A RISK-BASED INTEGRATED APPROACH FOR MANAGING TRANSBOUNDARY GROUNDWATER RESOURCES

RISK-BASED INTEGRATED TRANSBOUNDARY AQUIFER MANAGEMENT

JACQUES GANOULIS [*]
UNESCO Chair and Network INWEB: International Network of Water/Environment Centres for the Balkans, Department of Civil Engineering, Aristotle University of Thessaloniki,
54124 Thessaloniki, Greece
http://www.inweb.gr

Abstract. The increasing demand for water as a consequence of population increase, socio-economic growth and climate variations together with the deterioration in water quality from various pollution sources, has resulted in upgrading the role and importance of transboundary waters including transboundary aquifer resources. In this chapter, the UNESCO-ISARM (Internationally Shared Aquifer Resources Management) approach is formulated in terms of a risk-based methodology for integrated groundwater management.

Keywords: transboundary groundwater resources; risk; integrated transboundary aquifer resources management

1. Introduction

Although it is very difficult to evaluate the exact quantity of available groundwater resources, it is widely acknowledged that groundwater constitutes the most important and most precious freshwater resource on Earth. Even though estimations in the literature on the quantity of available groundwater resources at a global level vary by some orders of magnitude, it is generally accepted that among all other sources of freshwater this quantity is the most

[*]Corresponding author: Prof. Jacques Ganoulis, UNESCO Chair and Network INWEB, Department of Civil Engineering, Aristotle University of Thessaloniki, 54124 Thessaloniki, Greece; email: iganouli@civil.auth.gr

important, except for huge quantities of freshwater blocked in icecaps and glaciers. As shown in Fig.1, freshwater resources on Earth represent only 2.5% of the total water available, because the majority of water is salt water held in the oceans and seas (Shiklomanov, 2005).

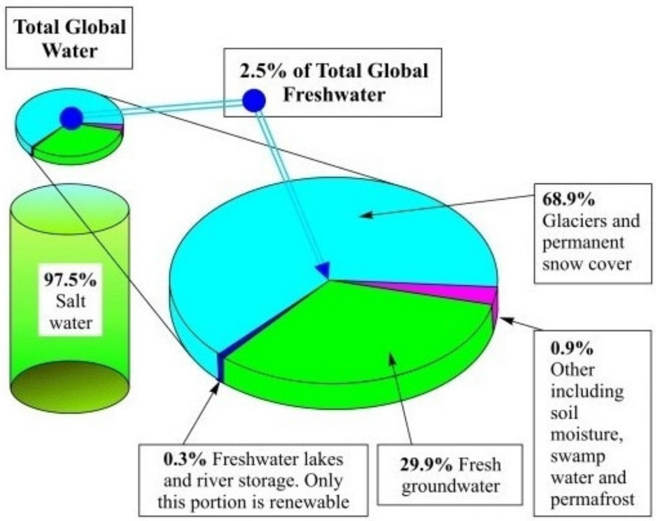


Figure 1. Distribution of water in the hydrosphere.

Except for freshwater trapped in glaciers and ice sheets, the majority of freshwater resources, i.e. about 30% of the total, are in the form of groundwater. Only 0.3% of freshwater is surface water in lakes (87%) and rivers (2%).

Groundwater is a key source of drinking water, particularly in rural and coastal areas. Table 1 shows the importance of groundwater for municipal water supply in Southern European countries (Llamas, 2004).

Transboundary water resources are far from negligible. The 2003 UN Report (UN WWDR, 2003) entitled “Water for Life Water for People”, listed 263 international transboundary basins. Apart from their significance in terms of area and conflict potential, it should be noted that these basins: -

- cover 45% of the land surface of the Earth
- affect 40% of the world’s population
- account for approximately 80% of global river flow
- cross the political boundaries of 145 nations

TABLE 1. Groundwater uses in some Mediterranean countries.

	Groundwater use by sector (Percentage of total abstractions)			Demand covered by groundwater (Percentage by sector)		
Country	Water Supply	Agriculture	Industry	Water Supply	Agriculture	Industry
Spain	17	80	3	26	21	–
France	63	6	31	71	4	55
Italy	39	57,5	3,5	91	25	7
Greece	37	58	5	–	20,5	–
Israel	20	75	5	45	60	20
Turkey	64	36	–	64	36	–

The distribution of transboundary basins among the continents in terms of number and as a proportion of the total surface is shown in Fig. 2. It can be seen that Europe comes first with 73 basins, followed by Africa and Asia.

