

Reliability Analysis for Preliminary Forecasts of Hydrogeological Unit Productivity

Claudio Alimonti¹ · Mara Lombardi²

Received: 11 June 2014 / Accepted: 3 May 2015 /

Published online: 17 June 2015

© Springer Science+Business Media Dordrecht 2015

Abstract The aim of this work is to find a probabilistic characterization of the productive capacity of a well in a geological formation hosting an aquifer. Such characterization in terms of productive capacity may allow a preliminary assessment to be made of the probability of success for a required productivity (i.e. target point). This evaluation is usually carried out by statistical analysis of a geological dataset, which is likely to be influenced by many parameters. Such datasets are often incomplete or unreliable. Therefore, a method for evaluating potential productivity, using probabilistic hydraulic conductivity data, is proposed. The hydraulic characterization of hydrogeologic units is based on the collection of information obtained mainly through pumping tests and their interpretation. The results, expressed in terms of hydraulic conductivity, are summarized in a range of variability that is strictly dependent on the number of performed tests and their spatial distribution in the unit itself. If this range is known, an estimate of well's yield can be made on a deterministic basis, through Thiem's relationship for steady state conditions, by setting a value of hydraulic conductivity that corresponds to the average value of the range. The proposed reliability analysis enables to overcome the limitations of the deterministic approach by correlating each calculated flow rate, which is taken to be a design flow rate exceeding the critical flow rate of the hydrogeologic unit, to its probability of failure. Therefore, this approach aims to evaluate the probability of failure of the water system. The preliminary result is to associate the values of aquifer exploitation with a probability failure function. This outcome can then be used to define the potential solutions in the optimal allocation of the withdrawal by means of reliability analysis that takes into account the uncertainty of the system.

Keywords First order reliability model (FORM) · Groundwater · Hydrogeologic unit (HU) · Monte Carlo simulation (MCS) · Reliability index (β) · Safety margin function (M) · Well productivity

✉ Claudio Alimonti
claudio.alimonti@uniroma1.it

¹ Dipartimento di Ingegneria Chimica Materiali Ambiente, Università degli Studi di Roma La Sapienza, Rome, Italy

² Safety Engineering Sapienza, Università degli Studi di Roma La Sapienza, Rome, Italy

1 Introduction

In water resources management the a priori assessment of a new withdrawal site is a specific goal. The well design requires the knowledge of the water supply and therefore the withdrawal flow rate.

The use of geologic information, such as lithology and rock properties, is very important to define conceptual and numerical hydrogeological models. This geologic information is difficult to apply explicitly to numerical modelling because it tends to be qualitative rather than quantitative (Guarascio et al. 2009). This study uses a dataset of hydraulic conductivity measurements to derive the probability distributions of a hydrogeologic unit.

Probability distributions of hydraulic conductivity for different rock types have been studied previously (Belcher et al. 2002); however, this study employs more detailed definition of hydrogeologic units based on lithostratigraphy, lithology, alteration and fracturing and compares the probability distributions to the aquifer test data. The results suggest that such distributions can be used for analysis involving, for example, numerical flow modelling, recharge, evapotranspiration, and rainfall runoff (Belcher et al. 2002).

HU is characterized by collecting hydraulic conductivity data from pumping tests to define the overall behaviour.

In order to suggest an operation of screening of the withdrawal capacity by HU, it is necessary to achieve the characterization of the hydraulic conductivity of the same. This measure is usually realized by pumping tests and it is subject to a variability that can be also very broad. Commonly, for this reason in the design the most frequent measured value (modal value) is selected. This characterization does not ensure that the calculated flow rate is the realistic flow rate and especially any probability of success is estimated.

According to define the probability of success, this analysis aims to consider this missing element of the required withdrawal.

The requirement to define the probability of the single contribution to the water demand is of interest in the preliminary assessment of induced effect (i.e. drawdown). Two separate cases were analysed to assess the Probability of Event (P(E)) related to the productivity of HU and to the induced drawdown.

2 State of the Art

Frequently, a conflict among the stakeholders, that use the resource, is shown. As the European Union has highlighted in the Water Directive, the water resource is unique and varied according to the different uses. Therefore, it is central to assess the sustainability of groundwater withdrawals from the aquifer system (Mays 2013).

Indeed, the sustainability of withdrawals on groundwater is a key factor in the management of water resources. In Italy, more than 95 % of water resources, distributed by waterworks entities, is taken from the underground through pumping systems installed in wells. In addition, the widespread “consumer culture” and the evolution of the welfare conditions push to consume resources more than necessary.

Therefore, it is important to introduce the concept of sustainability, which is the pivot of the research work. The sustainability index, adopted to evaluate the human pressure on the groundwater system, is represented by the ratio between the withdrawable volume of an aquifer and the total volume of water recharge. As for the extractable volume, three different

concepts can be distinguished: “Safe yield”, where the withdrawal is limited by the amount of groundwater recharge; “Sustainable yield”, where the withdrawal is limited by the achievable abstraction systems; “Sustainable groundwater development”, where the withdrawal is limited by the hydrological, environmental and socio-economic effects induced on the system (Smith et al. 2010; Mays 2013).

