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ORIGINAL PAPER

Application of geostatistical methods to estimation of water flow from upper reservoir of Azad pumped storage power plant

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Abstract The objective of this paper is to estimate water seepage from the upper reservoir of Azad pumped storage power plant, based on combined geotechnical investigations and geostatistical methods. In order to select the optimum water tightening alternative, such as clay blanket, concrete cover (or concrete lining), geomembrane, asphalt cover, etc., estimation of water seepage from the reservoir is essential. Six exploratory boreholes were drilled at the pumped storage reservoir area and permeability tests (Lugeon tests) were conducted in all of them. Records at the boreholes have been considered as the main source for seepage calculations. Due to expansion of upper reservoir and a few boreholes, distribution of permeability and permeability changes in the reservoir area is not an indicator for reservoir. In this research using geostatistical method (Kriging), Lugeon values have been estimated for walls of reservoir. According to correspondence between estimated permeability distribution and geological conditions, the estimated values are acceptable. In addition, results show that in about 60% of tests, permeability is very high and potential of water seepage is very dangerous. Afterward, seepage was estimated for reservoir by using both analytical (Vedernikov method) and numerical method. Results from both methods are very close together and the average seepage is around 280,000 m^3/day according to analytical and numerical results. Regarding results and general geological considerations, seepage is concentrated at fault zones. Results show that using appropriate permeability distribution, the estimated values of water seepage are acceptable and reliable. Due to the high amount of water seepage and economical value of water in this region, water tightening is necessary.

Keywords Seepage · Permeability distribution · Kriging

Introduction

The Azad pumped storage power plant (PSPP) project has aimed to store hydraulic potentiality using pumping system under low load conditions of the power supply network and generating electricity by turbine and generator under peak load conditions of the network. The Azad PSPP is located in the Sanandaj Province of Iran. This complex is composed of two reservoirs and a power plant. The lower reservoir is the Azad dam reservoir, and upper reservoir is made from an excavation at 1,900 m elevation.

One of the major practical difficulties often associated with PSPP construction is related to water seepage from the upper reservoir. In fact, some of the most disastrous experiences in reservoirs have been the result of interception of large flows of water from highly fractured water-saturated rocks. Seepage analysis and the control of fractured rock masses is a significant problem in hydropower engineering. The difficulty in characterizing rock fractures hidden below the surface, the diversity in rock types and the varying degrees of fracture development have posed significant problems in the search for a method of predicting seepage in fractured rock (Karasaki et al. 2000; Baghbanan and Jing 2007). Water seepage causes the decrease of wall stability

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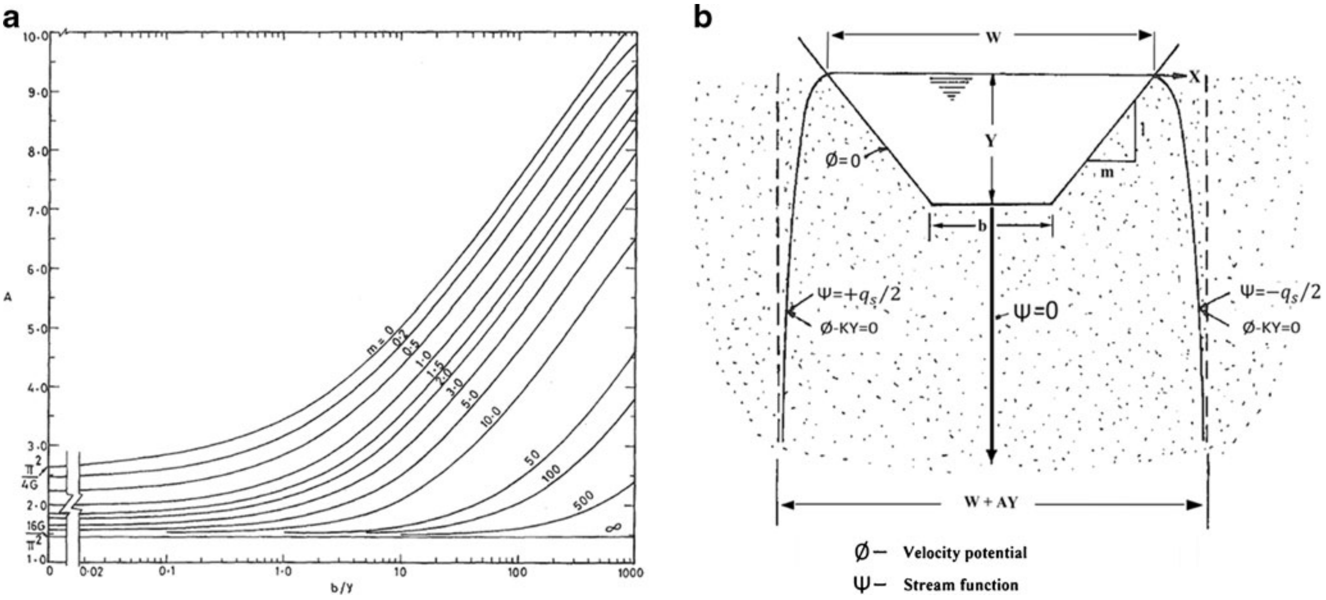