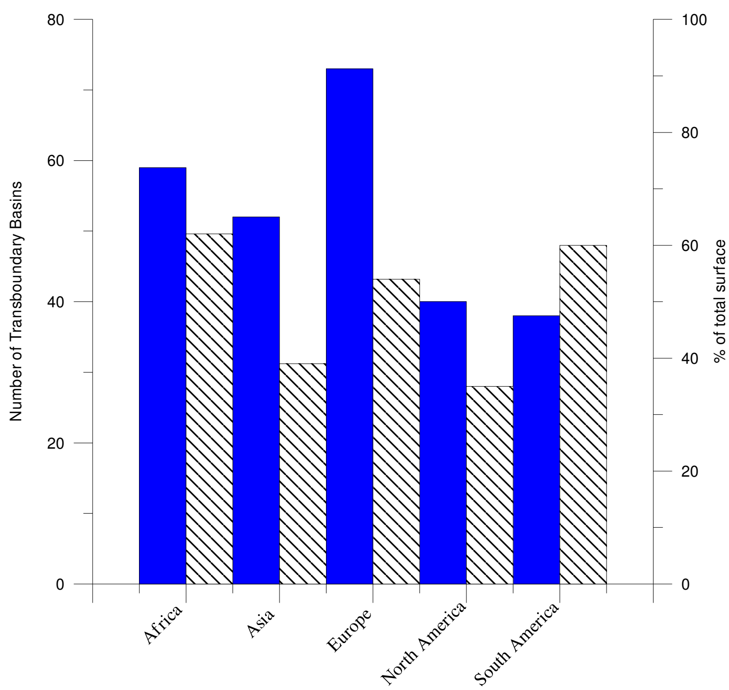


Figure 2. Distribution of transboundary basins among the continents.

In the case of internationally shared surface waters much progress has been made on how to determine what type of water resources problems need or will need to be resolved by bilateral or multilateral interstate agreements. A large number of such international agreements (more than 200 during the last 50 years) have been signed to resolve various types of interstate surface water resources problems. These are available for reference and act as precedents.

The situation is quite different in the case of internationally shared groundwater aquifer resources. Difficulties arise in scientific and technical matters (groundwater monitoring, data interpretation and modelling), and because of a lack of political willingness for cooperation and the weakness of the institutions involved. Major difficulties arise in designing groundwater development plans because groundwater flow and groundwater quality are subject to several types of uncertainties and are affected by these to a much greater degree than in surface water hydrology. These uncertainties are related to the high variability in space and time of the hydrogeological, chemical and biological processes. The principal challenge is to set up a cooperative framework between countries involved, so that institutions from both sides can work together effectively (Ganoulis et al., 1996).

In many real situations interactions between surface and groundwaters on both sides of the international border may create international disputes. As shown in Fig. 3 (UNESCO/ISARM, 2001) groundwater over-pumping on one side of the boundary may lower the water level of a shared surface lake or river or accelerate the sea water intrusion in a coastal zone located in the other country.

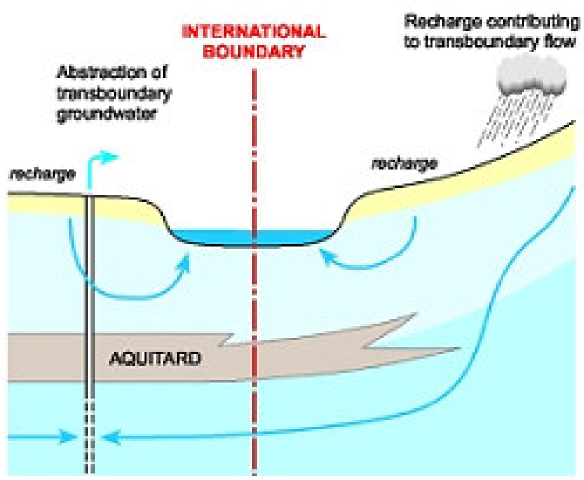


Figure 3. Interaction between transboundary surface and groundwater flows.

A very characteristic case of groundwater-surface water interdependencies can be found in the southern Balkans, in the region of the Doirani/Dojran Lake, which is internationally shared by Greece and the Former Yugoslav Republic of Macedonia (FYROM). In the many years of drought during the last decade, extensive evaporation together with over-pumping for irrigation purposes on the Greek side may have contributed to substantially lowering the lake's water level. In all cases cooperation between countries is of primary importance in order to understand the problems, to agree about the underlying causes and to try to develop reliable solutions (see www.inweb.gr).

2. Typology of Transboundary Aquifers

Water infiltrating into the soil circulates through various geological formations. Depending on the boundary conditions (impermeable or semi-permeable layers of soil, atmospheric pressure, rivers and lakes) the groundwater forms various types of subsurface reservoirs, called ***aquifers***. These are extensive permeable rock formations in which water partially accumulates and through which water partially flows. Fig. 4 gives an overview of different types of groundwater aquifers in various geological formations. According to their geological formation characteristics, aquifers may be classified in 3 main groups:

1. Alluvial and sedimentary aquifers
2. Limestone and karstic aquifers
3. Crystalline fractured aquifers.

(1) *Sedimentary and alluvial aquifers*: This category of aquifers is characterised by successive layers of different hydrogeological properties: permeable, semi-permeable or impermeable. The water circulates in the successive layers, which consist mostly of gravel, sand, clay and silt. Phreatic, confined or semi-confined (leaky) aquifers are formed.

