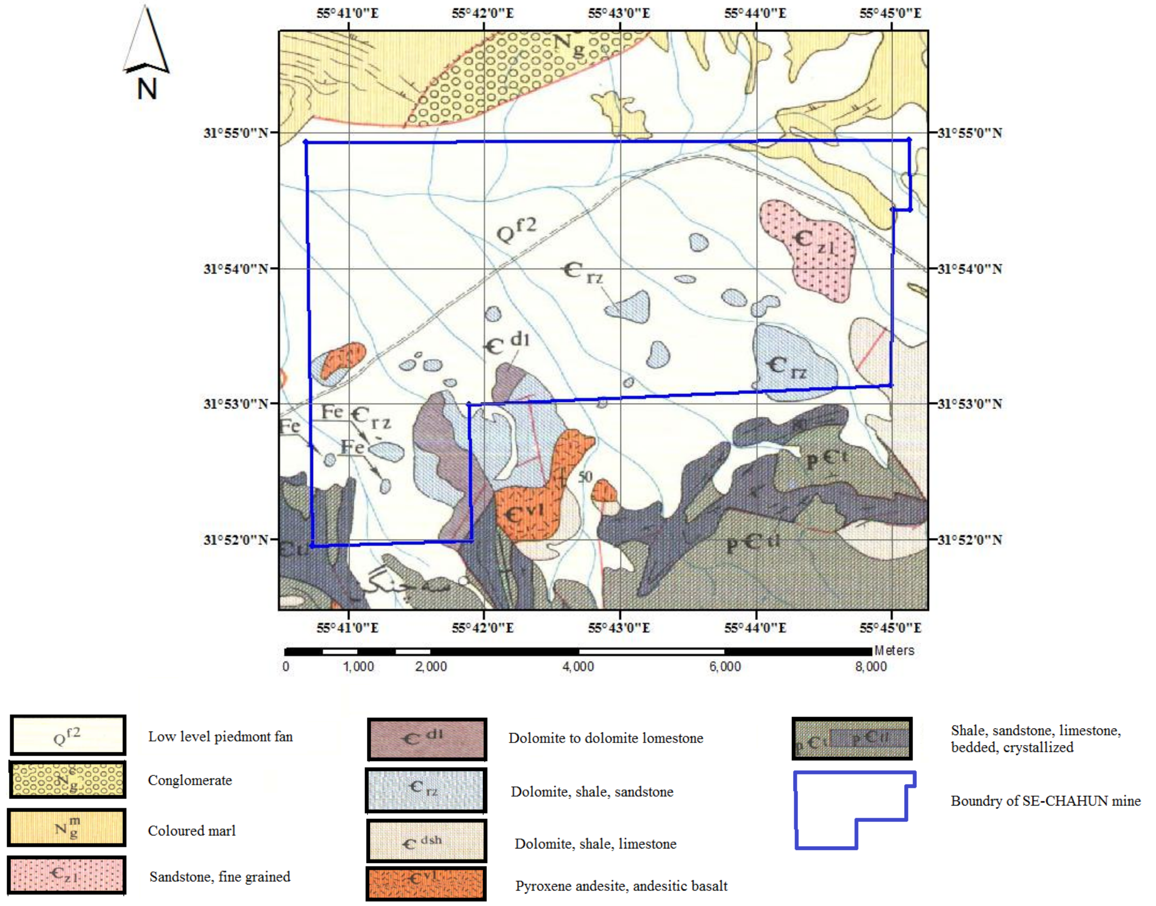

Figure 3. The 1:100000 geological map of the study area (after the 1:100000 geological map of Esfordi).

4. Numerical Modelling of the Sechahoon Mine Fractured Aquifer

4.1. Conceptual Model Design

The selected study area from the 1:250000 topography map is a watershed basin located between longitudes of 374000 to 386000 and latitudes of 3518000 to 3536000 of the UTM zone 40N. The area of the basin is 101 square kilometers.