Fig. 1 **a** Extended Vedernikov graph **b** flow field and boundary conditions for seepage from a channel. Schematic figure showing the Kiirunavaara orebody with production blocks and infrastructure

and in some occasions, a sudden intensive rush of water causes the occurrence of human casualties, high damage, and losses. Because of the impossibility of exact identifying and determining of all the effective factors on water flow from the reservoir, exact prediction of water in rock media is difficult. Analytical methods and equations have many applications in calculating water seepage rate into the tunnels, because of exploiting simplifications and practical theories.

In order to optimize the efficiency of hydropower engineering installations, effective seepage-control measures must be adopted to maintain an adequate water level in the upper reservoir. Therefore, a seepage analysis is needed to determine the leakage rate and distribution characteristics of the seepage field. This analysis allows optimization of the seepage-control scenarios. Thus controlling the leakage rate within a feasible range provides a basis and reference for designing seepage-control structures and facilitating decision-making.

The seepage from channels was estimated for different specific conditions. Vedernikov (1934, 1936, 1937, and 1939) presented an exact mathematical solution to unconfined steady-state seepage from a trapezoidal channel in a homogeneous isotropic porous medium of large depth. The solution was obtained using inversion of a hodograph and conformal mapping technique. A triangular channel is a particular case of the trapezoidal channel. The unconfined steady-state seepage from a channel in a homogenous and isotropic porous medium of infinite extent when the water table is at a very large depth was expressed by Vedernikov as:

$$q_s = kY\left(A + \frac{W}{Y}\right) \qquad (1)$$

Where q_s is the quantity of seepage per unit length of channel (in square meters per second), k is the hydraulic conductivity of the porous medium (in meters per second), Y is the maximum depth of water in channel (in meters), W is

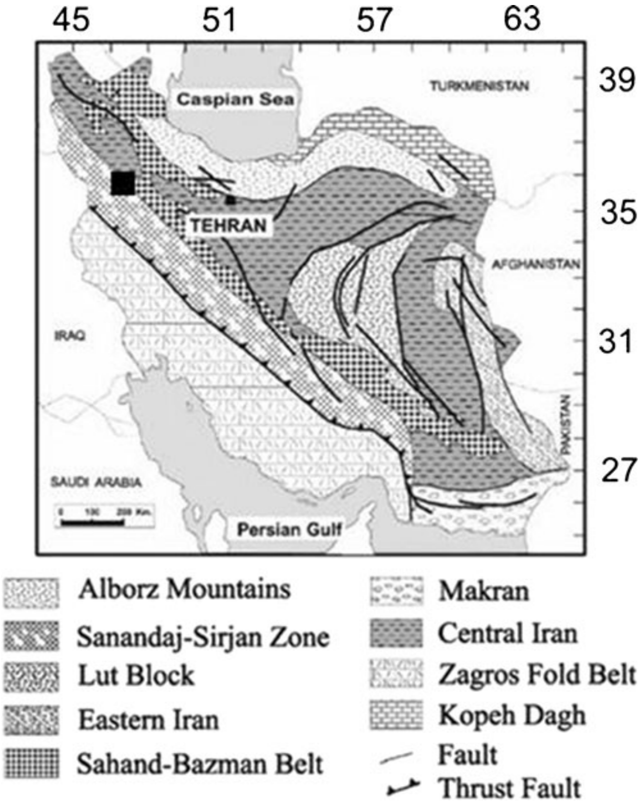


Fig. 2 Azad power plant on Iran geometry map (Hezarkhani 2006)

the width of channel at the water surface (in meters), and *A* is the seepage parameter (dimensionless), which is a function of channel geometry. Figure 1 shows *W* and *Y* for trapezoidal, triangular, rectangular, slit, and strip channel sections. Due to the geometry of the reservoir, it is assumed that the reservoir is like a channel with a limited size.