(2) *Limestone and karstic aquifers*: Solution processes caused by acidified rainwater increase the permeability of limestones and dolostones forming secondary aquifers. Karstic phenomena are extreme cases of such processes, creating subterranean fractures and water conduits of high permeability. In karstic regions surface runoff is almost nil and large volumes of groundwater can be found at various depths.

(3) *Crystalline rock aquifers*: The importance of groundwater resources in these rocks depends on two factors (a) the rate of fracturing and (b) the chemical weathering of the surface layer, through which precipitation water percolates into the rock. This geological formation is divided in several blocks by secondary and primary fractures.

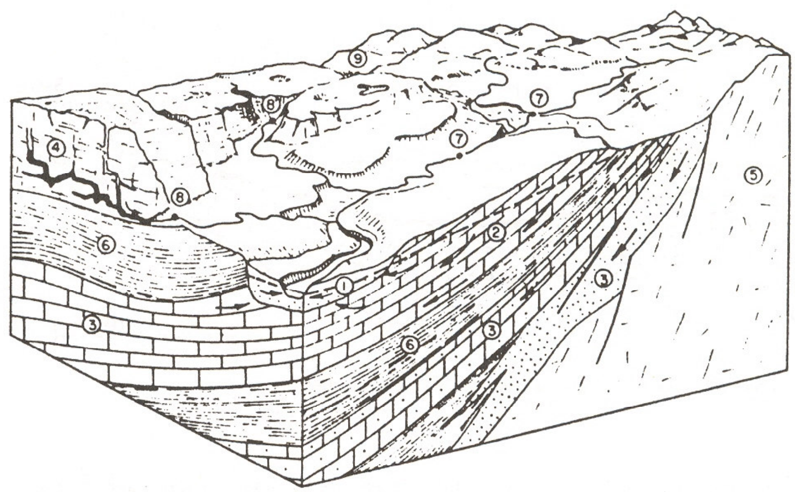


Figure 4. Groundwater in various geological formations (Bodelle and Margat, 1980).

In transboundary situations, depending on the location of the international border, sedimentary and alluvial aquifers may be classified in four different types, as follows: (Fig. 5, Chilton, personal communication, 2007)

Type (a): the state border follows the basin and groundwater divide. Very limited discharge occurs across the border.

Type (b): the state border is separate from the basin and groundwater divide. Recharge occurs in one country and discharge in the other one.

Type (c): the state border follows a transboundary river or lake. Little transboundary groundwater flow occurs in the alluvial aquifer connected to the river.

Type (d): Large deep aquifer, recharged far from the border. Transboundary groundwater flow not connected to the surface may be important.

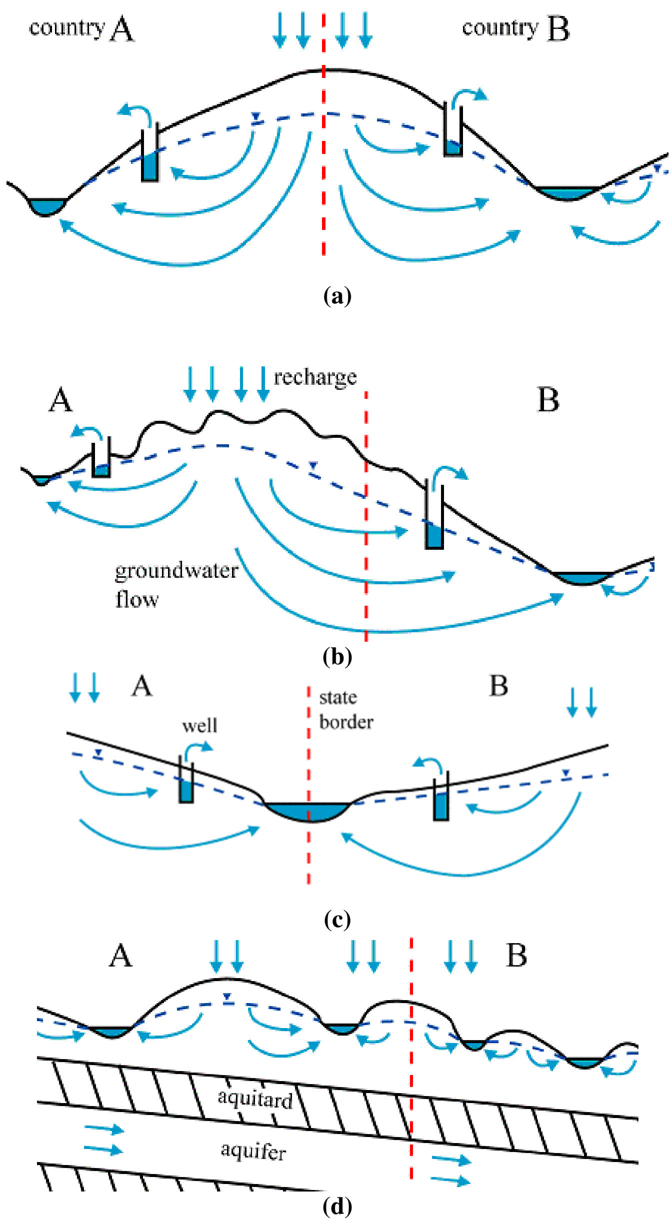


Figure 5. Types of transboundary sedimentary aquifers (Chilton, 2007).