The recharge volume of the aquifer is obtained by modelling the water cycle phenomena. A previous work (Mazza et al. 2014) has highlighted how is important to calculate the water balance on a hydrogeological basin in a distributed form, in order to consider the soil characteristics spatially variable and space and time dependent parameters, such as the rainfall.

Defined the sustainability concept and selected the anthropogenic pressure indicator, the compatibility of water uses should be evaluated. The management approach to a groundwater system has been addressed in complex ways. The optimization method between supply and demand assumes a set of constraints among them the drawdown, the water quality and the type of users. Despite their potential, those methods are limited to a deterministic evaluation. Actually, the knowledge of input data is affected by uncertainties due to the nature of the involved phenomena as well as to the level of knowledge developed on water system.

Several researchers have studied the conflicts among users of the water resource and each of them has used different models and methods of resolution. Some researchers have examined the conflict situation, brought by urbanization and industrialization, which origins from the allocation of the withdrawal between irrigation and other uses (Donevska et al. 2003). This issue has been analyzed with engineering solutions, like reduction of network losses and more efficient irrigation methods, building of reservoirs to catch the water in rainy periods and use it in drought ones, the transport of water from areas with a surplus in lacking areas as well as applying a more efficient management of basins.

A similar study was conducted by examining the multiple uses of water for irrigation (Jensen et al. 1998). The authors suggest that future scenarios, to keep the minimum sufficient to meet the domestic demand, will have to be cooperation rather than competition between irrigation and sources of supply. The weak point of these works, however, is the absence of a quantitative approach in the analysis of water resources distribution.

The application of multi-criteria decision-making (MCDM) methods to solve the problems of water resource management has a very extensive literature. Different methods have been used and some authors have also proposed procedures for the selection of methods and models (decision analysis) (Romijn and Tamminga 1982; Szidarovszky et al. 1986; Woldt and Bogardi 1992; Kapelan et al. 2005; Bekele and Nicklow 2005; Bogardi and Nachtnebel 1994; Duckstein 1984). The main obstacle in the decision-making procedures is not the availability of the necessary technical knowledge but the interaction between policy makers and academics. Indeed, technical tools and data may be available but the choices follow criteria not comply with the results.

The present analysis aims to use the methods for estimating the reliability of complex systems evaluating the uncertainties of dataset adopted for the purpose of the water balance. The question, often directed to the technical analysis of the data, is: “what is the probability of the system failure?”. The preliminary result is to associate the values of aquifer recharge by a probability function. Then, this result can be used to evaluate the potential solutions in the optimal allocation of the withdrawal in terms of their use. Therefore, the main goal of reliability analysis is to ensure the performance of the system without conflict with the economic interests linked to the design.

In groundwater engineering the term reliability is associated to the more general concept of sustainability of water supply systems or more specifically to the recharge of water resource

(Vogel and Bolognese 1995). Some interesting works have been done in a joint study by Mott MacDonald and the United Kingdom Water Industry Research (UKWIR) attending to a methodology to estimate the aquifer yield (Misstear and Beeson 2000). The approach is focused on the reliability of the well. The methodology is based on available data from wells and a new method has been developed to estimate the “Deployable Output” of groundwater abstraction wells (Tham 2012). The analytical or modelling approach presented in Misstear and Beeson (2000) and in Tham (2012) is based on Forchheimer transient flow equation. The main assumption is the value of the hydraulic conductivity (or transmissivity).

The point of interest in designing a new well and its deployable output is the uncertainty of the hydraulic conductivity value. Even if hypothesis of homogeneous medium is formulated, the hydraulic conductivity should be assumed as a random variable due to its spatial variability. According to this assumption, the evaluation of the well yield must be analysed in terms of probability of event.

The objective is to assess a methodology to obtain the probability of success related to a specific flow rate from water well. Characterised HU in terms of probability distribution of the hydraulic conductivity, thickness and other parameters, flow rates and reliability index of the withdrawal can be estimated.

3 Method

3.1 Reliability Analysis of Water System

The topic of this analysis is to evaluate the required performance of the hydrogeological system according to the economic interests limited to the sustainable exploitation of the resource.

This strategy defines a tendency aiming to reduce the environmental pressures caused by the production and consumption of natural resources, without compromising economic development, as required by the Communication Act of the European Commission (December 21, 2005) “Thematic Strategy for the sustainable use of natural resources”.

In this context, the reliability analysis, proposed in order to define the optimum performance of the hydrogeological system, well suited to the conditions of the uncertainty of parameters and therefore allows to verify the compliance of supply and demand according to the environmental balance.

The reliability of the required performance is defined as the capacity of the system to fulfil completely its function during operating activity and consists, therefore, in a probabilistic measure of a predetermined performance.

In water resources management, the reliability measure is associated with the maximum demand of water resource of the region compatible with the actual availability in the water basin.

However, it is not possible to determine the conditions of safety or failure since the parameters that control the system, in general, are not deterministically known. Therefore, the probability that a given system properly fulfils its function can be estimated. Indeed, the reliability is the probabilistic measure of the sustainable use of water resources. Consequently, the reliability of the withdrawal from a groundwater system coincides with its sustainability. The probability distribution obtained by the reliability analysis allows to define a probability value to the sustainability of the production system.

The well-established deterministic groundwater models do not take into account a variety of factors, that complicate the characterization, due to the uncertainties associated with parameters that describe on the one hand the effect of the exploitation of the HU (in terms of permeability, lowering of the water and radius of influence) and on the other hand the uncertainty of the request (in terms of seasonality and specific use).

