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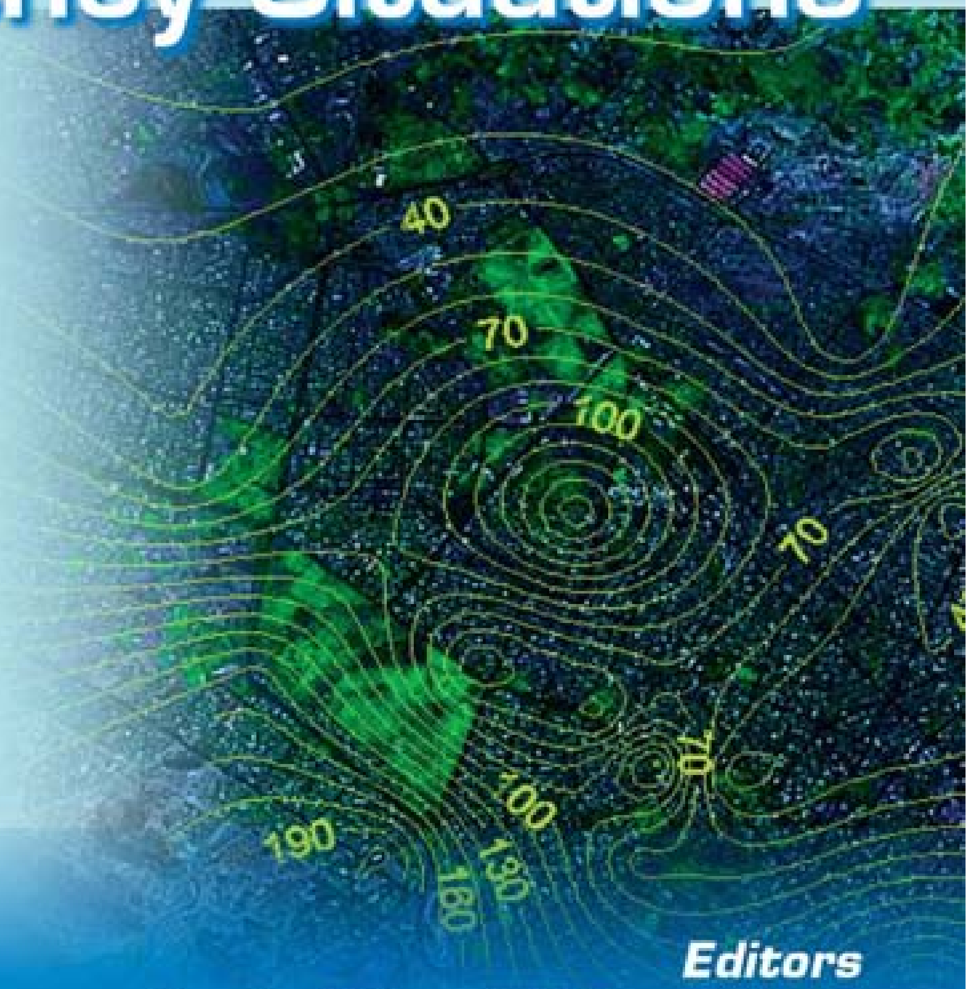
Groundwater for Emergency Situations



Editors
Jaroslav Vrba and Ali Reza Salamat

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FOREWORD

During the 15th session of the Intergovernmental Council of the International Hydrological Programme (IHP) the project 'Groundwater for Emergency Situations (GWES) was approved and included in the Implementation Plan of the Sixth Phase of the IHP (2002–2007) under the title 'Identification and management of strategic groundwater bodies to be used for emergency situations as a result of extreme events or in case of conflicts'.

The aim of the GWES project is 1/ to consider extreme events (natural and man-induced) that could adversely influence human health and life, 2/ to support countries repeatedly affected by such events in the setting up of emergency plans and mitigation schemes to secure drinking water supply, and 3/ to identify in advance potential safe groundwater resources which could temporarily replace damaged water supply systems. The results of this project will allow countries to minimize the dependence of threatened population on vulnerable drinking water supplies.

Groundwater bodies are naturally less vulnerable and more resistant than surface waters to external impact. Deep aquifers naturally protected from the earth surface by geological environment should be therefore, identified and evaluated. These groundwater bodies should be protected and adequately managed in order to substitute affected drinking water supplies and eliminate the consequences of drinking water scarcity for the time after the catastrophic events. The Tsunami disaster on December 26, 2004 has demonstrate that it is of utmost importance to find appropriate local safe drinking water resources that could be used immediately. The project also provide advice about the water supply related reconstruction activities and mitigation measures that have to undertaken by the affected countries.

The following are the main objectives of the GWES project:

- to elaborate effective methodologies for determining groundwater resources safe against extreme and catastrophic events (floods, droughts, earthquakes, tsunami, volcanic activities landslides, storms, pollution accidents);
- to organize workshops and seminars and to provide training in these fields;
- to introduce effective techniques into the investigation of such groundwater resources;
- to elaborate an inventory of resistant aquifers in selected pilot regions and present case studies of the participating countries;
- to publish guidelines for identification, investigation and management of strategic groundwater bodies to be used for emergency situations resulting from extreme climatic or geological events and in case of conflicts.

The International Workshop on Groundwater for Emergency situation held in Tehran, Islamic republic of Iran from 29 to 31 October 2006, organized by Regional Centre on Urban Water Management-Tehran (RCUWM-Tehran) and by UNESCO Tehran Cluster Office and supported by UNESCO Secretariat of International Hydrological Programme – Paris, France, is part of GWES project objectives related to the workshops and seminars focused on safe groundwater resources in areas affected by specific natural disasters. In case of Tehran International Workshop presented papers and discussions were focused on methodologies for investigation, planning and risk management of groundwater resources during drought and floods. 34 experts from 10 countries participated in the workshop.

Mr Abdin Salih, Director of UNESCO Tehran Cluster Office and Mr Reza Ardakanian, Director of RCUWM - Tehran both in the opening speeches emphasized the importance of groundwater resources for social and economic development of the Cluster countries. They also pointed out the importance of GWES International Workshop and the role of groundwater, as a emergency source of water in West Central Asia region repeatedly affected by natural disasters, particularly by droughts, floods and earthquakes.

J. Vrba, coordinator of GWES project, in the key note speech presented GWES project aim and objectives and informed about the main outcomes from GWES Framework Document. Background papers focused on drought and floods have been prepared by B. Verhagen (Republic of South Africa) and J. Silar (The Czech Republic). Groundwater management in areas affected by floods was discussed in the papers of T. Sommer (Germany) and S. Nairizi (Iran). Papers focused on groundwater resources management in areas affected by droughts have been presented by L. Wenpeng (China), H. Kazemi (Iran), Semsar Yazdi and L. Khaneiky (Iran), M. Janparvar and S. Nairizi (Iran). Contributions on risk and crisis management of groundwater resources discussed A.K. Sinha (India) and H.R. Jahani (Iran). On comprehensive discussions participated all workshop participants.

The GWES International Workshop and the topics discussed in that forum have provided significant support to the methodology of investigation, management and risk mitigation of groundwater resources in the West Central Asia region often affected by droughts and floods. Appreciation and thanks are expressed to the Iranian Water Research Institute which hosted the GWES International Workshop, particularly to Mr F. Yazdandoost, president of this institute and to Mr A.R. Salamat, from the organizing committee of the GWES workshop.

Alice Aureli
Responsible for Groundwater Resources Activities
Secretariat of the International Hydrological Programme
Division of Water Sciences, UNESCO, Paris

Jaroslav Vrba
Coordinator of the GWES project
UNESCO Consultant

PREFACE

Attention to sustainable groundwater management for supplying human needs is one of the most important components of RCUWM-Tehran activities.

It is worth mentioning that, in most of the parts of this region which cover RCUWM activities, groundwater is the only main resource of supplying water. In some countries almost 100 percent of the renewable water resources consist of groundwater. Therefore, it is apparent that, promotion of groundwater management in such a region with the above-mentioned characteristics gains a high priority due to the Centre's missions and objectives.

In addition to water scarcity, our region suffers from water disasters such as floods and droughts which is mainly accompanied by high frequency and intensity. These factors create severe financial and surviving losses for the governments and the inhabitants of the region.

In addition to the afore-mentioned phenomena, earthquakes and the critical conditions which normally occur after these disasters in the region, is another important challenge our region faces. Therefore supplying safe and hygienic potable water is one of the most important factors to be considered in such conditions.

From the other hand, climate change and its impacts on water resources in the region is another challenge. Although no systematic study has been carried out to assess climate change impacts in arid and semi-arid regions in the Middle East and North Africa (MENA), few investigations carried out demonstrate that there is no hopeful perspective due to climate change in the region. It seems that conditions will get worse in near future.

In this concern, the Regional Centre on Urban Water Management – Tehran as a regional entity has tried to attract the attention of the world society, governments as well as international and national governmental and non-governmental organizations toward the importance and high sensitivity of groundwater management, particularly in the period of extreme phenomena, such as droughts, earthquakes and floods.

By reviewing the centre's activities in the past few years, one can realize the Centre's focus in this concern. The 'International Workshop on Groundwater for Emergency Situations', which was held by the Regional Centre on Urban Water Management – Tehran in close cooperation with the International Hydrological Programme (IHP) of UNESCO and UNESCO Tehran Cluster Office in Tehran, 29–31 October 2006 was one of the important activities.

This proceeding is a compilation of articles presented in this event and it reflects the efforts taken. Apparently this international event would not have been successfully organized without Mr Jaroslav Vrba's contribution as the GWES project coordinator. Special thanks to Mr Vrba for his outstanding contribution. My sincere thanks is extended to Mrs. Alice Aureli, from the IHP Secretariat who has had a significant role in organizing this event on behalf of UNESCO-IHP.

I would also like to deeply thank Dr. Abdin Salih, the former Director of UNESCO Tehran

Cluster Office as an eminent expert who has gone out of his way during his mission to promote relevant water activities in the region. Thanks to Dr. Yazdandoost, as the president of Water Research Centre for hosting this event.

Finally, I would like to announce that our region's needs for implementing such activities and organizing similar events as well as carrying out research and studying projects is increasingly high. Therefore, I would like to ask those interested, to review this publication and update us with their view points and proposals, for being considered in our forthcoming events.

Reza Ardakanian
Founding Director, RCUWM- Tehran

OPENING ADDRESSES

Distinguished participants

Ladies and gentlemen,

I am honoured to be here in Tehran this morning to address you on behalf of the Director General of UNESCO, Mr Kochiro Matsuura, on my own behalf as the representative of UNESCO in the Islamic Republic of Iran and on behalf of my colleagues in the International Hydrological Programme (IHP) of UNESCO, on the occasion of the International Workshop on 'Groundwater for Emergency Situations (GWES)' which will come out with Methodologies for Investigation, Planning and Risk Management on Groundwater Resources during Drought, Flood and Earthquake. I am indeed pleased to convey UNESCO's warm greetings to the participants, the organizers and the distinguished invited guests attending the event.

In this occasion, I would like to express my profound gratitude to the Government of the I.R. of Iran and the Regional Centre on Urban Water Management for taking the initiative of organizing this very important event which is in fact the first International Activity of the GWES Project. I must also take this opportunity to express my great appreciations to the Government of the Islamic Republic of Iran for the successful cooperation that exists between Iran and UNESCO in all areas of its mandate, particularly in the field of Water and its Related Ecosystems as themain principal priority of the Science Sector of UNESCO.

It is my pleasure to welcome and thank all the Resource Persons and participants who have come together for the first time to share their knowledge on Groundwater during Emergency Situations. Your valuable inputs will help to make the project relevant and responsive to the Global needs.

Ladies and gentlemen,

Today, we open a major International Workshop, which is part of the activities of the sixth phase of the International Hydrological Programme (IHP) that started at the beginning of 2002 and will end by 2007. The aim of the IHP VI project entitled 'Identification and Management of Strategic Groundwater Bodies to be used for Emergency Situations as a Result of Extreme Hydrological Events or in Case of Conflicts (GWES)' is to identify ground water resources to be mobilized fastly to improve safe drinking water supply after natural disasters to the affected population. The climatic (floods and droughts) and geological (earthquakes, landslides, volcanic activities and as well as tsunami events as experienced in 2004) disasters in many regions of the world often generate serious emergency situation to secure safe drinking water supply to the needy population. The conventional water supply systems in such catastrophes would usually collapse and could take weeks or even months to restore. Apart from rescuing of the endangered population, securing access to safe drinking water becomes the most urgent among the emergency activities immediately needed after a natural disaster. Transporting clean water in tankers to the affected regions, importing water in bottles to prevent infections diseases – such measures are expensive and take time to implement and serve only as temporally measures.

Drinking water supply is a priority in emergency activities immediately after a natural disaster. Considering that the water supply infrastructure is normally wiped out in many places during disaster situation, UNESCO SC/HYD has initiated together with the International Groundwater Resources Assessment Centre (IGRAC) the establishment of an inventory on the effects of natural disasters on the local aquifer systems in areas repeatedly affected by natural disasters. This inventory will provide valuable information on the availabilities of groundwater resources that are secured from flooding and other natural impacts that leads to the spreading of pollutants from liquid and solid wastes, particularly organic chemicals. This inventory will also provide advice on the groundwater related restoration activities that have to be undertaken and the measures that must be applied to prepare future emergency plans. A network of water related regional institutions have to be identified to facilitate expert missions to visit the affected countries and work closely with them to achieve the goals as quickly as possible.

The GWES Project is implemented by an International Working Group composed of experts from UNESCO, IAH, IGRAC and others. The activities and objectives of the GWES project were formulated at the first meeting of the Working Group held in UNESCO, Paris during February 2004. The second meeting of a Working Group took place at the UNESCO New Delhi Office in India during April 2005. And today the first International Workshop is being launched in Tehran taking into consideration the specific climatic and geological hazardous events of this region.

Ladies and gentlemen,

Over some 40 years, the IHP and IHD of UNESCO has greatly contributed to the development of groundwater science and applied research, providing a bridge between advances in the developed world and demands from the developing countries. A holistic approach to water resources planning, policy and management constitutes a priority for the current IHP VI programme (2002–2007) 'Water Interactions: Systems at Risks and Social Challenges'. The program deals with the various aspects of integrated surface and groundwater resources management through a multi-disciplinary concept covering a wide spectrum of related social, economic and ecological aspects.

Over the years, UNESCO IHP has developed a strong groundwater programme with a variety of initiatives, projects and outputs. Among others, UNESCO has produced a considerable quantity of manuals, guidelines, proceedings, publications and training materials on groundwater. Some of the IHP's most recent projects on groundwater are related to the compilation of the world wide inventory of the aquifer systems shared by two or more countries (ISARM project) and development of Groundwater Indicators for Sustainable Development.

As a specialised UN agency, currently UNESCO is developing a substantive portfolio of projects that are being submitted to the Global Environment Facility for co-funding. In this and other GWES initiations, I must applaud the efforts of our colleague Ms Alice Aureli who was supposed to be with us here if not for very urgent case.

Ladies and gentlemen,

Before I end my address, I must take this opportunity to thank, on behalf of UNESCO, the Regional Centre on Urban Water Management, particularly its Director, Dr Ardakanian, and their wonderful team for a job well done. I must also thank the Water Research Centre for providing these facilities. Last, but certainly not least, my appreciation and thanks extend to all of you, the participants and the honourable guests.

In closing, I would like to extend to each and every one of you my best wishes for a fruitful exchange. I look forward to interesting discussions and recommendations over the three days Workshop.

Abdin Salih
Director & Representative
UNESCO Tehran Cluster Office

Dear Participants,

Distinguished Guests,

Ladies and Gentlemen:

It is my pleasure as the Director of the Regional Centre on Urban Water Management - Tehran under the auspices of UNESCO to participate and deliver a speech in this important event which is one of the most fundamental challenges of Water Resources Management, i.e., 'Groundwater for Emergency Situations'. This workshop has been organized by the Regional Center on Urban Water Management (RCUWM-Tehran), in close cooperation with UNESCO within the framework of the approved plans of the Fourth Governing Board Meeting, held in Tehran, Iran, 13 May 2006.

I would first like to express my profound gratitude to UNESCO for co-organizing this international event, especially Dr. Abdin Salih, as the Director of UNESCO Tehran Cluster Office, for all his supports toward the activities carried out by the Centre.

I believe that participation of managers, experts and decision makers of around 10 regional countries and other parts of the world in this event indicates the strong will of the governments and non-governmental organizations to cooperate with each other in different aspects and dimensions of groundwater management in this critical period of world water management history, in the framework of regional institutions such as the Regional Center on Urban Water Management (RCUWM-Tehran). I consider this event as a fruitful gathering and I intend presenting the achievements of this event in the next Governing Board Meeting of the Center requesting the Governing Board members to support the activities due to development and promotion of cooperation between regional countries to settle different problems of groundwater management, and adopt appropriate policies and plans.

Ladies and Gentlemen,

Certainly participants of this important event are aware that potable water demands in most parts of urban and rural regions worldwide, specifically in arid and semi-arid areas depends on groundwater resources. For instance in a big city like Tehran in spite of three large dams for providing potable water, 40 percent of this demand in normal situations still depends on groundwater. Any disorders due to emergency situations can lead to great social problems and risks.

To confront this challenge some predefined programs according to each region's characteristics and specifications should be prepared, as in emergency situations there will be time limitations to perform required actions. Compiling necessary methodologies by considering different scenarios and suggesting executive methods is one of the main purposes of this event. It's expected that by adding up theoretical ideas and experiences we can provide appropriate guidelines for decision makers, managers, experts and involved organizations. Certainly preparing appropriate and executive programs needs an extensive vision, which surely will be submitted throughout the presentations and discussions made during the workshop.

Indeed emergency situations management focusing on risk management requires capacity building and RCUWM as a regional entity is playing a vital role in this concern.

Ladies and Gentlemen,

At this stage, I would like to brief you on the Regional Centre on Urban Water Management, under the auspices of UNESCO, to have a glance at the background establishment procedure and its current activities at hand.

The Centre was inaugurated officially in Feb. 2002 with the presence of the General Director of UNESCO in I.R. Iran within the framework of a ceremony during which, an agreement between the I.R. Iran and UNESCO was signed and the Centre started working officially as one of the second type regional Centres under the auspices of UNESCO.

The mission of the Centre is transferring applicable scientific knowledge and increasing capacities in all cases and dimensions of urban water management in order to promote sustainable development and undertake activities in this field in order to enhance human welfare in the region.

The Centre is run by the Governing Board which enjoys the highest rank in decision making. At the moment the Governing Board includes 10 member countries namely, Afghanistan, Bangladesh, Germany, Iran, India, Kuwait, Lebanon, Oman, Syria and Tajikistan at the Ministerial level and governmental and non-governmental organizations including, UNESCO, International Water Association, The International Water Academy and Wageningen University. It is worth noting that the Republic of Yemen is amongst the countries at the ministerial level, of which its membership process is under its way. We will hopefully receive the approval of the Director General of UNESCO, shortly.

RCUWM – Tehran since its establishment (2003) managed to put a considerable number of studying projects, training workshops as well as technical and scientific seminars in its curriculum while it was being supported incrementally on behalf of some of the International Organizations and the I.R. Iran's Government.

It's my honor to inform you that so far around 2,000 persons / day (experts, university professors and decision makers) have participated in the Centre's Technical and Training events, which we believe is a significant number since the Centre's official inauguration.

The responsibility of some important projects have been left to this Centre including Afghanistan reconstruction projects in the water sector, which have been assigned on behalf of the I.R. Iran Government to the Centre as the Government's focal point.

We are organizing the following events to be held with our partners in near future.

- The 'Expert Group Meeting on Municipal Wastewater Reuse for Irrigation', This workshop will be held by RCUWM – Tehran in close cooperation with Wageningen University and Research Centre and the Water and Environmental Centre, affiliated to the University of Sana'a – Yemen, next week from 4–7 November 2006 in Sana'a' (Yemen). Several national, regional and international resource persons will present their new findings on:

    - Wastewater flows: Collection and treatment
    - Wastewater use: Management, health and productive value
    - Sustainability: Long term environmental effects

- International Conference on 'Water Resources Management in Islamic Countries', 19–20 February 2007. This event will be organized by RCUWM – Tehran, Islamic Educational, Scientific and Cultural Organization (ISESCO), UNESCO and the Water and Power University of Technology, affiliated to the Ministry of Energy, I.R. Iran.

- Regional Workshop on 'Women's Participation in Water Management' (date and place will be determined in near future)

Apparently, it is not possible to elaborate on the above-mentioned projects in my speech, but my colleagues will present the required documents to the participants for further information.

Ladies and Gentlemen,

I would like to thank Dr. Farhad Yazdandoost, as the president of the Water Research Institute, affiliated to the Ministry of Energy, I.R. Iran for providing the venue and its facilities.

I would like to deeply appreciate the sincere supports and efforts of my dear brother, Dr. Abdin Salih, Director of UNESCO Cluster Office and his colleagues who are the co-organizers of this workshop, Dr. Vrba as UNESCO Consultant along with his wonderful team who will serve as the International resource persons of this event and all the participants who promoted the scientific quality of this meeting. I would also like to thank my colleagues in the Regional Center on Water Resources Management (RCUWM-Tehran) for their taintless efforts in holding this significant event.

Last but certainly not least, I would like to thank the participants of this event who have traveled from all over the world.

I hope to meet you all in other organized events on behalf of RCUWM-Tehran, particularly the 'International Conference on Water Management in the Islamic Countries' which will be held in Tehran, Iran, 19–20 February 2007.

Reza Ardakanian
Director, RCUWM – Tehran

CONTENTS

GROUNDWATER FOR EMERGENCY SITUATIONS – UNESCO-IHP VI PROJECT

Jaroslav Vrba[1]

Abstract: The project Groundwater for Emergency Situations (GWES) is part of the activities of the International Hydrological Programme (IHP), sixth phase (2002 – 2007), Theme 2 'Integrated Watershed and Aquifer Dynamics'. The GWES project is implemented by an International Working Group composed mainly by experts from UNESCO, IAH, IAEA and IGRAC. The aim of the GWES project is to consider natural and man induced catastrophic events that could adversely influence human health and life and to identify potential safe, low vulnerability groundwater resources which could temporarily replace damaged water supply systems. This requires a special approach to the methods of groundwater resources investigation and development and formulation of risk management plans and risk mitigation policy with the objective of providing crucial first aid in the drinking water services to the affected population. This paper is a summary of the GWES Framework Document prepared by the experts of the above mentioned International Working Group and published by UNESCO in the year 2006.

Introduction

Immediately after physically securing an endangered population, the first priority of aid workers following a disaster is the distribution of drinking water. Such emergency situations are reported from many parts of the world following floods, droughts, rain-induced landslides, earthquakes, tsunami, pollution accidents and other extreme events. It is often difficult to organise a replacement water supply when regular water systems are compromised, damaged or even destroyed by natural or man-made disasters. Their restoration may take months or even years. Transporting water in tankers to the affected regions to prevent epidemics, importing large quantities of bottled water – such measures take time to implement, they are expensive and only temporary solutions. Groundwater resources, proven safe and protected by the physical environment, with

1. Dr. Jaroslav Vrba, Coordinator of GWES project, Chairman of Groundwater Protection Commission of the International Association of Hydrogeologists, Korandova street 32, 14700 Prague 4, The Czech Republic, Phone/Fax: 420 241727447, Email: javr@mymail.cz

long residence times and the necessary infrastructure for their exploitation, would provide populations with timeous replacement of vulnerable water supply systems and make rescue activities more rapid and effective. Such resources have to be identified and investigated, as a substitute for affected drinking water supplies thereby eliminating or reducing the impact of their failure following catastrophic events. Development of such policy and strategy for human security – both long term and short term – is therefore needed to decrease the vulnerability of populations threatened by extreme events particularly in areas such as flood plains, coastal areas, mountain slopes and arid zones. A very important aspect of GWES in drawing the attention of governments, organizations, and individuals to the concept of preparedness for establishing alternative emergency drinking water supplies, is empowerment, based particularly on local community knowledge and activities.

Groundwater as an emergency resource

A large part of the earth's surface is arid and suffers from scarcity of water resources, as well as the possible threat of floods. Thus humanity developed an awareness of water as the most important component of the biosphere, as both a danger and an indispensable part of the environment, a valuable commodity and very often a strategic resource for social and economic development.

This awareness of the ambiguous role of water varies according to local and temporal circumstances. Arid areas such as the Middle East and North Africa, notorious for scarcity of drinking water resources, experience flash floods which have caused considerable damage to lives and property. The rise and fall of historical cultures of the Middle East were often driven by their ability to manage water, its supply and use in irrigation. This remains true right into modern times, and influences recent political and social activities in various parts of the world.

Natural water resources are generally renewable. Groundwater renewability must be considered in terms of recharge, discharge and residence time. Each of these terms should be taken into account when studying groundwater regime on a regional scale and/or on geological time scales. Increasing rates of extraction of groundwater for human consumption, agriculture and industry, tends to overexploitation of resources in many parts of the world. The balance between recharge and discharge is disturbed and groundwater levels in vast regions are declining. Sustainable development and management of groundwater resources is advocated in order to counteract this trend.

However, in emergency situations where human lives are at stake and drinking water supply systems are compromised, this policy of sustainability cannot strictly be adhered to. In such cases, renewability becomes a secondary consideration and groundwater from deep resistant aquifers or even non-renewable 'fossil' water bodies need to be addressed and tested for providing adequate yields. Such an emergency supply should not be seen as a substitute for a regular resource. It should be earmarked for, and exploited only during emergencies – until the regular water supply system can be restored and re-activated both in quantity and quality.

Risk water management during an emergency often finds groundwater supply initiatives poorly prepared to prospect for and develop alternative emergency resources – even where groundwater is readily accessible locally. Such an effort can be successful only if it is based on the availability of results of a systematic hydrogeological investigation, of monitoring and mapping of groundwater resources, often employing supportive techniques like isotope hydrology, geophysics, remote sensing and others.

The key to selecting a strategy for resuscitating regular water supplies during or following catastrophic events is the knowledge of regional hydrogeological circumstances. In many areas it will be difficult or impossible to provide emergency supplies from completely separate groundwater systems. In such cases, the existing supply system and aquifer would have been thoroughly investigated i.t.o. temporary extensive exploitation to tide over the emergency. Governmental and municipal authorities, civil defence and the army should know where such groundwater resources are available in the areas repeatedly affected by, and prone to, natural hazards. A timely investigation and community participation are essential in developing the emergency infrastructure that will function successfully in case of emergency.

'Out of sight, out of mind' is a common attitude, and 'if there was a one-hundred-year flood/drought last year, we may be safe for the next 99 years'. A catastrophic event should be seen rather as a warning that should stimulate the public and the authorities alike to prepare water supply systems and strategies for exceptional circumstances.

Summing up: know your local hydrogeology, not only in terms of where groundwater circulates of but also where it stagnates and yet can produce adequate, short-term yields with acceptable quality; and adjust your thinking beyond the traditional approach to hydrogeological investigation and the conventional appraisal of groundwater resources.

Groundwater: a hidden part of the hydrogeological cycle

Groundwater portion in freshwater volume without glaciers and ice is more than 96% and amounts to about 8,300,000 km^3. In terms of volume stored, there is approximately one hundred times more groundwater than surface water stored on the globe (FAO, 2004). Large non-renewable ground water resources (about 1,500,000 km^3) were created mainly during Pleistocene climatic periods. Today a global withdrawal of 600 – 700 km^3 /year makes groundwater the world's most extracted row material. Globally more than 2,000 million people depend on ground water resources. About 60% of groundwater withdrawn is used in agriculture; the rest is almost equally divided between domestic and industrial sectors. Groundwater is the only safe source of drinking water in arid regions and deep aquifers are resistant to droughts, floods, tsunami and other natural hazards. Groundwater is a great facilitator for social and economic development: 70% of EU drinking water supplies and 80% or rural water supplies in Sub-Saharan Africa depend on groundwater. In India groundwater supplies about 80% of rural population and 70% of Indian agricultural production is supported by groundwater.

The distribution of recharge to groundwater resources is uneven across the latitudes, controlled by climate belts, ocean/atmosphere interactions, vegetation as well as physiographic and orographic conditions. Recharge occurs

- in desert regions (Verhagen et al., 1979), though highly irregular in time and space, and at very low rates (<5 mm/a);

- in semi-arid and tropical regions with major annual fluctuations and a ranges from less than 30 mm/a to some150 mm/a;

- in humid regions at an average of less than 300 mm/a;

- even through permafrost, albeit minimal, as shown by Michel & Fritz (1978).

The distribution of groundwater recharge is also uneven vertically, enhanced by differing hydraulic properties of the aquifer system. Numerical modelling for typical sequences of hydraulic conductivities in aquifer systems shows that on average more than 85% of the recharged groundwater discharges through near-surface (active recharge zone), and less than 15% through deep aquifers (passive recharge zone) (Seiler & Lindner, 1995). Both of these generalised recharge zones in turn overly connate water and are encountered in all continents, climate zones and rock types.

Groundwater in the active recharge zone is young (<50 years), quite susceptible to contaminants and reaches steady state conditions fairly rapidly if extraction does not exceed groundwater recharge. In the passive recharge zone groundwater is always older (>100 years), the longer time scales ensuring better protection against contaminants, provided that groundwater management takes account of depth related groundwater recharge; otherwise a transient hydraulic response may last decades or hundreds of years. This delayed mass transfer can be monitored through early warning systems. In the passive recharge zone groundwater could be more mineralised (higher ionic concentration) than in the active recharge zone, and sometimes is characterized by rare dissolved elements (e.g. As, I, F), because of high mean turn-over times, resulting in slower leaching than in the active recharge zone.

Groundwater resources integrated and risk management

Integrated Water Resources Management (IWRM) is based on holistic approach, reflects the social and economic value of surface water and groundwater and the integrity of terrestrial and aquatic ecosystems, includes both quantitative and qualitative attributes of water resources, is linked to land use planning and practices, attentive to cultural and historical traditions of the society and based on participatory approach, involving planners, policy and decision makers, managers, water stakeholders, local communities, and general public. IWMR vary in different social and economic conditions, however, its basic principles, efficiency and environmental sustainability are invariable. Lack of appropriate governance, coordination of management activities, protection policy institutional and technical capacities, cost-effectiveness of water investments and public and local community involvements, are the main obstacles in IWRM implementation.

Groundwater resources risk management. In emergency situations the policy of sustainability cannot be strictly implemented. Aquifers resistant to natural hazards, if available in the affected region, can be temporary overexploited to tide over the emergency until the regular water supply systems can be restored and reactivated both in quantity and quality. Identification of such aquifers requires the knowledge of regional circumstances and risk analysis with respect to their occurrence, accessibility, productivity, quality, vulnerability and resistance to the impact of natural disasters. A timely investigation, mapping, early warning monitoring, community participation and legal framework are essential attributes in developing groundwater emergency policy and implementation of risk management of groundwater resources safe to natural disasters. Such resources substitute affected water supplies, eliminate or reduce the impact of their failure following catastrophic events and make rescue and response activities more rapid and effective.

According to the terminology adopted by UN International Strategy for Disaster Reduction (ISDR) risk management is defined as the systematic application of management policies, procedures and practices that seek to minimize disaster risk at all levels and locations in a given society. The risk management framework need to include legal provisions defining the responsibilities for disaster damage and long-term social impacts.

Natural hazardous events tend to be recurrent. Thus it is important to determine from the historical records the frequency of hazardous events of a given magnitude in a particular period of time, which facilitates the estimation of recurrence interval. Catastrophic events causing the greatest havoc are much less frequent than events with lesser impact. Another important aspect is that certain regions of the globe are more susceptible than others to geologic or climatic hazards. Thus it become imperative in water risk management to delineate risk zones for climatic and geological hazards in each country or region.

Aquifers vulnerability to natural hazards and human impacts

The following types of aquifers are vulnerable to natural hazards and human impacts:

Shallow uppermost unconfined aquifers mainly in unconsolidated fluvial and glacial deposits overlain by permeable unsaturated zone of low thickness (less than 10 m), characterized by young groundwater and single flow system and interface with surface water.

Deeper unconfined aquifers in consolidated rocks (particularly sandstones) of regional extent, overlain by permeable unsaturated zone of variable thickness; consist usually by a number of laterally and vertically interconnected groundwater flow systems of appreciable dual porosity and permeability.