In the case of deep karst aquifers covered by sediments, recharge of groundwater may occur in one country and water can appear at the surface in the form of a spring in another country (Fig. 6). This occurs frequently in the Dinaric karst (Western Balkans), between Bosnia & Herzegovina (upstream) and Croatia (downstream, near the Adriatic coast).

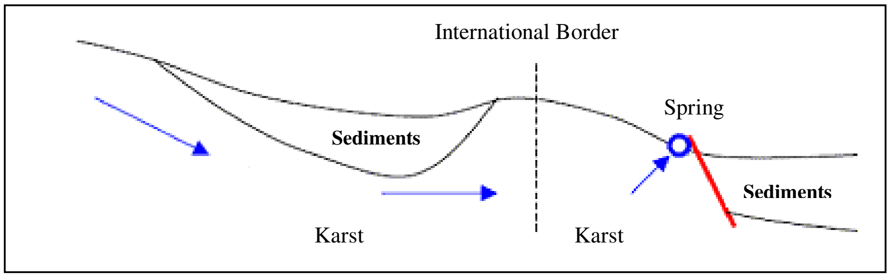


Figure 6. Large deep karst aquifer recharged in one country and forming a spring in a neighbouring country.

3. ISARM's Methodology

The UNESCO/ISARM Programme (UNESCO/ISARM, 2001) has identified the following five key focus areas for the sound management of transboundary aquifer water resources:

- scientific-hydrogeological approaches,
- legal aspects,
- socio-economic issues,
- institutional considerations, and
- environmental protection.

3.1. SCIENTIFIC-HYDROGEOLOGICAL APPROACHES

The management of groundwater quantity and quality is a complicated multidisciplinary scientific field requiring good cooperation between various disciplines, such as:

- *Hydrogeology*: geophysical and geological prospecting, drilling techniques, mapping

- *Groundwater hydrodynamics:* quantitative aspects of flows, mathematical modelling, calibration, and prediction scenarios
- *Groundwater management*: systems analysis, optimisation techniques, risk analysis and multi-objective decision-making methods
- *Hydrochemistry*: chemical composition of the soil and water
- *Hydrobiology*: biological properties of groundwater systems

Modern tools for groundwater development extensively use new information technologies, development of databases, computer software, mathematical modelling and remote sensing.

3.2. LEGAL ASPECTS

International conventions on tranboundary waters should include provisions for the monitoring and assessment of transboundary waters, including measurement systems and devices and analytical techniques for data processing and evaluation. Guidelines on how to effectively exchange information and monitoring data and undertake measures to reduce impacts from transboundary water pollution are also very important. As surface and groundwaters are interconnected, measures to protect ecosystems and drinking water supply should also include the monitoring and assessment of transboundary groundwaters.

An international convention has already been agreed upon for the monitoring and assessment of transboundary rivers and lakes (UNECE, 2000). No such international treaty yet exists for transboundary aquifers. The monitoring and assessment of surface waters are also part of the 1999 Protocol on Water and Health to the Convention on the Protection and Use of Transboundary Watercourses and International Lakes. This Protocol contains provisions regarding the establishment of joint or coordinated systems for surveillance and early-warning systems to identify issues related to water pollution and public health, including extreme weather conditions. It also includes the development of integrated information systems and databases, the exchange of information and the sharing of technical and legal knowledge and experience.

The complexities of groundwater law have been described by many authors in the technical literature. Over-pumping can cause groundwater quality to deteriorate through salinity problems, either by seawater intrusion or evaporation-deposition. Over-pumping of groundwater in one country can endanger the future freshwater supplies of another country. The Bellagio Draft Treaty, developed in 1989, attempts to provide a legal framework for groundwater negotiations. The treaty describes principles based on mutual respect, good neighbourliness and reciprocity for the joint management of shared aquifers. Although the draft is only a model treaty and not the result of accommodating actual state practice, and accepts that collecting groundwater data may be difficult and expensive and should rely on cooperation; it does provide a general framework for groundwater negotiations.

Only three bilateral agreements are known to deal with groundwater supply (the 1910 convention between Great Britain and the Sultan of Abdali, the 1994 Jordan-Israel peace treaty and the Palestinian-Israeli accords (Oslo II). In addition, the 1977 Geneva Aquifer Convention is also an important reference for the internationalisation of shared aquifer management and regulation by intra-State authorities for transboundary cooperation. Treaties that focus on pollution usually mention groundwater but do not quantitatively address the issue. In August 2005 the third report on shared groundwater resources was presented in Geneva to the United Nations International Law Commission (UN-ILC, 2005). In this report a set of articles for a draft international convention on the law of transboundary aquifers is proposed.