In addition to analytical equations that are around the computation of the quantity of water seepage from the reservoir, numerical flow models are simplified representations of an aquifer. The numerical methods aim at capturing the most relevant features of water flow. Several conceptual models have been proposed for water flow through fractured

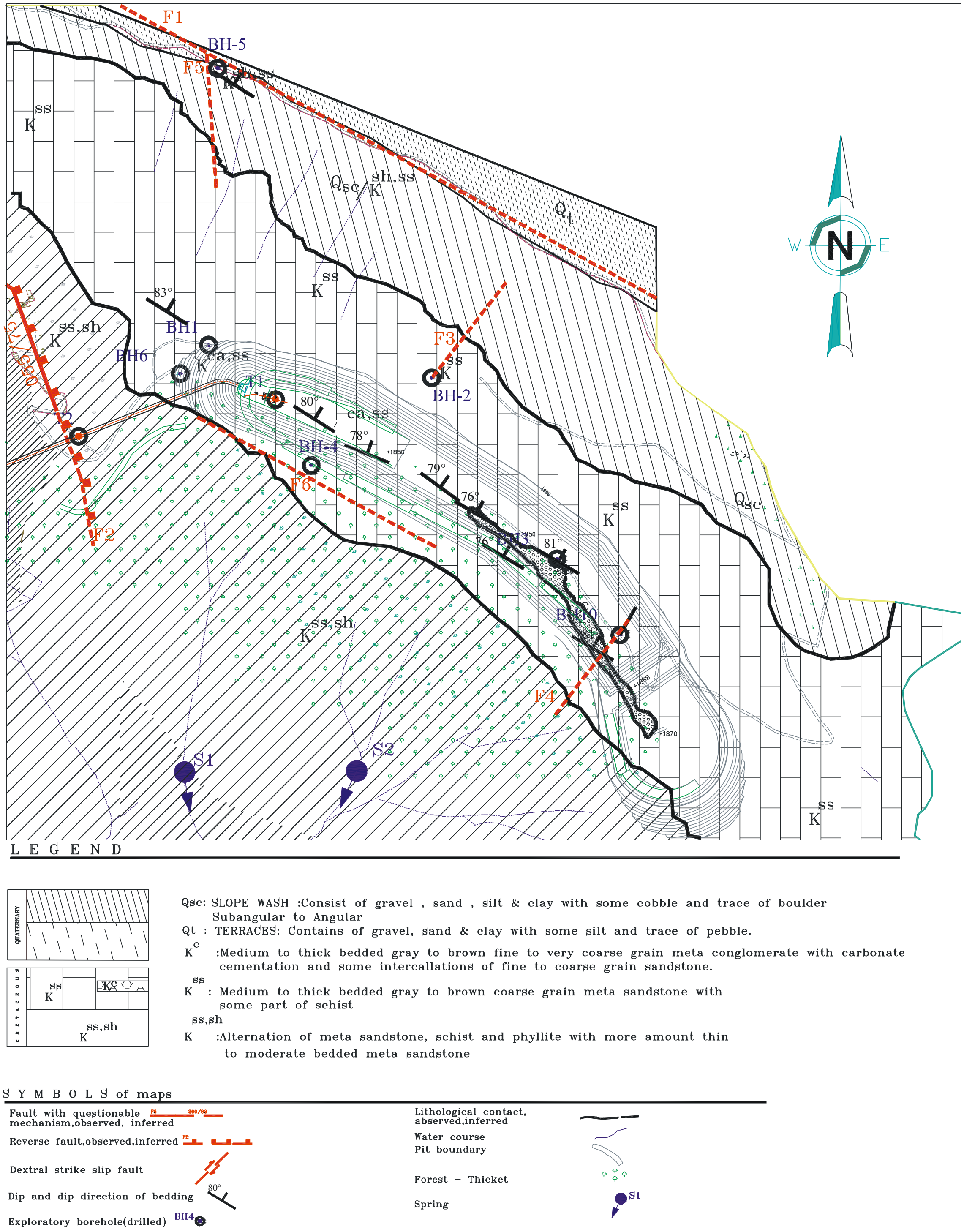


Fig. 3 Geological conditions in Azad pumped storage power plant (Aalianvari et al. 2010)