3.2 Description of Stochastic Model “FORM”

A methodology for the stochastic modelling of the water resource exploitation is given by adopting the reliability methods of first order generally applied to the theory of structural reliability. In some cases, the reliability analysis, in order to assess the probability of failure in a complex system, results in a lower computational load than traditional simulation Monte Carlo methods (Hamed et al. 1995; Mantoglou and Kourakos 2007).

The methods of reliability of the first order, developed in structural engineering assessment and related to the probability of failure, are here proposed by adopting the same notations (Baecher and Christian 2003).

The reliability of a system can be characterized by analysing the random behaviour of two characteristic parameters:

- Supply (X)
- Demand (Y)

The value of the probability $P(X > Y)$ is an effective quantification of the reliability of system; vice versa, the probability of the complementary event $P(X < Y)$ corresponds to the measure of the system failure.

The probability of failure (the probability that the supply is less than the demand) is given by:

$$p_F = P(X < Y) = \sum_y P(X < Y | Y = y)P(Y = y) \tag{1}$$

According to the Bayes Theorem, the Eq. (1) is:

$$P(X < Y | Y = y)P(Y = y) \equiv P[(X < Y) \cap (Y = y)] \tag{2}$$

If the random variables X and Y are statistically independent, the relation becomes:

$$P(X < Y | Y = y) \equiv P(X < Y)$$

Hence, the following equation (probability of failure) in the case of statistically independent variables:

$$p_F = P(X < Y) = \sum_y P(X < y)P(Y = y) \tag{3}$$

The aim of achieving the point of equilibrium between supply and demand can be formulated in terms of “safety margin function” (M) defined as:

$$M = X - Y \tag{4}$$

The state of failure occurs when $M < 0$.

In terms of probability, the Eq. (3) could be expressed as:

$$p_F = P(M < 0) = P[(X-Y) < 0] \quad (5)$$

Typically, the random variables X and Y , indicating respectively the provided availability and the required performance, are not known a priori, namely the probability distribution, that characterizes them, is not known. To solve this problem, the formulation of the second moments should be used. This formulation requires the knowledge of the moments of first and second order μ_X , μ_Y and σ_X , σ_Y , related to the random variables X and Y , included in the function M .

Starting from the safety margin Eq. (4), the safety conditions of the system are given when $X-Y > 0$ and are outlined in Fig. 1 as the half-plan $M > 0$.

The second-order approximation involves the standardized variables according to follow expressions:

$$X' = \frac{X - \mu_X}{\sigma_X}, Y' = \frac{Y - \mu_Y}{\sigma_Y} \quad (6)$$

where the first and second order parameters (μ , σ) are known.

Substituting the Eq. (6) the safety margin function (Eq. (4)) is obtained as follow:

$$M = X - Y = \sigma_X X' - \sigma_Y Y' + \mu_X - \mu_Y \quad (7)$$

The limit state surface, $M=0$, is the approximated tangent plane given by FORM (Fig. 1).

The point on the tangent plane, closest to the origin, is called the design point and represents the most plausible failure point in the failure standard plane. The reliability index β represents the value of minimum distance between the design point and the origin of the standard normal plane. The first order solution of the failure probability is:

$$P_{F_{FORM}} = \Phi(-\beta) \quad (8)$$

where $\Phi(\cdot)$ is the standard normal cumulative distribution function.

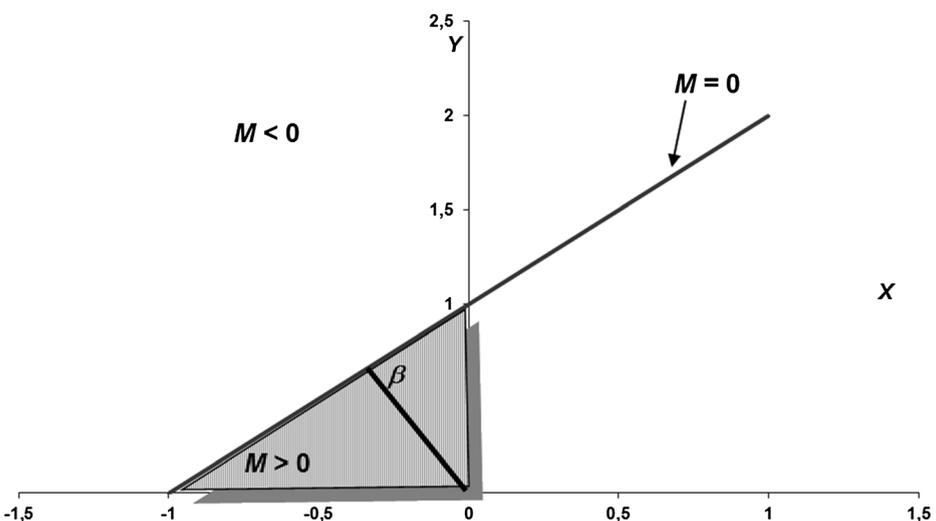


Fig. 1 Limit state surface in the standard plane and reliability index β

4 Case Study

4.1 Groundwater RBD

The proposed scheme is inspired to the Honjo’s work (2011). The scheme consists of three parts: (I) the uncertainty analysis of basic variables (i.e. definition of random variables), (II) the groundwater analysis (i.e. definition of hydrogeological parameters) and (III) the reliability analysis of withdrawal (i.e. definition of reliability index) (Fig. 2a).