3.3. SOCIO-ECONOMIC ISSUES

It is widely accepted today that the use of water resources, the protection of the environment and economic development are not separate challenges. Development cannot take place when water and environmental resources are deteriorating, and similarly the environment cannot be protected and enhanced when growth plans consistently fail to consider the costs of environmental destruction. Nowadays it is clear that most environmental problems arise as 'negative externalities' of an economic system that takes for granted - and thus undervalues - many aspects of the environment. The integration of environmental and economic issues is a key requirement in the concept of sustainability, not only for the protection of the environment, but also for the promotion of sustainable long-term economic development, especially in areas where water is scarce.

The ISARM Framework Document (UNESCO/ISARM, 2001) makes a preliminary overview of different socio-economic aspects of transboundary aquifer management. The main driving forces behind the over-exploitation of groundwater resources resulting in negative impacts are: population growth, concentration of people in big cities and inefficient use of water for agricultural irrigation. The agricultural sector is most often mainly responsible for groundwater over-exploitation. The situation becomes particularly difficult when neigbouring countries share common transboundary groundwater resources, as a number of differences arise in:

- socio-economic level

- political, social, and institutional structures, including strict region-specific positions on national sovereignty
- objectives, benefits, and economic instruments
- international relations, national legislation and regulation.

Competition for the use of groundwater for different purposes on one or both sides of the border may generate potential conflicts. Effective governance should consider specific hydrogeological conditions, aquifer recharge rates and multi-objective use of renewable groundwater resources involving multidisciplinary regional working groups.

3.4. INSTITUTIONAL CONSIDERATIONS

International commissions have proved to be the most effective institutional settings for transboundary surface water resources management for transboundary watercourses and lakes. No such common institutions exist for transboundary groundwaters. Whether transboundary groundwater management should be a specific task of one or more specialised committees belonging to the same international river or lake committee, or whether a separate common institutional body should be created for this purpose, remains a question unanswered. In view of the physical interactions between surface and groundwaters, coordination between different specialised institutions is necessary for the overall sustainable management of water resources.

In the present situation national institutions dealing with groundwater are not sufficiently or effectively prepared to be able to undertake the joint management of transboundary groundwaters. Groundwater management units, when they exist, are often a mere side-line or even invisible in surface water dominated water administrations and groundwater is not explicitly addressed in national water legislations. Capacity building is essential, especially the development of joint capacity and consultation mechanisms at decision-maker level, including the harmonisation of domestic groundwater law supported by common monitoring systems and the sharing of information and data,. The role of regional partnerships between different decision makers, scientists from different disciplines, and other water stakeholders is also important for preventing conflicts and enhancing cooperation. It is important to link and reconcile transboundary aquifer management with land management, and with regional political, social and economic regional cooperation and development policy.

3.5. ENVIRONMENTAL ISSUES

Preservation of groundwater quality and ecosystem biodiversity should be an important objective for sustainability. Environmental protection should be realistically based on Environmental Risk Analysis (ERA) rather than on some precautionary principles, which may not lead to any action. ERA is a general and very useful approach for studying risks related to over-use or pollution of water in sensitive areas.

The application of ERA consists of two main phases:

1. the assessment of risk, and
2. risk management.

4. Risk-Based Integrated Transboundary Aquifer Management (RITAM)

Sustainable management of transboundary groundwater resources should be based on current best practices, which are grouped under the term of Integrated Water Resources Management (IWRM). The term was first coined in 1977 at the UN Conference in Mar del Plata and according to the Global Water Partnership (GWP) - an NGO based in Stockholm - IWRM is defined as "a process which promotes the coordinated development and management of water, land and related resources to maximise the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems." According to IWRM, groundwater should be considered in relation to surface waters and should be studied at the river basin scale, which is the most appropriate unit of water management. Scientific-technical, environmental, economic and social issues should be taken into account, as explained in UNESO-ISARM's approach.

In what follows, the UNESCO-ISARM approach is formulated in terms of a risk-based multidisciplinary methodology called RITAM. For the integrated management of shared groundwater resources four important risk indices are defined: technical, environmental, economic and social. It is explained how under alternative socio-economic and climate scenarios, different modelling techniques or expert judgments may be used in order to quantify risks. Risk quantification is an important step for initiating the process of risk management and sustainable use of transboundary aquifer resources.

Furthermore, in Chapter 22, Risk-based Multicriterion Decision Analysis (RMCDA) is presented as a tool for risk management and conflict resolution in internationally shared groundwater resources.

4.1. DEFINITION OF THE ENGINEERING RISK

In a typical problem of technical failure under conditions of uncertainty, there are three main questions, which may be addressed in three successive steps:

1. When should the system fail?
2. How often is failure expected?
3. What are the likely consequences?

The first two steps are part of the uncertainty analysis of the system. The answer to question 1 is given by the formulation of a critical condition, producing the failure of the system. To find an adequate answer to question 2 it is necessary to consider the frequency or the likelihood of failure. This can be done by use of the probability calculus. Consequences from failure (question 3) may be accounted for in terms of economic losses or profits.