media (Berkowitz 1994) which include: (1) equivalent porous media models, (2) discrete fracture networks models and, (3) hybrid models. In this research, at first by using geostatistical methods (Kriging), Lugeon values have been estimated for walls of the reservoir. Afterward, seepage is estimated for reservoir using the analytical (Vedernikov method) and numerical methods (finite element).

Azad pumped storage power plant

The Azad pumped storage power plant is located in the west part of Iran, at 35/21 N and 46/34 E on the Kumasi River (Fig 2).

The upper reservoir of the power plant site is located in the Sanandaj–Sirjan formation with alternation of sandstone, schist, phylite, and conglomerate. Figure 3 shows geological conditions and faults in the Azad pumped storage power plant.

In order to investigate the geological and hydrological conditions of the reservoir, six exploratory boreholes have been drilled in different depths and permeability tests performed in all of them.

Geostatistics

Geostatistics involves the study of spatially correlated data observed in mining and environmental applications. Spatial correlation is present in all natural phenomena. In earth sciences, samples taken at close distances to one another tend to be more similar to each other compared to samples taken from points located far apart. Geostatistical kriging techniques make use of spatial correlations that exist among samples to determine an average value at an unsampled location (Kasmaee et al., 2010).

The most common geostatistical tool to model the spatial correlation is the semivariogram (Fig. 4). Semivariograms reveal important details of the geological generation since they provide an analytical means to quantify the anisotropy and the range of the underlying forming process. To speak in statistical terms, semivariograms quantify the distance (range) at which samples become uncorrelated from each other and they give an idea of the direction of the best and worst spatial correlation (Marinoni 2003)

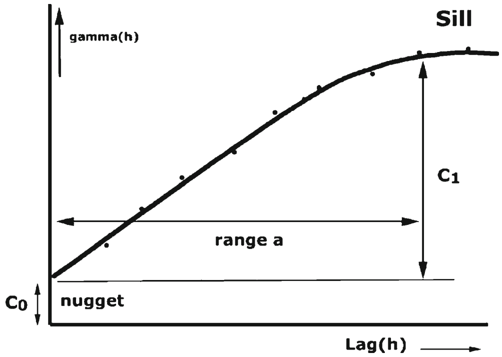


Fig. 4 Experimental semivariogram (*black dots*) and theoretical semivariogram (*curve*; from Burrough and McDonnell 1998)

Statistical analysis of the input data

At the first step, the histogram of data was drawn and statistical parameters of Lu(Lugeon) data were calculated. As can be seen in Fig. 5, the histogram of data does not show a symmetrical distribution and the presence of two groups of data can be seen clearly: the first group, data which have values equal to 100; and the second group, data which have Lu values that are less than 100. In terms of spatial location, all the data from the first group have been picked from the 1,680 m level, which is associated with the crushed zone. Table 1 shows the summery of statistical parameters of Lu data.

Semivariogram analysis of the input data

The semivariogram is a quantitative, descriptive statistic that can be graphically represented in a manner that characterizes the spatial continuity of a data set. Each point on the semivariogram diagram represents the value of a measure of spatial variability between pairs for the corresponding magnitude of a separation vector h.