Based on the exploratory drillings over the region, the geophysical data of the Sechahoon mine, water table measurements, data of Logan and Lufran tests and field observations, water can invade all formations, and faults are the main media for transporting the flow in the region. In other words, one cannot determine a given aquifer in the region. Therefore, a geometric model of a layer has been considered for the basin (Figure 4). Rainfall and evapotranspiration are another input data that are measured byweather stations. The main input data are including the specific storage, transmissivity, transmissivity coefficient, water table, the topography of surface and bedrock, and faults as discrete features.

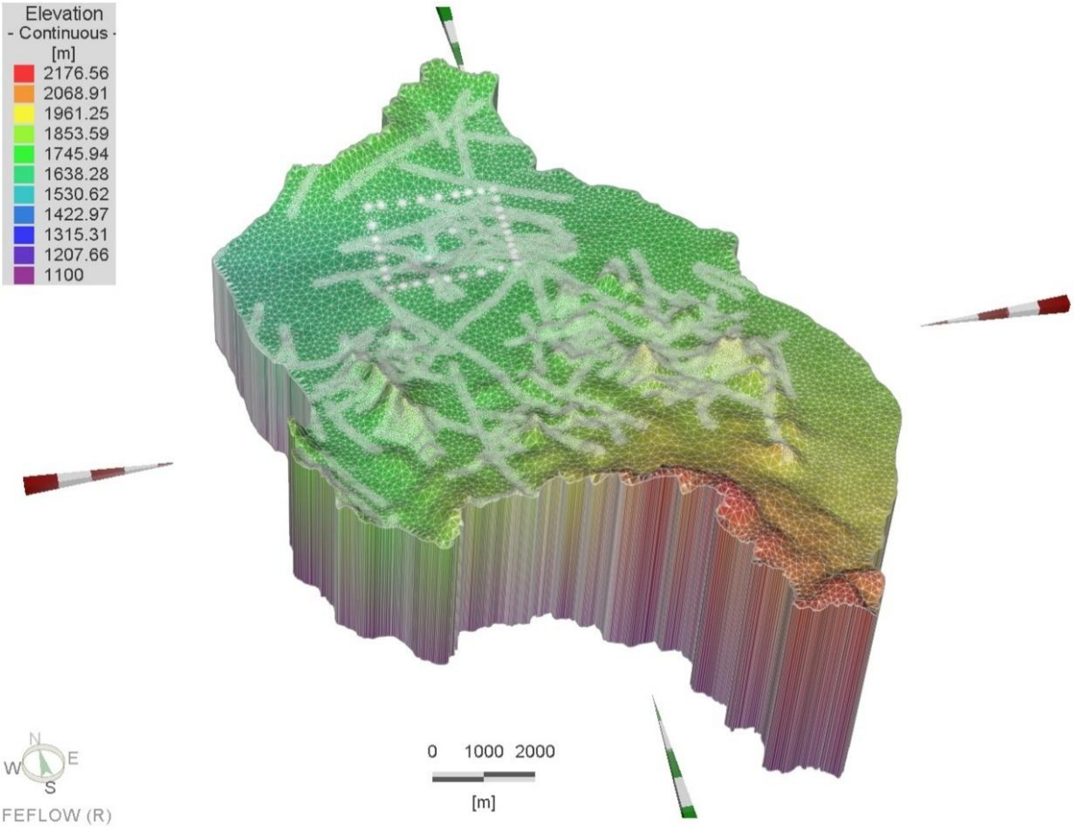

Figure 4. Geometrical characteristics of the model for the watershed basin.

4.2. Determining the Topography and the bedrock Depth

In order to determine the topography, the satellite DEM images of the region were used. Since there is no specific information about the watershed basin bedrock, based only on a limited drilling into the pit, the constant depth of 1100 meters of schist rocks was considered as the bedrock's limits. The topographic elevation in the region has been shown in figure 5.