Karstic aquifers in carbonate rocks with groundwater flow in conduits, large open fissures and openings along bedding plates; typically with high groundwater flow velocities (hundreds m/ per day) and secondary permeability; springs are important phenomena of groundwater karstic regime.

Coastal aquifers – in natural conditions seawater intrusion into coastal aquifers is controlled by tidal fluctuations, stream flow changes, gradient and volume of groundwater flow towards the seashore and geological environment. Human impact (groundwater pumping) influence significantly on groundwater – seawater interface.

Recharge areas of all type of aquifers.

The following types of aquifers are resistant to natural hazards and human impacts:

Deep confined aquifers or aquifer systems mostly in sedimentary rocks overlain by thick low permeable or impermeable unsaturated zone with entirely modern recharge which may last hundreds or thousands of years.

Deep mostly confined aquifers with non-renewable groundwater overlain by thick low permeable or impermeable unsaturated zone. Groundwater originated in geological past and is not part of the recent hydrological cycle. Low intensity of groundwater circulation, very limited aquifer replenishment and very large aquifer storage are typical characteristics of non-renewable groundwater resources. A possible limited criterion for non-renewable groundwater could be that the average annual aquifer renewal is less than 0.1% of the aquifer storage – the average renewal period would be at least 1,000 years (Margat, 2006).

Connate water entrapped in the sediments of low permeability at the time of their deposition.

Identification and investigation of groundwater resources for emergency situations

Within the objectives of GWES project the development of groundwater resources of low vulnerability resistant to natural hazards is seen mainly in deep-seated, mostly confined aquifers with renewable or non-renewable groundwater. The identification and investigation of such groundwater resources is very exacting and requires an interdisciplinary approach. It also involves the implementation of more sophisticated methods directed towards an understanding of the geological environment and structures which form aquifers.

The more classical methods of groundwater investigation like geology, hydrogeology and hydrochemistry are complemented with the methods of geophysics, isotope hydrology, remote sensing and mathematical modelling. Integrating these methods facilitates establishing a conceptual model of a groundwater system, identifying the groundwater flow regime and origin and assessing residence time – all needed to define conditions for the exploitation of groundwater for emergency situations. Hydrogeological maps depicting the occurrence of aquifers containing good quality groundwater water and groundwater vulnerability maps are both important means by which to present the outcomes of such complex investigations of groundwater resources.

An important stage in the investigation and development of groundwater system resistant to natural hazards is the initial understanding of the behaviour of the system: setting up a conceptual model. The conceptual model must identify the crucial factors influencing the system (natural and anthropogenic); whether the observed behaviour appears to be predictable and whether mathematical approximations can be used to describe its behaviour (McMahon et al., 2001). This is equally important for water supply systems reserved for emergency situations.

Requirements for institutional and technical capacities

The establishment of disaster mitigation and management plans is a complex process, the implementation of which strongly depends on all the dimensions of a country's institutional and technical capacity building, and whether such capacities are applied in a coherent manner. The importance of national and local institutional and technical capacity building to effectively address disaster prevention, preparedness, emergency response, recovery and mitigation. was discussed on the World Conference on Disaster Reduction (Kobe, Hyogo, Japan, 2005).

Institutional capacity building refers to governmental authorities, the legal framework, control mechanisms, the availability of human resources and public participation, information and education.

Governmental authorities at all levels are responsible for the coordination of water governance activities and implementation of water risk management and disaster mitigation plans, for preparedness strategy and timely warning – as well as for distribution of responsibilities and flow of information and communication between all involved sectors of society in particular policy and decision makers, civil society institutions, water managers and stakeholders, the scientific community and the general public. Many countries have established multi-sectoral national disaster risk mitigation mechanisms and special aid teams with representatives of governmental authorities, the army and civil protection forces and local communities to enhance governance for disaster risk reduction and to effectively manage post disaster rescue activities including the distribution of drinking water during and after disaster events. Formulation of community based disaster mitigation policy, considering all phases and actors of disaster mitigation process is the key instrument of governance in the protection of population in regions repeatedly affected by natural disasters.

The establishment of a legal framework and regulatory status to support disaster risk reduction is essential for the implementation of effective environmental and water protection management and policy. In water legislation of many countries specific emergency acts or articles in water law are related to the water management in emergency situations and to the land and water use rights. In many countries within the legal framework are included preventive protection measures of water resources like water supply protection zones and operation of early warning monitoring systems as well as the public right to information.

Control mechanisms established by environmental and water governmental authorities are focussed primarily on the protection of water resources against natural and man-made hazards. Monitoring and warning systems feed data on natural and man-induced hazards to the effective governmental control security mechanisms. The maintenance of stream networks, river regulation works, and control of land use in flood, tsunami and land slides-prone areas and groundwater recharge an vulnerable areas are important protective measures in reducing the vulnerability of populations to natural disasters and have to be controlled by relevant governmental authorities.

Human resources, properly qualified, experienced, trained and motivated, are a crucial non-structural component in all phases of coping with the impact of disasters on water resources. In the anticipatory and warning phase engineering services prevail. During the impact phase the main role is played by special aid teams, civil protection forces and disaster experts, physicians and other medical personnel, psychologists, water quality advisers and NGO volunteers. In the rehabilitation phase building and structural technicians, land use planners, water managers, hydro(geo)logists and policy makers are the key specialists in the implementation of reconstruction work, the restoration of damaged drinking water supplies and water and sanitary distribution networks. Many less developed countries lack the human resources to implement prevention and reconstruction programmes, and to apply relevant measures following disastrous events. Therefore, as proposed in the Hyogo Declaration, a very urgent task in the building the resilience of developing countries to disaster is to establish training and learning programmes in disaster risk reduction targeted on specific sectors.

Active public participation, information and education in the prevention and mitigation of natural and man induced impacts on water resources are further extremely important measures in governmental disaster mitigation policy. Decentralization in decision-making and raising awareness and empowerment of local communities and their active role in actions and plans for disaster preparedness measures and rapid and effective disaster responses both are critical issues in water governance policy. Democratic countries place on a legal basis public right to be inform about the present status of the environment, plans which may influence the environment, water management and disaster preparedness and mitigation policy. Developing countries may face low literacy levels and have to introduce specific measures to inform, educate, motivate and involve the local population in all aspects of reduction of disaster risk and disaster impacts. Another important task in disaster-prone developed countries is to develop knowledge: training programmes and information systems focused on disaster prevention and mitigation.

Technical and scientific capacity building refers particularly to groundwater systems analysis, the identification of potential and existing pollution sources and natural hazards, establishment and operation of early warning monitoring systems, to interdisciplinary research and knowledge transfer.

Groundwater systems analysis has to refer to both recent and earlier hydrological cycles. Setting up a conceptual model of the studied area is based on the identification and investigation of groundwater for emergency situations and on the vulnerability assessment and risk management of groundwater resources in disaster-prone regions.

Identifying and inventorising natural disasters and groundwater pollution sources. Compiling an inventory of and evaluating historical data about the nature, extent, frequency and impact of natural disasters in regions prone to natural events are important components of disaster prevention and mitigation policy and management. Investigation of existing groundwater pollution sources (origin and extent) and assessment and mapping of groundwater intrinsic vulnerability to potential pollution problems both support groundwater protection policy and management.

Establishment and operation of early warning monitoring systems focused on observation of natural and man induced impacts support disaster prevention policy and disaster mitigation activities. The frequency and magnitude of disastrous events is increasing worldwide. Therefore, the operation of integrated early warning monitoring systems to collect and disseminate data required for the timeous identification and better understanding of potential disaster risk and impact on the population and environment is strongly recommended. However, the operation of such monitoring systems is scare at present. Relatively well developed are surface water monitoring networks established in many national and international river basins and early warning monitoring systems in areas affected by earthquakes and volcanic activities. Groundwater monitoring networks are less well developed. At the global scale, early warning environmental monitoring systems are underdeveloped and coordination is often lacking.

Interdisciplinary research and the transfer of knowledge and expertise are needed for the innovation, improvement and development of methods of early warning monitoring and methods of forecasting and evaluating the risk of natural disasters. Both permit better understanding of the processes related to the occurrence and prediction of disasters and make water resources risk management more effective. The World Conference on Disaster Reduction (2005) and especially the agreed expected outcomes and strategic goals, pointed out the transfer of knowledge, technology and expertise to enhance capacity building for disaster risk reduction and the sharing of research findings, lessons learned and best practices.

Prevention and mitigation of natural and man induced disasters

Dooge (2004) formulated five phases of disaster – anticipatory, warning, impact, relief and rehabilitation – in areas repeatedly affected by sudden cataclysmic water (floods) and geological (earthquakes, volcanic activity) disasters or by the effect of both like tsunami, land slides and mud flows. Episodes of hydrological drought, el Niño phenomena, sudden rain and wind storm surges are also classified as repeatedly occurring disaster events. Climatological drought could constitute a long term disaster, leading to hydrological drought, or even to water war or regional armed conflicts. These could last several years e.g. the Sahel drought events. Both types of disasters have serious social, health and economic impacts on the local population. The following activities related to public and domestic drinking water supplies have to be implemented within the specific phases of disaster prevention and mitigation.

The most important activities of the **anticipatory phase** in drinking water services are the identification and assessment of the potential risk to and vulnerability of existing public and domestic water supply systems – both surface and groundwater – and the identification, investigation, delineation and evaluation of groundwater resources resistant to natural hazards. These steps require interdisciplinary cooperation between hydrologists, hydrogeologists, water managers, land use planners, legal experts, emergency specialists, decision and policy makers and in particular the participation of local governmental authorities and communities. Volume of groundwater resources resistant to natural hazards has to be compare to the drinking water requirements of endangered population. Land use and especially urban and rural planning are important preventive protective issues in emergency situations. Maps depicting geology, hydrogeology, water vulnerability and land use, combined with disaster risk and disaster vulnerability maps are important tools for the identification and location of groundwater resources resistant to natural hazards and human impacts.

The warning phase. Strongly related to the activities described above is the establishment and operation of early warning monitoring systems for the different hazards posed by climate, hydrology or geology. Geological monitoring systems are developed in many areas affected by earthquakes and volcanic activities and help to forecast and mitigate the impact of hazardous events, reduce human social and economic vulnerability and give early warning to local populations for timely evacuation. Often absent, however, are integrated hydro-climatological monitoring systems and flood and drought early warning systems. The formulation of suitable indicators of disaster risk and vulnerability and relevant groundwater indicators and operation of early warning monitoring systems are both important elements of the warning phase focused on disaster preventive protection and mitigation policy.

The impact and relief phase is mainly focused on rescue efforts during and after disastrous events and on immediate external help. Among the first priorities is the distribution of drinking water because existing water supply systems are usually out of operation and surface water and shallow groundwater aquifers are polluted. Where safe and physically protected emergency water resources have already been identified, developed and set aside rescue activities for the immediate emergency, related to the distribution of drinking water, will be rapid and effective. Such a conceptual approach has been implemented in only a few countries. In absence of hydrogeological knowledge and preparedness, relief responses can be severely delayed and the impact on social and health conditions of population will be significantly larger. Above described approach to the identification and development of groundwater resources resistant to the natural disasters can not be often applied in regions affected by earthquakes or volcanic activities, because groundwater system and regime in such regions usually significantly change. In many regions affected by natural disasters populations water supplies depend on the import of bottled water or on transport of water by tankers from surrounding areas outside of the disasters influence. These are at best temporary measures, are expensive, and emphasize the population´s dependency on outside help.

The rehabilitation phase of drinking water distribution is usually long term. Reconstruction of water supply systems and water distribution infrastructure may take weeks or months, remediation of polluted water could take years. One effective and often rapid solution mentioned above is intensive pumping of existing deep wells tapping water from deep aquifers resistant to natural and human impacts or to develop deeper aquifers of low vulnerability in areas where their occurrence and properties are known. With respect to the domestic wells and small rural water supply systems affected by flood, tsunami or other natural disasters well cleaning, rehabilitation of both well and pumping mechanism and well dewatering and desinfection are the most effective emergency activities. In case of drought and groundwater depletion impact, well deepening is a desirable emergency task. Another important activity is a post-evaluation of all phases of the rescue process, the preparation of plans for rehabilitation, including water management plans, and assessment of emergency costs. Developing a more effective policy to reduce disaster risks and social and economic vulnerability of the population was pointed out in the Hyogo framework for action 2005 – 2015: Building the future drinking water protection policy and formulation of risk water management plans is of extreme importance in view of reducing human suffering in future disasters.

Disaster risk water management plans are part of the complex strategy for e**stablishing disaster risk mitigation plans,** which principles include the obligations of governmental authorities, local communities, social groups and individuals in the effort to reduce disaster risk. The assessment of disaster risk, evaluation of physical, social and economic vulnerability of a population and disaster preparedness, are important elements of disaster prevention and mitigation plans and policy, which principles are described among others by Dooge (2004), Plate (2003), Affeltranger (2001), Young at al. (1994), and Blaikie at al. (1994) and specified in the documents of various UN Organizations. During the International Decade for Natural Disaster Reduction (1990–2000) many UN activities were implemented to increase community protection against disastrous events and public active participation in disaster prevention and mitigation processes. Among its key objectives the Millennium Declaration (2000) proposed the intensification of international cooperation to reduce the number and effects of natural and man-made disasters. The World Summit on Sustainable Development held in Johannesburg (2002) in its Plan of Implementation pointed out the following actions: 'An integrated, multi-hazard, inclusive approach to address vulnerability, risk assessment and disaster management, including prevention, mitigation, preparedness, response and recovery, is an essential element of a safer world in the 21st century'. In the Declaration of the World Conference on Disaster Reduction held in Kobe (Japan) in January 2005, followed very soon after the devastating tsunami disaster in the South-East Asian region (December 2004), the vital role of the UN system in disaster reduction was reaffirmed.

Several projects implemented within the sixth phase (2002–2007) of the International Hydrological Programme (IHP) coordinated by UNESCO are focused on extreme events in land and water resources management. Particularly under Theme 2 of the IHP several projects are implemented with the objective to 1/ develop a framework for reducing ecological and socio-economic vulnerability to hydrological events and 2/ analyse extreme events by integrating various sources of data (historical, instrumental, satellite) to secure an improved understanding over large scales in time and space. The project 'Groundwater for Emergency Situations' is one of the key IHP projects supporting the International Decade for Natural Disaster Reduction and the Johannesburg Plan of Implementation of the World Summit on Sustainable Development.

The future activities of GWES

Secure drinking water for endangered populations is one of the highest priorities during and immediately after disasters. This lies at the core of the UNESCO / IHP project Groundwater for Emergency Situations (GWES), its main objective being the analysis of methods for the identification, investigation, assessment and risk management of safe groundwater resources. Such methods are summarised in GWES Framework Document published by UNESCO in 2006. This is but the first step of the project. Organising workshops and seminars focused on groundwater in various types of emergency situations is another important topic of the GWES project activities. Workshop in Tehran (Iran) is a good example of cooperation between UNESCO, Regional Centre on Urban Water Management (RCUWM - Tehran and GWES project.

The core outcome of the GWES project will be the publication of methodological guidelines complemented by case studies and an inventory of groundwater bodies resistant to natural and human impacts. These will be identified in selected pilot regions, preferably those repeatedly affected by disasters, such as South-East Asia. The final stage of the GWES project activities will be the organization of an international symposium to disseminate and summarize in its proceedings the existing knowledge and experience in the identification, investigation and management of groundwater bodies suitable as a source of drinking water for emergency situations.

References, selected notes and future reading

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FLOODS AND GROUNDWATER RESOURCES IN EMERGENCY SITUATIONS

Jan Šilar[1]

Abstract: Recently, groundwater resources in different regions of the world have been affected by floods or by other natural hazards. Floods affected a large number of wells used for drinking water purposes. Many conventional public water supplies and domestic wells collapsed or groundwater was polluted. The substitution of water supply by import of drinking water in bottles and tanks became one of the most topical tasks of the emergency activities Often, groundwater resources resistant to floods occur in the affected region, however they are not investigated and developed. In the paper are described methods of identification and investigation of deep aquifers with groundwater safe to the impact of floods. Special regard is given to the description of isotope hydrology methods. Groundwater risk mitigation and risk management measures in relation to floods are analysed with respect to social, economic and environmental attributes.

1. Water related disasters

From 1996 to 2006 about 80% of all natural disasters were of meteorological or hydrological origin. In the last decades, between 1960 and 2004, there has been a significant rise in water related extreme events.

Floods are the most frequent catastrophic evens which people have to face. They are caused most frequently by a coincidence of meteorological and hydrological circumstances but often the flooding of lands has geological or anthropic reasons. A flood is a temporary rise of water level in a stream caused by an abrupt increase of discharge (or by a temporary decrease of the bankfull discharge due to the clogging of the stream channel by ice pack, landslide, etc.). Usually it is accompanied by flooding of the adjacent banks and flood plain. Evidently, evaluation of the frequency of such events is a matter of statistics. The catastrophic floods are linked with meteorological situation and climatic events as floods along river tracts or during hurricanes, and even with the geological setting of the region as tsunamis in unstable tectonic zones, or in combination with morphology (landslides damming a stream). Floods depend on the rainfall-runoff relation. Urbanisation causes a tremendous number of changes in these relations in increasing the runoff with increasing impervious areas and storm coverage (Keller, 1976).

Note : Author of this paper during preparation of this paper died. Final version of the paper was prepared by Jaroslav Vrba.

1. Prof. Ing. Jan Šilar, DrSc., Professor Emeritus, Dept. of Hydrogeology, Charles University, Albertov 6, 12483, Praha 2, Czech Republic; fax: (+420) 221951556; telephone: (+420) 221951566 ; email: silar@natur.cuni.cz.

As population in valleys since prehistory has spread along streams, the water supply of communities usually depends on groundwater in aquifers in fluvial deposits in the flood plain. The frequent pollution in such shallow vulnerable aquifers is a phenomenon which depends on the stochastic characteristics of the floods (Figure 1). Because of this, even the substitution of drinking water should be observed and analysed with respect to the probability and areal extent of floods. In flood-prone areas the taxonomy and statistics of floods should be therefore, also respected in groundwater studies.

The circumstances causing the occurrence of a flood are changing during time due to the natural evolution of the river bed and due to the human activities. E.g., Xue Songgui (2005) quotes that the main channel of the Yellow river in China is seriously silted up and shrinking, the trend for a secondary suspended river has developed very fast and the main channel bankfull discharge is reducing rapidly.

Figure 1. View on the alluvial plain of the Labe River during the flood in August 2002 in the Czech Republic. The shallow highly vulnerable aquifer in fluvial deposits in alluvial plain is underlain by thick Cretaceous sediments (100 - 225 m), with an unconfined aquifer at the base (photograph by Raudenský and Dorazil, 2002)

According to their origin, the following types of floods can be distinguished (Jeggle, 2005): marine, riverine, 'run off", low lying, wave and tidal, storm surge, marine encroachment. The latter may be caused even by land subsidence along a coast. A flash flood can occur also due to the burst of a lake impounded behind a mass of a landslide or a mountain glacier.

The earthquake in Kashmir on 8 October 2005, caused damming and flooding of valley bottoms (Figure 2). After saving lives and rendering first health aid, the next step was to supply water, food and shelter for survival. The earthquake destroyed water supply systems in five districts of the North West Frontier Province in Pakistan and in three districts of the Azad Jammu Province in

India. 3.2 million people affected needed help. Thanks to the activities of the Red Cross, Red Crescent and other welfare organizations, the rescuing activities started immediately after the disaster (Berger, Olafsdottir, 2005).

Figure 2. A narrow flood plain of a stream dammed by a large landslide in Kashmir due to the earthquake on 8 October 2005 (photo David Ševcík, People in Need)

It should be noted that flash floods occur even in arid regions where they can cause tremendous damage of communities in wadis, where groundwater resources are located in dry stream beds.

The floods of a longer duration caused by regional rains should be distinguished from the flash floods. In some climatic zones, floods are a very regular phenomenon linked with regular precipitation, e.g. in the monsoon regions of South-East Asia and especially in the tropical zones. They considerably afflict large rural regions with groundwater supply from shallow wells in extended flood plains and often result in epidemic diseases.

In some regions, more or less regular changes in the climatic pattern have been observed. Examples of these changes are case histories of the El Niño events which almost regularly occur in Peru and along the Pacific coast of South America. Looking at the history of heavy rains registered in the usually dry Peruvian coast, the climatologist Victor Eguiguren found 14 El Niño events in the 19th century. The 'Servicio Nacional de Meteorología e Hidrología' registered 18 events in the 20th century the last one in1997-98. The 1997-1998 El Niño event had even a positive effect: the formation of a large lake in a former desert area in northern Peru increased the surface water storage and the recharge of aquifers. On the other hand, the negative effects were registered too: damage of water intake structures and of other equipment, collapse of potable water and sewage piping systems, water supply contamination, damage of water-supply wells, damage of the environment, and sedimentation in reservoirs (Rojas Molina, 2006).

Floods have been always a part of the geological history. Radiocarbon dating of fluvial sediments of the Labe (Elbe) River in the Czech Republic imply that several abrupt changes in temperature and precipitation occurred during the Holocene climatic catastrophes, and they may correlate with global events, as suggested by studies of Holocene floodplains in other regions (Jílek et al., 1995).

2. Probability and recurrence of floods

The probability of occurrence of a flood with a certain discharge is expressed as its recurrence interval T in years. This is the average number of years during which an event of a given magnitude may be expected to occur once, and it is computed according to the equation (Butler, 1957)

$$T = (\frac{1}{F}) \cdot 100$$

where F is the percentage of years. In other words: If the length of the monitoring period is 100 years and the number of occurrences of a certain culminating discharge during floods within this period is 5, then the recurrence interval T in years (or return period) of such a flood is every 20 years. This expression, however, does not mean that the flood would repeat after 20 years. It expresses just the probability. The frequency of hydrological phenomena is a matter of statistics. For introduction into the hydrological statistics and calculation of the recurrence intervals see e.g. Butler (1957), Ven Te Chow (1964).

The devastating effects of other natural disasters can be similar, can combine, or can pass into one another. They usually damage on a large scale the infrastructure, including water supply systems (Figure 3).

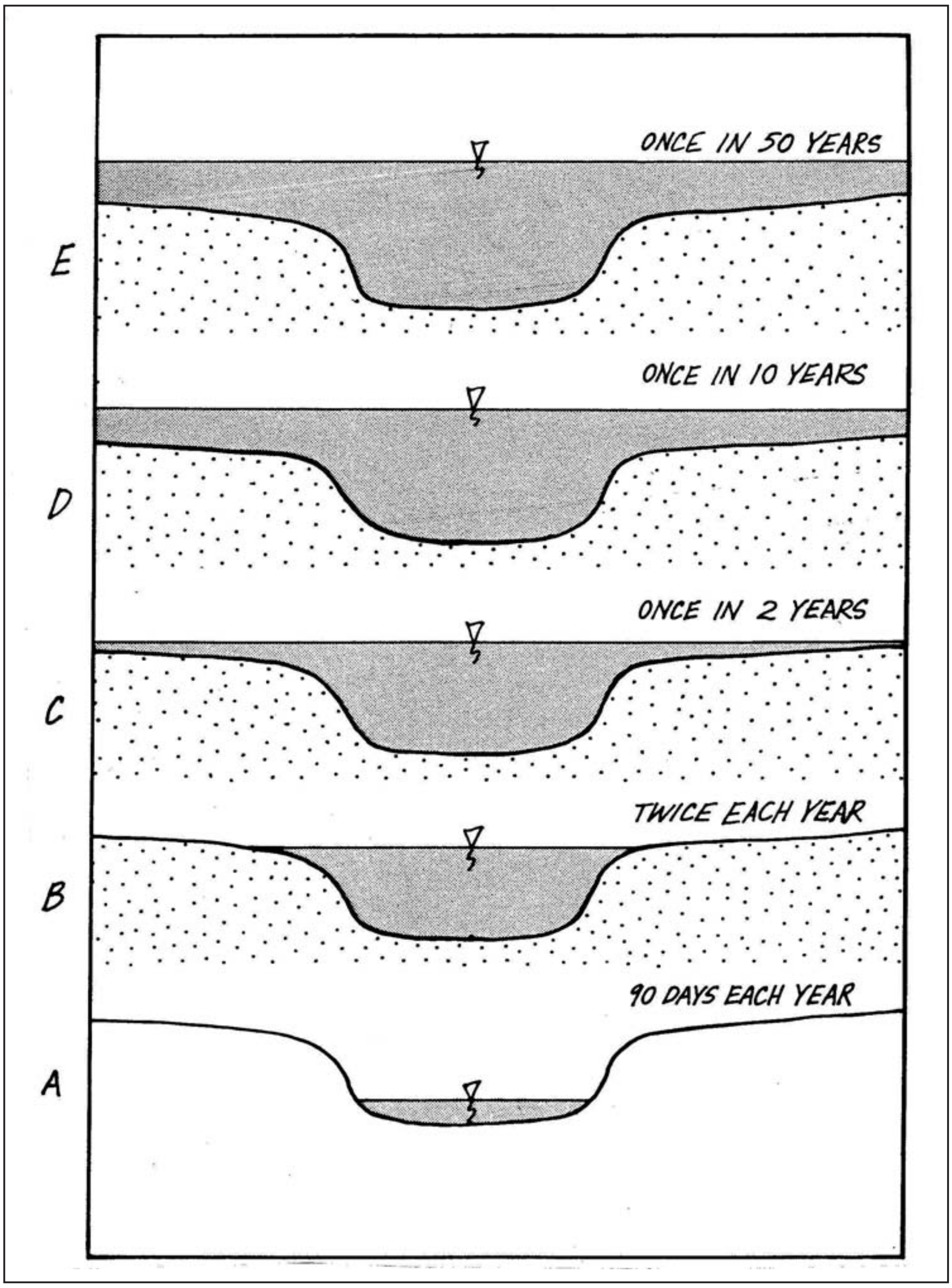


Figure 3. Water levels of different recurrence intervals in a stream (Manning, 1987)

3. Groundwater in the hydrological cycle and its residence time

Groundwater is a part of the hydrosphere which is in a continuous motion and forms the hydrological cycle. The residence time of groundwater according to the isotope dating usually exceeds one hydrological year and very often, it has to be considered in thousands of years and in the geological time scale, i.e., it could have been recharged under different climatic conditions. Generally: The longer the residence time of groundwater in the aquifer, the lower its vulnerability.

An example of the use of the residence time of groundwater in prospecting for emergency groundwater resources is the case of the August 2002 flood on the Vltava and Labe (Elbe) Rivers in the western part of the Czech Republic. An extraordinary meteorological situation (two successive significant pressure lows within one week) brought extreme floods in Central Europe. In Ústí nad Labem, the district capital in northern part of the Czech Republic, the mean and minimum discharges of the Labe River normally are 293 $m^3 \cdot s^{-1}$ and 58 $m^3 \cdot s^{-1}$, respectively. However, during the 2002 flood the discharge reached 5,100 $m^3 \cdot s^{-1}$. Its recurrence interval has been 500 years (Hladný et al. (eds.), 2005).

Groundwater dating and stable isotope analyses were found adequate, together with conventional hydrogeological working methods, for investigating emergency groundwater resources. The results of the isotope dating were evaluated by means of a histogram. The samples from the deep Cretaceous aquifers in the lower reaches of the Labe River are specific by a high radiocarbon age (Figure 4). 75% of the groundwater samples from deep wells show a Pleistocene age, the remaining 25% are of Holocene age. Groundwater of modern age was not found in any of the deep wells (Šilar, 2003).

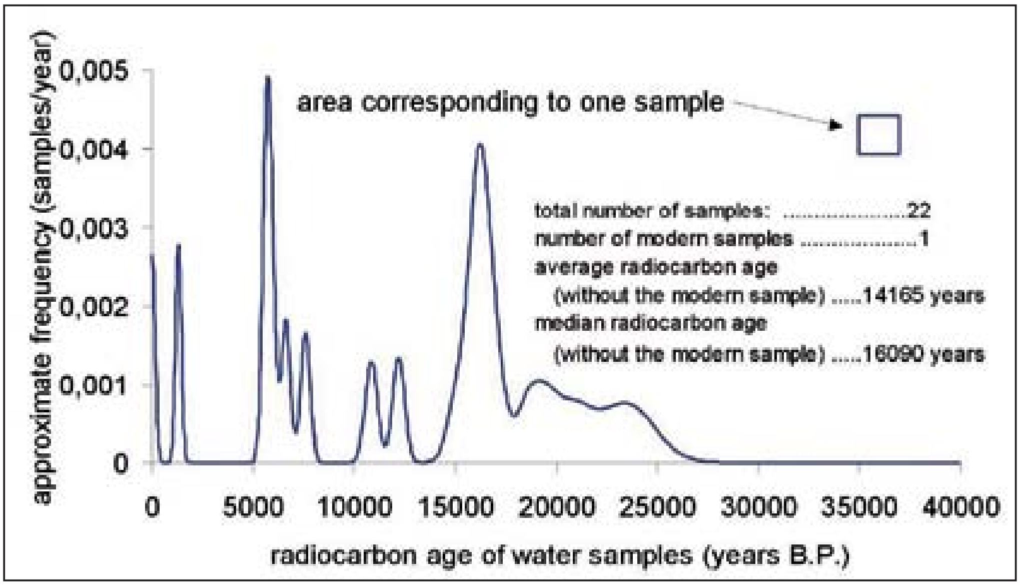


Figure 4. Histogram of radiocarbon ages of groundwater from the lower reaches of the Labe (Elbe) River in the Czech Republic (Šilar, 2003)

4. Where to search for emergency water resources

The search for emergency groundwater requires some basic hydrogeological knowledge of the affected region. The potential emergency water resources should be known before the flood comes. The deep-reaching groundwater systems are more resistant to contamination, while shallow aquifers (e.g. sediments of the flood plains) are vulnerable and often contaminated.

In wide valleys, in the fluvial sediments of the flood plains are developed the most vulnerable aquifers. In basin structures with stratified aquifers underlying the alluvial plain, the deeper aquifers should be preferred.

In hard-rock environment, the hydrogeological investigation should be focused on evaluation of the local flow pattern in the fissured bedrock.

In groundwater-poor regions, even groundwater of shallow origin in springs and in quanats is used for emergency water supply. However, its harmless quality should be analytically proved.

Hydrogeological textbooks present numerous examples of systems in different geological environments, see e.g. Davis, DeWiest (1966), Fetter (1988), Freeze, Cherry (1979), Heath (1983), publications of the United Nations, UNESCO, and regional hydrogeological literature of national geological and water-management institutions.

5. Vulnerability of the population and ecosystems to floods

The most urgent activity after a disastrous flood is the first aid to save the lives of people. The next step is to supply the surviving with food and drinking water and to care for sanitation. The health authorities should control access to the conventional water supply facilities affected by the flood in order to prevent people against water-born diseases. Floods also cause damage in the local and regional ecosystems due to a large-scale erosion along the streams. E.g., the estuary of the Huang He River (the Yellow River) in China changed its position south of the Shangdong Peninsula in 1852 to the north of Shangdong (Metelka et al., 1924).

The suspension of drinking water distribution forces people to reach water often at insecure resources, especially in rural areas. A prompt substitution of the damaged water supply is therefore, a very urgent task. For this purpose, the water resources (adequate wells, boreholes, springs, etc.) should be known and registered in advance. If local safe drinking water resources are not available drinking water has to be imported.

6. Groundwater vulnerability

The vulnerability of groundwater depends of its susceptibility to natural disasters, particularly on a) the geological setting of the groundwater system and b) on the residence time ('age') of groundwater in the earth crust.

In general, the deeper the hydrogeological structure and the longer the groundwater residence time, the lower its vulnerability. In basin structures the deep confined aquifers fulfil the requirement for low vulnerable groundwater (Figure 5). Development of groundwater resources in deep aquifers requires, however, a knowledge of the geological setting of the region and hence hydrogeological investigation is desirable. Wells have to be located beyond the alluvial plain however, if such well location due to some circumstances will not be possible, the mouth of the well shaft and of the casing should be above the level of the expected flood (Figure 6). The residence time of groundwater in the deep aquifers should be considered in thousands of years and in the geological time scale. Thus, when prospecting for groundwater to substitute the damaged supplies, the hydrogeological structure as well as the groundwater residence time should be investigated using conventional hydrogeological survey and isotope-hydrology techniques.