The uncertainty analysis is the main part of the reliability assessment procedure. In this approach the statistical analysis plays a central role. The reliability assessment is based on uncertainty analysis and the “simple” Monte Carlo Simulation (MCS) could evaluate the performance function. However a more rigorous approach could be followed using FORM or more complex ones (Baecher and Christian 2003).

The main aspect in groundwater analysis is the availability of data and their level of uncertainty. For this reason, the scheme in Fig. 2a has been adopted, where the groundwater analysis is separated from the uncertainty analysis.

The groundwater engineering is based on usual design approach for water wells. Predetermined the basic variables, the behaviour of the aquifer is known.

The case study concerns the reliability analysis on a single well plant based on the procedure presented in Fig. 2b. The HU is characterized by the hydraulic conductivity through pumping tests on existing wells.

The reference scheme assumed for the site is reported in Fig. 3. It concerns a confined aquifer with a thickness b of 20 m and a hydraulic head of 30 m on the bottom of the aquifer. The bottom layer, as well as the top one, consists of impermeable geological formation.

4.2 Uncertainty Analysis

4.2.1 Statistical Analysis: Characterization of the Hydrogeological Unit Conductivity

The HU is the Monte Morello formation. This is a sedimentary mainly limestone-marl and, secondary, calcarenitic, with interbedded calcareous sandstones, marls and shales. The

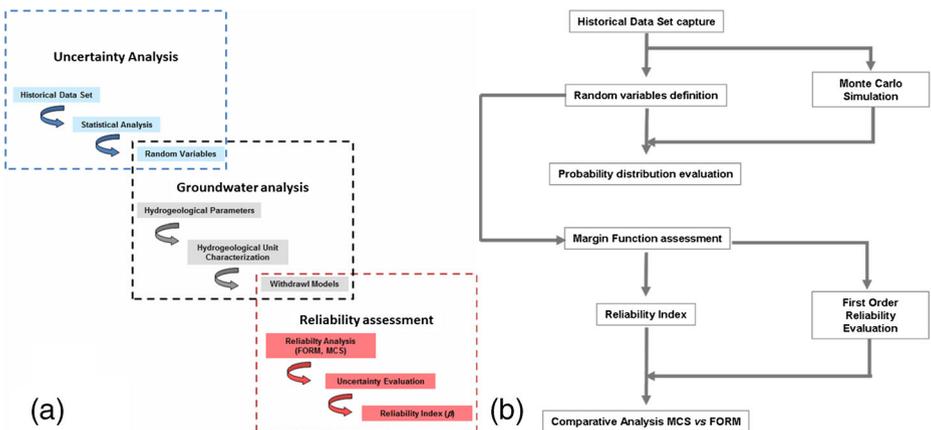


Fig. 2 a) Honjo’s scheme: groundwater reliability analysis b) Flowchart of the reliability analysis procedure

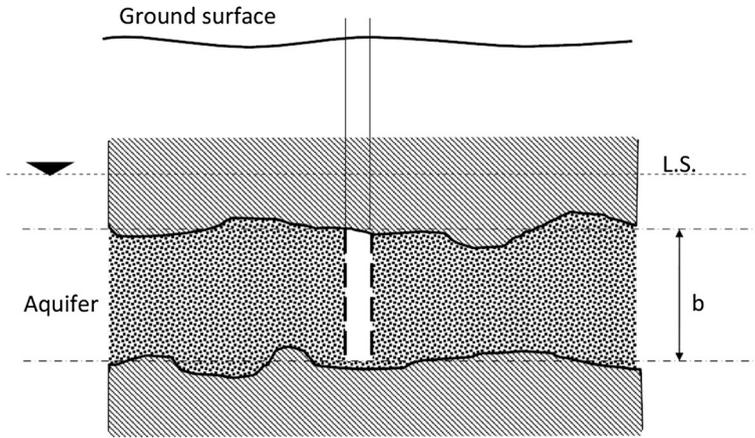


Fig. 3 Case study: water well in a confined aquifer

calcareous component is on average higher, but there are stratigraphic intervals with a predominance of marl and even intervals clearly silty.

The hydraulic conductivity has been evaluated from a set of pumping tests carried out on existing wells. The data set is formed by 54 samples. The statistical descriptive analysis has been conducted and the frequency distribution function has been established to be log-normal, as expected (Belcher et al. 2002). In Fig. 4a the histogram of empirical frequency and the cumulative frequency function are presented.

The Monte Carlo simulation method has been applied in order to improve the accuracy of the log-normal distribution function. In Fig. 4b the comparison between field and simulated data, obtained by 20,000 samples, is presented (Mantoglou and Kourakos 2007). The sample size ensures the convergence of the estimated distribution.

The probability distribution function of the hydraulic conductivity has been characterized by mean and standard deviation values (Table 1).