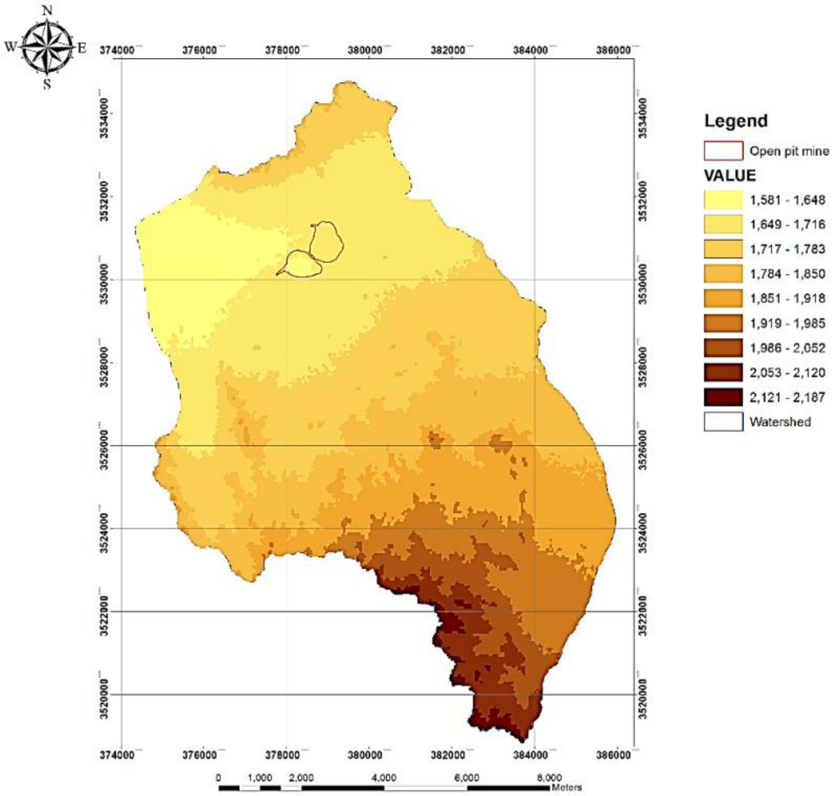

Figure 5. The contour elevation map of the Sechahoon watershed basin (the location of the pit shows with red line).

4.3. Determining the Hydrodynamic Coefficients of the Aquifer

Unfortunately, no pumping tests have been carried out over the area, but Lufran analysis was done in lithic aquifers and Logan analysis in alluvium aquifers to determine the hydraulic conductivity. Lufran analysis in every 1 meters of 4 boreholes was carried out, with constant load (K_c) and falling load (K_f), to determine the hydraulic coefficients of free alluvium aquifer. Using these information, the vertical hydraulic conductivity profile of the aquifer was drawn, as shown in diagram 1. In diagram 2, the results of Logan analysis in lithic systems are illustrated.

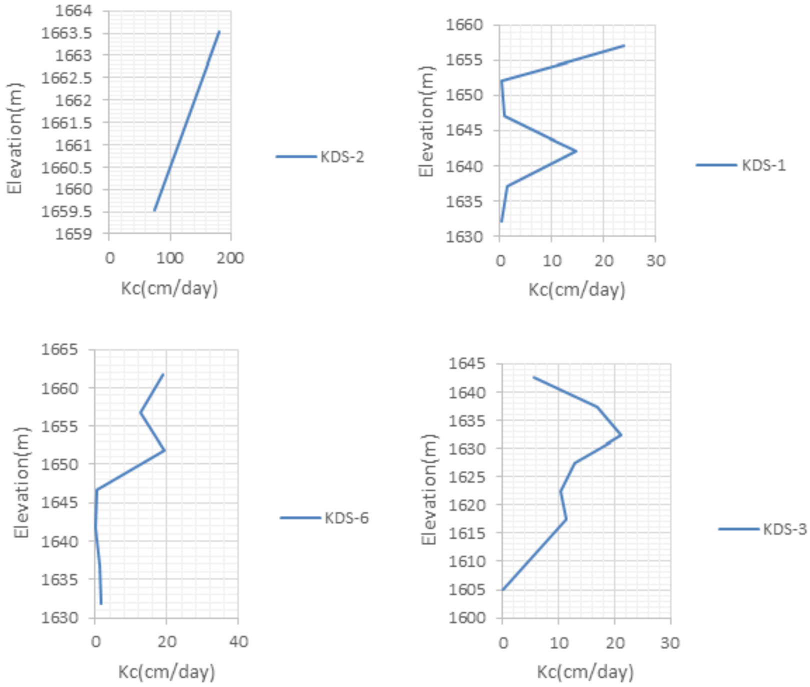

Diagram 1. Hydraulic conductivity values of Lufran analysis in alluvium aquifers.