Semivariogram analysis is normally performed on data sets to quantify spatial correlation between paired samples as distance between them varies. If spatial continuity exists, further checks are done with respect to anisotropies in different directions (Kasmaee et al. 2010). The semivariogram is defined as half of the average squared difference between two attribute values separated by a vector *h*:

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} (Z(x_i) - Z(x_i + h))^2 \tag{2}$$

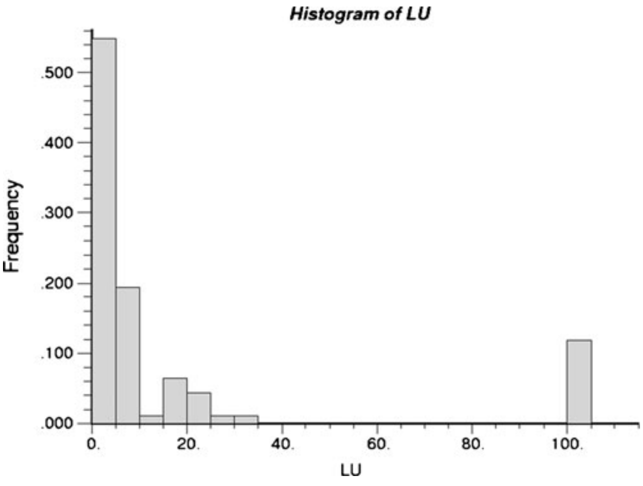


Fig. 5 Histogram of Lu

Table 1 Statistical parameters of Lu data

Number of data	Mean	Median	Standard deviation	variance	Kurtosis	Skewness	Max	Min
93	15.63	3	30.09	905.15	4.10	2.39	100	1

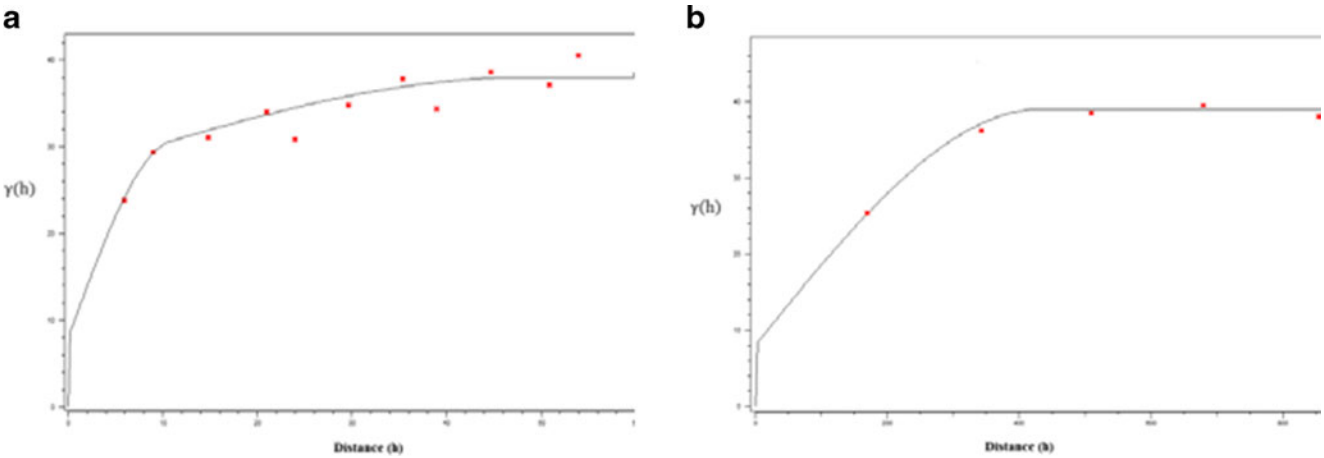


Fig. 6 **a** Horizontal experimental semivarigram and its fitted model **b** vertical experimental semivariogram and its fitted model

Table 2 Parameters of horizontal variogram

Model	Number of structures	Az	Dip	Horizontal tolerance	Sill (%)	Nugget effect (%)	Range (m)
Spherical	One structure	0	0	90	39	8	430

Where $\gamma(h)$ is the semivariogram, $N(h)$ is the number of pairs, $Z(x_i)$ is value of interested variable at location (X_i) and his defined as a separation vector having a direction and distance.

The fitting of a theoretical semivariogram (curve) is an important step in the semivariogram analysis. Hereby, the 'sill' is the total variance σ^2 of the variable, the 'range' is the maximal spatial extent of spatial correlation between observations of the variable, and the 'nugget' is the random error (Fig. 4). The theoretical semivariogram can be composed of nested models or structures. Common models are the nugget model, spherical model, exponential model, Gaussian model, and power model (Verfaillie et al., 2006).