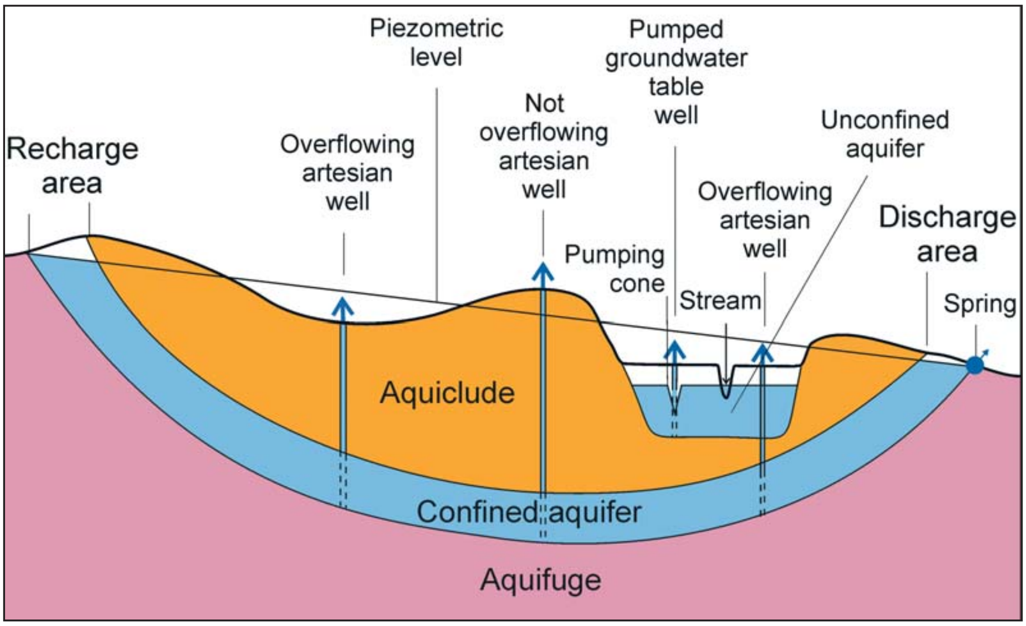


Figure 5. Example of a shallow vulnerable aquifer in a flood plain underlain by a confined (artesian) aquifer resistant to pollution from the surface (Vrba, Verhagen (eds.), 2006).

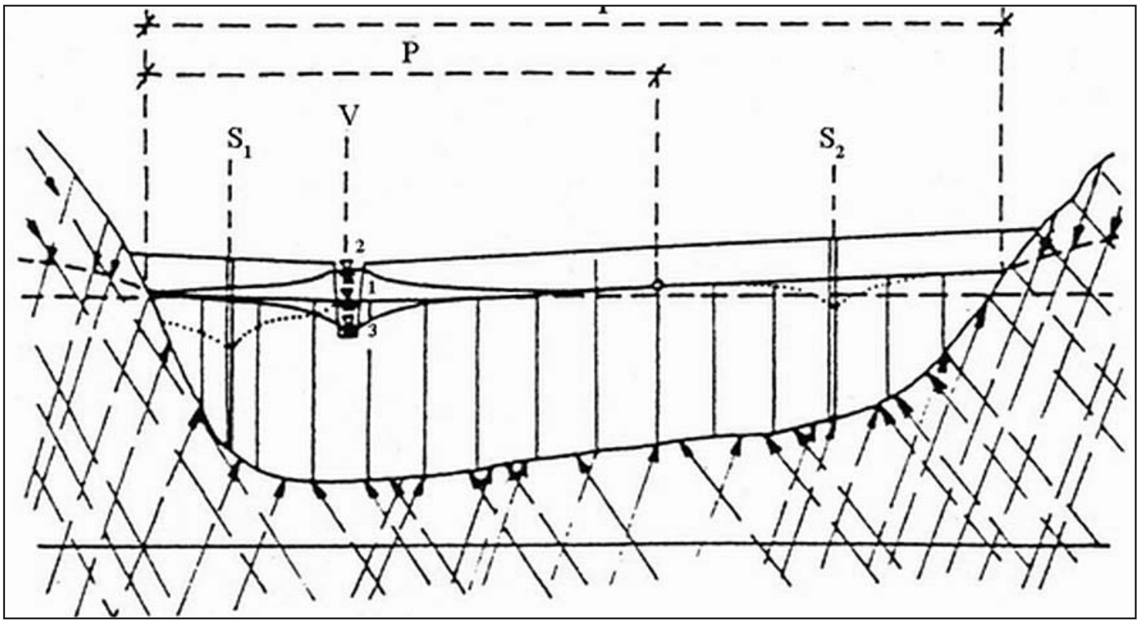


Figure 6. The relation of water in fluvial sediments to the water in a stream. The well S_2 pumps groundwater from the aquifer in fluvial deposits. Bank infiltration may be induced from the river when pumping from the well S_1. If the surface of the plain is flooded, aquifer in fluvial sediments may be polluted (after Hynie, 1961)

Isotope-hydrology investigation includes determination of the residence time of water in isolated or trapped aquifers, the ratio of replenishments to withdrawals of water in aquifers under exploitation, natural recharge into stream bed formations from rivers, natural or artificial recharge into groundwater bodies, underground storage of fresh water in a brackish aquifer – or vice versa, aquifers contamination by sea water and determination of hydrologic parameters of groundwater systems (Aggarwal, Gat, Froehlich (eds.), 2005).

7. Aquifers vulnerability to floods

In general, the most vulnerable groundwater resources are those, which are in a direct contact with the earth surface where groundwater recharge occurs, as e.g. in sediments of the flood plain, in outcrops of permeable rocks (e.g. of sandstone) or in karstified areas.

Under normal conventional conditions, flood plains provide large amounts of groundwater resources which usually has to be treated. But in case of floods or other natural or human made accidents, they are very vulnerable and thus cannot be usually used for substitution as drinking water source. E.g. in case of the Indian Ocean 2004 tsunami, groundwater in the coastal aquifers was polluted by marine water from the surface and had to be carefully extracted without sucking the underlying brackish water.(Figure 7).

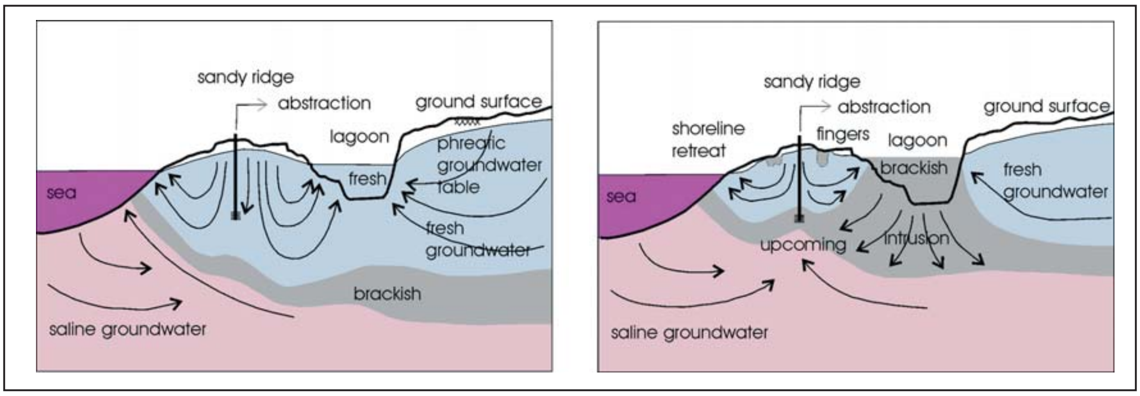


Figure 7. Schematic presentation of a mechanism of tsunami events affecting a coastal groundwater system (Keshari et al., 2006). Left: before the tsunami. Right: after the tsunami.

In mountainous regions, the risk of floods is limited to the valley bottom, but substituting water resources can be found in springs in the slopes beyond the alluvial plain and in the alluvial fans at the foot of slopes.

In alluvial fans, water resources and their development by qanats have been known to the ancient populations of the arid regions in the Middle East. A quanat, also qanat or foggara (or rhettara, used in Morocco) or karez (used in Baluchistan) is a subsurface gallery for water supply starting from below the water table and sloping downwards to the ground surface with a gradient flatter than both the water table and the ground surface (Sine, 1974). Quanats use has been brought to a considerably high level and they are still a very effective method of groundwater development. Use of groundwater resources from quanats should be based on hydrogeological knowledge and protection of their infiltration area to make sure that groundwater will be not contaminated.

8. Aquifers resistant to the effects of floods

Considering the resistant groundwater resources for substitution of the damaged water supply system, the prime condition is its harmless quality as drinking water to serve as drinking water source or the possibility of its treatment using simple techniques. Such resistant groundwater can be found in 1/ confined aquifers with a piezometric surface above the ground which hydraulic pressure and overlying confining bed prevent the intrusion of surface water and pollutants into the groundwater bodies, 2/ aquifers overlying by rock formations of low hydraulic conductivity which reduces the infiltration of surface water into the ground, and 3/ groundwater flow systems with a hydraulic potential increasing with depth, i.e. with a natural upward flow. The gradient of hydraulic potential makes difficult in discharge areas for intrusion of surface water into the ground (Figure 8).

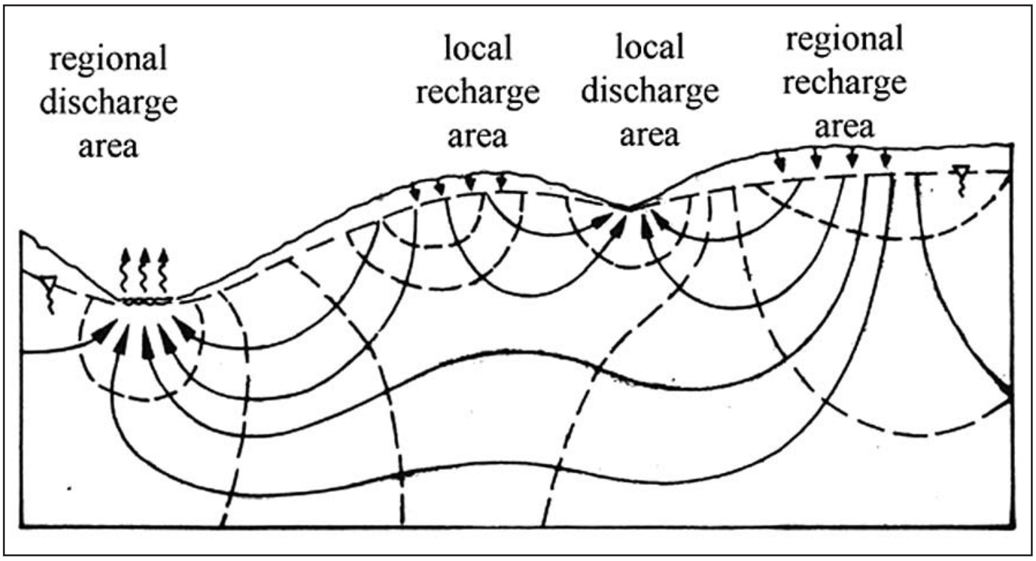


Figure 8. Flow net in a vertical section through an inclined rolling area. Full lines: flow lines; dashed lines: equipotential lines. It is evident that even in water table aquifers an upward flow of groundwater can occur.

Changes of water level in the borehole during its drilling can be used for determining the gradient of hydraulic potential and thus estimating the vertical component of the groundwater flow (Figure 9). The drilling crews should be instructed to measure the groundwater level and its changes during the whole drilling operations.

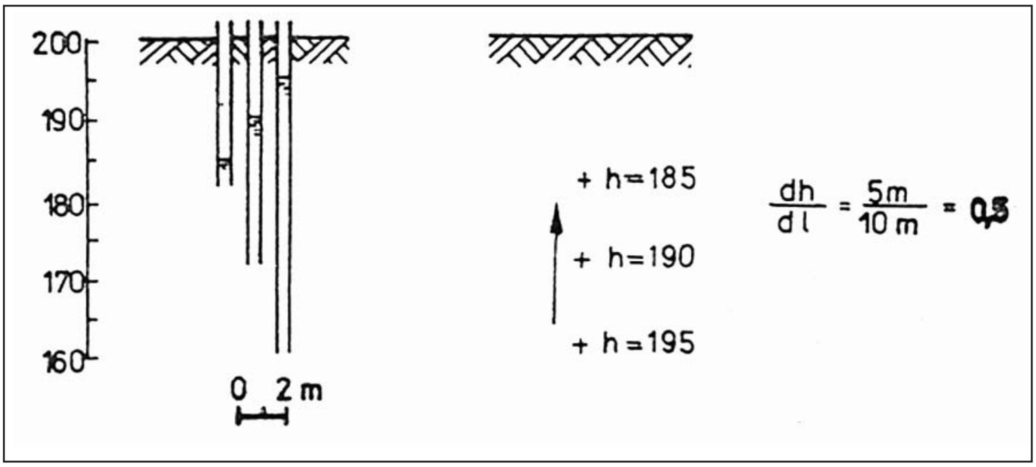


Figure 9. Decrease of hydraulic head in a group of closely spaced boreholes indicates an upward component of groundwater flow. Vertical scale at the left: elevation in m a.s.l. (modified after Freeze, Cherry, 1979)

An upward regional flow of groundwater can be recognised during field investigation by the presence of wet spots in otherwise dry ground, phreatophytic plants, increased temperature of springs, and by other phenomena (Figure 10).

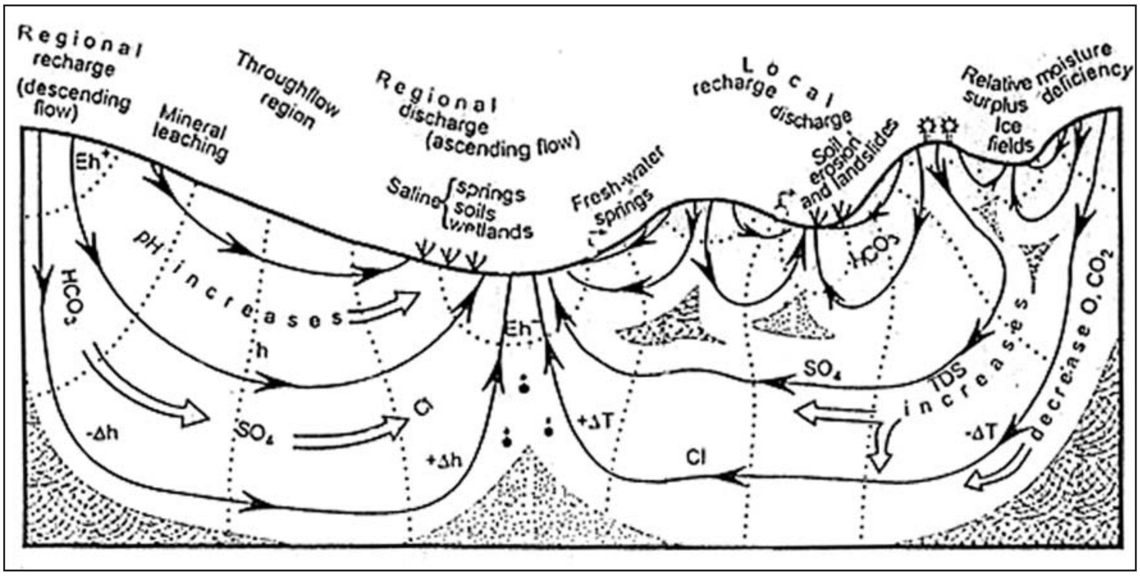


Figure 10. Local and regional systems of groundwater flow (After Tóth, 1980)

When investigating the groundwater-flow system, one should distinguish between humid and arid regions. In case of a flood, the consequences of flooding are quite different. In case of a flash flood in an arid region, the surface water from the wadis infiltrates into the ground and can pollute the groundwater below (Figure 11, point D).

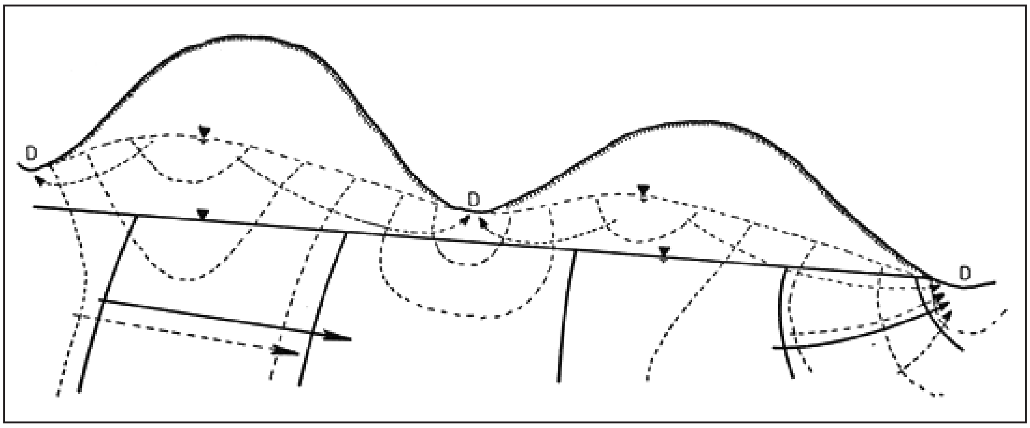
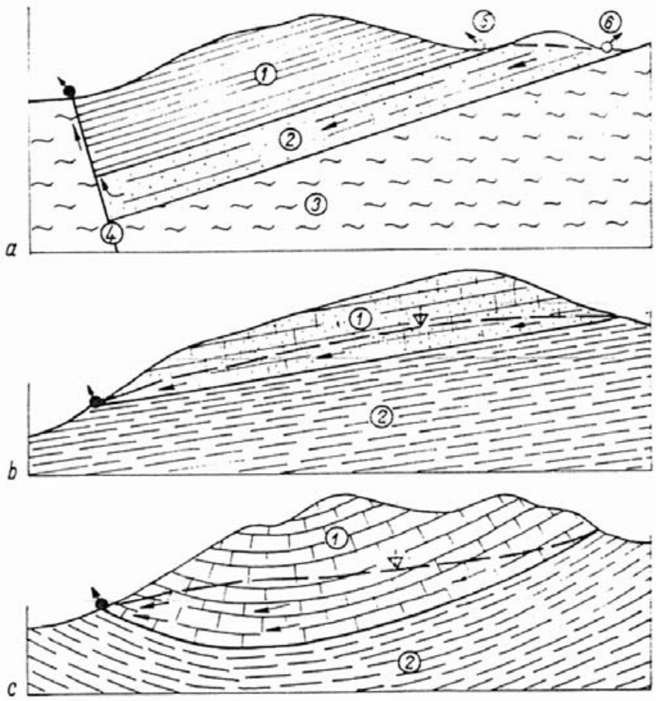


Figure 11. Groundwater flow field in humid areas (dashed lines) and in arid areas (full lines); D = discharge to rivers (Seiler, Rodriguez, 1980)

In hilly regions springs can be used for emergency water supply. However, their hydrogeological and hydraulic conditions should be considered and evaluated (Figure 12 and Figure 13).



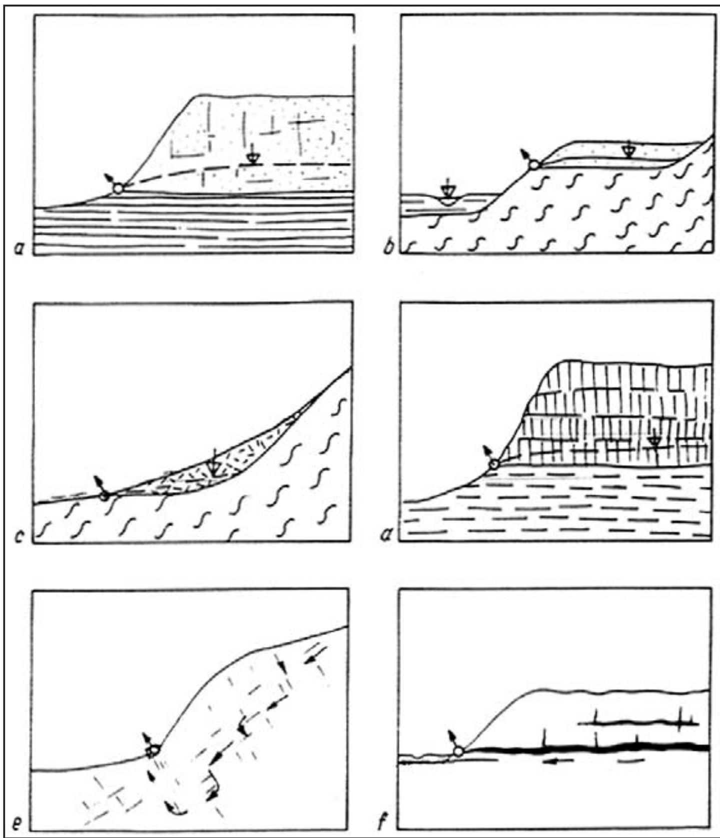
a) ascending spring:
1-impermeable marl,
2-permeable sandstone,
3-impermeable gneiss,
4-permeable fault,
5, 6-intermittent springs;

b) descending spring :
1-permeable sandstone,
2-impermeable marl;

c) overflowing spring:
1-permeable limestone,
2-impermeable shale.

Figure 12. Springs according to the direction of groundwater flow

For emergency water supply, the springs *ad a)* are most suitable because groundwater is protected from direct contact with surface, while the springs *ad b*) and *ad c)* are less suitable.



a) contact spring in permeable sandstone overlying impermeable bedrock,
b) contact spring in a fluvial deposits of river terrace overlying impermeable bedrock,
c) talus spring in talus deposits overlying impermeable bedrock,
d) contact spring in a fissured lava flow overlying an impermeable layer of volcanic tuff,
e) fissure spring along a fractured zone in igneous or metamorphic rocks,
f) karst springs in karstified limestones.

Figure 13. Springs according to the geological origin

For emergency water-supply development, the springs *ad a,), ad d)* and *ad e)* are relatively suitable, while the type of the springs *ad b)*, *ad c)* and *ad f)* are less suitable because of the risk of pollution.

9. Methods of identification and investigation of low-vulnerability aquifers

The most useful strategy when preparing emergency water supply in some region is to get acquainted with:

- the already published geological papers and file reports,
- the topographic and geological maps,
- the hydrogeological and hydrochemistry maps if these are available,
- the existing water-management devices like wells, boreholes and springs and the pertinent information about water quality.

Above mentioned data are usually available in libraries, archives of geological and hydrological institutes and universities. An introduction to the hydrogeological investigation can be found e.g. in Brassington (1988) and in Alley et al (1999).

Principal types of data and methods of data compilation required for evaluation of groundwater system have been formulated by Alley ad al. (1999):

Physical framework

- Topographic maps showing the stream drainage network, surface-water bodies, landforms, cultural features, and locations of structures and activities related to water
- Geological maps
- Hydrogeological maps showing extent and boundaries of aquifers and confining units
- Maps of tops and bottoms of aquifers and confining units
- Saturated-thickness maps of unconfined (water-table) and confined aquifers
- Average hydraulic-conductivity maps for aquifers and confining units and transmissivity maps for aquifers
- Maps showing variations in storage coefficient for aquifers
- Estimates of age of groundwater at selected locations in aquifers

Hydrologic budgets and stresses

- Precipitation data
- Evaporation data
- Stream flow data, including gain and loss of stream flow between gaging stations
- Maps of the stream drainage network showing extent of average perennial and seasonal flow and dry channels
- Estimates of total groundwater discharge to streams
- Measurements of spring discharge
- Measurements of surface-water diversions and return flows

- Quantities and locations of inter-basin diversions
- History and spatial distribution of pumping rates in aquifers
- Amount of groundwater used by different sectors (e.g. water supply, agriculture, industry) and spatial distribution of return flows
- Well hydrographs and historical head (water-level maps) for aquifers
- Location of recharge areas (recharge from precipitation, losing streams, irrigated areas, and recharge wells or other facilities), and estimates of recharge

Chemical framework

- Geochemical characteristics of rock environment and naturally occurring groundwater in aquifers and confining units
- Spatial distribution of water quality in aquifers
- Temporal changes in water quality, particularly for contaminated aquifers
- Sources and types of potential contaminants
- Chemical characteristics of artificially introduced waters or waste liquids
- Stream flow quality particularly during periods of low flow

However, it has to be noted that such extensive set of data will be available only exceptionally (particularly in less developed countries) and hydrogeologist usually have to made groundwater evaluation from lower set of data.

When searching for emergency groundwater resources, the following procedure can be recommended:

a) Process the results of the hitherto accomplished hydrogeological investigation of the particular area, especially with regard to the geological setting and to the groundwater flow system and natural and man made hydrogeological phenomena (springs, fens, boreholes, wells, etc.)

b) Summarize the results of the hitherto available isotope analyses. They are very efficient when investigating vulnerability of groundwater resources, particularly:

   Analyses of stable isotopes: 1/ hydrogen (deuterium ^2H) and oxygen (^{18}O), which clarify the origin of groundwater and the potential evaporation in the past and 2/ carbon ^{13}C in the dissolved bicarbonates, which clarify the origin of carbon (in the organic matter of the soil, in the carbonate bedrock or due to the admixture of magmatic carbon dioxide). Stable-isotope analysis is a useful means for identification of groundwater origin in regional studies. The isotope composition indicates the climatic conditions under which ground water originated at the time of recharge. Analyses of precipitation and water which have not been subjected to evaporation show a good linear relationship of ^2H and ^{18}O of the general type

$$\delta^2H = 8\ \delta^{18}O + y$$

   where δ^2H and $\delta^{18}O$ are the isotopic deviations of deuterium (^2H) and oxygen (^{18}O) expressed in ‰ with respect to the world standards respectively; y is the excess of deuterium when $\delta^{18}O$. It may vary, but is normally +10‰ (Figure 14).

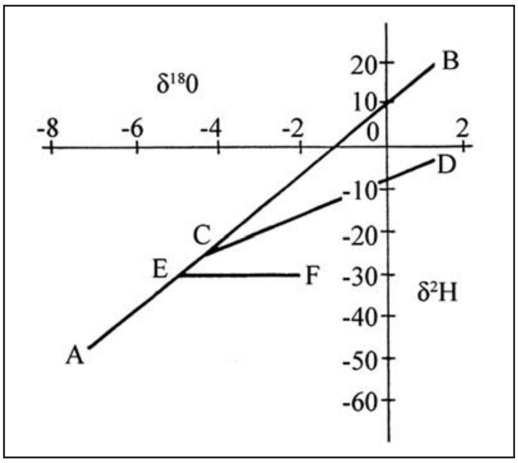


Figure 14. A schematic δ^2H - δ^{18}O diagram (Payne, Halevy, 1968), showing the fractionation of heavy-water molecules from those of light water (for explanation see the text)

The relation of δ^2H - δ^{18}O is shown by the line AB in Figure 14. Water which has been subjected to evaporation is found to fall off the general line of slope 8 (line CD). Geothermal water or steam which exchanged its ^{18}O isotope with that of the rock medium is represented by the horizontal line EF (because there occurred no exchange of deuterium ^{2}H. Plotting the data for different types of water from the investigated region, a plot of the type shown in the Figure 14 may be obtained and the origin of groundwater clarified. This phenomenon (fractionation, which is the separation of water molecules containing different isotopes of hydrogen and oxygen) is particularly sensitive to temperature at the time of evaporation and condensation: the lower the temperature the greater the depletion in heavy isotope content. Thus, precipitation in high geographic latitudes and in high mountains is marked by depletion of heavy stable isotopes relative to precipitation in nearby lower lands (Payne, Halevy, 1968). This is significant when deciding about its emergency development and when the recharge (infiltration) area of springs is searched for.

Analyses of radionuclides:: 1/ tritium ^{3}H : its presence in groundwater indicates recent origin of groundwater and a potential contamination and 2/ radiocarbon ^{14}C : its low concentration indicates a long residence time ('age') of groundwater and its fossil origin; resident time as much as about 50,000 years reaching to Pleistocene can be determined.

Simultaneous low concentration of ^{14}C and higher concentration of ^{3}H may indicate admixture of modern water into old or fossil groundwater and its potential contamination.

c) Take additional groundwater samples from topical aquifers if necessary; instruct the charged personnel about sampling methods.

d) Select suitable hydrodynamic models of the investigated hydrogeological structure.

e) Evaluate the results of modelling and isotope analyses.

f) Assign the groundwater to the relevant hydrological cycles (present or past).

g) Evaluate the gained isotope data with respect to the determination of groundwater vulnerability.

h) Identify low-vulnerable groundwater resources to be used as drinking water source in case of emergencies.

i) Propose and develop groundwater monitoring network to serve as early warning and trend detection system.

j) Propose effective methods of groundwater protection in order to preserve them as resources of drinking water for emergency situations.

k) Propose criteria for ground-water management in emergency situations.

10. Groundwater risk management

Risk management is the systematic application of policies, procedures and practices that seek to minimize disaster risks at all levels and locations in a given society. Risk management is normally based on a comprehensive strategy for increased awareness, assessment, analysis/evaluation, reduction and management measures. The risk management frameworks need to include legal provisions defining the responsibilities for disaster damage and longer-term social impacts and losses. (Sine, 2004*a*). In relationship to floods and groundwater resources, it means administrative decisions, technical measures and participation of the public that should prevent water-supply and sanitation facilities against natural disasters in general and against floods in particular. It requires risk assessment and disaster formulation of risk reduction framework composed by the following actions (Sine, 2004b):

- Risk awareness and assessment including hazard analysis and vulnerability/capacity analysis.
- Knowledge development including education, training, research and information.
- Public commitment and institutional frameworks, including organisational, policy, legislation and community action.
- Application of measures including environmental management, land-use and urban planning, protection of critical facilities (e.g. adjusting of water supply wells to protect them from potential flooding), application of science and technology, partnership and networking, and financial instruments.
- Early-warning systems including forecasting, dissemination of warnings, preparedness measures and reaction capacities.

In other words, it includes preventive, organisational and technical activities the aim of which is to prepare the society for the flood and to moderate its consequences; the floods cannot be prevented but we can moderated their detriments.

The hydrological data (water level, stream discharge, recurrence of floods, extent of the flooded area, and the morphology of the flood plain) should be known when planning wells location and construction. This is extremely important when deciding about urban planning in flood plains, because the developers and decision-makers are tempted to use such areas as suitable sites for construction of various facilities. Development of flood plains should be always based on a geological and morphological survey of the surface of the flood plains ground. The water-management authorities should know in advance the measures which should be applied to protect the wells and springs in case of floods. The administration authorities, civil defence, fire-brigades and volunteer organisations (Red Cross and Red Crescent) should be informed in time about an expected flood. They should mutually coordinate their activities and inform and protect the population. They should be also informed about ancient wells, springs and other water resources which are not used at present and keep them in a state allowing groundwater extraction during or after the flood. New wells in low vulnerable aquifers should be proposed, drilled and tested to serve as emergency water resources. The public should be informed about the location of the emergency drinking water resources. In case that emergency water resources are not available, a system of water supply by mobile cisterns should be established and vehicles have to be prepared for drinking water distribution.

In the past, human population spread in zones with adequate water resources, i.e. along rivers, or in close vicinity of springs. In case of flood-prone zones, ‘floods become a problem to man only when he competes with rivers for the use of the river flood plains’ (Bue, 1972). This shows the necessity of careful urban planning to prevent flood damage as much as possible. Flooding of alluvial plains seriously affects municipal as well as individual water supply of communities living along streams.

To conclude, groundwater risk management is based on the preventive control and protection of drinking water supplies and relevant technical devices (e.g. pumping stations) with the scope to reduce the impact of the flood on water supply and distribution systems as much as possible. Local population play important role in risk management activities. Jeggle (2005) stated, that ‘The most important aspects of effective disaster management are precisely those activities that are undertaken and pursued at the times when there is no disaster”.