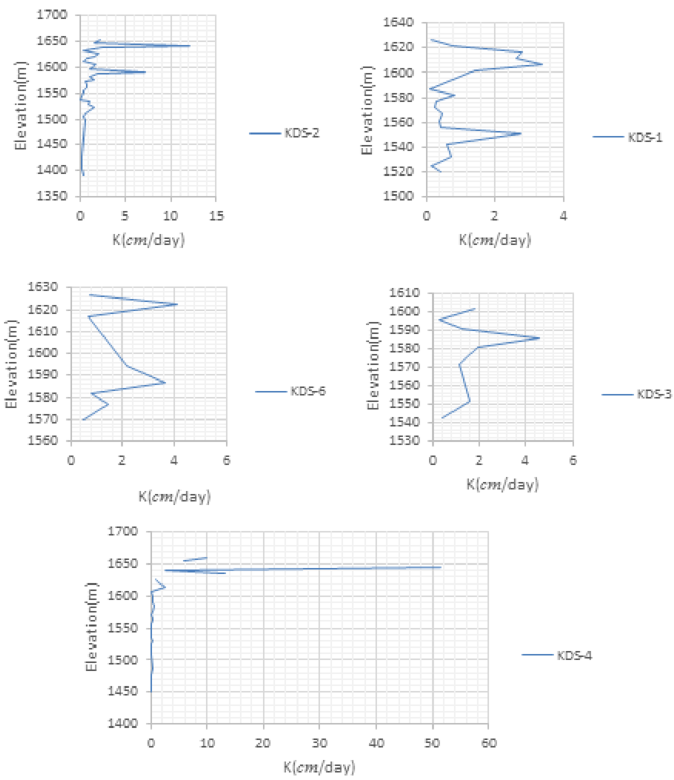

Diagram 2. Hydraulic conductivity values of Logan analysis in lithic systems.

Having studied these diagrams and produced an average from them, the average values of each of the alluvium and lithic parts, were separately given to the model. It was supposed that the alluvium and faulted parts were the flow media which is proved through the following diagrams. Figure 6 presents the lithic (blue color), alluvium (orange color), and faulted parts over the area.

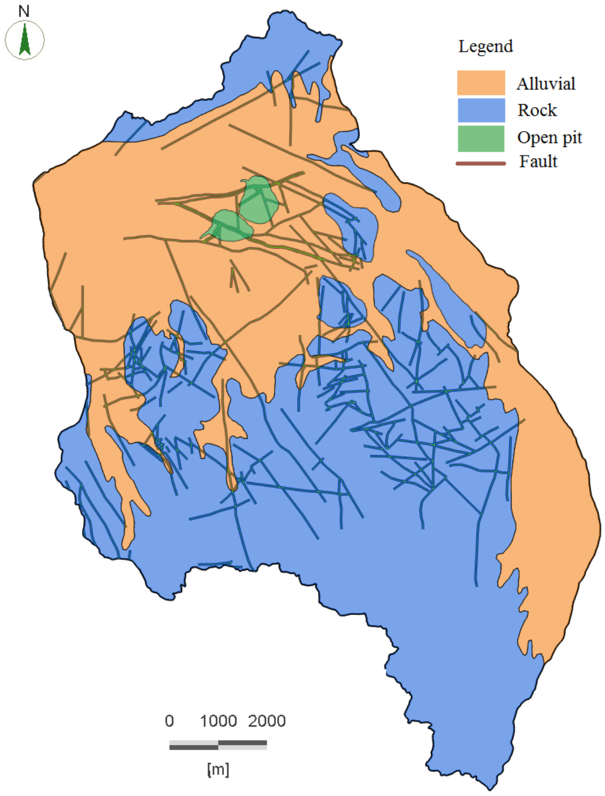

Figure 6. Separation of lithic and alluvium parts for determining the permeability, and hydraulic conductively, the pit's location.