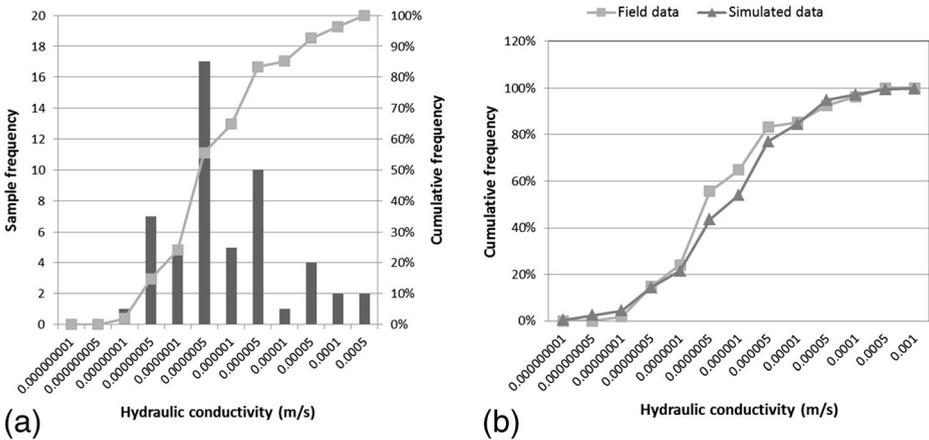


Fig. 4 a) Histogram and cumulative frequency distribution for hydraulic conductivity data; b) Comparison between field and simulated cumulative frequency curves

Table 1 Main parameters and probability distribution functions of random variables

Random variables	Notation	Mean	Standard deviation	Probability distribution function
Layer thickness	<i>b</i>	20	2	Normal
Hydraulic conductivity (par. 4.2.1)	<i>K</i>	2,73 e-5	9,52 e-5	Lognormal
Radius of action	<i>R</i>	300	200	Uniform

4.2.2 Random Variables: Probability Distribution Function Evaluation

Most part of the uncertainty in groundwater analysis is the lack of knowledge due to the difficulty to access the system. This contributes to uncertainty of input variables (initial and boundary conditions), of output variables (observation for model calibration) and of basic parameters (i.e. layer thickness, hydraulic conductivity). The uncertainties are also due to the model assumptions. Therefore, it is important to analyse the problem in order to characterise all possible causes of the uncertainty.

The basic random variables are the layer thickness (*b*), the hydraulic conductivity (*K*) and the radius of action of the well (*R*).

Characterized the hydraulic conductivity, in order to evaluate the specific yield (or the draw-down) in a well, the variability of the layer thickness and of the radius of action must be analyzed.

The layer thickness has been assumed to vary between the maximum and the minimum value equal to respectively 24 and 16 m ($\pm 20\%$ of the thickness of the aquifer). Therefore, a normal distribution function (mean value of 20 m and a standard deviation of 2 m) has been assumed.

The radius of action of the well has been assumed to vary between two limiting values following a uniform distribution. Influence radii less than 100 m are not considered as well as radii greater than 500 m. The uniform probability distribution has a mean value of 300 m and a standard deviation of 200 m.

In Table 1 the main parameters and the probability distribution functions for each analyzed random variable have been summarised.

4.3 Groundwater Analysis

The groundwater analysis has been made on two steps: firstly, the evaluation of possible withdrawal as the goal of design; subsequently, the water level drawdown according to regulation office requirements.

To evaluate the well productivity, an analytical steady state model has been assumed. The relationship is the equation of Thiem for a confined aquifer (de Marsily 1986):

$$Q = 2\pi bK \frac{\Delta H}{\ln(R/r)} \tag{9}$$

where: *Q* is the flow rate, *b* is the aquifer thickness, ΔH is the drawdown, *K* is the hydraulic conductivity, *R* in the radius of action and *r* is the well radius equal to 0,2 m.

In order to reduce the number of unknowns and to give a more general approach, the definition of specific yield or productivity has been adopted as follows:

$$q = \frac{Q}{\Delta H} = \frac{2\pi b}{\ln(R/r)} K \tag{10}$$

To evaluate the drawdown effect, from Eq. (9) the following relationship is derived:

$$\Delta H = Q \frac{\ln(R/r)}{2\pi bK} \tag{11}$$

4.4 Reliability Assessment

The characterization of the withdrawal of aquifer can be made by the specific yield. The problem is formulated in terms of specific yield as follows: estimate the probability to have a specific yield q from the well greater than a pre-determined design value q^* . The safety margin function is:

$$M = q - q^* \tag{12}$$

4.4.1 Reliability Analysis: Monte Carlo Simulation (MCS)

The classical Monte-Carlo simulation method calculates the specific yield of the withdrawal starting from the probability distribution functions (Table 1).

The estimate of the system reliability is derived by Eq. (12) comparing the calculated values (q) with the design value (q^*). The relative frequency to overcome this value is the estimate of reliability.

For the purpose of MCS analysis, the specific yield has been calculated from Eq. (10). Therefore, for each random variable 20,000 values (convergence of the result) have been extracted.

To highlight the dependence of the reliability function by each random variable, the results of failure probability, fixed the mean value of two random variables and extract the value of the third one, have been compared in Fig. 5a.

The probability of failure depends on the hydraulic conductivity rather than on layer thickness and radius of action (D.A. Baù 2012). Indeed, the comparison between the reliability function evaluated by the hydraulic conductivity as the only random variable and that obtained by the three random variables confirms the previous statement (Fig. 5b).