11. Groundwater risk mitigation

Mitigation are structural and non-structural measures undertaken to limit the adverse impacts of natural hazards, environmental degradation and technological hazards (Sine, 2004*b*). They include the following activities:

- Switch off polluted wells, because use of polluted water can cause infectious diseases.
- Activate emergency water resources (deep wells, springs, etc.).
- Provide import of groundwater in mobile tanks if local emergency water resources are not available Inform population about location of emergency water resources.
- In case of water scarcity determine rules of the use of emergency water resources to prevent wasting of water.
- If there is not water substitution possible and the water from the affected wells should be used, the water should be treated and its quality supervised by competent institutions.
- Rapid restoration of the conventional water supply systems after the flood is desirable.

12. Preparedness phase activities

Because of the random characteristics of the hydrological and climate phenomena and of the catastrophic events, the population should be always prepared to their occurrence. Such events which occurred in the past should be recorded according to the memory of the contemporaries before they are forgotten. The dissemination of information on catastrophic events and on water supply and sanitation is a matter of institutions responsible of water management, but it should be a part of information and education of the population.

In this respect, the meritorious activities of the Red Cross and of the Red Crescent and of similar National and International organizations should be mentioned. Some of the official authorities have published useful guides for this purpose. E.g., the Institute of Aqueducts and Sewerage of Nicaragua (El Instituto Nicaragüense de Acueductos y Alcantarillados, INAA) published guides for elaboration of reports focused on the on water supply and sanitation systems, a guide on general terms for elaboration of analysis of vulnerability and emergency planning of drinking water and sanitation systems and a technical guide for reduction of the water supply and sanitation systems vulnerability (Sine, 2006).

It has been pointed out in the previous chapters, that the preparedness activities focused on substitution of the damaged water-supply systems should be prepared in advance. The emergency groundwater resources should be delineated according to a thorough hydrogeological investigation and their quantitative and qualitative properties should be well known. Moreover, it should be emphasized to the politicians at the time when they are about to allocate money, that the preparedness activities and mitigation of the consequences of disasters is also their responsibility, because they are responsible to distribute the financial funds (N mec, 2006, in discussion to Jeggle (2006)).

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GROUNDWATER MANAGEMENT – A PART OF FLOOD RISK MANAGEMENT

Thomas Sommer [1]

Abstract: Flood events of the last years caused significant damages in urban areas because great values are cumulated in these areas. Groundwater is one of the reasons for damages. In the flood event August 2002, 16% of the damages in premises of the State of Saxony were caused by groundwater. Infiltration fluxes of overland-flow, flow through sewerage und groundwater flow from the recharge areas can cause increasing groundwater levels. The impacts of fast increasing groundwater level can result in instability of houses by buoyancy effects, infiltration of groundwater in the sewerage, recontamination of soil by polluted groundwater, remobilization of pollutants and endangering of drinking water stations. Therefore an integrated risk management must also include the impacts of flood on the groundwater. One form of risk assessment is the assessment of the groundwater dynamic under conditions of flood. After the risk assessment, the areas of the urban land-use planning can be ranked in areas with temporary protection or general protection against 'groundwater flood'. Therefore, urban land-use planning can be used as a possibility of risk mitigation. Coupled groundwater modelling in urban areas is an efficient way for integrated risk assessment and risk management and will be discussed in a case study in this article.

Problem

Flood events of the last years caused significant damages in urban areas because great values are cumulated in these areas. Groundwater can be one reason for damages. During the flood event August 2002 (the highest for 100 years), 16% of the damages on premises of the Free State of Saxony were caused by groundwater (Figure 1).

Reasons for rising groundwater level can be:

- infiltration of flood water directly into the aquifer,
- infiltration of overland flow in sewer system and following from the sewer system into the groundwater,
- increasing inflow from the recharge areas.

1. Dr. Thomas Sommer: Dresden Groundwater Research Centre (DGFZ); Meraner Straße 10, D-01217 Dresden, Germany; Fon: ++49-351-4050665; Fax: ++49-351-4050679, Email: tsommer@dgfz.de

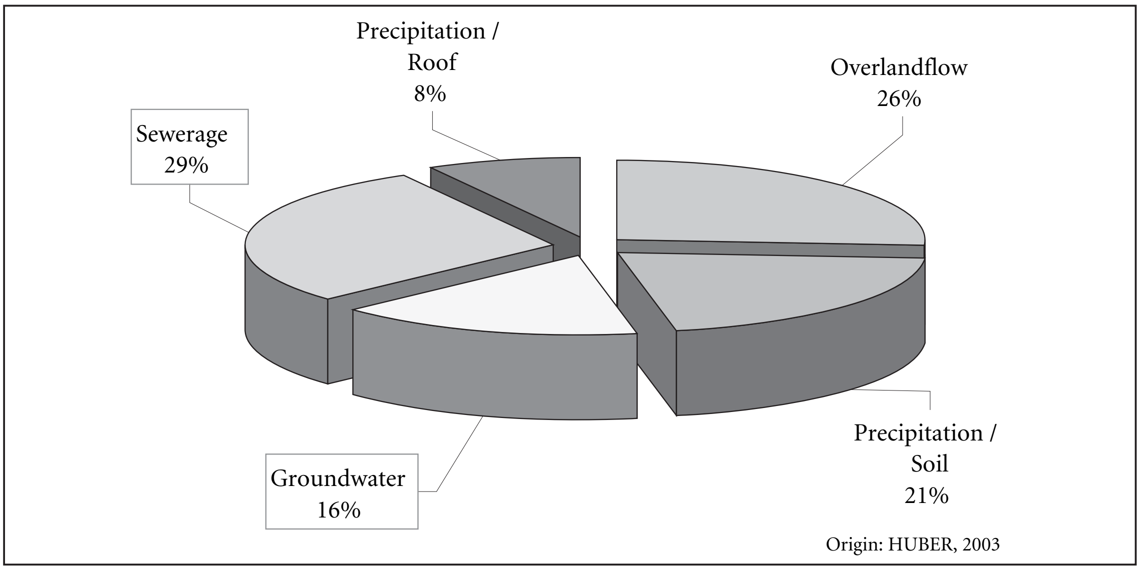


Figure 1. Causes of flood damages during 2002 August flood on premises of the Free State of Saxony (after HUBER 2003)

Study area – Location and hydrogeology

Dresden, capital of Free State of Saxony (Germany) was the study area for the investigations of impacts of flood events on groundwater (Figure 2). The investigation area is located in the Elbe zone. This zone is a tectonic element between the granite massive of Lusitia in northeast and the variscic Ore Mountains in southwest with a direction of strike from northwest to southeast. Cretaceous sediments (sandstone and limestone) are the footwall of the Quaternary aquifer. The Cretaceous sediments form a lower solid rock aquifer, which is not relevant for the interaction between flood water and groundwater.

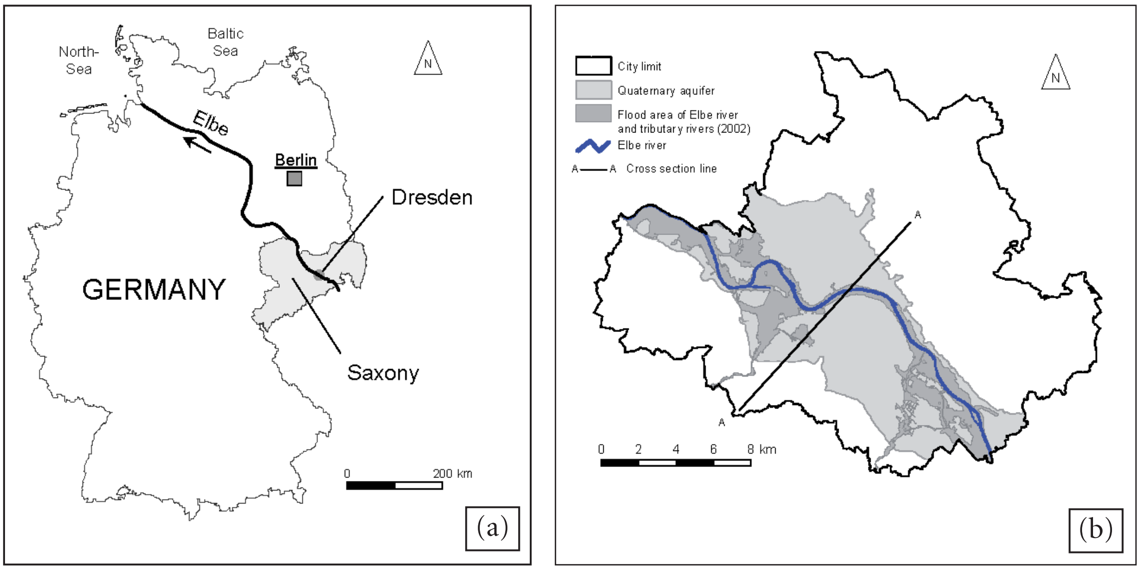


Figure 2. Map of Germany with study area (a) and map of Dresden (b) with line of geological cross section (Figure 3). The quaternary aquifer is the area of investigation

Gravel and sand of the glacio-fluviatile series of Elsterian (Mindel), Saalian (Riss) and Weichselian (Würm) with thicknesses from < 10 m in the south part of the aquifer to 60 m in the north part are the main sediments of the *quaternary aquifer* in the Elbe river valley. The lowest layers are fluviatile and glacio-fluviatile gravel of Elsterian-II-sedimentation with thickness between up to 15 meter. The sediments include rubble blocks with diameter to 80 cm. Permeability of this layer is $> 1 \cdot 10^{-3}$ m s^{-1}. The next layers, sediments of Saalian-cycle consist of sand and fine gravel with thickness to 10 meters and permeability between $2 \cdot 10^{-4}$ and $1 \cdot 10^{-5}$ m s^{-1}. The sediments of the glacio-fluviatile cycle of Weichselian also consist of sand and fine gravel. They build the low-terrace with thickness to 12 meter. Aquicludes between the glacio-fluviatile sand and gravel mostly consist of silt with fine sand, with thickness to 2 meter. The aquicludes are not widespread over the whole area of quaternary aquifer; therefore the aquifer can be seen as a uniform sediment complex. Silt of low-terrace (Weichselian) and Holocene alluvial clay with thickness between 1 and 4 meter are the upper end of the Quaternary profile. These sediments are not widespread over the whole aquifer. The existence of alluvial clay and silt of the lower terrace has an important effect on infiltration of flood water into aquifer.

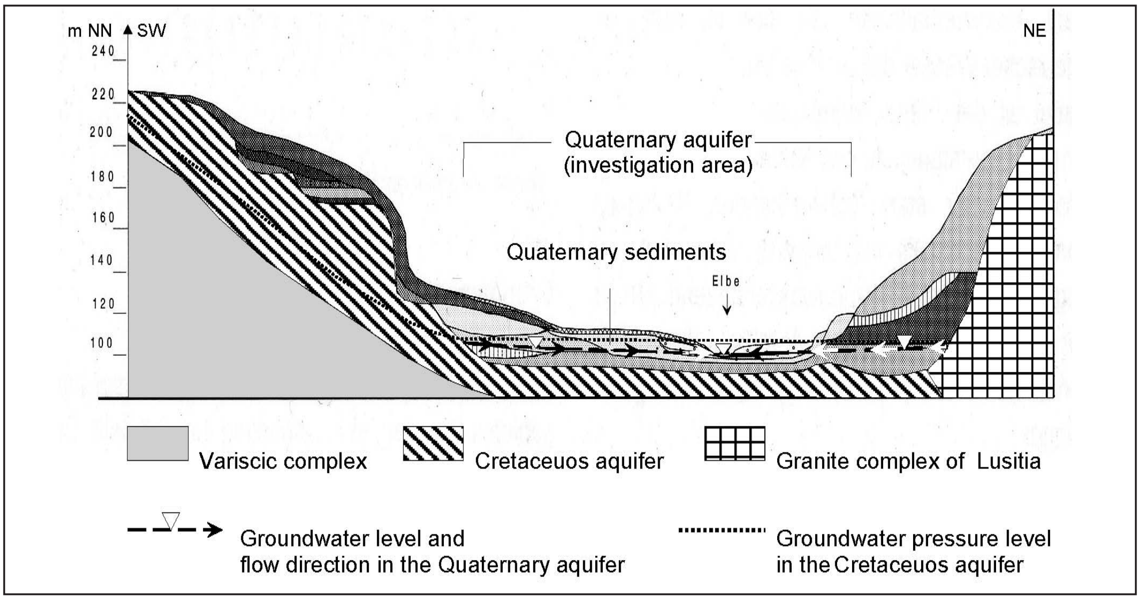


***Figure 3.** Schematic geological cross section through Elbe river valley (after Environmental Office, City of Dresden)*

Impacts

The influence of flood events on groundwater can be subdivided into impacts of groundwater dynamic and impacts of groundwater quality.

Groundwater dynamic

Increasing groundwater level in a short period of time can be the most noticeable effect of the impact of a flood on the groundwater. During the flood event in August 2002, in Dresden the groundwater level increased with a rate of 30 cm/h. Another effect was the remaining of high groundwater level over long period of time. At some measure points, the groundwater level stayed of 1.5 m above the mean high water level for one year or longer (s. Figure 4).

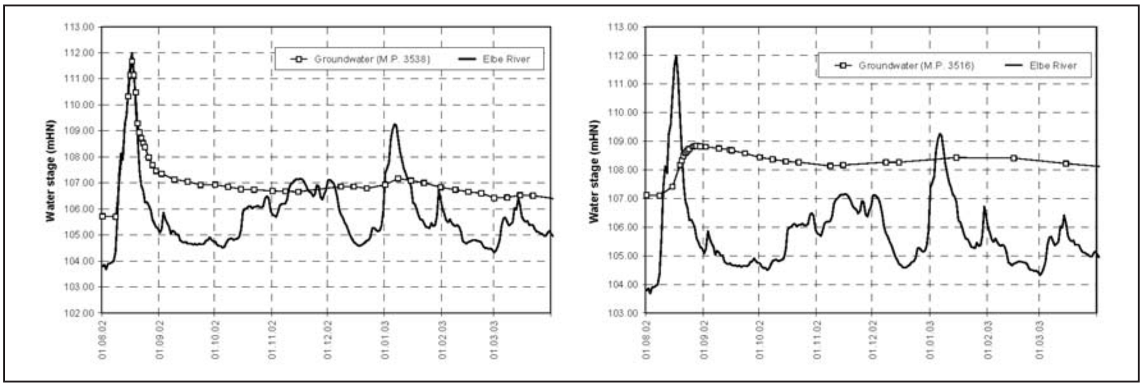


Figure 4. Hydrographs of groundwater and Elbe River in Dresden during 2002 August Flood Data source: Saxon Regional Agency of Environment and Geology.

This groundwater rise directly caused instability of houses by buoyancy effects and infiltration of groundwater into the sewerage. The protection of the instable houses was realised by static extra load. Therefore, it was necessary to leave the water (floodwater or infiltrated groundwater) in the basements for a period of more than one or two weeks.

Groundwater quality

Solution of pollutants from contaminated soils in the aquifer and the reaction of pollutants can be impacts of increased groundwater level on groundwater quality. If contaminated groundwater has contact drinking water wells, the groundwater rise can endanger drinking water supply.

Figure 5 shows two examples for the development of the groundwater quality during and after flood event August 2002.

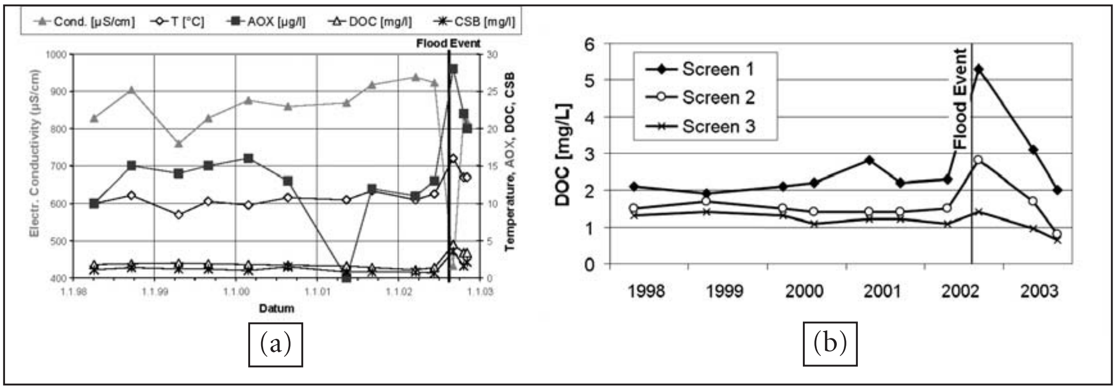


Figure 5. Parameters in near surface groundwater wells under the flood plain of 2002 August flood in Dresden. (a) Parameters in near-surface measuring point (Sommer & Ullrich, 2003); (b) DOC in a three-screen measuring point, Screen 1 – upper screen; Screen 2 – middle screen, Screen 3 – lower screen, thickness of the aquifer about 12 m (Marre et al. 2005).

The analysis of groundwater quality in Dresden during the 2002 August Flood showed two main facts (Marre et al. 2005):

- The groundwater chemistry was affected by infiltrated floodwater for around three months.
- Groundwater quality downstream of pollutant sites did not show consistent trends and was depending on kind of pollution.

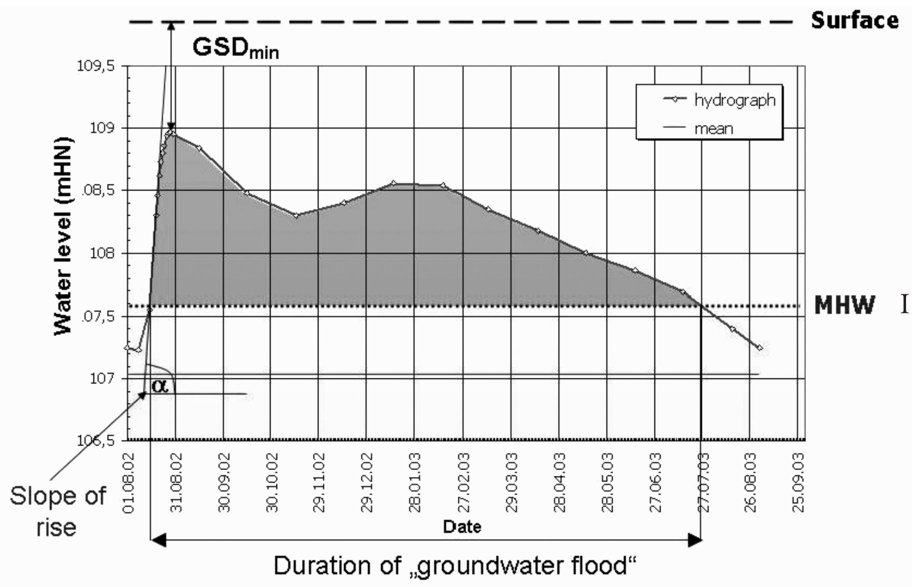
Risk assessment of 'Groundwater flood'

Definition of groundwater flood hazard

Flood risk is the of flood hazard in relation to vulnerability. Flood hazard means the endangerment of an object or building by floods. Vulnerability means the potential of damage in endangered areas, e.g. values of buildings and inventory. Based on these definitions, flood-damage-functions are in use for flood risk assessment. Flood hazard is the product of intensity of the flood multiplied by probability of the event.

These definitions apply to flood by overland-flow. In our context, 'groundwater flood' is defined by rising groundwater and groundwater on a high level over a long period. Therefore, new approaches of flood risk assessment for damages by groundwater flood have to be found.

$$I = [1/d]$$



$$I = \frac{\tan\alpha}{GSD_{min}} \; [1/d]$$

Figure 6. Parameters of 'Groundwater Flood Intensity' I and duration of 'groundwater flood'. The equation gives the definition of 'Groundwater Flood Intensity'.

The groundwater hydrographs were analysed concerning their slope during rise, difference between peak and surface as well as the duration of groundwater level above the mean high water level, based on measurements of groundwater levels during the 2002 flood in Dresden. The intensity I of 'groundwater flood' means the ratio of the slope during rise (tan a) and minimal difference between peak and surface (groundwater surface difference – GSDmin) (s. Figure 6). The intensity and the duration of groundwater flood of the analysed measuring points are mapped in a grid of hazard potential (Figure 7).

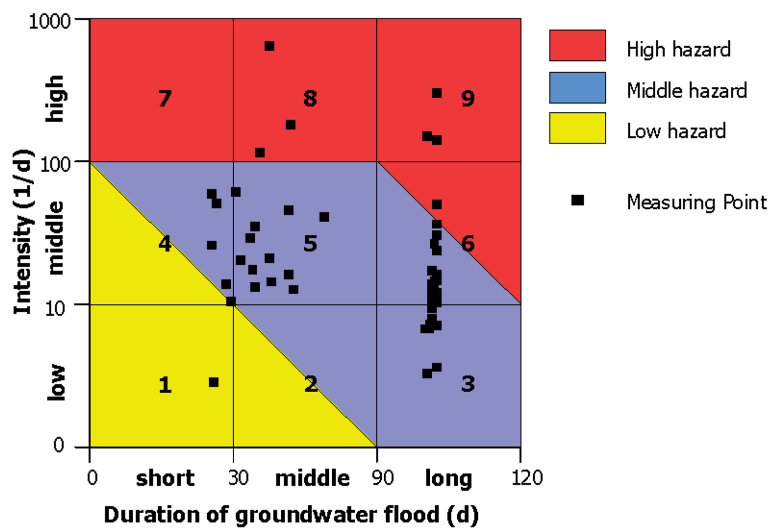


Figure 7. Grid of hazard potential with the measuring points during the 2002 flood in Dresden (Sommer & Ullrich, 2005)

Maps of groundwater flood hazard

The analysis of groundwater flood hazard was made at specific groundwater monitoring wells. Generation of groundwater flood hazard maps is the next step. Figure 8 shows a map of groundwater flood hazard, based on the classified groundwater monitoring wells. The classification of the wells was deduced from the position of the measuring point in the hazard grid (Figure 7).

For some monitoring wells the groundwater flood hazard had to be estimated, due to the small database of groundwater dynamic parameters during the flood event in august 2002 in these wells.

Risk mitigation of 'groundwater flood'

Risk assessment of groundwater flood is a necessary basic for risk mitigation of groundwater flood in urban areas. After regionalising subsurface hazard potential, it was possible to create maps of groundwater flood hazard. The aim of these maps is to indicate areas with need of protection of basements against groundwater flood. Flood control and flood prevention strategies will be configured as a pyramid of measures (Figure 9). ***Temporary flood control*** means measures during flood against damages caused by rising groundwater, e.g. groundwater drawdown as well

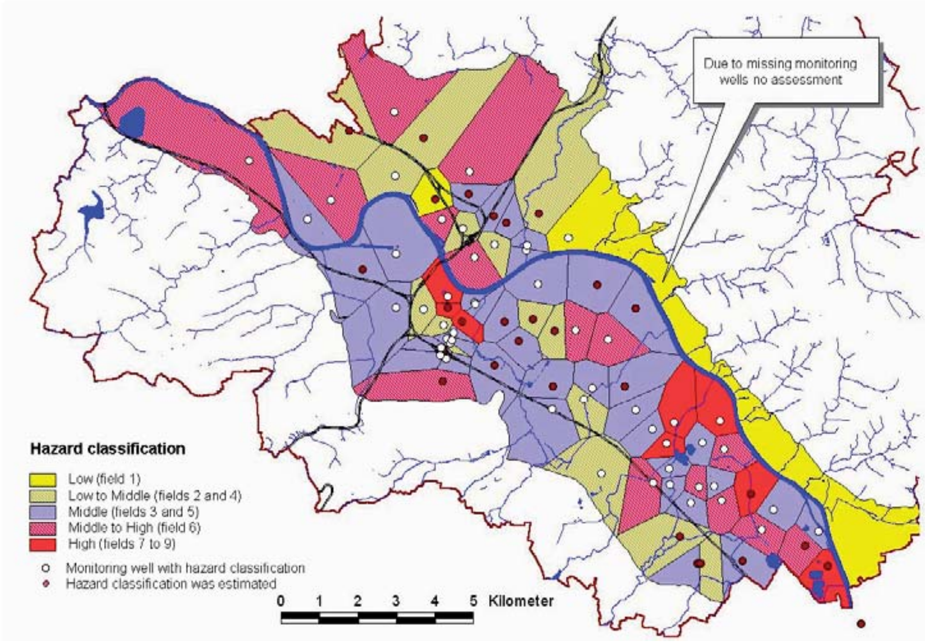


Figure 8. Map of classified groundwater flood hazard. The field numbers are the field numbers in the grid of hazard potential (s. Figure 7)

as loading or basement flooding. ***General flood control*** means prevention measures on building, e.g. 'White basements' or buildings without basement. Concerning the groundwater flood hazard grid, the temporary flood control measures are recommended in areas with long duration of groundwater flood (fields no. 3 and 6 in Figure 7). General flood control measures are recommended in areas with high intensity of groundwater flood (e.g. fields no. 7 and 8 in Figure 7). While the building owner is responsible for temporary and general flood control measures, the communal authority should decree restrictions for buildings or prohibition of basements by urban land-use planning for areas with high hazard potential.

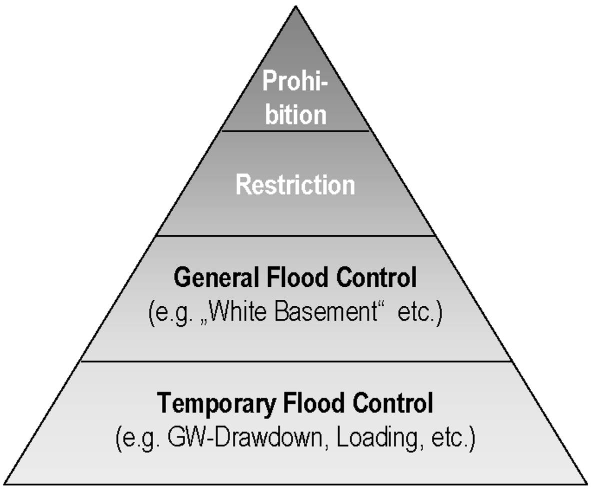


Figure 9. Graduation of control measures against groundwater flood in urban areas (Sommer & Ullrich 2005)

Modelling

The described strategy of assessment and mitigation of groundwater flood risk has been developed on the 2002 flood event in Dresden. The next step is modelling of scenarios of groundwater flood caused by flood events. These scenarios should integrate the different reasons of groundwater rise during flood events.

Therefore, integrated flood risk management in urban areas requires simulating all relevant flow processes including runoff, flow through sewerage, and groundwater flow. While individual solutions for one or at most two coupled processes exist, there is still a lack of modelling more complex systems that integrate all three flow regimes.

Coupled modelling systems will be helpful instruments to calculate the impact of floodwater and sewerage water to groundwater. An hydrodynamic model (TrimR2D) will calculate the spatial distribution of the runoff as input parameter for the groundwater model and the sewer system model. The programme HYSTEM-EXTRAN is a modelling system for the flow in the sewer system. The codes RisoSurf and HAMOKA calculate the overland flow and the flow in sewerage in local areas with high resolution. The programme PCGEOFIM calculates the groundwater flow with interaction to overland flow and flow in sewerage. The coupling software MpCCI manages communication between the single models. The communication comprises synchronisation of the tools, mapping between the different model geometries, and the interpolation between the different time scales of the involved processes (Figure 10).

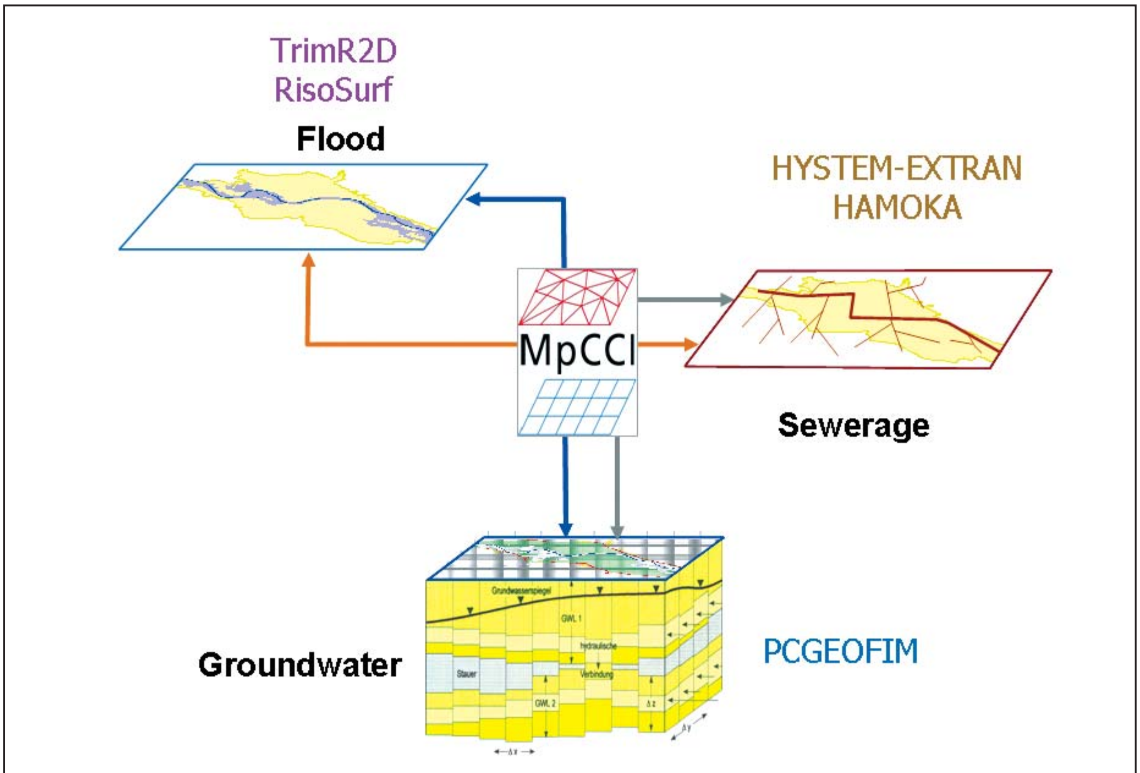


Figure 10. Strategy of coupled modelling with the names of the coupled modelling programmes (GRIMEX 2006)

A reliable process analysis is the beginning of model coupling. The process analysis has two main steps.

The definition of the relevant water flows between the individual components of the flow system is the first step. It includes the diverse states depending on the expansion of the flood. Each of the individual models works with its own set boundary conditions (INPUT/OUTPUT).

The definition of the period for the coupled modelling is the second step. In Dresden the river Elbe overflows at a level of circa 5 m at gauge Dresden. This date is the start of the coupled modelling. The end of the coupled modelling is various. The interaction between the groundwater model and the flood model stops when water level of river Elbe decreases below 5 m at gauge Dresden. Below this level the groundwater model and the flood model compute without coupling. The period of communication between sewerage model and groundwater model depends on the level of the groundwater table relating to sewerage attitude.

The picture of a test model shows the coupling approach (Figure 11). The test model includes all relevant processes of the interaction between the three main flow paths overland flow, flow in sewerage and groundwater flow. The part of overland flow comprises the main river, a tributary stream and a closed depression without outflow. The sewerage lies under and outside of the flood area. The upper layers of the groundwater model must be subdivided into thin layers because the processes of interaction between groundwater and sewerage and accordingly the infiltration of surface water are focused in these layers.