4.4. Meshing the Aquifer

To solve the differential equation of underground water flow, the aquifer has to be divided into small elements called cells. In FEM, the study area is usually divided using the triangular networking. In order to acquire reliable results, this network is refined around faults and observation and extraction wells. Usually, the number of nodes is determined based on the region's area and available information.

The selected area of the Sechahoon watershed basin was divided into 500 triangles with a buffer of 50 meters around the faults which was composed of 64000 nodes. The distances less than 10 meters around the faults and observation and extraction wells were meshed finer, as illustrated in figure 7. As discussed earlier, the points locating on the study area have been shown as active cells.

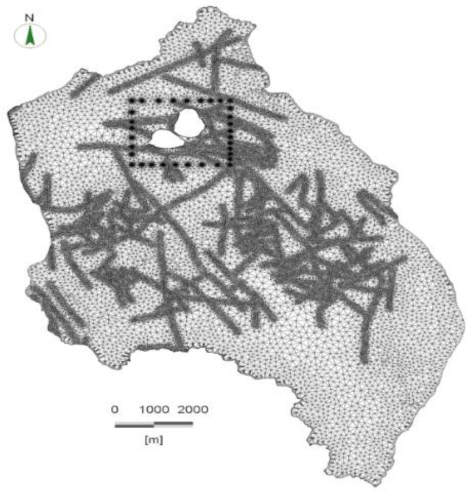

Figure 7. Mesh model of the Sechahoon watershed basin

4.5. Initial Condition

The model was formed in the transient state. Since the hydrogeological information of the region start from the year 2000, it is considered as the model's basis. According to the existing piezometeric water level over the plain during this year, through interpolation of these values, the initial water level for all of the active cells was determined and given to the model. It is necessary to note that the number of piezometers in 2000 was small, and therefore, the information related to 2004 and 2014 in the mutual wells were also considered in a level variation of the water table.

4.6. Pumping Wells

Since there are no pumping wells over the region, the only considered runoff water was the pumped water from the pit bottom. Taking into account one well for each extraction workplace, the output model was determined. Based on the pumping information from the pit bottom, the discharge value of each well is 80 m^3/d.

5. Running the Numerical Model

After providing all the necessary parameters for the model, one of the calculation packages should be selected to run it. The common point in all calculation packages is the criterion of hydraulic load variations for convergence and the maximum number of allowed repetition. Once the maximum hydraulic load variation in each model's cell is less than or equal to the threshold hydraulic load variation, the repetition process stops. We have used the Picar Method in running this model. The results do not completely match with field observations, and the model was calibrated to achieve a more reliable result.

Calibration of the transient model was carried out using the recorded water table level over the year 2000. Through this calibration, the storage coefficient, hydraulic conductivity, aquifer replenishment value, faults hydraulic conductivity and their aperture were changed. Figure 8 and diagram 3 are respectively showing the model-calculated water table level, and observed and calculated water table level by the model of the transient watershed basin over 2014. The closer the points locating on the diagonal line on the diagram, the closer the calculated values of water table level to each other, and the better the model calibration. As it can be seen from these diagrams, although there had been limited information regarding the region area, the distribution of points around the diagonal line presents a good calibration. The results from numerical modelling of the aquifer are presented in the following.