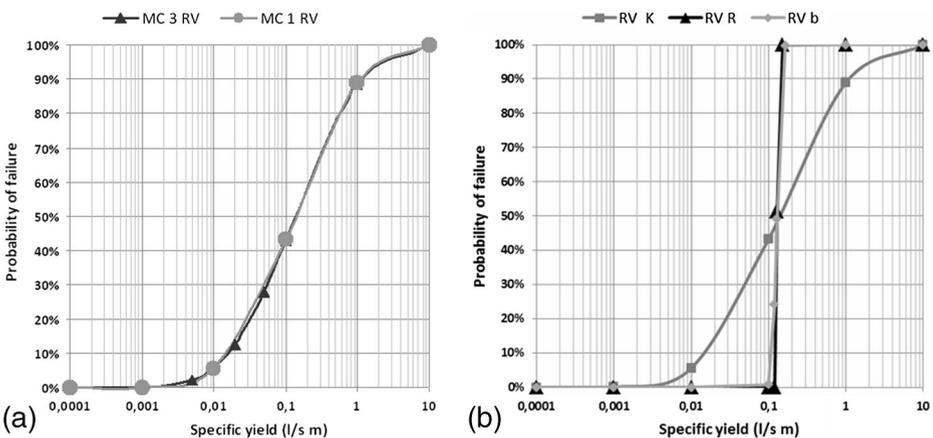


Fig. 5 a) Reliability function vs specific yield (Single Random Variables); b) Comparison between reliability functions of single random variable (K) and of three random variables

4.4.2 Reliability Analysis: First Order Reliability Method (FORM)

Defined the model to assess the productivity of the well, the sustainability of the withdrawal is evaluated. In order to validate the procedure, the reliability will be compared with specific flow rate and induced drawdown. Following the previous results in the MCS analysis, in the FORM approach only the hydraulic conductivity as random variable has been considered.

To apply the reliability method, the parameters of the log-normal distribution of hydraulic conductivity should be normalised. The mean m and standard deviation s of the normal distribution are:

$$m = \ln\left(\frac{\mu_K^2}{\sqrt{\mu_K^2 + \sigma_K^2}}\right) \tag{13}$$

$$s = \sqrt{\ln\left[\left(\frac{\sigma_K}{\mu_K}\right)^2 + 1\right]} \tag{14}$$

where μ_K and σ_K are the log-normal distribution parameters (Table 2).

In order to know the probability of failure, introducing the Eq. (10) in the expression (12), the Safety Margin function is written as:

$$M = \frac{2\pi b}{\ln(R/r)} K^{-q^*}$$

The Safety Margin function is modified replacing the random variable normally distributed:

$$M = \ln\left(\frac{2\pi b}{\ln(R/r)} K\right) - \ln(q^*) = \ln\left(\frac{2\pi b}{\ln(R/r)}\right) + \ln(K) - \ln(q^*)$$

The result is a linear function in the random variable $\ln(K)$. For linear Safety Margin the reliability index is calculated as:

$$\beta = \frac{\mu_M}{\sigma_M}$$

where μ_M is the mean value and σ_M the standard deviation of the safety margin function. Therefore, the reliability index is:

$$\beta = \frac{\ln\left(\frac{2\pi b}{\ln(R/r)}\right) + m + \ln(q^*)}{s}$$

Table 2 Hydraulic conductivity -Log-normal and Normal distribution parameters

Hydraulic conductivity	Log-normal	Normalised
Mean	1.59 10 ⁻⁰⁵	-12.268
Standard deviation	5.17 10 ⁻⁰⁵	1.563

The probability of failure can be derived by the cumulative standard function of normal distribution:

$$P_F = \Phi(-\beta)$$

The reliability function of the withdrawal is obtained by means of the probability of failure for different values of q^* (Fig. 6a).

The probability of failure can be also evaluated starting from the induced drawdown by the pumping. Imposed the maximum value of drawdown H_x , in order to know the probability of drawdown greater than H_x , the Safety Margin function can be defined as follows:

$$M = H_x - \Delta H$$

Replacing the expression of drawdown (11), the Safety Margin function results:

$$M = H_x - Q \frac{\ln(R/r)}{2\pi bK}$$

The Safety Margin function is modified through the random variable normally distributed,

$$M = \ln(H_x) - \ln\left(\frac{Q \frac{\ln(R/r)}{2\pi bK}}{K}\right) = \ln(H_x) - \ln\left(Q \frac{\ln(R/r)}{2\pi bK}\right) + \ln(K)$$

The result is a linear function in the random variable $\ln(K)$. For linear Safety Margin the reliability index may be calculated as:

$$\beta = \frac{\mu_M}{\sigma_M}$$

where μ_M is the mean value and σ_M the standard deviation of the safety margin function.