For semivariogram analysis, a large amount of experimental variogram in a variety of azimuths and dips and different lengths of lag were calculated. Among all these semivariograms, just vertical and horizontal variogram showed the appropriate spatial structure and fitting the semivariogram models were carried out on these two semivariograms (Fig. 6).

Table 3 Parameters of vertical variogram

Model	Number of structures	Az	Dip	Vertical tolerance	Sill of first structure (%)	Total sill (%)	Nugget effect (%)	Range of first structure (m)	Total range (m)
Spherical	Two structures	0	90	22.5	19	38	8	11	49

Fig. 7 Block model made of the study area

The parameters of these semivariogram are presented in Tables 2 and 3.

Ordinary kriging and estimation

Kriging is a form of weighted average estimator. The weights are assigned on the basis of a model fitted to a function, such as the semivariogram, which represents spatial structure in the variable of interest (Lloyd and Atkinson 2001). In the last decades, kriging has been proven to be a powerful interpolation technique, which is recognized and accepted in various fields of the geosciences and related disciplines like hydrogeology, hydrology, soil sciences, mining sciences, etc. (Akin and Siemes, 1988). The most frequently used form of kriging is ordinary kriging (OK). The OK algorithm uses a weighted linear combination of sampled points situated inside a neighborhood around the location X_0:

$$Z^*(X_0) = \sum_{i=1}^{n} (\lambda_i Z(x_i)) \tag{3}$$

and

$$\sum_{i=1}^{n} \lambda_i = 1 \tag{4}$$

where $Z^*(X_0)$ is the estimated value at location X_0,$Z(X_i)$ is the available sample at location X_i, and λ_i is the weight assigned to the ith sample value, and n is the number of samples being considered in the estimation.

The estimation of Lu at an unsampled location within the upper reservoir of Azad PSPP was performed with Datamine and using the OK method. For this purpose, the interested area was divided to blocks with size 15×15×15 (Fig. 7).

Considering the existence of a crushed zone at the level of 1,860 m, Lu value equal to 100 was dedicated to all the blocks at this level and the rest of the blocks were estimated with ordinary kriging.

Figures 8 and 9 show the results of estimated values of Lu along sections 13 and 10. In addition, Fig. 10 shows the estimated values of Lu at levels 1,880 and 1,890 m.

Based on comparison between estimated values and geological considerations, we conclude that the areas with higher Lu values corresponded to the fault zones.

Seepage analysis

There are different methods to calculate water seepage from the reservoir such as analytical and numerical methods. In this research, after calculating the permeability distribution with geostatistical method, water seepage from the upper reservoir of Azad pumped storage has been estimated with both methods (Vedernikov equation and SEEP/W software).

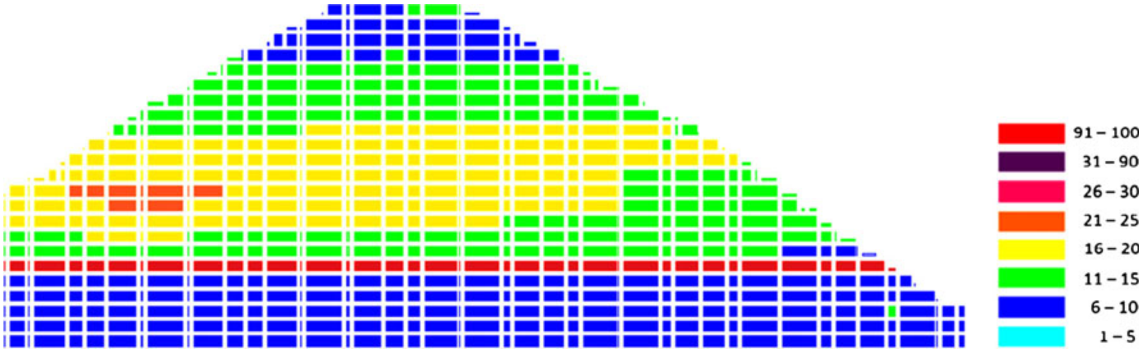
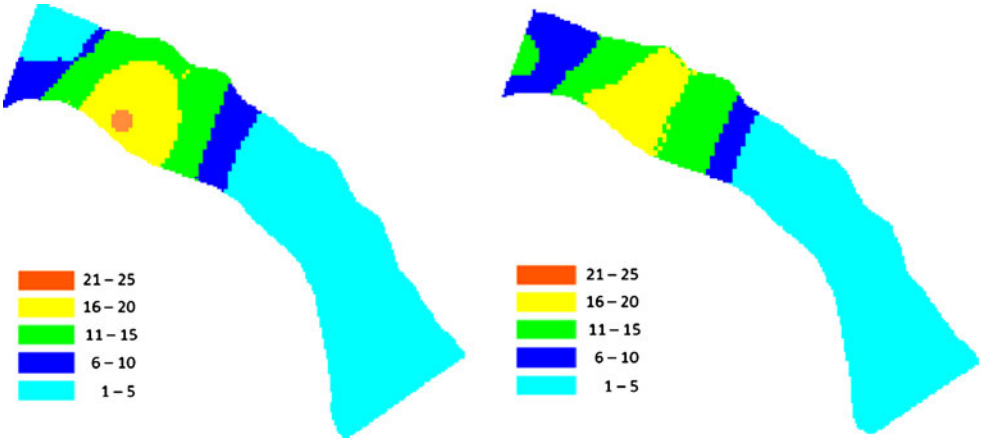