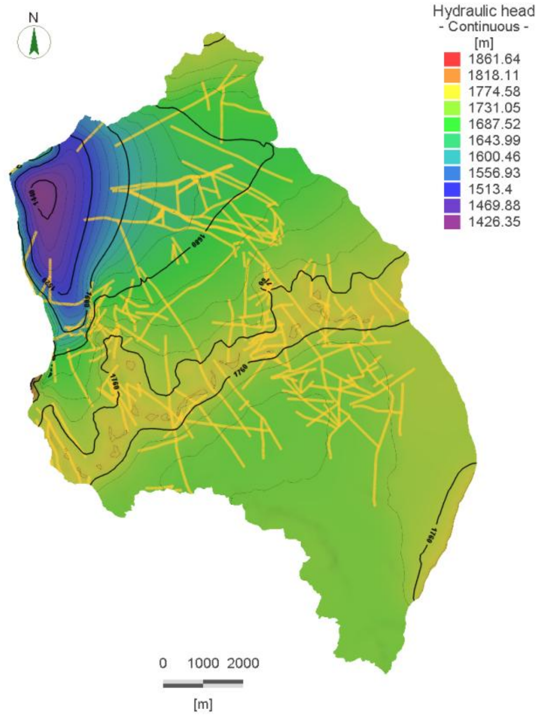

Figure 8. The values of water table level calculated from the transient model in 2014.

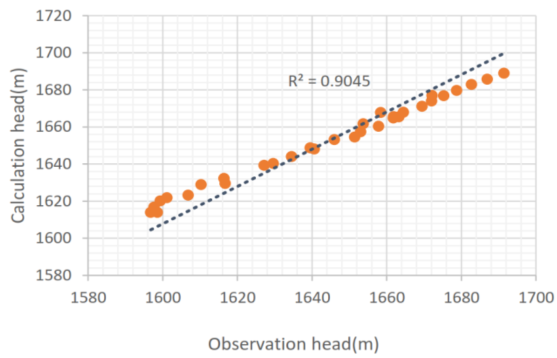

Diagram 3. Observed and calculated water table level in fall 2014 (5088 days).

In order to investigate the variations in water table level over the modelling time, and also to determine the points with the maximum drop, we provided several north-south and east-west cross sections. The direction of these sections is illustrated in figure 9. At the beginning of the modelling, since the effect of the region's faults and fractures was not considered in the model, the water table level was smooth. Upon starting the modeling along the north-south direction (the direction of region's faults), the variations in water table level was not much fluctuating. On the other hand, along the east-west faults, the variations in water table level was intensively fluctuating with a high hydraulic conductivity. Figures 10 and 11 show these variations. As illustrated in figure 12, the maximum flowing water is along the region's faults. On the other side, the direction of the flow in local scales has changed due to the presence of faults and formed closed contours in water table contour-lines over the region.

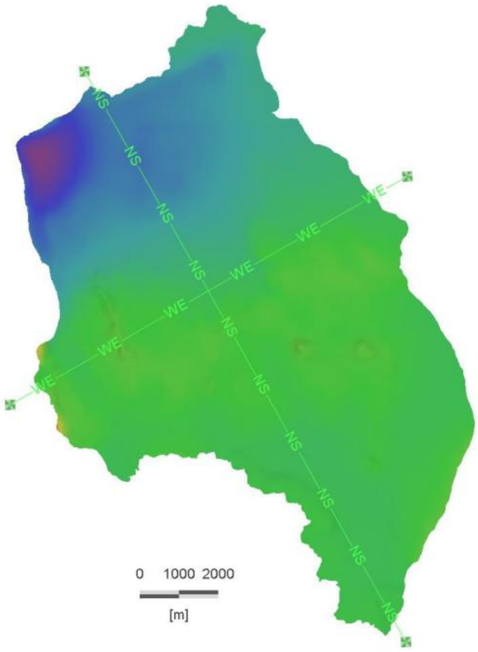

Figure 9. The direction of drawn north-south and east-west cross sections.