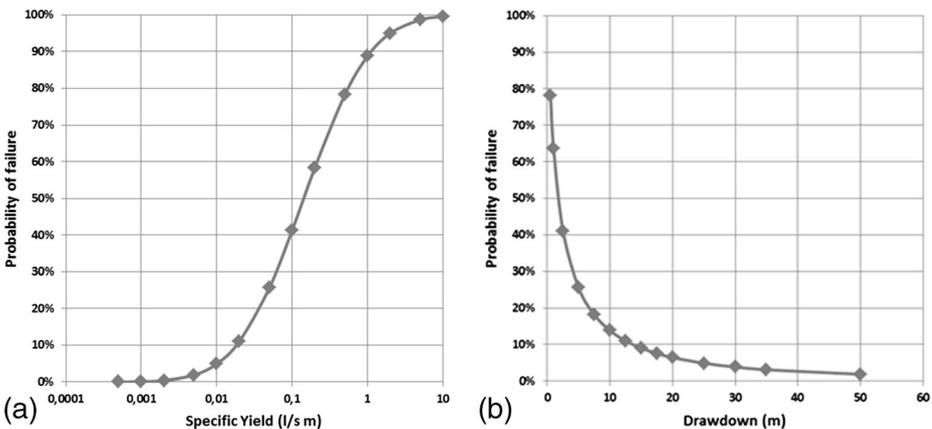


Fig. 6 a) Reliability function of the withdrawal vs specific yield. b) Reliability function of the withdrawal vs drawdown ($Q=0,25$ l/s)

Therefore, the reliability index is calculated as:

$$\beta = \frac{\ln(q^*) - \ln\left(Q \frac{\ln(R/r)}{2\pi bK}\right) + m}{s}$$

The probability of failure can be derived by the cumulative standard function of normal distribution:

$$P_F = \Phi(-\beta)$$

The reliability function of withdrawal is obtained by means of the probability of failure for different values of H_x .

In Fig. 6b the calculated reliability function for the case study ($Q=0,25$ l/s) is presented.

4.4.3 Comparative Analysis Results

The comparative analysis between two probability distribution functions, one obtained by MCS and one obtained by FORM, highlights the overlapping of the distribution curves (Fig. 7). This allows to adopt, according to preliminary analysis, the FORM approach taking as random variable the only hydraulic conductivity. This assumption has been improved indeed by sensitivity analysis above.

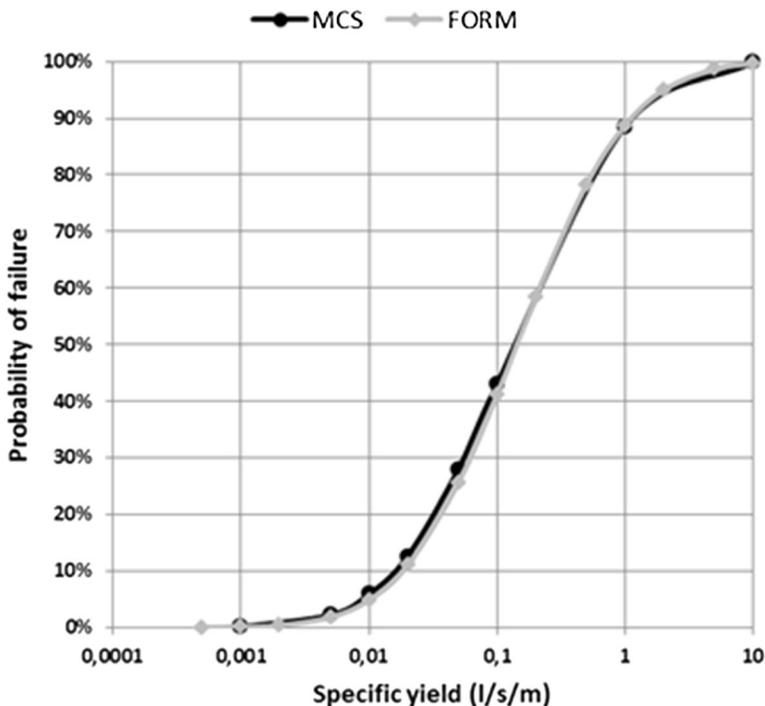


Fig. 7 Comparison between MCS and FORM reliability functions

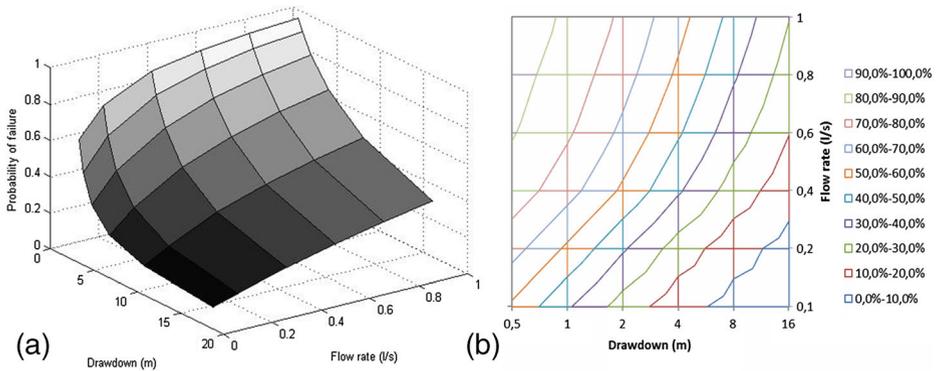


Fig. 8 a) Reliability surface b) Probability of failure: Flow rate (l/s) vs Drawdown (m)

5 Conclusions

The summary of outcomes, discussed above, is based on the Eq. (12) where the flow rate values, starting from the specific yield and defined values of the drawdown, have been stated (Fig. 8a). The aerial projection of this surface on the plane drawdown-flow rate identify iso-probability curves that allow to size the withdrawal design according to specific target of groundwater system sustainability (Fig. 8b).