Fig. 8 Estimated values of Lu along section 13

Fig. 9 Estimated values of Lu along section 10

Fig. 10 Estimated values of LU at two different levels



a) Level 1880 (m)

b) Level 1890 (m)

Analytical method

Using the Vedernikov equation, water seepage from the upper reservoir was estimated. In this method, the reservoir was divided into four sections with different elevations (1,840, 1,850, 1,860, and 1,870 m). Therefore, it can be assumed that a reservoir is like a four-channel section with different depths (30, 40, 50, and 60 m; Fig. 11).

Permeability distribution which was obtained from kriging method has been used to estimate water seepage in four sections. Based on results from analytical equation, the water seepage from the upper reservoir of the Azad pumped storage is 260,000 m^3/day, which is about 7% of reservoir volume. This amount, with attention to the high value of water in this region is much higher. Table 4 shows the obtained results from the Vedernikov method.

Numerical method

Numerical simulation of water flow and transport has become a standard tool in water resources management. In contrast to analytical solutions, numerical simulations can easily be

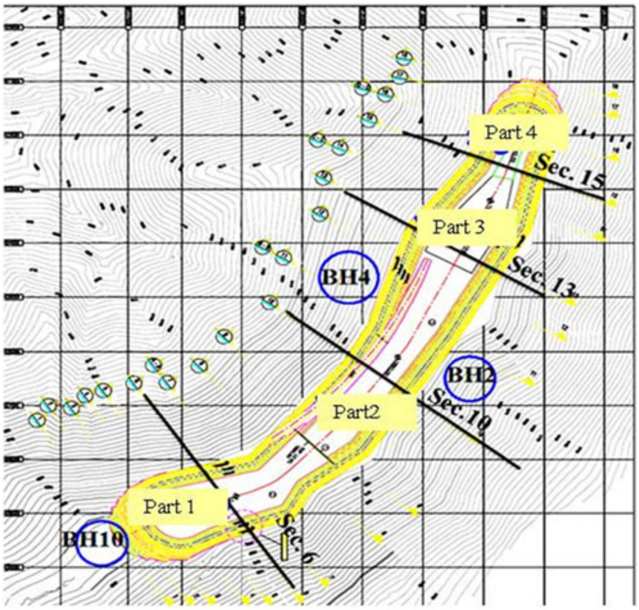


Fig. 11 Upper reservoir, exploratory boreholes and estimated seepage sections

Table 4 Required parameters and results from Vedernikov method

Vedernikov parameters	Section 6	Section 10	Section 13	Section 15	Total reservoir
w	132	118	164	116	
y	20	40	50	60	
b	86	60	95	35	
b/y	3/4	1/5	1/9	0.58	
A	3.5	3	2.8	2.5	
q (m^3/day)	227	267	341	299	
L (channel length)	240	410	180	120	
Q (m^3/day)	54,480	109,470	61,380	35,880	261,210