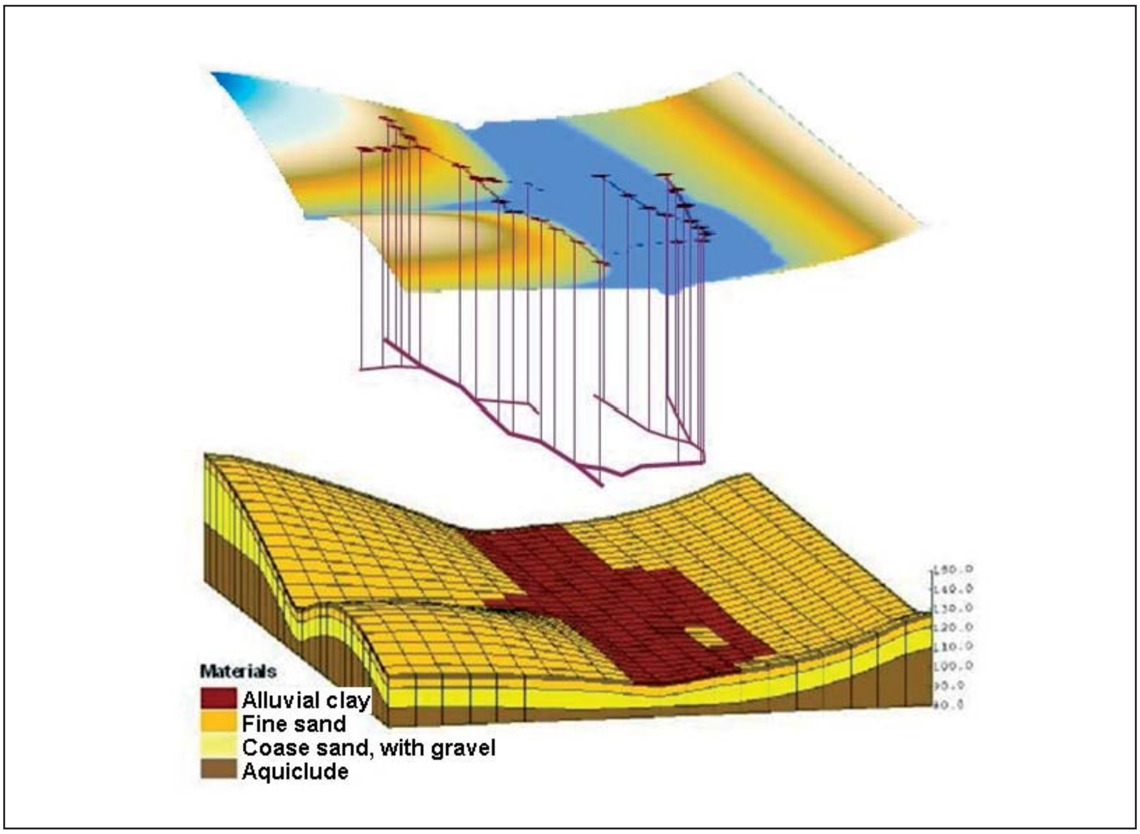


Figure 11. Example for coupled models (GRIMEX 2006)

The main aim of the coupled modelling is to detect relevant flows between the overland flow, the flow in the sewerage and the groundwater flow.

The coupled system will contribute to holistic flood risk management and will support planning of measures for preventive protection of the subsurface infrastructure.

Acknowledgements

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DROUGHT: IDENTIFICATION, INVESTIGATION, PLANNING AND RISK MANAGEMENT

Balthazar Th. Verhagen[1]

Abstract: Drought is a recurrent phenomenon in all climates and can affect both developed and developing populations. Yet, it is difficult to define, as it is a relative concept. This paper examines different definitions of drought. It looks at the impacts of meteorlogical drought and and consequential impacts, criteria for its mitigation, the use of drought vulnerability mapping, early warning systems of the onset of drought and triggers for the various mitigation steps to be taken. A brief overview is given of two case studies in South Africa in which potential emergency groundwater supplies were identified making use of environmental isotope techniques.

Introduction

In preparing this introductory talk, I delved into a large variety of sources and began to appreciate the daunting intricacy of the phenomenon of drought. Even more daunting is addressing the complex issue of drought planning, preparedness and mitigation. The interrelation of a miriad of factors determines its impact as well as the large variety of responses originating in the spectrum of lifestyles, cultures, economies and infrastructures of the people affected.

Often I thought that I had a clear appreciation of and even a strong opinion on, a certain aspect of drought mitigation and in particular the role of groundwater – the subject matter of GWES – only to find on further reading and reflection that I had changed my mind.

I therefore present to you a compendium of the material I have waded through, hopefully with some coherence and personal insight thrown in here and there. My presentation will not pretend to be an exhaustive resumé of the subject, only work in progress. I hope it will act as an adequate framework for the case studies to be presented and perhaps will generate some debate.

1. Dr. Balthazar Th. Verhagen, Honorary Research Fellow, School of Geosciences, University of the Witwatersrand, Johannesburg, South Africa. Email: verhagenb@geosciences.wits.ac.za

Tehran Regional Drought Seminar 2001

A Regional Seminar on Drought Mitigation was held in Tehran 28 – 19 August 2001 with the theme: 'The current cycle of drought is the worst in 30 years. Persisting droughts highlight the need to discuss and evaluate national programmes against drought'. Participants were drawn from a large range of countries, such as Iran, Afghanistan, India, Pakistan, Tajikistan and Uzbekistan and representatives and of agencies such as ERD Senior advisors, FAO, Global Mechanism of UNCCD, UNESCO, UNHCR, UNIC, UNICEF, OCHA, WFP, WMO etc.

Issues addressed in the seminar included: national strategies for emergency response; experiences of participating countries in preparing for droughts; food security and consequences of drought; water management policies from a national and regional perspective and the establishment of links for regional drought response.

The conclusions/recommendations included a few strategies that countries can adopt to mitigate the effects of drought, such as:

- Reducing hazard (prevention) e.g. better water management, irrigation water efficiency, reduced consumption;
- Reducing vulnerability (mitigation). e.g. crop substitution; balance livestock and rangeland production; avoiding urban growth exceeding water availability;
- Optimal use of watershed management e.g. water harvesting, spreading and conservation;
- Increased public awareness e.g. efficient water use; rangeland and watershed management;
- Establishment of early warning system especially vulnerability warnings and drought information networks.

It is noteworthy that the 2001 Tehran seminar report does not specifically deal with the role of groundwater in drought emergency preparedness and mitigation. It is gratifying that in the present Tehran 2006 GWES workshop so many contributions have been forthcoming from the region *specifically on groundwater* under the theme of drought.

A lesson from southern Africa

In 1992 I was invited to present a series of lectures in an IAEA regional training course on isotope hydrology in Harare, Zimbabwe. The years 1991 and 1992 have gone down in the annals as the worst drought that the region experienced since records were kept, worse than the recent drought of 2004/2005 which was only partially responsible for Zimbabwe's present famine and general economic and humanitarian disaster.

As part of the 1992 isotope course the participants were taken on a field excursion into the countryside. Amongst them were west Africans from the arid Sahel region. They were amazed and puzzled: 'look how green everything is, and this is supposed to be a terrible *drought* ?' they asked incredulously.

This underlines the vagueness of the concept of 'drought', and the difficulty in defining the term. Conditions at the time in Zimbabwe constituted a severe *agricultural* drought, the failure of dryland crops, that affected mainly the small-scale traditional farmers in the so-called communal areas.

These farmers, who in good rainfall years produced enough maize to market and feed the entire internal consumption of the country, could not even produce enough food for their own families. On the other hand, the natural vegetation, which is lush in that part of the world, had not yet begun to be stressed. The stage of a *hydrological* drought had not yet been reached.

The mainstay of Zimbabwe's economy used to be agriculture. The *commercial* farmers, who ran their large farms as businesses, had developed a good infrastructure – in particular irrigation, which to a large extent is based on groundwater. These farmers concentrated largely on export crops, which were responsible for the country then being labelled the 'breadbasket' of the region.

Of course, the commercial farmers had to irrigate more in the drought years 1991/2 but – and that is the point – they were able to bridge the gap left by the failure of the traditional farmers, as happened during earlier dry periods. Disaster was avoided, and the country did not go hungry – then.

The ideologically-based land re-distribution campaign that started in the year 2000 saw the wholesale eviction of commercial farmers from their land. With the resulting collapse of the agricultural infrastructure, the country became totally exposed to the ravages of the less severe 2004/5 drought. Agriculture collapsed, the knock-on effects on the economy crippling support systems down to the level even of drinking water supply.

There are lessons to be learnt from the recent history of a once thriving country such as Zimbabwe…

- The principal lesson is that supply infrastructures are intrinsically vulnerable and need stable social and emergency support systems;
- A further lesson is that with proper national management the catastrophic consequences of natural stresses can be mitigated – what works in normal times can be applied during droughts;
- Third lesson is that human conflict, even internal political instability, can play havoc with an entire country – to the extent that even emergency drinking water supply is affected.

Unique aspects of drought, as opposed to other emergencies

- Drought emergencies tend to *differ from other emergencies* (e.g. floods, earthquakes) in the rate of their onset, duration, and knock-on effects;
- Even the *definition* of what constitutes a drought can be vague;
- Drought – the lack of precipitation – may (or may not, depending on how long and severe it is) affect soil moisture, streams and, eventually, groundwater;
- The criteria for the development and management of drought emergency groundwater supplies do not differ substantially from those of normal sustainable groundwater resources ;
- The two terms: *drought* and *aridity* should explicitly be separated:
  - Drought is a recurrent natural climatic event, occurring in all geographical zones (Figure 1), but its characteristics vary significantly from one region to another,
  - Aridity (low annual rainfall) is a perennial condition of a geographic region, which can experience periods of more extreme aridity, or drought.

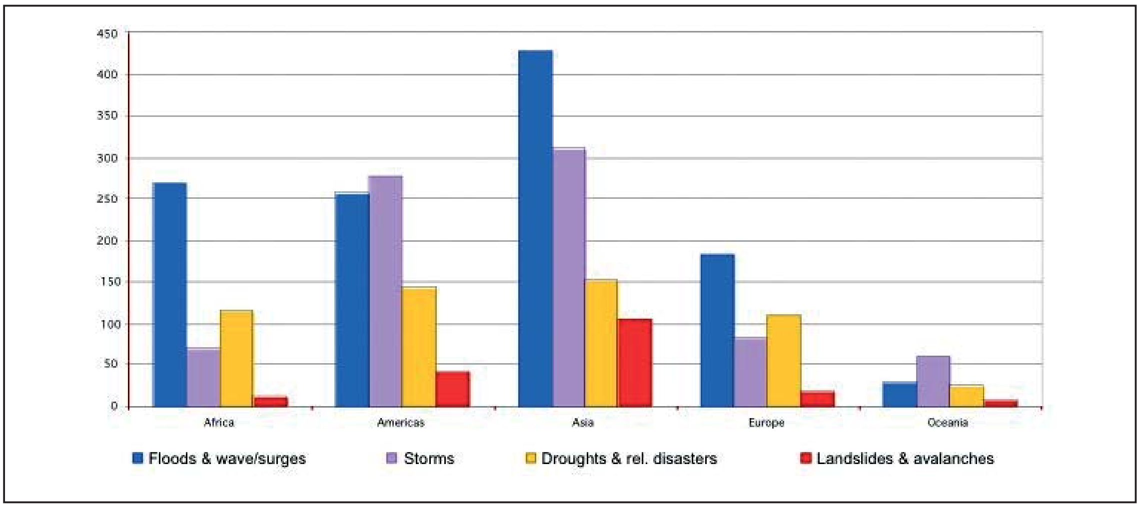


Figure 1. Great natural disasters 1950 – 1999 (GWES 2006)
(Note: similar prominence and occurrence of drought in all environments)

Operational definitions of drought

- identify the beginning, end, spatial extent and severity of a drought,
- are often region specific and are based on scientific reasoning, and are beneficial in developing drought policies, monitoring systems, mitigation strategies and preparedness plans (SADC 2003):
  - *Meteorological drought.* Every drought event effectively results from the lack of precipitation. Depending on its duration and intensity (Figure 2), meteorological drought may or may not develop into agricultural or hydrological droughts,

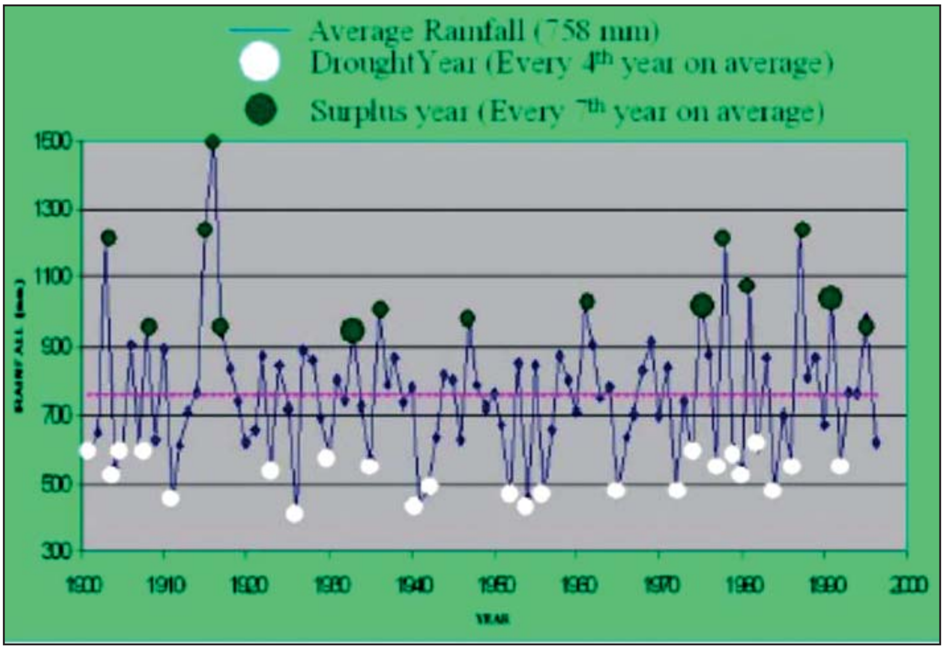


Figure 2. Example of long-term rainfall data: 20th century in Andra Pradesh, India. On average, every 4th year is a drought year. However, there are longer periods during which drought years predominate (GWES 2006)

- *Agro-meteorological (agricultural) drought.* An agricultural perspective on water shortages. Natural vegetation may not yet show moisture deficit stress but root-zone soil moisture is insufficient to sustain crops between rainfall events in dryland agriculture,
- *Hydrological (flow and groundwater) droughts.* Impacts on hydrological systems are referred to as 'flow drought'. 'Groundwater drought' – lagging behind the deficient precipitation – is a rather subjective and vague concept often due to the lack of long-term data on e.g. groundwater levels,
- *The response of groundwater to meteorological drought* is poorly understood, and may be out of phase with other impacts, due in part to the unique complexity of hydrogeological systems.

Impact of a meteorological drought

The impact of a meteorological drought on groundwater may depend on many different factors, including:

- *Severity and duration of the drought episode*. If groundwater responds slowly to rainfall deficit it generally also recovers more slowly after drought, resulting in complex and seemingly unrelated linkages between rainfall and impact on groundwater resources.

- *Design and location of the groundwater well or borehole*. Hand-dug wells may be expected to be more sensitive to recharge variations than deeper boreholes. Drought will thus impact sources that are shallow, that rely entirely on seasonal storage replenishment, significantly more quickly than sources that tap deeper groundwater.

- *Hydraulic characteristics of the aquifer.* The connectivity of the aquifer to recharge sources and the storage properties of the aquifer itself. In basement aquifers connectivity may be good but aquifer storage can be highly variable and will depend to a large extent on the degree of near-surface weathering. In more productive, unconsolidated aquifers. the source may be able to meet even the high demands placed upon it during a drought.

- *Excessive demand and source failure.* Often, sources are sufficiently few in number for abstraction not to exceed *long term* aquifer recharge. Localised depletion during drought makes failure of the pump more likely, increasing demand on a neighbouring source, thus increasing stress and probability of failure – exacerbated by poor maintenance as relief drilling programmes take priority.

- *Long term increases in demand.* Long-term increase in demand can eventually push seasonal and drought-related fluctuations to such a level that demand will exceed supply. The cause may be population growth (natural, or as a result of migration), or economic change, such as the introduction of irrigation or other water-intensive activities.

- *Long term changes in climate* affect recharge processes and put both high and low yielding sources at risk. Recovery of groundwater depends upon adequate recharge during subsequent rainfall periods. Removal of vegetation and erosion of the soil cover as a result of climatic and demographic changes may increase runoff and reduce recharge.

Specific topics

Specific topics of drought risk assessment and mitigation that could be elaborated in the discussion, some of which feature in this workshop:

- Actual and potential effects of climatic change in scenario building,
- Instituting programmes of ground water monitoring and historical data collection to establish long-term information on existing ground water systems,
- Developing programmes of ongoing testing, maintenance and renewal of existing production wells and equipment,
- Through GIS, hydrogeological and geophysical techniques, identify aquifers potentially able to act as emergency supplies,
- Hydrogeological, hydrochemical and isotope hydrology techniques to evaluate vulnerable areas and especially deep aquifers for emergency supply (e.g. Verhagen et al. 2006),
- Establishing emergency supplies from deep aquifers; deepening existing boreholes to extend their supplies through drought (SADC 2003); setting aside wells in sections of aquifers for emergencies,
- Developing integrated risk management strategies, including longer-term demographics, and agriculture which address short to medium term sustainability of emergency supplies.

Criteria for a drought emergency groundwater supply

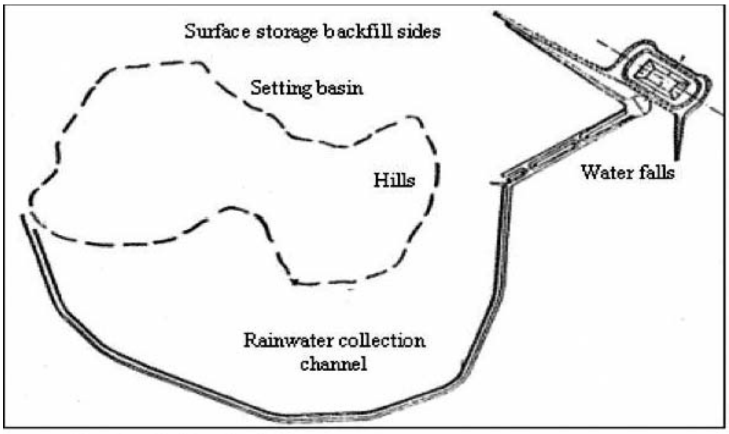
The criteria for a drought emergency groundwater supply have features in common with those of a normal, sustainable and protected groundwater resource. Water requirements under a drought emergency differ substantially from those of volcanic eruptions, earthquakes, floods or tsunamis. In these, normal supplies are interrupted or degraded abruptly, the emergency supply having to deliver at a sufficient rate for weeks, up to a few months

The onset of a drought is usually gradual and it may take some time to tighten its grip, setting off a series of 'triggers', activating the emergency supply as normal, existing supplies begin to fail. It will then have to deliver for at least a year, under conditions of water use restrictions and involving other innovative water supply measures (Figure 3) – often much longer, as normal supplies will take time to recover

It should furthermore be kept in mind that emergency groundwater supplies will themselves experience the longer-term effects of the drought; the reduced or zero rain recharge having to be factored into the sustainability assessment

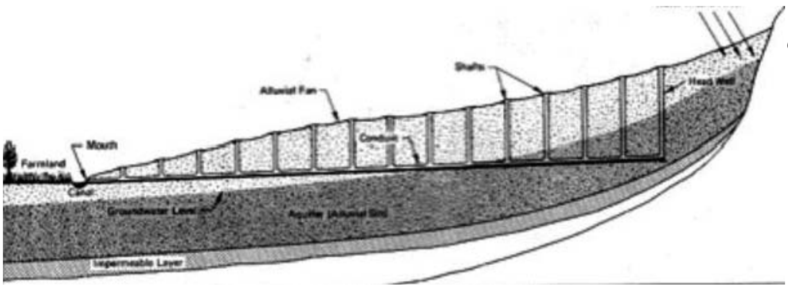
Where there is little or no anthropogenic threat of eg. pollution, protection will be a second-order concern as the emergency situation, in itself, is not threatening the infrastructure. Deep groundwater resources will therefore not necessarily be a primary target, except where, when available, their sustainability has been assessed, e.g. in terms of residence time and of storage

All sources, shallow and deep, will have to be considered, depending on the hydrogeological and demographic situation. As such resources will have to be kept in reserve, strict management control will have to be exercised. Drought-prone communities tend to be vulnerable in other ways, and the longer-term temptation of utilising emergency supplies will be great. This might even be the case in urban environments, where there could also be pressure from commerce and industry (Figure 4).



a) Hafir rain water runoff harvesting and storage systems of N Africa and the Middle East

b) Gatdamme – a South African innovation for rainfall harvesting from playa lakes and storage in excavations (E. van Wyk, priv.comm..)



c) Qanats: traditional and sophisticated systems of gravitational groundwater harvesting of the Middle East (Prinz et al. 2000)

Figure 3. Some traditional surface/groundwater harvesting systems

As sustained exploitation will be the norm during a drought emergency, it is important that exploitation will be sufficiently diffuse to prevent the 'pump failure domino effect'. Furthermore, pumps and boreholes will need to be regularly tested and maintained on an ongoing basis to ensure their full operation when required.

The long-term behaviour of the aquifer needs to be understood. Sustainability both both in quantity and in quality needs to be assured. Even where exploitation is maintained to balance recharge, long-term hydraulic disturbance can cause the eventual drawing-in of lower quality or saline water in the same aquifer (Figure 5).

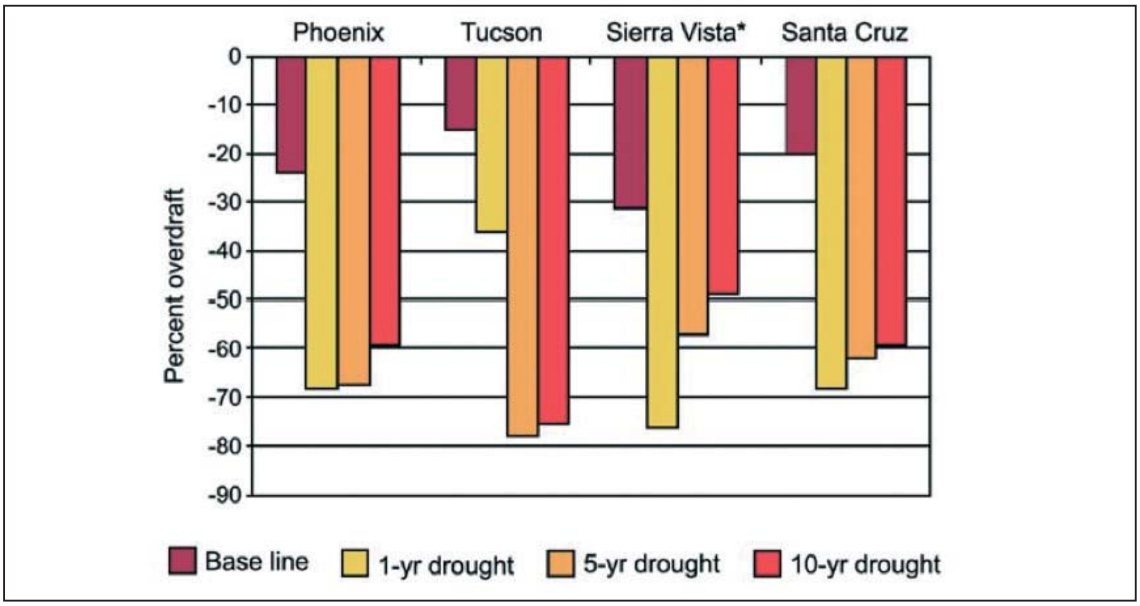
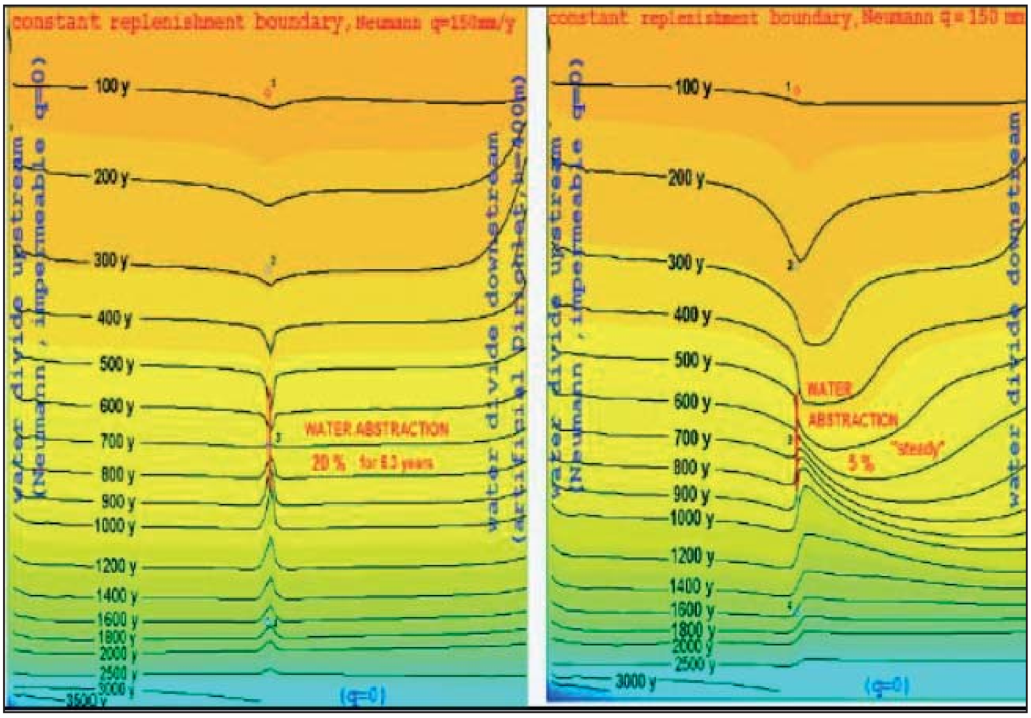


Figure 4. Urban groundwater drought impact study – Arizona (FY 2003).
A study of how severe future drought impacts would be based on records of severest o ne-year (1900), five-year (1914-19), and ten-year (1946-1955) droughts. Stringent groundwater management is mandated under the 1980 Arizona Groundwater Management Act. achieving 'safe yield,' although supply and demand balance remains uncertain. Future severe droughts are shown to have the potential to cause significant economic and social impacts.



Abstraction from 150 m at 20% MAR
for 6.3 years - little disturbance of isochrones

Long-term abstraction from 150 m at 5% MAR
- major disturbance of isochrones

Figure 5. The effect on isochrones (lines of equal groundwater age) of short-term intensive and long-term moderate abstraction from a phreatic aquifer with water quality stratification after K.P. Seiler (GWES 2006)

Drought Vulnerability Maps

Drought vulnerability maps, as useful management tools, should include a variety of influencing factors. They are central to the optimum use of groundwater during drought and should indicate regions which are more vulnerable to *groundwater drought.*

Key determinants are:

- aquifer type,
- depth of the weathered zone,
- well and borehole yields,
- rainfall (amount and variability.

These factors alone do not determine vulnerability to groundwater drought. Some *communities* will be more vulnerable to groundwater droughts than others. e.g.:

- low water supply coverage and high population density
- areas heavily dependent on traditional sources
- Vulnerability maps incorporate different indices, or 'layers' and typically present the superposition of two sets of information:
    - a *sociological* dataset that analyses the distribution of demand,
    - a *physical* dataset that identifies resource availability and ease of access (Figure 6).
    - help in identifying vulnerable communities,
    - target these communities to provide drought proofing in pre-drought periods,
    - ensure appropriate drilling methods and design of wells and boreholes (see various examples in Figure 7).

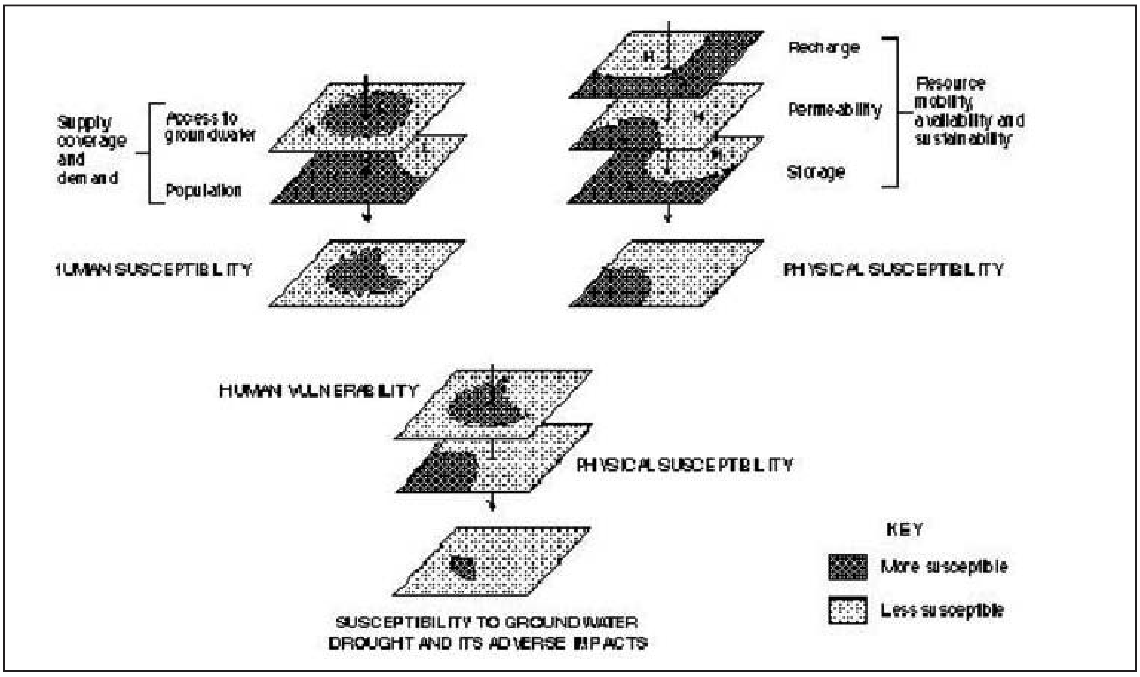
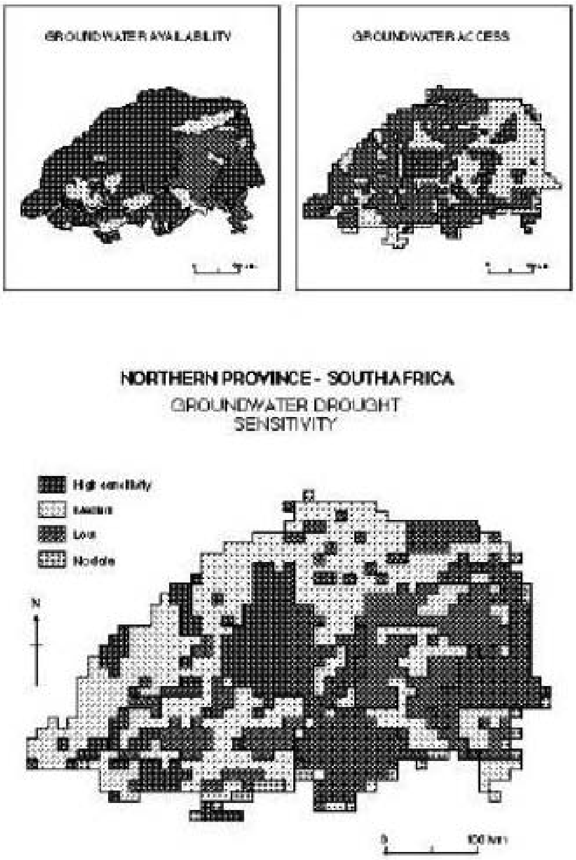
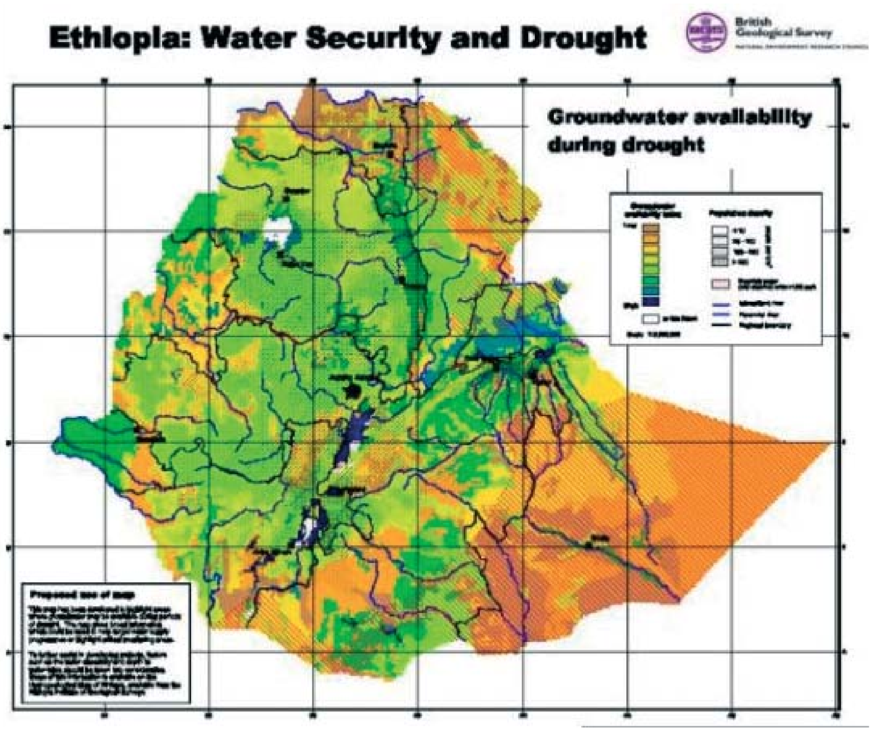


Figure 6 . Superposition of human (social) susceptibility and groundwater resource geographic factors produce a map of drought susceptibility/vulnerability (SADC 2003)



a) Northern (Limpopo) Province of South Africa. Former 'homelands' are at risk due to a combination of skewed ideologic demographic coverage, concentrated demand and difficult hydrogeological conditions (SADC 2003)



b) Ethiopia groundwater vulnerability map. Groundwater conditionss in colours are overlain by demographics as.shading (BGS 2001)

Figure 7. Examples of drought susceptibility / vulnerability Maps

Communities can themselves make choices of different water supply options, or menu:

- the menu ensures that options are appropriate to hydrogeological conditions,
- maps provide a useful focus for coordinating different organisations undertaking water supply projects, prompting discussion and exchange of data and ideas on water supply priorities.