In the present study, a probabilistic approach of groundwater exploitation has been introduced starting from a preliminary sensitivity analysis aimed for verify the feedback of random variables on the reliability analysis.

The FORM approach results in a lower computational load than the traditional simulation Monte Carlo method. This result allows to carry out a preliminary sizing of the withdrawal system.

The sensitivity analysis has emphasized the direct dependence of the reliability index on hydraulic conductivity only. The opportunity to define the probability that the single HU can contribute to the water demand may be of interest in the preliminary assessment of the induced effects. This evaluation can be simplified by using the operating tool of iso-probability curves.

The analysis assumes preliminarily steady state conditions and therefore does not consider the variability of the time-dependent parameters. The further research will involve the time-dependent variability of parameters that controls the withdrawal models.

References

- Baecher GB, Christian JT (2003) Reliability and statistics in geotechnical engineering. Wiley, England, ISBN: 0-471-49833-5
- Baù DA (2012) Planning of groundwater supply systems subject to uncertainty using stochastic flow reduced models and multi-objective evolutionary optimization. *Water Resour Manag* 26:2513–2536. doi:10.1007/s11269-012-0030-4
- Bekele EG, Nicklow JW (2005) Multiobjective management of ecosystem services by integrative watershed modeling and evolutionary algorithms. *Water Resour Manag* 41:W10406. doi:10.1029/2005WR004090
- Belcher WR, Sweetkind DS, Elliot PE (2002) Probability distributions of hydraulic conductivity for the hydrogeologic units of the death valley regional ground-water flow system, Nevada and California, Water-Resources Investigations Report 02-4212, USGS

- Bogardi JJ, Nachtnebel HP (1994) Multicriteria decision analysis in water resources management. UNESCO Publ, Parigi
- de Marsily G (1986) Quantitative hydrogeology. Academic, London
- Donevska K, Dodeva S, Tadeva J (2003) Urban and agricultural competition for water in the Republic of Macedonia, in Consensus to resolve irrigation and water use conflicts in the Euromediterranean Region. Proceedings ICID 20th European Regional Conference, Montpellier, France, 14–19 September 2003
- Duckstein L (1984) Selection of multiobjective technique for water resources problem under uncertainty. In: Multiobjective analysis in water resources, American Society of Civil Engineers, New York, pp. 179–202
- Guarascio M, Lombardi M, Rossi G, Sciarra G (2009) Geostatistics/reliability based risk analysis of the Vajont landslide. *WIT Trans Built Environ* 108:607–615, **ISSN: 17433509**
- Hamed MM, Conte JP, Bedient PB (1995) Probabilistic screening tool for ground-water contamination assessment. *J Environ Eng* 121:767–775
- Honjo Y (2011) Challenges in geotechnical reliability based design. ISGSR 2011 - Vogt, Schuppener, Straub & Bräu, ISBN 978-3-939230-01-4
- Jensen PK, Hock WVD, Konradsen F, Jehangir WA (1998) Domestic use of irrigation water in Punjab, in 24th WEDC Conference Sanitation and Water for All, Islamabad, Pakistan
- Kapelan ZS, Savic DA, Walters GA (2005) Multiobjective design of water distribution systems under uncertainty. *Water Resour Manag* 41:W11407. doi:10.1029/2004WR003787
- Mantoglou A, Kourakos G (2007) Optimal groundwater remediation under uncertainty using multi-objective optimization. *Water Resour Manag* 21:835–847. doi:10.1007/s11269-006-9109-0
- Mays LW (2013) Groundwater resources sustainability: past, present and future. *Water Resour Manag* 27:4409–4424. doi:10.1007/s11269-013-0436-7
- Mazza R, La Vigna F, Alimonti C (2014) Evaluating the available regional groundwater resources using the distributed hydrogeological budget. *Water Resour Manag* 11:1–17, **ISSN: 09204741**
- Missteat BDR, Beeson S (2000) Using operational data to estimate the reliable yield of water-supply wells. *Hydrogeol J* 8:177–187
- Romijn E, Tamminga M (1982) Allocation of water resources in the eastern part of Netherlands. In: Optimal allocation of water resources: Proceedings of the Exeter Symposium July 1982, IAHS Publ. n.135
- Smith AJ, Walker G, Turner J (2010) Aquifer sustainability factor: a review of previous estimates, Groundwater 2010 the challenge of sustainable management, Canberra, Australia, 31 October–4 November 2010
- Szidarovszky F, Gershon NM, Duckstein L (1986) Techniques for multiobjective decision making in systems management. Elsevier, Amsterdam
- Tham AG (2012) Modelling deployable output for groundwater abstraction wells. 1st Civil and Environmental Engineering Student Conference 25–26 June 2012, Imperial College London
- Vogel RM, Bolognese RA (1995) Storage-reliability-resilience-yield relations for over-year water supply systems. *Water Resour Res* 31(3):645–654, **ISSN: 1944-7973**
- Woldt W, Bogardi L (1992) Ground water monitoring network design using multiple criteria decision making (ant) geostatistics. *JAWRA J Am Water Resour Assoc* 28:45–62. doi:10.1111/j.1752-1688.1992.tb03153.x