As explained in the book by Ganoulis (1994), a variable reflecting certain external conditions of stress or loading may be defined as *load* ℓ. There is also a characteristic variable describing the capacity of the system to overcome this external load. This system variable may be called *resistance* r. A *failure* or an *incident* occurs when the load exceeds this resistance, i.e.,

Failure or Incident: $\ell > r$

Otherwise we have:

Safety or Reliability: $\ell \leq r$

In a probabilistic framework, ℓ and r are taken as random or stochastic variables and the chance of failure occurring is defined as the *engineering risk*. In this case we have

Risk = *Probability of failure* = $P(\ell > r)$

This simple definition of engineering risk as the probability of exceeding a certain value of load is not unique (Duckstein and Plate, 1987). Generally speaking, risk is a complex function of the probability of failure and its consequences. In the literature the product of the probability and its consequences are often taken as the risk function. However, different risk indices may be found in the literature for describing economic and social risks.

4.2. TECHNICAL, ENVIRONMENTAL, ECONOMIC AND SOCIAL RISKS

The RITAM approach for transboundary groundwater resources planning and operation aims to reduce not only technical and economic but also environmental and social risks in order to achieve 4 main objectives (Fig. 7):

(1) Technical reliability, (2) Economic effectiveness, (3) Environmental safety, and (4) Social equity.

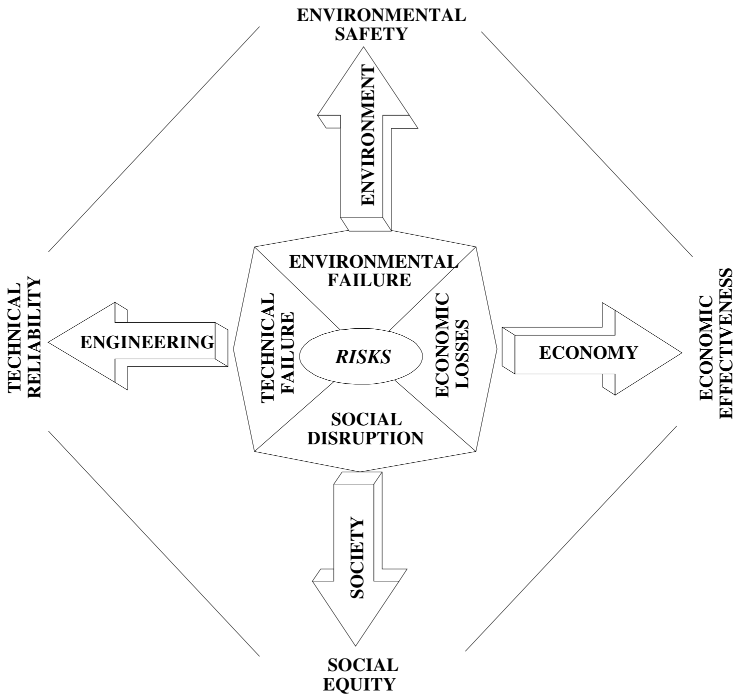


Figure 7. Technical, environmental, economic and social objectives for RITAM.

5. Risk Quantification in Aquifer Resources Management

Aquifer formations are complex hydrogeological systems with properties and hydrodynamic characteristics varying both in space and time. Any planning strategy for groundwater resources development and protection depends upon two main conditions:

1. the ability to predict the multiple risks and consequences from alternative strategies or operational policies under different socio-economic and climate scenaria and,

2. the ability to analyse and rank the reliability of various strategies or operational policies by use of multiple quantitative criteria.

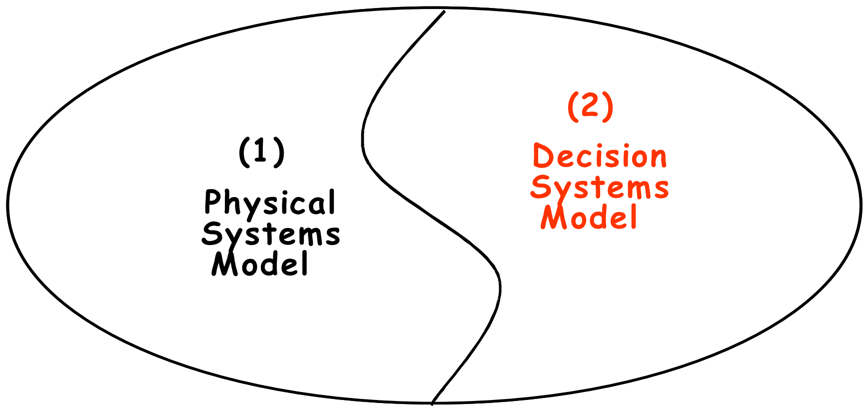


Figure 8. The duality of modelling physical and decision systems for RITAM.