Drought early warning systems

- The concept of drought vulnerability mapping and its issues are separate from issues of **early warning** based on longer-term meteorological forecasting.

- Adequate early warning systems are often in place with regard to regional food security and *meteorological* drought.

- No comparable systems are usually in place to predict the onset of *groundwater* drought.

- Groundwater drought early warning can be carried out at two levels:
    1. the global level (international meteorological community) – climate and climate variation, including possible long-term change;
    2. a regional scale (governments, donors and NGO's) – local signals flag progress of ground-water drought and likely consequences given certain courses of intervention.

- Meaningful groundwater drought early warning is tied to reliable data and long term meteorological and hydrological trends.

- Basic requirements are to:
    a. compile and analyse data from observational networks,
    b. determine user needs in terms of specific data requirements,
    c. develop triggers and an early warning system,
    d. identify drought management areas.

- Early warning systems require
    a. monitoring data for antecedent meteorological and hydrological conditions,
    b. groundwater indicators (e.g. water levels and yields).

- thresholds once exceeded should trigger actions defined in the drought plan.

- indicators of water stress could also be incorporated eg. incidence of water-related diseases from clinics.

Drought mitigation triggers

- During prolonged drought periods, supply and demand may become greatly imbalanced, with water demand exceeding available supplies. The goal of an emergency response plan must be to balance demands with remaining available supplies for the duration of the event.

- The greatest difficulty will be to know when to implement these measures. Therefore, drought indicator criteria or *triggers* have to be developed which will accurately identify the onset of drought occurrences in a timely fashion.
- Drought triggers and responses should be staged with progressively stricter and more severe response measures reserved for truly emergency situations.

- A good drought contingency plan would consist of a series of staged water supply extension and water demand reduction measures which would be triggered by monitoring key sources of supply.

- A number of drought indicator parameters are available for monitoring and triggering drought stages. These include reservoir storage levels, groundwater levels, and streamflows. Regional drought indicator criteria such as accumulated precipitation deficiencies, and soil moisture indices may be used in combination with individual system supply indicators.

- Central to our discussion in GWES is the utilization of an *emergency source of supply*. This could simply involve bringing on line a reserve well for temporary use and/or it could entail the temporary development of a variety of new sources of supply such as springs, reservoirs, lakes, ponds.

- A well-conceived drought contingency plan can greatly enhance the provision of adequate potable water for the health and safety of the population, even during moderate to severe drought events. The adoption of a drought contingency plan prior to drought events may eliminate the need for emergency meetings as well as the confusion and indecisiveness that often accompanies last minute planning efforts.

- To sum up – effective planning can facilitate the transition into and out of drought events.

Case studies of emergency groundwater resource identification

Amongst the tools available to identify and assess groundwater supplies for emergency situations, *environmental isotopes* are increasingly being employed. Two case studies from South Africa are summarised briefly to illustrate the multi-disciplinary approach, with isotope hydrology as a major component, to identify potential resources in water-stressed, drought-prone areas.

Both these studies were undertaken to improve the assessment of identified and exploited resources. In both, isotope hydrology, allied with hydrochemistry, geohydrology and geophysics, revealed more extensive resources potentially suited to emergency supply

The Western Cape has been recognised as a region likely to experience increasing frequency and severity of drought with progressive global warming. The highly metamorphosed quartzitic sediments of the Table Mountain sandstone are pure fracture aquifers. In a high mountain valley, a small well field had been exploited at balance with recharge and spring flow for several years. Lithological structure studies allowed an estimate of the volume of water held in the country rock above the spring datum level. Stable isotope measurements prove the connection through deep, albeit sluggish, circulation between such mountain catchments and minor thermal springs in intermontane valleys. Reliable radiocarbon values provide a mean residence time of some 1700 years for groundwater in the catchment, which should have a storage of some 12x the structural estimate for drainage by the spring. A substantial, renewable and protected resource of high quality water therefore exists in the deep keystone fracturing of the anticline, that can be tapped through deep wells to act as an emergency supply for drought relief in the highly seasonal rainfall regime of the area.(Verhagen et al. 2004).

Limpopo Province is a semi-arid area with growing problems of water provision to an impoverished, semi-urban rural population. Shallow, phreatic groundwater is encountered mainly in basaltic and metamorphic crystalline rocks, often at unacceptably high nitrate levels. In a sustainability study of a proposed groundwater supply scheme, environmental isotopes and hydrochemistry, allied with hydrogeological and geophysical studies, proved that the recharge rate of a basalt aquifer was of the order of 10% of the originally assumed value, placing the viability of the scheme in doubt. Anomalously low radiocarbon values observed along sections of a regional fault, associated with depleted stable isotope values encountered along a mountain range 25 km further southwards, suggested that an important part of the regional groundwater transport is occurring through deeper sandstone, previously dismissed as being a poor aquifer. Test drilling revealed that, contrary to expectations, the sandstone is a high-yielding, dual porosity aquifer producing high quality water. Test wells are already pumped as an emergency supply for a small town. Further studies are underway to produce a management model for the conjunctive use of the two aquifers to maintain acceptable supply quality (Verhagen et al. 2006).

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THE DROUGHT OF 2001 AND THE MEASURES TAKEN BY YAZD REGIONAL WATER AUTHORITY

Ali Asghar Semsar Yazdi [1]
Majid Labbaf Khaneiki [1]

Abstract: The climate condition of the central plateau of Iran is so vulnerable to any fluctuation in the amount of rainfall that can frequently bring about severe droughts. This paper presents some facts about the drought of 2001 which gripped nearly the whole province of Yazd and inflicted damage on agricultural and industrial sectors. Therefore, it is necessary to establish an integrated drought monitoring and data acquisition system in order to provide early warning of impending drought so that government and people can contemplate appropriate mitigation and reasonable reaction in a timely manner. This paper briefly takes up the basic concepts in terms of drought and then some facts about the nature of drought in Yazd and how it was managed.

1. Definition of drought

Drought is a normal, recurrent feature of climate, although many consider it as a rare and random event. A drought may pass quickly or last a decade and ruin tens of millions of hectares of farmlands, so in the course of human history droughts have been responsible for the end of numerous civilizations.

Drought is a condition of moisture deficit sufficient to have an adverse effect on vegetation, animals, and man over a sizeable area (Warwick, 1975). To determine the onset of a drought we should take into account the average annual precipitation in a given area as well as the basic water demand of agricultural and industrial sectors in the same area.

1. Dr. Ali Asghar Semsar Yazdi and Majid Labbaf Khaneiki, International Center on Qanat and Historic Hydraulic Structures (ICQHS), P.O. Box: 89165-1553 Yazd, Iran. Tel. and Fax: 0098-351-8250553.

2. Chronologic and locative characteristics of drought

2.1 Onset and termination of drought

Though its onset and termination are difficult to determine because there is no single definition for drought, but we can consider some criteria to limit this natural event. The drought would start when the moisture stored in soil is over and the crops no longer have any water around their root area to feed on, and it would end when a rainfall occurs being able to provide the crops with sufficient moisture. It means the drought is at an end, when the dry rivers begin running and the groundwater reserves begin being recharged.

2.2 Intensity of drought

Intensity of drought is related to two factors; 1) how much the amount of precipitation drops in comparison with the average number 2) how long the dry condition persists.

2.3 Frequency of drought

Frequency of drought means the number of droughts that came up during a given period. Calculating this factor enables us to better predict the coming droughts. For example if we consider a period of 10 years and then our data show two significant departures from the average, so we can deduce that there are two droughts. In this case frequency of drought is 2 during the period or 20 percent. The drought indices make it easy to spot the droughts over a given period, taking the climatological data into account.

2.4 Regional extent of drought

This term refers to a given area which is less and more under the influence of the scarcity of rainfall.

3. Drought index

In fact a drought index assimilates thousands of data on rainfall, runoff and other water-supply indicators into a comprehensible picture. A drought index is typically a single number, far more useful than raw data for decision making. There are several indices such as Palmer Drought Severity Index (PDSI) (Palmer, 1965), Crop Moisture Index (CMI), Surface Water Supply Index (SWSI)(Shafer and Dezman, 1982), Standard Precipitation Index (SPI) and Reclamation Drought Index (RDI / USBR)(Salamat, 2001), that measure how much precipitation for a given period of time has deviated from historically established norms. Some indices are better suited than others for certain uses. For example, the Palmer Drought Severity Index (PDSI) has been widely used by the U.S. Department of Agriculture to determine when to grant emergency drought assistance and the PDSI is better suited for large areas with uniform topography.

4. Essential facts about drought in Iran

Iran is a large country that enjoys various climate conditions due to geographical and topographical differences. An estimated Iran has an annual precipitation of 224-275 millimeter on average that is less than one forth of the world average (1123 ml.), that is why Iran is ranked among the arid regions of the world. In addition to the shortage of rainfall, intensive fluctuations in the amount of precipitation or inequitable distribution of rainfall during a period of time make us unable to rely on the minimum rainfall expected to regulate water supply and demand in the sectors of agriculture and industry. Bearing in mind such a climatic condition, many severe or mild droughts are inevitable to come up. Any drought can inflict a severe damage on the agricultural and industrial sectors of the country.

Some surveys show that frequency of droughts is significantly high. Bandar Abbas is struck by the droughts with a frequency of 50 percent. In the regions of Zabol, Zahedan, Yazd, Iranshahr, and Kerman this rate drops to 46.5, 43, 42, 40 and 27 percent respectively. The main concentration of the droughts is mostly in the southern and central parts of the country that is attributable to subtropical high systems keeping the northern and western systems from affecting the southern regions.

5. The characteristics of drought in the Province of Yazd

The Province of Yazd with an area of 131,000 square kilometer is located in central plateau of Iran enjoying a warm and arid climate. Lying on the desert belt of the northern hemisphere, having low elevation, being far away from surface water bodies, dry anticyclones, topographical conditions coupled with sharp sunlight cause this region to be so arid and rough. The province of Yazd is 1,568 meters above sea level on average, the highest spot in the region (Shirkooh Mount) is 4,075 and the lowest one (the northeastern desert) is 666 meters above sea level. The average annual rainfall amounts to 109.4 millimeters in the province and 59.1 millimeters in Yazd. In this region, annual average evaporation is 3,193 millimeters, temperature is 17°, and annual relative humidity does not exceed 43 percent. The above mentioned conditions account for the lack of any permanent surface stream in the whole area, in fact there is no permanent rivers but some seasonal temporary rivers running down the mountain of Shirkooh for a few months just in case of a wet year. Therefore, it is only the groundwater reserves that supply water to the agricultural, industrial and domestic sectors.

In 2001 the province of Yazd faced a problematic decline in the amount of precipitation that aggravated the last year drought and resulted in a considerable depletion in water table and annihilation of some water resources. During spring, all rainfall this province received was not more than 5 millimeters. Therefore the pastures started to get poorer and poorer, and a considerable part of vegetation withered away. So the villagers who had to buy forage for the cattle and flock instead of grazing, could no longer afford the installments of the loans they had already undertaken to pay. The farmers witnessed their crops perish due to the lack of water, without they can do anything to save them, but it was nothing in compression with the orchards that dried up after appropriating a lot of labor and cost over a long period of time.

6. Drought indicators in Yazd, 2000-2001

6.1 Decrease in precipitation

Needless to say the impact of a drought would extend to the next year resulting in a more intensive drought if the dry condition would still persist. For example in 2001 the discharge of the Gharbalbiz Spring that was considered as an observation source, dropped to a minimum amount over the past 29 years. Meanwhile in the province of Yazd there was a decrease of 72 percent in the amount of rainfall during 1999-2000 in comparison to the average precipitation, and it led to depletion of water table especially in mountainous areas. The entire rainfall next year could only offset a part of depletion of groundwater.

According to the records of 21 meteorological stations, one can compare the statistics of precipitation as the following Table 1 shows:

	Month												
Year	*October*	*November*	*December*	*January*	*February*	*March*	*April*	*May*	*June*	*July*	*August*	*Septemeber*	*Annaul*
2000-2001	5.6	22.6	19.2	6.7	18	12.6	7.9	1.6	1.8	0	1.5	0	97.5
Average of the statistical period	1.6	3.5	13.6	18.8	20.1	24.2	16	9.3	0.7	1.3	0.2	0.1	109.4
Percentage of the increase or decrease	+250	+550	+40	-60	-10	-50	-50	-80	+160	-100	+650	-100	-11

Table 1. A comparison between the monthly rainfalls during 2000-2001 and the average precipitation (millimeters)

The table above tells that the amount of rainfall during October, November and December exceeded the average amount of the statistical period, but after January (apart from June and August) there was a decline of 80 percent in the amount of rainfall. Totally in autumn the province received 47.4 millimeters rainfall that was 49 percent of the overall amount during 2000-2001. A considerable decrease occurred in precipitation in other seasons; winter, spring and summer. So, one can deduce from these data that the distribution of rainfall during the above mentioned period was not so suitable that it can meet the water demand in the province. The lack of sufficient rainfall particularly in winter and spring can inflict damage on the surface and underground water resources and eventually expose the region to a catastrophic drought. As a result, none of the seasonal rivers ran, and many springs and qanats fell into decay.

The overall rainfall in 2000-2001 amounted to 97.5 millimeters that shows a decrease of 11 percent in comparison to the average amount of the statistical period, though it was more than the last year rainfall. The researches show that the drought is not only attributable to the shortage of precipitation during 1999-2000, but it also correlates with the temporal distribution of the rainfall during 2000-2001 (Table 2).

No.	Month	Location						
		Yazd	Aqda	Taft	Deh bala	Abar kooh	Behabad	Marvast
1	October	1.8	0	8	15	6	6.5	4.5
2	November	9.8	11	43	48.5	28.8	15	17.5
3	December	3.3	16.5	17.5	78	9.5	5.5	3.5
4	January	9.2	3	13	42	2.5	6	12
5	February	7.8	24	43.5	43	25	21.5	11
6	March	11.6	25	25	24	8	9	4.5
7	April	4.4	6	8	29	3	10	0
8	May	0	4	0	7.7	0	3	0
9	June	0	3	1	20.5	0	0	2
10	July	0	0	0	0	0	0	0
11	August	0	0	3	3.5	0	0.5	0
12	September	0	0	0	0	1.5	0	0
13	2000-2001	47.9	92.5	162	311.2	82.8	77	55
14	Average of the statistical period	59.1	84.3	135	320.2	61.9	83.1	75.2

Table 2. Temporal and spatial distribution of precipitation recorded at the meteorological stations in 2000-2001 (millimeters)

6.2 Distribution of rainfall

Inequitable distribution of rainfall based on time and location can not come up with sufficient water for human uses. For example most of the rain in autumn would not be of much use, because it does not have a considerable effect on the pasture lands or orchards. That was what happened between 2000 and 2001, so a large part of precipitation occurred in fall and early winter, and neither pasture lands nor farm lands did not profit from it. But spring rainfall can work to the advantage of both pasture lands and water resources and prevent drought. In 2001 the spring rainfall did not exceed 5.4 millimeters that was just one third of the average amount. It should be mentioned that the province of Yazd is ranked among the four provinces of Iran which receive the minimum spring rainfall.

6.3 Intensity and amount of rainfall

Intensity and amount of rain has a significant effect on surface and ground water resources. Every time it may rain less than 5 millimeters that can not be of any use, because such a rain would evaporate immediately before it makes a runoff or recharge the aquifer.

6.4 Runoffs

The number of runoffs can indicate the effectiveness of the rainfall. An estimated between 2000 and 2001 there was a decrease of 89 percent in the number of surface streams all over the province that damaged many springs and qanats.

6.5 Relative humidity

Relative humidity can be another indicator for the drought. The lower relative humidity, the higher evaporation, so it can aggravate the dry condition and place more pressure on water resources.

6.6 Temperature

During 2000-2001, the maximum temperature reached a peak that was without precedent over the past 20 years. Such an increase in temperature can easily speed up evaporation and worsen the dry condition.

7. The effects of the drought

The drought has a deep impact on the groundwater resources, so that 800 qanats (25 percent of 3,170 qanats in Yazd) dried up. Over 83 percent of the qanats in Yazd run along the valleys or across the mountainous areas, so they can not be so deep that they can drain out the deeper water bearing zones being safer from the fluctuation in the rainfall. Almost all the agricultural areas in Yazd live off the groundwater resources extracted by the system of qanat or the pumping deep wells, so any decline in the groundwater can bring about a serious loss to the agricultural sector.

Drought could destroy a vast area of farms and orchards, but obviously it was more difficult to revive the orchards than the farms. A lot of orchards were not irrigated for several months, so the trees dried and wasted all the money, time and labor the villagers had spent on them in the hope that the trees would bear fruit after several years. Usually the effect of the drought on the farms can not cause the villagers to immigrate to the cities, because they are still able to put things right next year, but in terms of the orchards the effect of the drought is so acute that it may encourage many to abandon the villages. Also, the drought damaged the agricultural sector through the annihilation of the pasture lands due to the shortage of rain in spring that is vital for the desert vegetation.

Drought not only affects the quantity of water resources, but also ruins their quality. Full exploitation of groundwater in case of drought can move saline water toward fresh water. The more groundwater is extracted, the further saline water advances through fresh water zone mixing together. This process can change the quality of water and spell crisis for the cities and villages through the lack of fresh water required for livestock, irrigation of farmlands and drinking.

9. Groundwater balance calculation in Yazd-Ardakan plain in 2001[1]

One of the main aquifers of the province of Yazd lies in Yazd-Ardakan plain that houses 10 towns and thousands of villages. The groundwater balance of this plain can be expressed mathematically as:

$$\text{Recharge} - \text{discharge} = \pm\Delta V = \text{rate of change of storage in the aquifer system}$$

$$(\text{Inflow} + \text{recycled water} + \text{seepage from floods}) - (\text{discharge} + \text{outflow}) = \pm\Delta V$$

According to a report prepared by Yazd Regional Water Authority, the output flow was equal to 82.22 million cubic meters in 2001. The term 'recycled water' means a replenishing leakage which comes from a part of the water supplied to agricultural, industrial and domestic sectors. This replenishment may occur through irrigation or sewage systems. An estimated the rate of withdrawal in this plain in 2001 amounted to 455 million cubic meters out of which 91 percent went to the agricultural sector and 9 percent went to the industrial and domestic sectors. Besides, 30,745,204 cubic meters water was transferred from Zayandeh rood river to Yazd just for industrial and domestic sectors. Given the common method of irrigation in the region which is flood irrigation[2], 30 percent of the water brought to the fields returns to the aquifer as calculated below:

$$30\% \times (91\% \times 455{,}000{,}000) = 124{,}215{,}000 \text{ m}^3$$

Also given the leakage from the lawns and sewage wells to the aquifer, one can attribute the coefficient of 60% to the recycled water of the industrial and domestic sectors as:

$$60\% \times (9\% \times 455{,}000{,}000 + 30{,}745{,}204) = 43{,}017{,}122 \text{ m}^3$$

So the amount of the recycled water can be calculated as:

$$\text{Recycled water} = 124{,}215{,}000 + 43{,}017{,}122 = 167{,}232{,}122$$

Taking into account that there was an intensive drop in the amount of precipitation during 2001, the seepage from floods was so little that it can be overlooked.

During 2001 the amount of discharge from the aquifer in the plain was 455,000,000 cubic meters out of which 335,853,000 was pumped by the wells, 116,886,000 was drained out by the qanats and 2,357,000 was discharged by the natural springs.

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[1]. Thanks to Ms. Samira Askarzade who kindly contributed to writing this topic.

[2] In this system of irrigation water is pumped or brought to the fields and is allowed to flow along the ground among the crops. This method is simple and cheap, and is widely used in central Iran. The problem is, about one-half of the water used ends up not getting to the crops.

During 2001 the outflow of groundwater in the plain was 4.72 million cubic meters, so the balance equation of the plain can be calculated as:

$$\left(82.22\times10^{6}+16{,}7232{,}122+0\right)-\left(455\times10^{6}+4.72\times10^{6}\right)=-210{,}267{,}877$$

Therefore during 2001 the plain had a negative groundwater balance amounting to 210,3 million cubic meters. An increase in the amount of precipitation resulting in some floods could mitigate such a negative balance.

9. Groundwater quality

Another important problem with the drought is potential water quality deterioration. According to the report of Yazd Regional Water Authority, during 2001 the average EC (electrical conductivity) of the aquifer in Yazd-Ardakan plain was 3,861 μmhos/cm and the average amount of chlorine was 873.7 mgr/lit, whereas in upstream areas the EC dropped to 1,000 μmhos/cm even suitable for drinking and in downstream areas the EC was up to 15,000 μmhos/cm.

In this year, the whole domestic wastewater seeped into the aquifer, which was naturally treated due to the considerable thickness of the sedimentary layers. At the present time (2007) the wastewater treatment plant of Yazd has become operational and is able to receive a large part of the domestic wastewater in order to be used in irrigation.

10. Classification of the regions based on the effects of drought

According to the information gathered during the drought of 2000-2001, the villages and the towns in the grip of drought were specified taking into account the indications of drought there. This study will help to better recognize the regions that are subject to drought in case of an impending dry condition. Doing so, we can find a solution for the likely problems caused by the upcoming drought in order to mitigate the consequences of the drought in the region. Needless to say the consequences of the drought vary from region to region. In other words in a particular region the drought may be so severe that deeply affect agriculture, livestock, industry and drinking, but in another region the existing water may be enough for livestock, industry and drinking though just agriculture suffers from drought. Therefore, it is necessary to specify the regions vulnerable to drought and to predict the types of the impacts of drought. This information can help us make appropriate decisions to minimize the consequences of drought even before it occurs. So in a nutshell one can classify the regions based on the impacts and the importance of drought into three categories as follows.

10.1 The towns and villages in trouble with the scarcity of drinking water

Provision of drinking water has priority, so it is necessary to first recognize the regions that may run out of drinking water in case of an impending drought. The experience of the drought of 2000-2001 tells us such regions are as follows:

A) Ahmad Abad-e Ardakan: the quality of water in this town is not satisfactory that correlates with the geohydrological conditions of the desert.

B) Nir: due to the thinness of the aquifer, the steepness of the hydraulic gradient and a high rate of discharge, groundwater in this region is too vulnerable to the fluctuations of rainfall.

C) Abarkooh: this region is short of drinking water due to the type of its alluvial deposits with very small particles as well as movement of saline water toward fresh water.

D) Bafgh: due to the general conditions of the desert and the lack of any kind of surface stream, this region does not have a satisfactory supply of drinking water.

E) Mehriz: this town suffers the shortage of drinking water especially when a drought comes up, because the alluvial deposits are too thin to store a considerable supply of groundwater. So these geological formations would be emptied of water quickly.

F) Rural region of Aghda: due to the shortage of precipitation, the groundwater reserves are not sufficient.

G) Northern regions of Ardakan: due to the general conditions of the desert, the quality of drinking water is low.

H) Rural region of Abarkooh: because of a low precipitation, the groundwater is in very short supply.

I) Mountainous area of Shirkooh: the steep gradient of this area makes the surface runoffs run outward, so the aquifer cannot be well recharged. Meanwhile, the water bearing zone is not thick enough to keep a considerable amount of water.

J) Western regions of Harat and Marvast: the aquifer in this region is strongly dependant on the amount of precipitation, so any fluctuation in rainfall affects the groundwater.

K) Southeast of Bahabad: the alluvial deposits in this mountainous area are too thin to retain a sufficient supply of groundwater, so any drought can bring about a serious crisis.

L) East of Marvast: in the past this region enjoyed several qanats conveying groundwater from a long distance, but now all of them have dried up, and people have to pump up groundwater through the deep wells instead. The groundwater extracted in this way does not keep pace with the recharge of aquifer done by the rainfalls, so the region can easily run out of groundwater.

10.2 The regions in trouble with the scarcity of water for livestock

The shortage of precipitation affects the pasture lands and vegetations inflicting damage on animal husbandry. Animal husbandry units based in the regions with thin alluvial deposits are more vulnerable to the risks a drought brings about. In such regions it is difficult to provide the animal husbandry units with potable water.

During the drought of 2000-2001, the regions of animal husbandry which were under the pressure of drought – even though forage was provided from other regions – were distinguished. Bearing in mind this information, we can better manage the future drought in the distinguished regions to reduce the expected risks.

10.3 The regions in trouble with the scarcity of water for irrigation

Water for irrigation is ranked as our last emergency. We learnt from the experience of the drought of 2000-2001 that in some regions, groundwater resources do not afford to supply water to agricultural units.

In such regions the alluvial fans are not thick enough to form a large water bearing zone; on the other hand the steep surface slope does not let the streams seep into the aquifer effectively. That is why such regions are fully correlated with the fluctuation of rainfall. Based on the study done on whole province, such regions have been recognized so that we can direct the farmers to take some actions in case of an impending drought to better overcome it.

11. The measures taken to safeguard groundwater resources against the drought

Taking into account the hydrological conditions of the province as well as the fact that 91 percent of the available groundwater is being consuming by the agricultural sector, it is a must to find a remedy for the depletion of the groundwater reserves. So some funds were allocated to the groundwater protection by several governmental organizations as follows:

A) rehabilitation and repair of qanats,

B) construction of artificial recharge dams,

C) implementation of cloud seeding projects,

D) intensifying the legal penalties in case of over pumping without official permit,

E) reducing the withdrawal from aquifer by means of modifying and limiting the existing permits,

F) replacing the diesel pumps with the electric ones to make it possible to control the amount of water extracted through the electricity consumed,

G) installing volume meter on the wells.

Needless to say, going on taking such measures can mitigate the effects of the drought.

12. The measures taken by Yazd Regional Water Authority to mitigate the crisis of the drought

In a nutshell Yazd Regional Water Authority deals with drought rather than any other organization, so some of the measures taken by it are as follows:

A) processing the permit of four new wells needed to irrigate the farmlands struck by the drought in the villages of Khansar, Hasan Abad, Chenar and Neyestan, the district of Khatam,

B) drilling four new wells in Taft and Mehriz under the supervision of Yazd Regional Water Authority to supply required water by means of trucks. The people who are badly in need of water for irrigation or livestock can get a truck full of water after declaring a draft given by Yazd Regional Water Authority. These wells are located in near Mojibian garden and Feyz Abad in Taft, and near the governing headquarter and agricultural training center in Mehriz,

C) providing the facilities needed to withdraw water from the pipe line transferring water from Zayande Rood to Yazd at the station of Khalil Abad. By this means, the surrounding villages can get access to this water,

D) giving official permit to Agricultural Authority and Rural Water & Waste Water Authority to make use of three other wells already inactivated. These wells are located in Sadegh Abad near Taft and Gowd-e Galime and Arnan near Mehriz,

E) issuing official permit to re-operate the wells of Hak and Shahr Abad in Abarkooh and Akramiye,

F) issuing a temporary permit to exploit a well drilled in the animal husbandry complex of Deh Arab in Abarkooh in order to supply drinking water to the village of Deh Arab,

G) approving an increase in the amount of water withdrawn from a well in Eslamiye near Taft in order to facilitate getting drinking water to the surrounding villages,

H) approving to reactivate a well in Nodooshan in order to provide the gardens with the required water,

I) approving to make use of the extra water of the well of Zardin in supplying drinking water

J) carrying out some programs to enhance public awareness about water and drought,

K) recording and documenting all the information about the impacts of the drought, the measures taken and how these measures worked out. We can build on the documents and reports we got form the experience of the drought in order to face any other drought in future more effectively.

13. Adjusting irrigation to drought

In Yazd, traditional irrigation has an inherent mechanism to adapt the existing water to the environmental conditions. This mechanism works through the technical factors as well as the water management. In case of drought, the users of qanat have two choices to cope with this situation technically that are to extend the gallery of qanat by digging it up through the aquifer and to adjust the area of farm lands to the available water. The farm lands are divided into two parts for trees and for vegetables. A special ratio should be considered between the areas of orchards and farms so that the maximum amount of the available water would be able to meet the irrigational need of the total area. They adjust the area of the cultivated lands and the cropping pattern to the existing discharge rather than place pressure on the groundwater sources in order to go through a drought. We witnessed many cases in Yazd that could mitigate the effect of the drought this way.

Traditional water management is also very flexible to the environmental conditions. First of all, it is necessary to explain that a qanat may belong to hundreds of farmers who take turns getting their water to irrigate their lands. Irrigation rights are based on time shares within a certain period of rotation. This water division system can match up with all likely changes in the volume of water during a year, while satisfying the farmers' irrigational needs. For example, if the volume of water decreases due to drought, the each farmer receives his water two times more than his normal shares but once every two periods, doing so this amount of water can reach every corner of his farm.

15. Some suggestions to better overcome the drought

Needless to say the agricultural sector that appropriate 91 percent of the whole water supply of the province would incur the greatest loss in case of drought. Sustainable management of groundwater reserves should be based on a reasonable and economical exploitation of such natural resources. Bearing in mind the agricultural sector is the greatest consumer of groundwater, we should do our best to encourage the agricultural system that is more consistent with the hydrological circumstances of the region. Our existing agricultural methods should be modified so that we can gain more valuable crop in return for minimum consumption of water. If we can optimize the irrigational methods to reach a 5 percent decrease in their water consumption, this 5 percent is on a par with the whole water needed for the present industries, mines, towns and villages. Therefore, first of all we had better figure out how to economize on water being consumed by the agricultural sector. Some solutions can be as follows:

A) Introducing the right cropping pattern to the region taking this arid climate into account. This cropping pattern should consist of the plants genetically modified to be more resistant against the shortage of water and salinity,

B) Promoting the irrigational methods and using the modern methods such as drip irrigation that can reduce the water consumption,

C) Convincing the farmers to make use of the treated domestic wastewater in irrigation

D) Coming up with a special fund to support the farmers who are willing to enhance their irrigational method,

E) Investing a budget in the construction of irrigational pools and water transfer canals,

F) Supporting the cloud seeding projects,

G) Construction of new artificial recharge dams and rehabilitation of the former ones,

H) Construction of water reservoirs along with water transfer networks,

I) Rehabilitation and maintenance of qanats,

J) Records of all wells drilled in villages especially where are subject to drought should be kept to better control them,

K) Drilling emergency deep wells under supervision of Yazd Regional Water Authority to aid the regions gripped by a likely drought with supplying water,

L) Setting up an educational campaign to enhance the public opinion about the importance of the water resources to prompt people to take care of this vital material.

15. Conclusion

We learnt from the drought of 2001 that:

A) We should reflect upon the experience of a likely drought, even though the next year rainfall can offset all the loss the drought brings about. If we forget about the effect of a drought, we cannot be prepared enough for a similar condition in future.