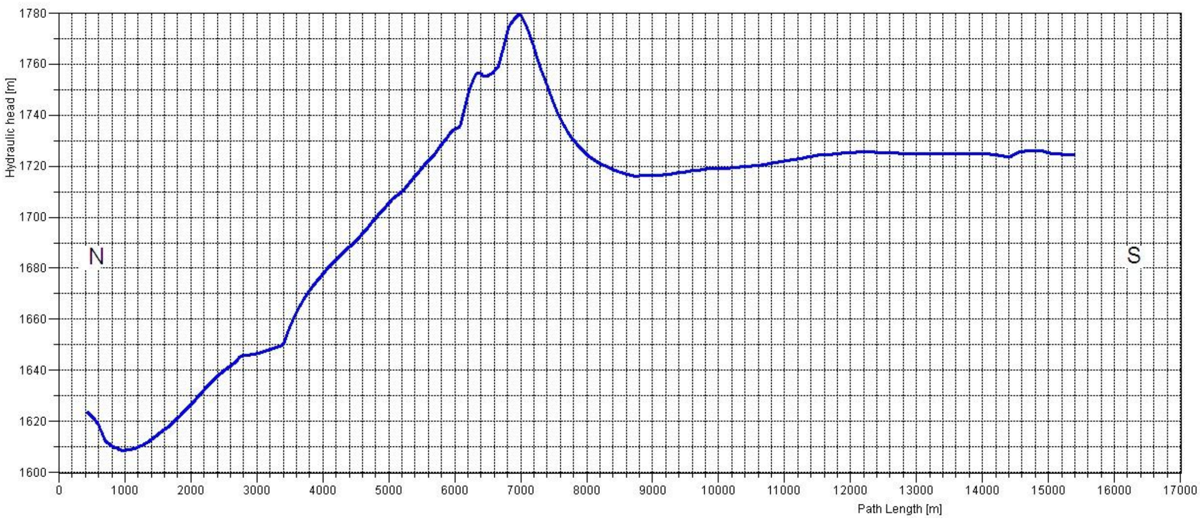

Figure 10. The calculated north-south cross-sections through modelling the watershed basin.

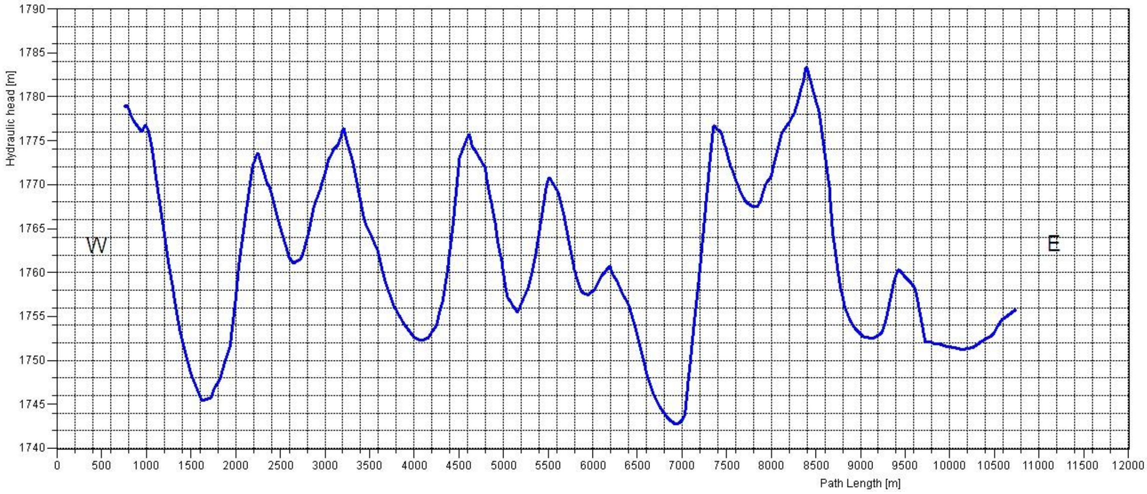

Figure 11. The calculated east-west cross sections through modelling the watershed basin.