As shown schematically in Fig.8, the previous two conditions reflect the duality of modelling the physical and decision-making or societal parts of the process. In fact, the first condition may be fulfilled through various modelling techniques of groundwater flows, environmental impacts (like groundwater pollution and ecosystem analysis) and also modelling socio-economic risks. The second condition may be based on different decision analysis tools using multiple criteria under risk. Although important progress has been made in developing sophisticated modelling techniques, final judgments are actually based on experts' opinions or intuitive political considerations. However, physical modelling, optimisation and application of risk and reliability techniques may be found to be useful tools for decision makers.

5.1. MODELLING GROUNDWATER FLOW

For groundwater hydrodynamics, conceptual models were developed as idealisations of natural aquifer systems (form, areal extension, physical properties of the aquifers) and their constituent processes (flow conditions, boundary conditions). Vertically integrated equations are usually used to represent flow in regional aquifers. These equations are obtained in the horizontal plane x-y by application of two basic laws:

- the law of mass conservation and
- Darcy's law

Introducing the *piezometric head* or *hydraulic head* h as the sum of the *pressure head* p/ρg and the *elevation* z, i.e. h = p/(ρg)+z and using the definition of the storage coefficient S, (Ganoulis, 1994) the general mass balance differential equation for confined or unconfined groundwater flow takes the following form:

$$S(\frac{\partial h}{\partial t}) = \nabla(KC\nabla h) - \sum_i q_i \delta_i \qquad (1)$$

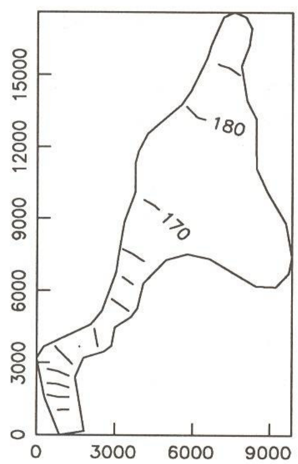
where K is Darcy's permeability coefficient
C=h for unconfined aquifer or C=b=thickness of a confined aquifer
qi > 0 for pumping wells (in m3/s/m2)
qi < 0 for recharging wells (in m3/s/m2)
and δi is the Dirac delta function for point i.

For modelling groundwater flows in regional aquifers, several analytical methods, finite difference and finite element numerical algorithms and, more recently, stochastic approaches of various levels of sophistication have been developed. These techniques for simulating the aquifer's hydrodynamics have been validated using physical models in the laboratory and in-situ measurements in real, relatively homogeneous aquifers of limited extent.

The results of a numerical simulation representing the distribution of the water table elevation of the Gallikos Aquifer in two and three dimensions are given in Fig. 9.. This is an almost homogeneous, unconfined alluvial aquifer, located near the River Axios in Macedonia, Greece, which partly supplies the city of Thessaloniki with water (Ganoulis, 1994).

Because of the natural variability in space and time, the main problem for evaluating risks in groundwater flow and aquifer contamination is the fact that physical parameters and variables of the aquifer show random deviations in space. To this randomness, one must add various other uncertainties due to the scarcity of the information concerning the inputs (flow rates and pollutant loads), the value of parameters (measurement and sampling uncertainties) and also the imperfection of models (modelling uncertainties).

The natural variability of aquifer parameters and uncertainties in boundary conditions can be simulated using stochastic modelling and fuzzy logic approximation techniques (Ganoulis, 1994). In fact, during the last years, there has been an increasing number of publications on the application of stochastic and fuzzy logic-based methods to groundwater flow in aquifers. This indicates that more and more scientists are engaged in this area and the stochastic modelling and management of groundwater resources is an active subject of research.



(a)

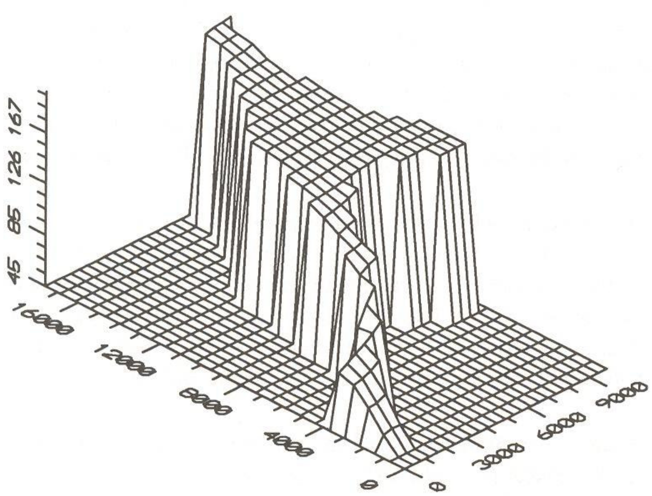


Figure 9. Modelling the water table elevation of the Gallikos aquifer (in metres).