B) If a drought prompts us to start some research or executive projects, we had better continue working on these projects until we reach the expected results, even thought we no longer face any drought. In terms of the drought of 2001, some projects were funded to be carried out but are still under process, so it is necessary to accomplish them even though that drought has already passed by.

C) It is a must for us to record and equip the water wells that can be used to supply water to their surroundings in case of drought. These wells should be able to be operated very quickly in emergency situations.

D) Drought is a natural disaster and humans are not able to prevent it, but we can build on the information we collect about the past drought to organize an integrated management to better take over the impending droughts and reduce its risks.

E) We should exchange our experiences with other provinces, to do so it seems necessary to establish a center to coordinate the practices adopted by the different provinces and prevent any overlap between their activities.

F) In case of a drought, it can be very helpful to install the volume meters on the pipe lines and the wells measuring the amount of water supplied in order to restrict the withdrawal.

G) Our traditional irrigation has a great potential to better manage water in case of drought. Many generations of farmers have obtained these methods that are in a perfect harmony with the climatic condition through thousands of years of trial and error, so it is not wise to belittle this knowledge just for it is not written. We should take it serious and study the remains of the traditional methods in the rural areas, so that we can be inspired by them and incorporate them into our new management system.

H) It is necessary to provide the maps of the regions that are subject to drought showing the type of impact an impending drought may have on the different areas. We should collect the maps of water resources (wells, water transfer pipe line, etc) so that we would be able to better handle a drought as soon as we predict it to prevent its damages.

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EMERGENCY PLAN FOR WATER SUPPLY IN CONSECUTIVE DROUGHT AND SUSTAINABLE WATER RESOURCES MANAGEMENT IN BEIJING

Li Wenpeng[1], Hao Aibing[1], Ye Chao[2] and Zheng Yuejun[1]

Abstract: The total available water resources per capita in Beijing is only 300 m^3/a. More miserable is that Beijing has experienced an 8-year consecutive drought since 1999; shortage of water resources has become one of the most important factors limiting the economical and social development. The top priority task at present is to ensure the Capital's water supply before the completion of the project 'diverting water from the south to the north' (Nanshui Beidiao) in 2010. Based on the exploration results in Beijing, a plan for the construction of 6 well fields as emergency water supply is proposed in this paper and different abstraction rates and corresponding managing measures is also discussed. In terms of long-term consideration, it is pointed out, that once the Nanshui Beidiao project has been completed, the use of the aquifer as a reservoir and joint use of surface water and groundwater are essential to ensure the water safety and sustainable water resources management for Beijing.

Introduction

Beijing, the capital city of China with 16 million population and only about 300 m^3/a of water resources available per capita, is one of the cities fazed by serious water shortage. More miserable is that it has experienced an 8-year consecutive drought since 1999. Shortage of water resources has become one of the most important factors limiting the economical and social development. The top priority task at present is to ensure the Capital's water supply before the completion of the project 'diverting water from the south to the north' (Nanshui Beidiao) in 2010. Taking the regional hydro-geological conditions of Beijing into account, over exploitation of groundwater has existed for a long time but the aquifer has large storage, it is feasible to construct some well fields for emergency water supply. In terms of long-term consideration, after the completion of the project Nanshui Beidiao, the use of aquifers as reservoirs is one of the key measures to promote the joint use of surface- and groundwater and the sustainable water resources management.

1. Li Wenpeng, Hao Aibing and Zheng Yuejun, China Institute for Geo-Environmental Monitoring, Beijing, China, 100081.
Li Wenpeng is professor and the chief engineer in the CIGEM and he has been engaged in the hydrogeological survey and study of drought area for 20 years. Address: No 20,Dahuisi Road, Haidian District,Beijing,10081, China, Fax: 861062173426, Tel:861062137033, E-mail:Liwp@mail.cigem.gov.cn

2. Ye Chao, Beijing Geo-Environment Monitoring Station, Beijing, China, 100037.

1. Overview of the water resources and the water supply in Beijing

Beijing, located in the northwest part of the North Plain of China, covers an area of 16,800 km^2 consisting of the mountainous areas in the west and the north (10,400 km^2) and the Beijing plain in the south-east (6,400 km^2). The Beijing plain slopes slowly from northwest to southeast. With a typical continental semi-humid monsoon climate and distinctive seasons (dry and cold in winter, wet and hot in summer), the annual average rainfall is around 600mm (from 1950 to 2005) and results in surface runoff of 2.3 billion m^3/a. The annual rainfall only reaches 70% of the average during the 7-year consecutive drought since 1999 (Figure 1).

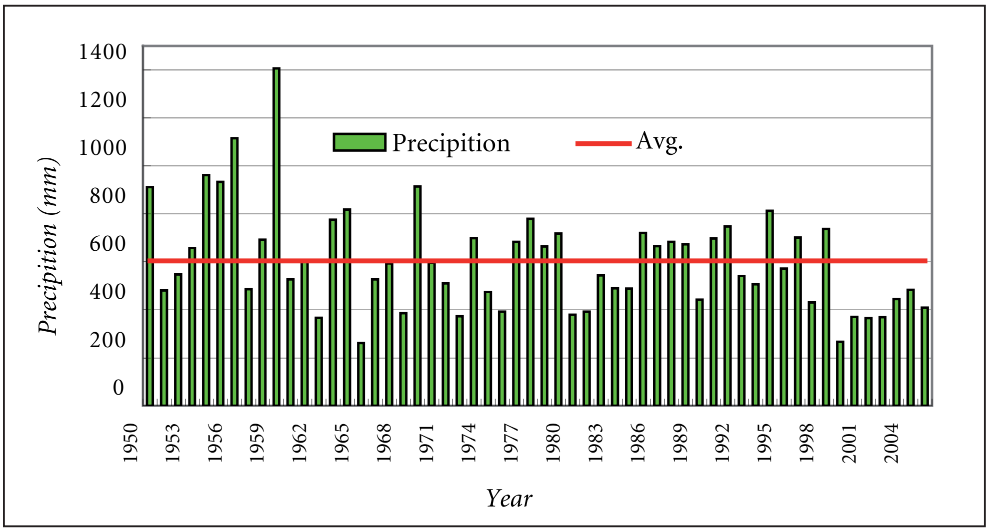

Figure 1. Map of multi-year precipitation in Beijing

Beijing area belongs to the Haihe River Basin and can be divided in to five branch river catchments named as, from east to west, the Jiyun River, the Chaobai River, the Beiyun River, the Yongding River and the Daqing River separately (Figure 2). All the rivers are originated from outside of Beijing except the Beiyun Rive. Among them the inflows of the Chaobai- and the Yongding River together occupy 95% of the total inflow from outside Beijing.

85 surface reservoirs have been constructed in Beijing area since 1950s. This has lead to the dry up of river beds in the plain area except short floods. Because a large number of surface reservoirs were also constructed outside Beijing in the upper reaches of the Chaobai River catchments and the Yongding River catchments, the two rivers' inflow into Beijing has declined from 3.68 billion m^3/a in 1956 to 0.87 billion m^3/a in 1997. The Miyun Reservoir, the largest surface reservoirs in Beijing which is the most important water supply of the city and receives mainly the inflow of the Chaobai River, has left only the dead reserve in recent years. The Guanting Reservoir, the second largest reservoir in Beijing which receives mainly the inflow of the Yongding River, has lost the function of water supply because of pollution (the inflow decrease is one of the important reasons making pollution more serious). These have further intensified the water crisis in Beijing.

Pore groundwater in the plain and karst groundwater in the surrounding mountain areas are most important groundwater resources in Beijing (Figure 3). Pore groundwater is mainly

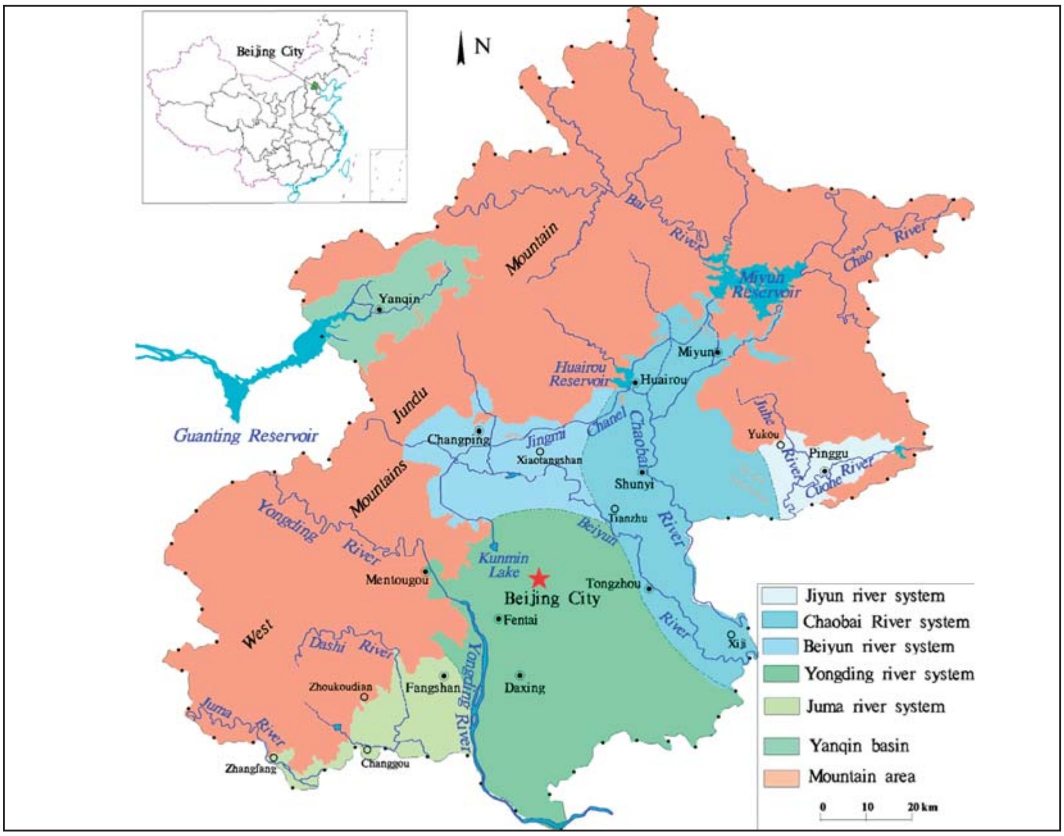

Figure 2. Distribution map of groundwater system in Beijing

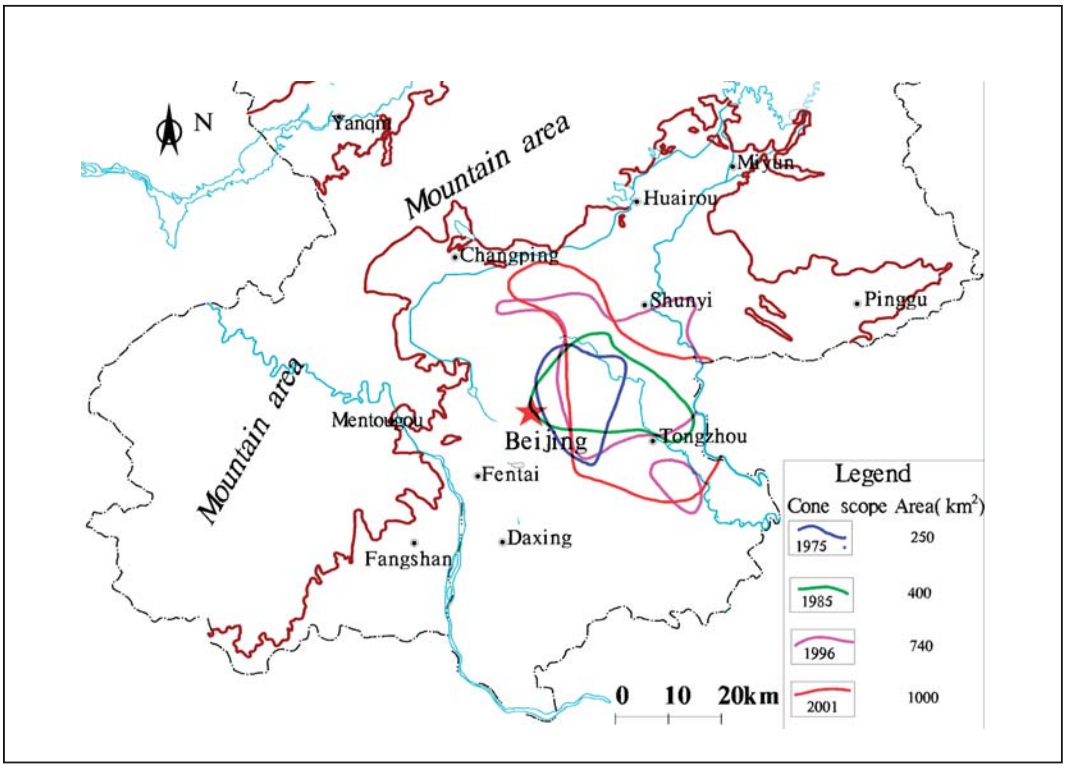

Figure 3. Dynamic map of groundwater depression cone in Beijing

recharged from precipitation, and other recharges include leakages of surface water and irrigation. The groundwater flow direction is generally from northwest to southeast, but will change near the depression cones in the concentrated exploitation areas (Figure 4). Karst groundwater in the mountain areas mainly receive recharges from precipitation. Some karst aquifers can extend to the beneath of the plain. Natural groundwater recharge in Beijing is 3.375 billion m^3/a, from which 2.73 billion m^3/a are available for abstraction (0.178 billion m^3/a in the mountains, and 2.455 billion m^3/a in the plain).

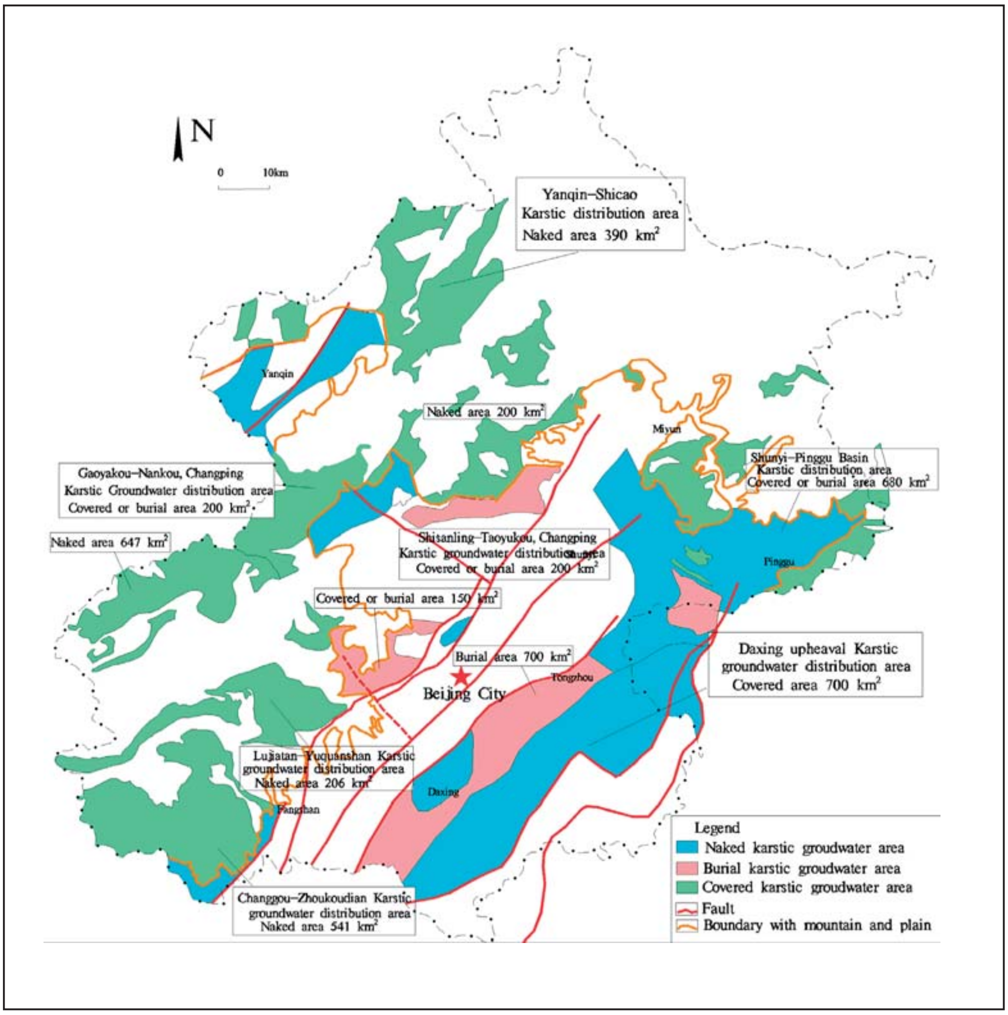

Figure 4. Distribution map of karst water in Beijing

With the blooming social-economic development, the amount of groundwater exploitation has increased continually and occupied more and more proportion in the city's water supply. The total water supply at recent years is around 4.0-4.2 billion m^3/a, to which groundwater contributes 2.7 billion m^3/a (about 2/3 of the total water supply) and surface water 1.4 billion m^3/a. Since the 1980s, the over abstraction of groundwater in the Beijing Plain is around 0.1-0.2 billion m^3/a. As a result, the regional groundwater head in the Beijing plain continuously declined leading to land subsidence (Figure 5 and Figure 6).

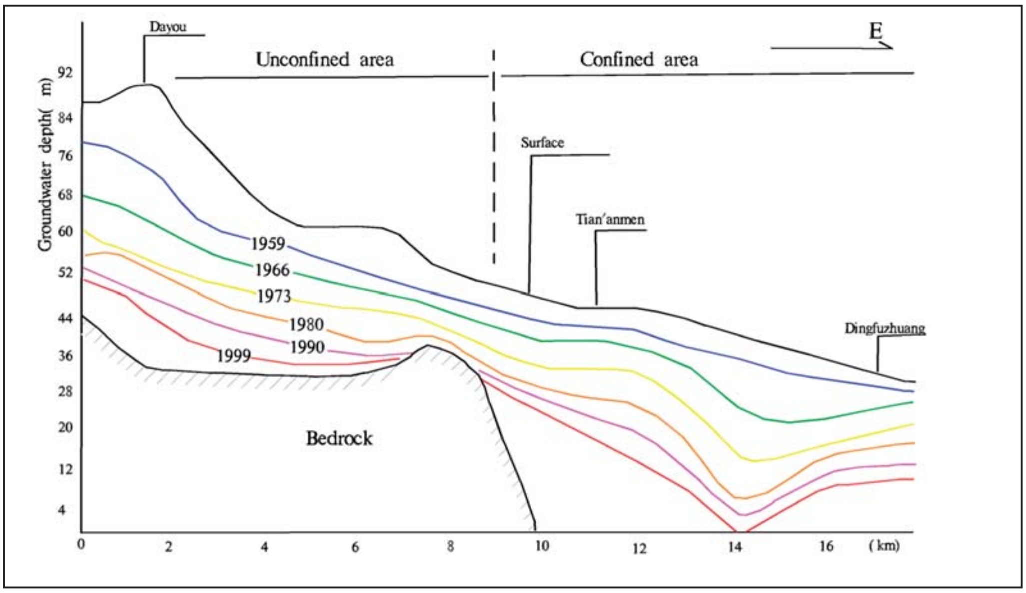

Figure 5. Dynamic map of groundwater level in the suburban of Beijing

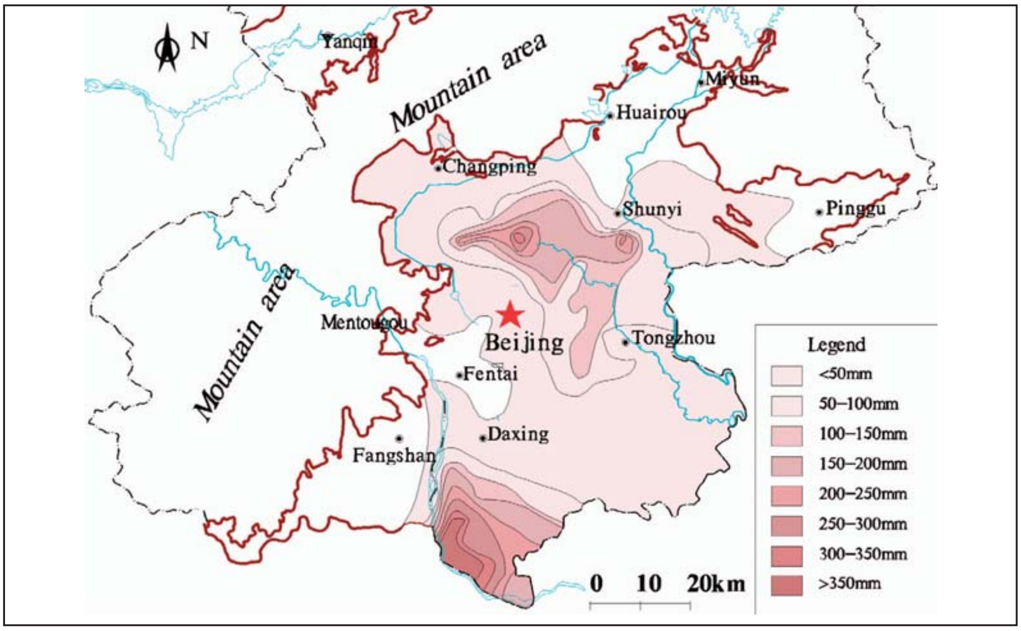

Figure 6. Distribution map of land subsidence in Beijing

2. Emergency plan for water supply in consecutive drought

To address the serious water shortage since 1999, the State Council (2001) of China organized Beijing city and other provinces and cities compiled a plan for the sustainable development of the Capital's water resources at the beginning of 21st century. The suggestions and measures proposed in this plan include water saving techniques, recycled water utilization, rain water and flood water collection, the Nanshui Beidiao Project, and the joint use of water resources.

Following this plan, from 2000 to 2005, 5 new sewage disposal plants and 2 new reclaimed water plants were built and the waste water treatment rate upraised from 43% to 70% in Beijing. In 2005 the total treatment capability of waste water in the urban area reaches to 2.74 million m^3/d (about 1 billion m^3/a) and of which 26% (0.26 billion m^3/a) was reused for water supply.

In order to meet the urgent need of urban water supply, an assessment of well field exploration for emergency water supply has been launched and an emergency plan has been advanced. The emergency plan include 6 well fields, which can be divided into 3 groundwater types, and the total water supply can reach 0.39 billion m^3/a. The 3 types of emergency well fields are (Figure 7): (1) well field for pumping pore groundwater including the Huairou well field and the Juma well field; (2) well field for pumping karst groundwater, including the Zhangfang-Changgou well field, the Xijiao well field and the Changping well field; (3) well field for joint use of pore- and karst groundwater including Pinggu-shunyin well field only.

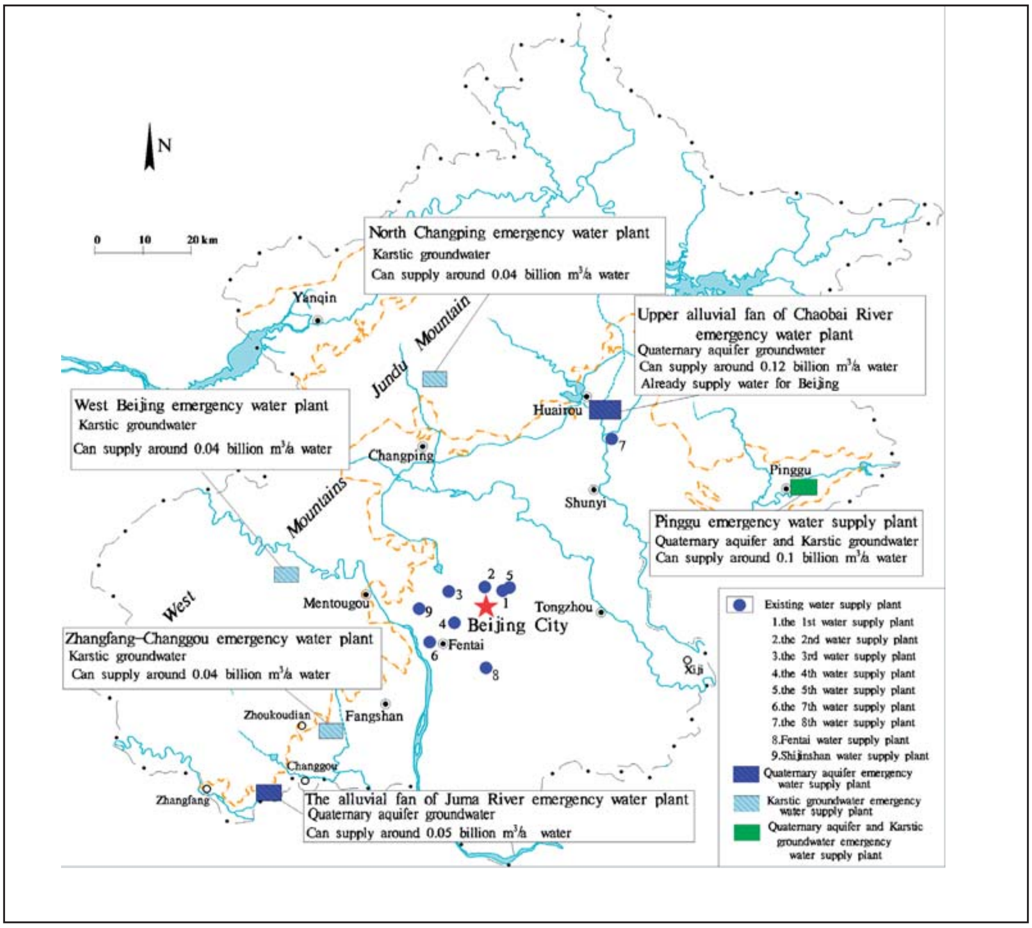

Figure 7. Distribution map of well fields for emergency water supply in Beijing

The Huairou well field

It is located in the north part of the Beijing plain and the upper parts of the alluvial fan of the Chaobai River. The local hydro-geological conditions in this area are: thick aquifer with single structure, strong permeability and easy recharge, large storage with function of multiyear balance of groundwater. This area can be considered to be a huge groundwater reservoir. The groundwater level is stable in recent years with slightly up rise in flood season and decline in dry season. The quality of groundwater in Huairou well field is good for drinking water supply with chemical type of HCO_3-Ca · Mg and TDS 238-360 mg/l. It is an ideal place to construct well field for emergency water supply. Explorations show that the annual emergency water supply of this well field can reaches 0.12 billion m^3/a. 21 groups of wells (42 wells in total) was completed in 2004 and have been putting into the city's water supply system.

The Juma Well field

It is located in the alluvial fan of the Juma River which is a cross boundary aquifer system between Beijing and Hebei province. The thickness of the Quaternary deposits in the upper parts of the alluvial fan is from 20 m to 60 m consisting of coarse grain, and in the middle and lower parts is from 170 m to 450 m consisting of coarse and middle sand. The shallow aquifer is unconfined and the deep aquifers are semi-confined. Groundwater in the alluvial fan is mainly recharged from precipitation and Juma River and usually has good quality. The estimated emergency water supply is 20 million m^3/a (150 thousand m^3/d).

The Zhangfang-Changgou Well field

It is located within a large karst area named as the Fangshan-Zhoukoudian karst area in the southwestern mountainous area of Beijing. A water resistant fault named as Babaoshan fault blocked the connections of the karst groundwater in the mountain area and the pore groundwater in the Beijing plain. The karst outcrops near the Zhangfang-Changgou Well field covers an area of 541 km^2, and can receive precipitation recharge of 0.12 billion m^3/a and river recharge of 0.015 to 0.02 billion m^3/a. This area is one of the few areas where have potential for groundwater exploitation in Beijing. This well field can offer an amount of water supply of 100 thousand m^3/d. The TDS of the karqt groundwater is 350-550 mg/l, which is good for drinking.

The Xijiao Well field

It is located in the western suburban near the famous Yuquan Mountain. The aquifers in this well field consist of Cambrian and Ordovician karst rocks underlying the pore aquifer. The karst groundwater mainly receives lateral recharge from mountain area and has very good quality. A primary assessment shows that this well field can offer an amount of emergency water supply of 36 million m^3/a (100 thousand m^3/d). In the consecutive drought and dry season, part of the storage can be used.

The Changping Well field

It is located in the north part of Changping district. The aquifers in this well field consist of Precambrian dolomite rocks with well developed karstic fissures and strong transmissivity. Precipitation is the main recharge source of groundwater, and other recharges include the rive leakage and downward flow of the pore groundwater. The total recharge from precipitation is 56.42 million m^3/a. Groundwater usually has good quality with TDS 250-300 mg/l. The estimated emergency water supply of this well field is about 100 thousand m^3/d.

The Pinggu-Shunyi Well field

It is located in the Pinggu Basin in the east part of Beijing. The Pinggu Basin is a fault basin surrounded by mountains in the east, north, west and southeast. There is only one exit in the southwest connecting the Beijing Plain. There are abundant karst groundwater resources under the basin and in the surrounding mountain areas. Because of good recharge conditions and rich of fissures, the well yield can reach 1,500 to 3,000 m^3/d and even more. The thickness of the Quaternary deposits within the basin increases from the margin to basin center, and the biggest thickness is 715 m. Pore groundwater and karst groundwater have close hydraulic connections and both receive the recharge of precipitation. The groundwater levels are keep stable in recent years. The explorations proved that the Pinggu-Shunyi Well field can offer an emergency water supply of 2.74 million m^3/d. Two well fields named as Wangduzhuang and Zhongqiao were constructed in 2005 and have been putting into the city's water supply system. The TDS of the karstic groundwater is 225-291 mg/l, and the chemical type HCO_3-Ca · Mg.

3. Development management of the emergency well fields

Most of the well fields presented above are considered based on the following factors: temporally using storage of aquifer or intercepting the recharges from the mountain areas to the plain. It should be stressed that the pumping amount of each well field, except the Zhangfang-Changgou well field, can not be confirmed in long time. Individual development management must be carried out according to the specific hydro-geological conditions and the emergency supply need.

The Huairou well field is close to an existing groundwater plant located in the downstream of the alluvial fan of the Chaobai River. In the assessment report of this well field it is pointed out that a few years pumping will not produce obvious impact on the existing groundwater plant. Considering that the aquifer system has large storage but only a limited amount of groundwater recharge, it is sure that long-time pumping will influence the production of the existing groundwater plant. Therefore the 'emergency' should be emphasized for this well field and unlimited pumping should be avoided. In years of with rich precipitation the pumping should be stopped, and it is recommended to release some flood water from the Huairou- and Miyun reservoir for recharging and recovering the alluvial fan aquifers.

The Juma well field is located in a cross boundary aquifer unit between Beijing and Hebei Province. There has potential for groundwater development, but there are no clear definitions in law for the water right between Beijing and Hebei Province. So it is necessary to build a coordination mechanism for evaluating and negotiating the groundwater abstraction and the economic compensation between Beijing and Hebei province.

The Zhangfang-Changgou well field can receive a fixed recharge. Because the karst groundwater system and the pore groundwater system (in the plain) are separated by the blocking fault, this well field can be considered as a permanent one. However, the cycle mechanism of the karst groundwater system should be studied in detail. To ensure a sustainable development of this well field, it is also recommended to do more exploration works for making clear the hydraulic connection between the karst system and the plain aquifers.

The Xijiao well field and the Changping well field have close hydraulic connection with the plain aquifers. Therefore they can only be regarded as temporal well fields for emergency water supply in extreme dry year or season.

The Pinggu-Shunyi well field has thick aquifer system and good recharge conditions. Groundwater storage can be used for water supply in dry season and consecutive drought. After stopping to pump in flood season or flood year, the aquifer can recover easily.

4. Strategies for sustainable water resources management

Before the competition of Nanshui Beidiao, there currently are no alternatives to over-pumping groundwater in case of a long drought. The project Nanshui Beidiao will provide Beijing with 1 billion m^3/a of water from 2010. This will offset the water shortage of Beijing obviously, but it is still a city with water shortage (The total available water resources per capita is only around 400 m^3/a together with the project Naishui Beidiao). It is undoubted that the water saving techniques, recycled water utilization and pollution prevention are most important, but on the other hand to improve the development management is also key factor to ensure the city's water safety and to achieve sustainable water resources management.