adopted in order to accommodate irregular geometries, spatial variability of hydraulic properties, and time varying boundary conditions. Increasing computer power and progress in the development of accurate and efficient schemes has made it possible to simulate multi-dimensional systems accounting for most of the natural structures within aquifers. Numerical models do not have the limitations of analytical solutions. Numerical models are suitable for the simulation of all aquifer conditions. Furthermore, numerical models can provide a more realistic representation of the interaction between groundwater systems and mine excavations. In this paper, a numerical finite element model using SEEP/W software (Geo-Slope International Ltd, 2006) is presented. It is capable to predict the water inflow and estimate the height of the seepage face in a deep pit. The SEEP/W model is able to analyze different flow conditions such as saturated/unsaturated flow, confined/unconfined aquifer in a two-dimensional situation. Figure 12 shows a generated model in SEEP/W. In this model, unlike the Vedernikov equation, actual geometry of the reservoir has been done.

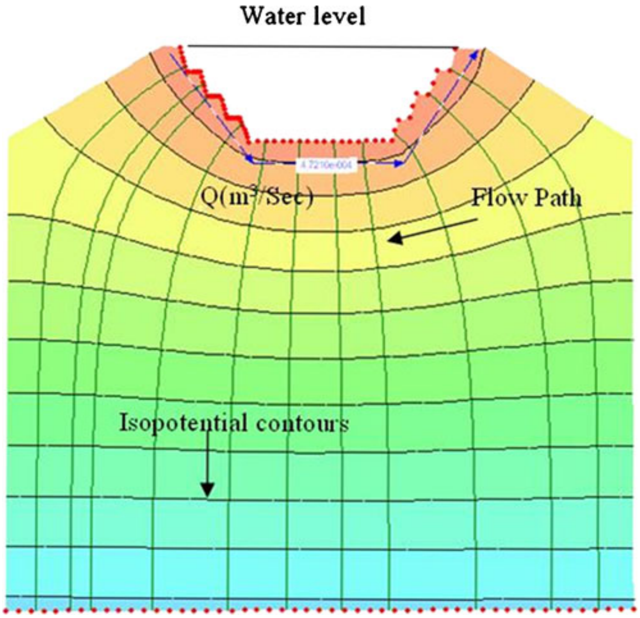


Fig. 12 Geometry of model in section 10

Table 5 Estimated Seepage with use of SEEP/W

	Section 6	Section 10	Section 13	Section 15	Total
Q (m^3/day)	63,995	119,875	62,986	40,486	287,073

Table 5 shows the obtained results from SEEP/W.

Comparison of analytical and numerical results

Table 6 shows the results of water seepage from the upper reservoir of Azad pumped storage power plant which were obtained from analytical and numerical method (results from analytical equation and numerical method were compared).

Results show that because of considering permeability distribution in both numerical and analytical method, results are very close together. In fact, the difference between these results is due to the fact that the reservoir in the Vedernikov equation assumed as an isotropic medium but in the numerical method reservoir is in actual conditions. Because of using actual conditions and applying appropriate permeability distribution (obtained from geostatistical method) in the numerical method, the results of numerical method are more acceptable than analytical method

Conclusion

In this paper, because of the lack of adequate information on the permeability of the reservoir, geostatistical method (kriging) has been used to estimate permeability distribution in the upper reservoir of Azad (PSPP). Results show the acceptable accuracy and application of this method for the same conditions. Results of several case studies in various geological conditions roughly show that it can be used to determine the permeability distribution. Using this method, the cost of drilling exploratory boreholes will be optimized. By using the

Table 6 Obtained results from Analytical equation and numerical method

	Amount of seepage(m^3/day)				
Sections	Section 6 (part 1)	Section 10 (part 2)	Section 13 (part 3)	Section 15 (part 4)	Total reservoir
Vedernikov analytical method	54,480	109,470	61,380	35,880	261,210
SEEP/W	63,995	119,875	62,986	40,486	287,342

results which were obtained from geostatistical method, the amount of water flow from the upper reservoir was calculated with numerical and analytical methods.

As the results show, according to both methods (numerical and analytical), crushed zones are the major problems in the reservoir that can conduct a large amount of water from the pit. The average seepage is around 280,000 m^3/day according to analytical and numerical results.

Based on the modeling, most of this seepage takes place through a small portion of the reservoir length conforming to the crushed zones and the remaining of the inflow takes place through a large portion of the pit.

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