5.2. MODELLING GROUNDWATER POLLUTION

For conservative pollutants, such as saline waters, this interaction is negligible and for regional 2-D groundwater flows, the following dispersive convection equation may be used

$$\frac{\partial C}{\partial t} + u\frac{\partial C}{\partial x} + v\frac{\partial C}{\partial y} = D_x \frac{\partial^2 C}{\partial x^2} + D_y \frac{\partial^2 C}{\partial y^2} \qquad (2)$$

where

C(x, y, t) is the pollutant concentration (M/L^3)
u(x,y,t), v(x,y,t) are the groundwater velocity components (L/T)
Dx, Dy :are the dispersion coefficients (L^2/T)

In fact, equation (2) is a random partial differential equation. The causes of randomness and variability are (i) the random variation of the velocity components (u, v) owing to the spatial variability of the aquifer parameters (porosity, permeability), and (ii) the variation of the dispersion coefficient D as a result of the random fluctuations of the velocity components. In general, stochastic simulation and risk analysis techniques can be used to quantify the effect of various uncertainties in the dispersion process (Ganoulis, 1994).

Several particle-oriented models in hydrological applications have been developed in the past (Bear and Verruijt, 1992). It seems that particle methods based on random walks are more flexible and easier to use and lead to relatively accurate results.

Consider at time t=n Δt a large number of particles N located at the positions

$$\vec{r}_{n,p} = (x_{n,p}, y_{n,p}) \qquad p = 1, 2, ..., N \qquad (3)$$

According to the random walk principle the probability of finding a particle at a given position after time Δt follows a Gaussian law of mean value 0 and variance $s^2=2\Delta tD$, where D is the dispersion coefficient. The particles move from time t=nΔt to time t+Δt=(n+1)Δt according to the relations

$$x_{n+1,p} = x_{n,p} + u\Delta t + \xi \qquad (4)$$

$$y_{n+1,p} = y_{n,p} + v\Delta t + \eta \qquad (5)$$

where u, v are the velocity components and ξ, η random variables following a normal distribution of mean value 0 and variance $s^2=2\Delta tD$.

This is illustrated in the case of the Gallikos aquifer, where vulnerability of the groundwater from pollutant sources has been investigated using random walks. Introducing the corresponding velocity field, the groundwater pollution from a point source is obtained, as shown in Fig. 10.

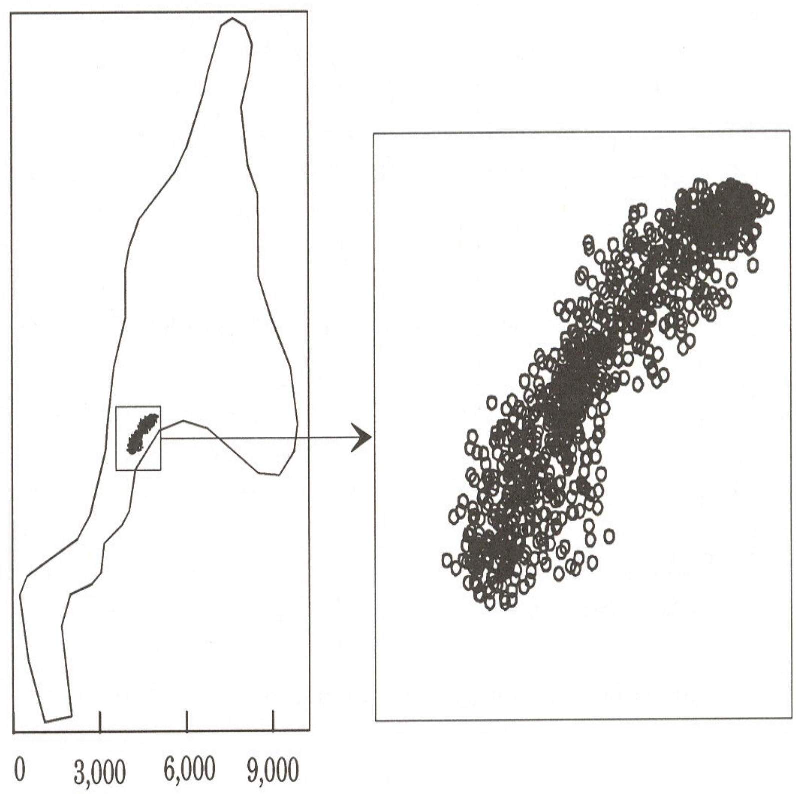


Figure 10. Random walk simulation in the Gallikos Aquifer (dimensions are in meters).

6. Conclusions

Risk-based Integrated Transboundary Aquifer Management (RITAM) methodology is proposed in order to integrate multiple risk indices into a multi-objective planning and decision-making process for sustainable transboundary groundwater use. Modelling techniques or expert judgments may be used to evaluate not only technical reliability and cost effectiveness but also environmental safety and social equity.

In order to achieve sustainability of transboundary aquifer resources, multiple risk indices are defined, such as technical, environmental, economic and social. These are used in Chapter 22 in order to rank alternative strategies for transboundary groundwater resources management and conflict resolution.

Using particle tracking and random walks, the risk quantification methodology is illustrated for evaluating risk of groundwater pollution in the Gallikos Aquifer, Macedonia, Greece.

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