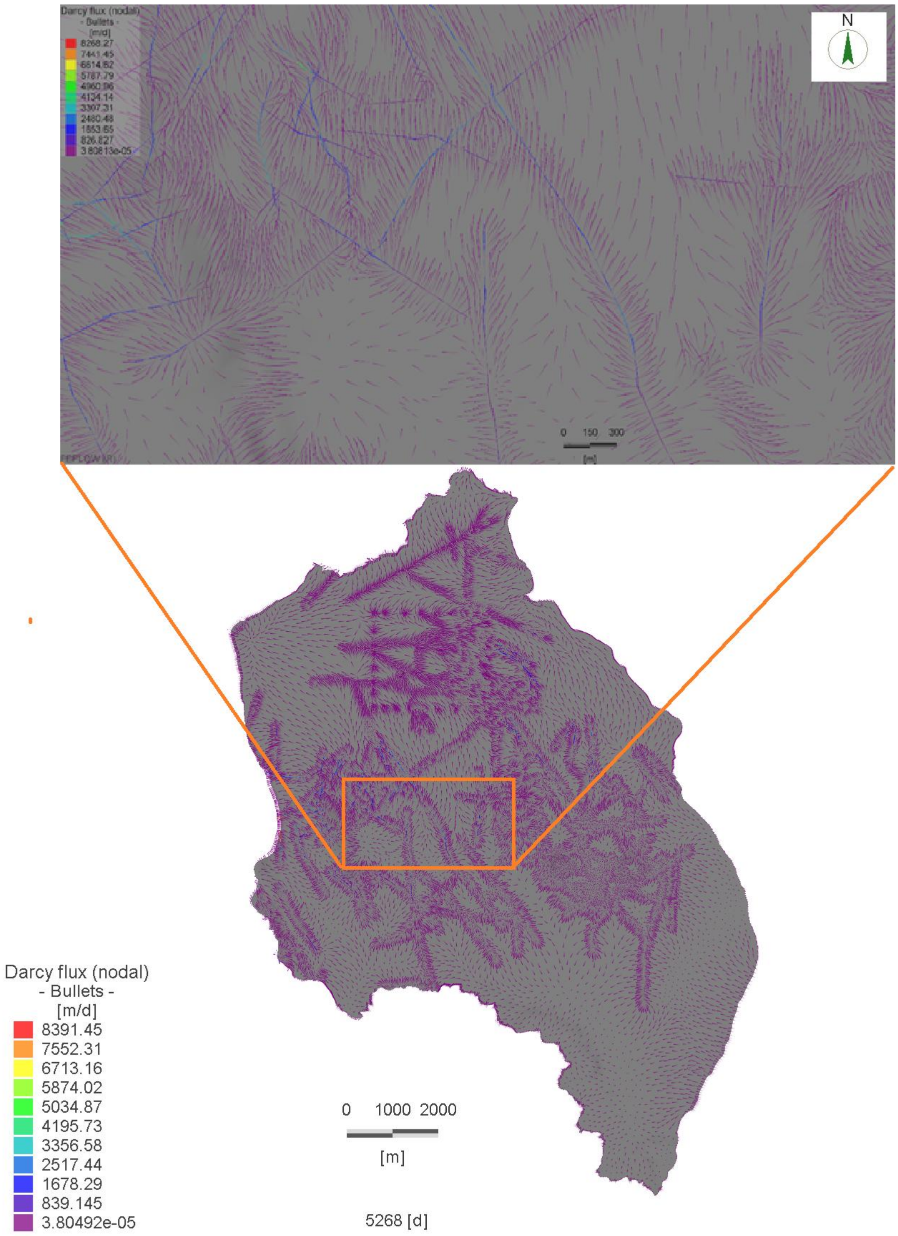

Figure 12. The direction of flow calculated through numerical modelling (Darcy flow velocity model).

6. Conclusions

The results from the calculation of water table level in 2014 proved that the alluvium formations have no containing water. Logan and Lufran analyses showed that the alluvium and faulted parts are the main media of the flow, and a slight amount of water can penetrate into the lithic part. This was also proved using the calculated flow velocity and direction from Darcy velocity model. The transient numerical modelling of the Sechahoon watershed basin showed that the flow direction is mainly from eastern-south to western-north. The 90% correlation of results from the model in 2014 prove a profound ability of FEM method used in FeFlow software in modelling the fractured formations. Furthermore, investigation of water table cross sections related to the transient model showed a slight variation in north-south direction and intense variation along east-west, respectively related to be parallel and perpendicular to the direction of region's faults. The modelling results produced closed water table contour-lines. This contours resulted due to the variation of flow direction along the existing faults, which are a characteristic of heterogeneous aquifers in fractured formations. These flow variations along the faults were proved by Darcy velocity model, as well.

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