Limited by the physical geography, there is no suitable place in Beijing to construct surface reservoir for the project Nanshui Beidiao. How to utilize the inflow of 10 m^3/a efficiently is an important issue need to study further, which is also the key to achieve the sustainable water resources management in Beijing.

Excessive groundwater abstraction over the past 20 years has emptied the aquifer with a huge space of over 6 billion m^3, from which 0.62 billion m^3 are located in the alluvial fan of Chaobai River and 0.6 billion m^3 in the Yongding River. This means that a huge storage potential for water. From the beginning of 1970s to the beginning of 1990s, rain water, flood water as well as the superfluous water from Guanting Reservoir had been used for artificial groundwater recharge. Good results had been achieved. However, this work had to be stopped due to the lack of water for artificial recharge. Groundwater monitoring carried out in 1974 in the alluvial fan of the Chaobai River showed that the simple infrastructure construction like rubber dam may greatly increase the groundwater recharge from the superfluous water of Miyun Reservoir. From all the results above we can conclude that Beijing city has the advantage of using aquifers (especially in the alluvial fan) to storage water.

In all, after the completion of the project Nanshui Beidiao, the joint use of surface- and groundwater and the use of the aquifer as a storage reservoir is an important measure to achieve sustainable water resource management and to ensure the Capital's water supply. Rational utilization of aquifers for water resources storage will not only reduce the inefficient evaporation of water resources, but will also play a significant role for land subsidence control and environmental protection.

5. Conclusions

(1) Beijing is city facing serious water shortage. Before the completion of the project Naishui Beidiao, there are no alternatives to pumping groundwater for emergency water supply in terms of seasonal and long drought.

(2) Six emergency well fields with total supply of 0.39 billion m^3/a are proposed and described. Individual development management are given and discussed based on the hydrogeological conditions and emergency water supply need.

(3) After the completion of the project Nanshui Beidiao, the use of the aquifer as a storage reservoir is an important measure to achieve sustainable water resources management and to ensure the Capital's water supply.

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MASHHAD PLAIN GROUNDWATER MANAGEMENT UNDER DROUGHT CONDITIONS

Mehdi Janparvar[1], Saeed Nairizi[2]

Abstract: Droughts have affected Mashhad plain since old time in different scales. Due to continues urban, industrial and agricultural development plan in the region, drought is increasingly becoming a major problem and threatens the future livelihood of the people living in plain. In this paper the characteristics of recent drought occurrences and their sever consequences on the plain bio-ecosystem are discussed. Regional water shortage for municipal and agricultural supply, in these periods, was the great concern among people and officials. Various management approach were introduced to overcome the last summer drinking water shortage are presented, as examples for further analysis. Future statuses of the aquifer under drought condition are demonstrated by using groundwater model results if the business goes as usual. Several appropriate comments and management policies are put forward to mitigate the future drought impacts as a risk management approaches.

Introduction

Mashhad plain is situated in Kashaf roud river catchments in North of Khorasan province between longitudes 58-20, 60-08 E and latitudes 35-40, 36-03 N.

Total basin area is 9,909 km^2, out of which 3,351 km^2 is plains and 6,558 km^2 is heights.

The plain is limited to the North by Hezar Masjid (Kopeh dagh) heights, to the South by Binaloud Mountain, North-West by Atrak river basin, and to the South-East by Jam roud river basin. Both mountain chains stretch from North-West to South-East. To the South-East the ground slopes gently to form the plain.

Binaloud peak is the most elevated point in the basin with an altitude of 3,300 meter above sea level (masl) located in the South-west, and Tangal-shour as the outlet of the basin is the lowest point in the South-East with an altitude of 880 masl.

1. Dr. Mehdi Janparvar, MSc Hydrogeology, Tooss Ab consulting Eng co., Iran.
2. Dr. Saeed Nairizi, PhD Civil Eng. Managing Director of ToossAB consulting Eng co., Iran.

Definition of drought

There is no exact and definite applicable definition of drought phenomena to cover all its features. But, as a general, drought can be defined as a lack of precipitation over an extended period of time relative to the normal status of precipitation, followed by a shortage of water affecting the bio-ecosystems and consequences of socio-economical damages.

Drought occurrence in Mashhad plain

Kashaf Roud river as the main drain of the catchments' area, flows West-eastwards, joining to Hariroud river at the Iran-Turkmenistan frontiers.

It is a highly flooded river during wet years, because of poor lands cover.

There are 9 tributaries flowing into Kashaf Roud river, out of which two tributary rivers, i.e. Toroq and Kardeh, having proper long time recorded data which are selected to evaluate wet and dry periods in Mashhad plain.

Figure 1 shows Kashaf Roud river catchments and location of Mashhad.

Figures 2 and 3 demonstrate mean, mean annual discharge and 3–5 years move mean of Kardeh and Toroq rivers.

It can be observed that the wet and dry periods have occurred in Mashhad plain in recent decades. As figures show, Mashhad plain has experienced four drought periods since the first recorded data. They are 1957 to 66, 1981 to 89, 1993 to 98 and 1999 to the present.

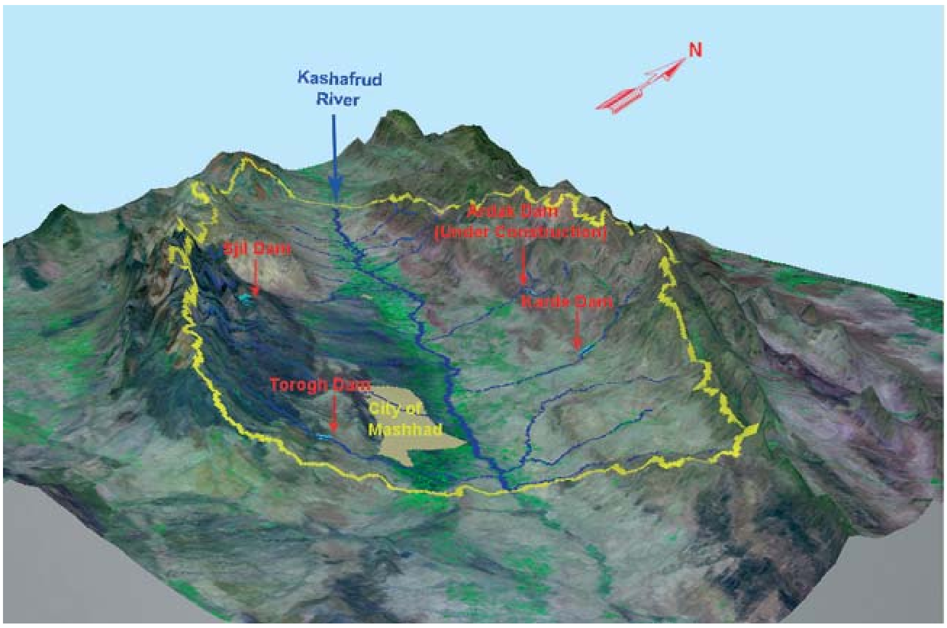

Figure 1. Kashaf Roud river catchments and location of Mashhad city.

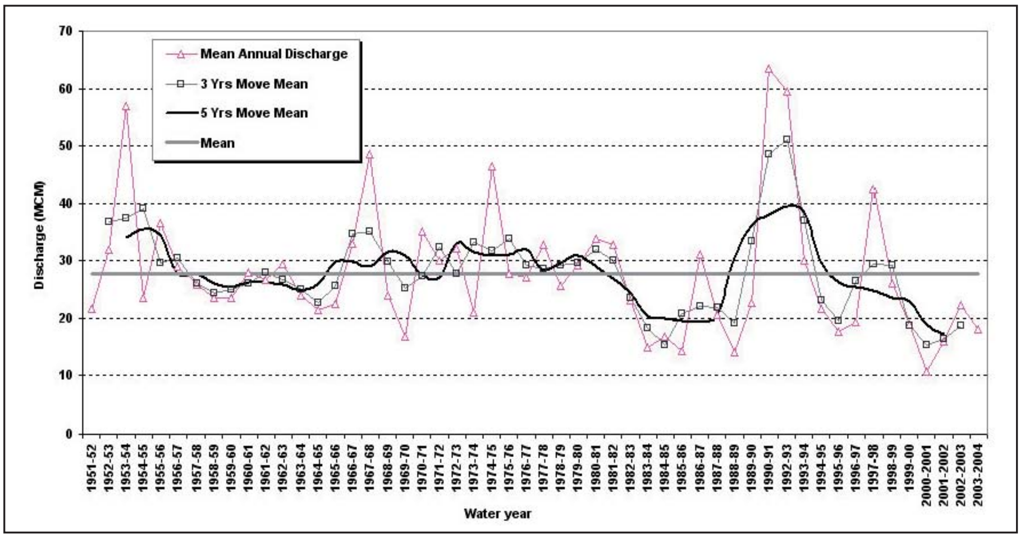

Figure 2. Mean, mean annual discharge and 3–5 yrs move mean of Karde River

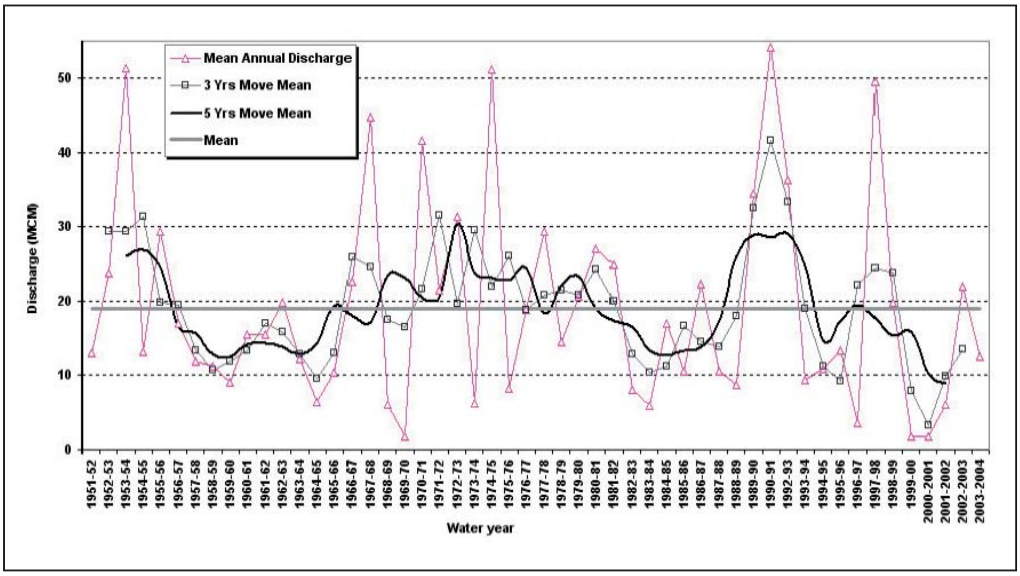

Figure 3. Mean, mean annual discharge and 3–5 yrs move mean of Toroq River

Groundwater

Aquifer

According to borehole logs of exploration wells, the plain aquifer is of leaky unconfined which comprises of alluvial layers having various hydraulic conductivity. Yet no layer recognized as a perfect barrier. Alluvial deposits within the aquifer consist of river alluvium, alluvial fan deposits and evaporate. Generally, groundwater flows northwest – southeastward in accordance with the plain general slope. Toward the north, depth to groundwater decreases gradually. Figures 4 to 7 show cross section locations and geological correlation between some exploration wells in various directions within the aquifer. Hydrodynamic properties of the aquifer are influenced by the type of aquifer materials and vary from 45 to 4,950 square meter per day. Fig 8 illustrates

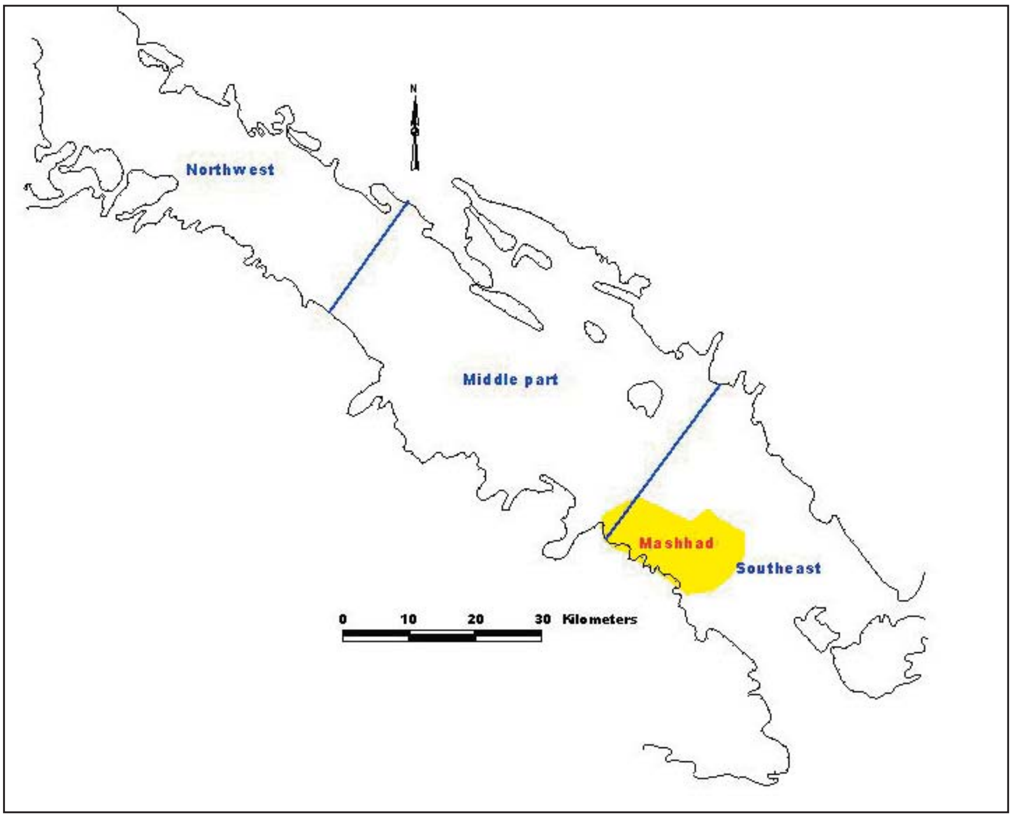

Figure 4. Geological cross section area within the aquifer

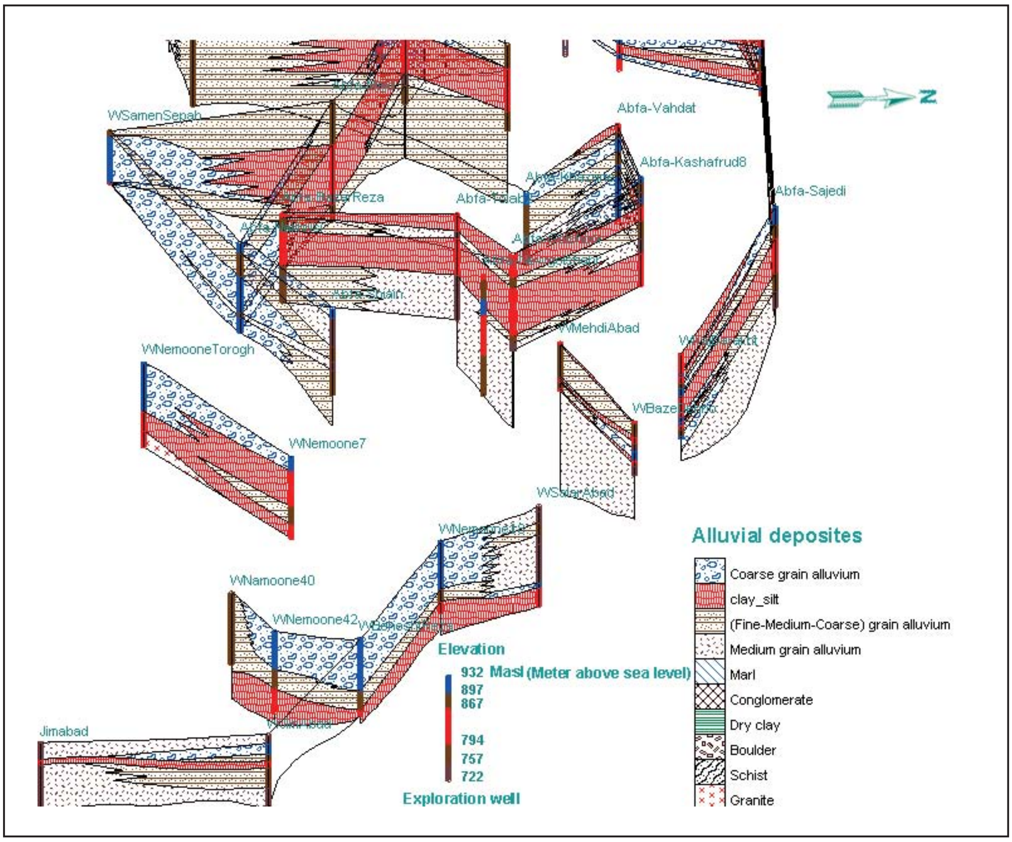

Figure 5. Geological cross sections in southeast of the aquifer

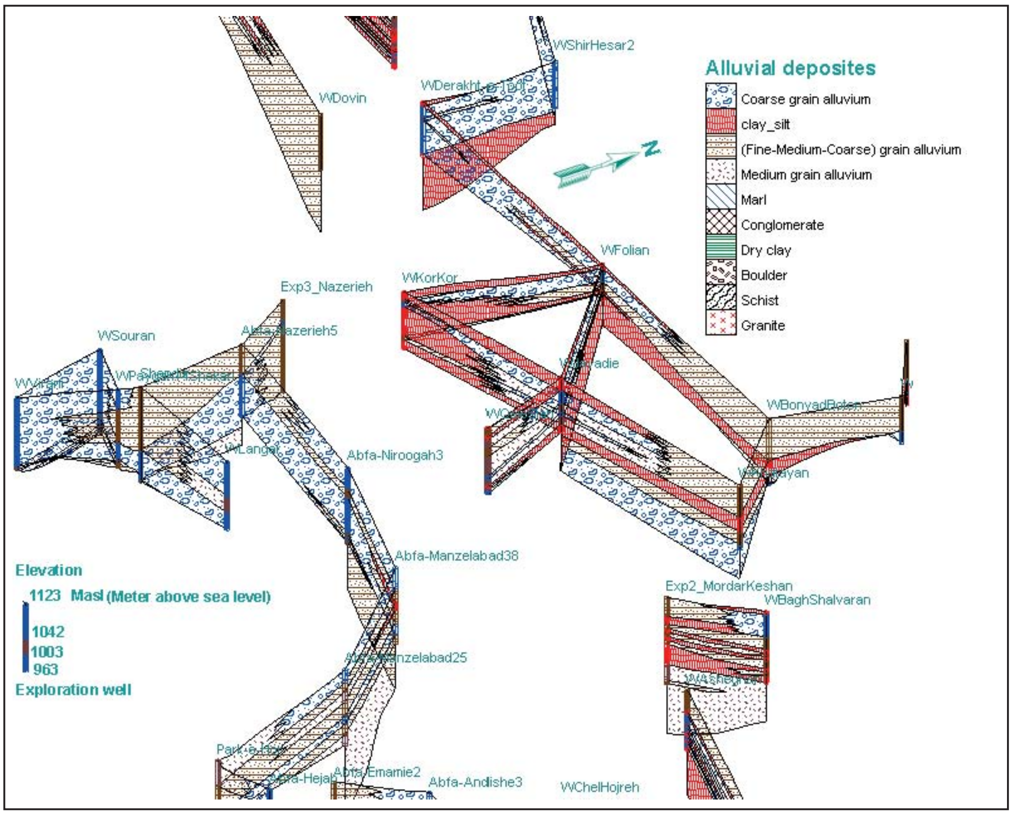

Figure 6. Geological cross sections in the middle part of the aquifer

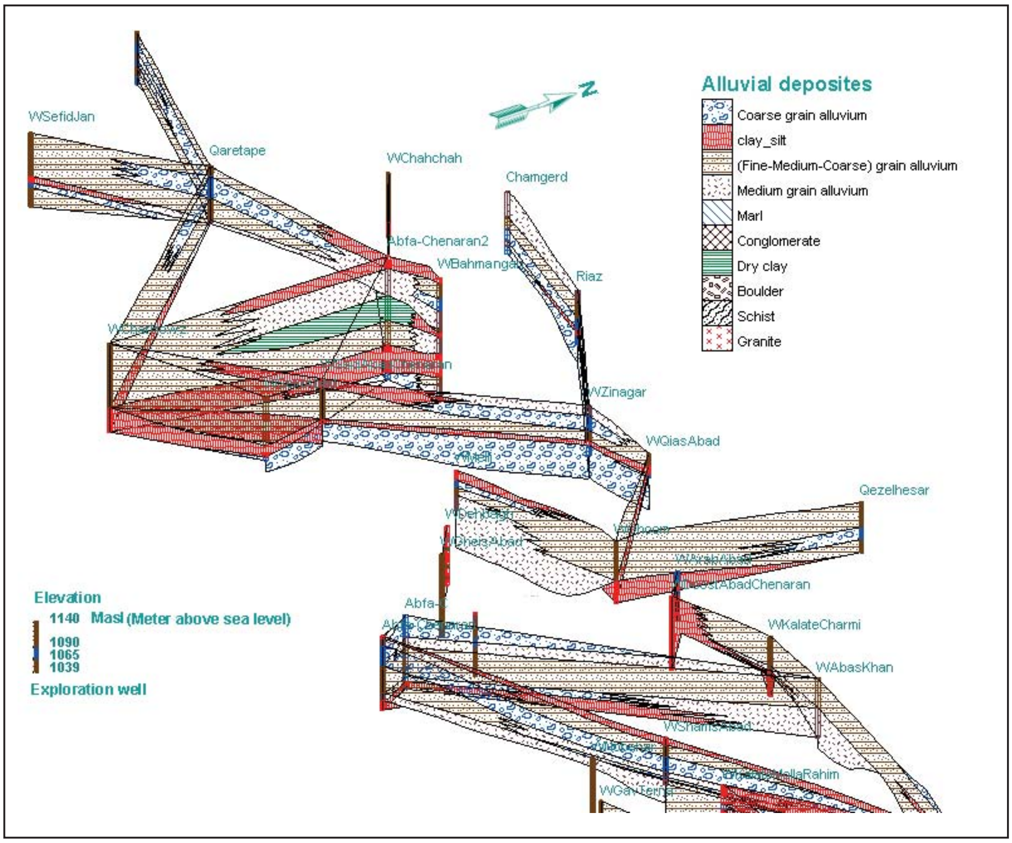

Figure 7. Geological cross sections in northwest of the aquifer

places in which aquifer transmissivites were measured through pumping test. The aquifer extends north-west, south-east horizontally with a length of approximately 150 Km. Average width and saturated thickness of the aquifer are 8 Km and 66 M respectively. Fig 9 shows 3D view of the plain aquifer.

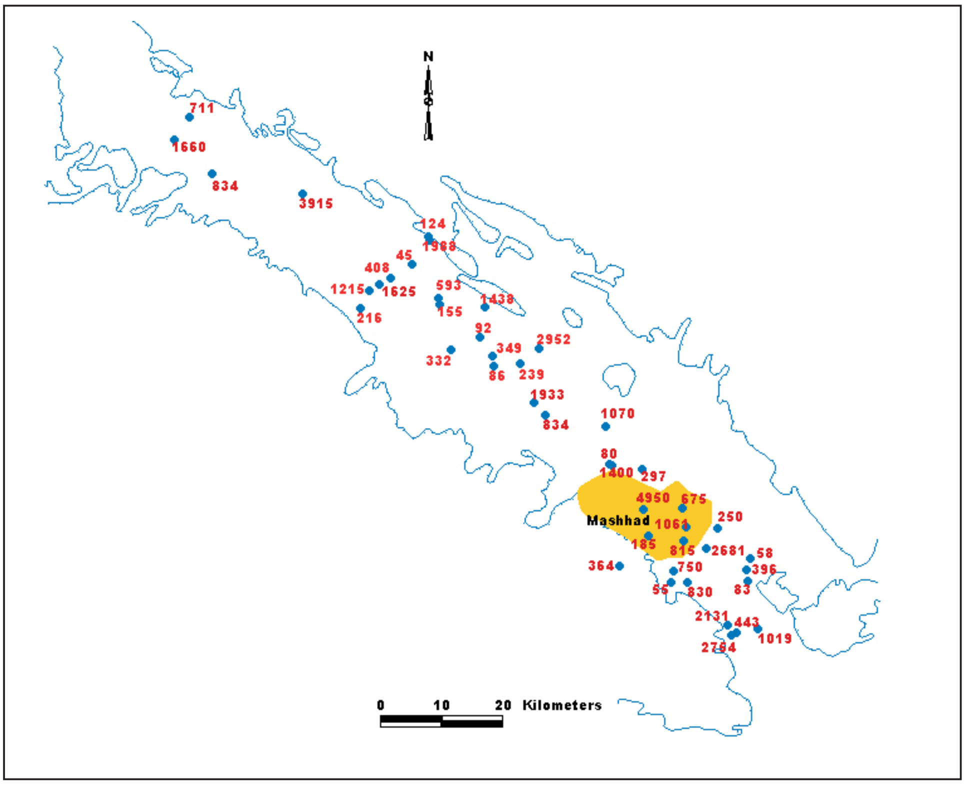

Figure 8. Aquifer transmissivity data (M^2/Day)

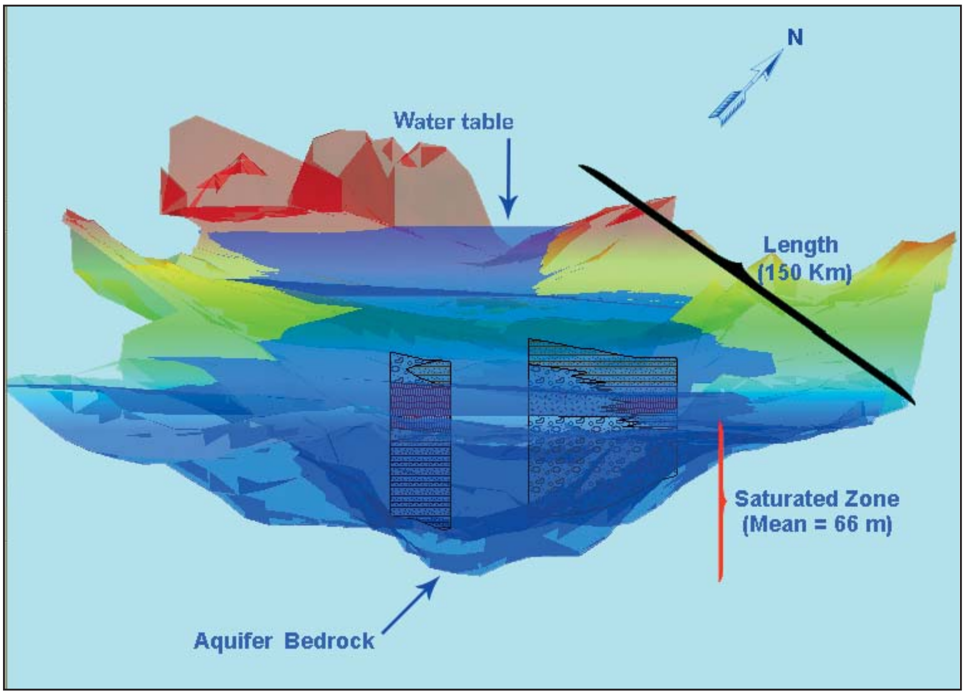

Figure 9. 3D view of Mashhad plain aquifer

Monitoring network

There are 82 observation wells in the aquifer, that water level fluctuations are checked monthly through them. Figure 10 shows aquifer observation wells and isopotential map of the aquifer in 2004.

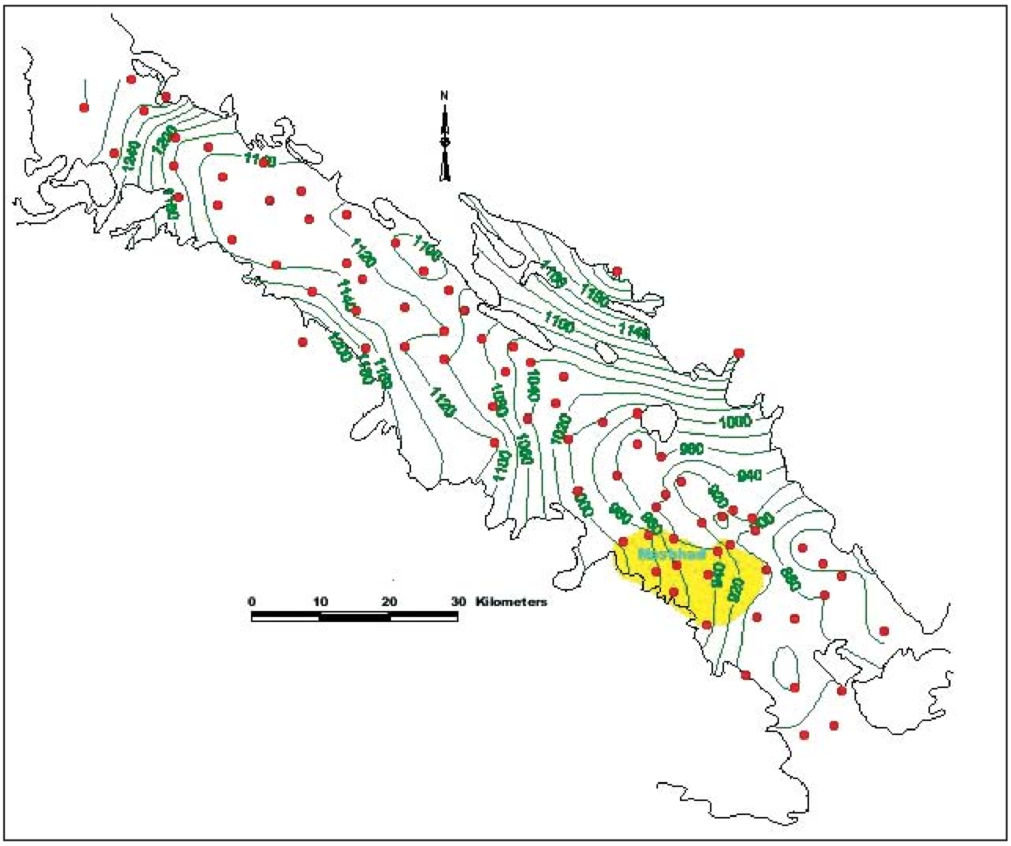

Figure 10. Observation well and aquifer is potential map in the year 2004

Groundwater is mostly recharged by agricultural and municipal return flow, floods and surface runoff flows from south mountains and some direct infiltration from precipitations.

Groundwater resources

According to the water budget data in 2000 (Table 1), the existing over drafting from aquifer to an amount of 183.7 MCM per year depletion resulted fall in its static level, which is projected to continue in future if the current situation extends. The data collected in 2003 from Mashhad plain (Table 2) shows, 6,319 wells have been dug for agriculture, industry and drinking purposes, from which about 1,060 MCM/year is drawn-off. Additionally there are 403 springs and 895 Qanats draining annually about 90 MCM and 85 MCM of water from the aquifer respectively. Figure 11 shows distribution of water resources within the basin. Figure 12 and 13 show unit hydrograph of the aquifer and the amount of rainfall in Mashhad plain.

Flow In(MCM/Year)		Flow Out (MCM/Year)	
Groundwater Inflow	198.4	Evapotranspiration	2
Infiltration From Sewerage	167.6	Groundwater Outflow and Drainage	3
Infiltration From Surface Flow	104.3	Discharge (Well, Qanat, Spring)	865.4
Irrigation Return Flow	216.3		
Total Inflow	686.6	Total Outflow	870.4
Change In Aquifer Reservoir (MCM/Year)	–183.7		

Table 1. Groundwater budget of the aquifer in the year 2000

Water Resources	Well	Spring	Qanat
Number of WR	6,319	403	895
Extraction (Per Year) - MCM	1,060	90	85
Total Extraction (Per Year) - MCM	1,235		

Table 2. Groundwater extraction from Mashhad plain in 2003

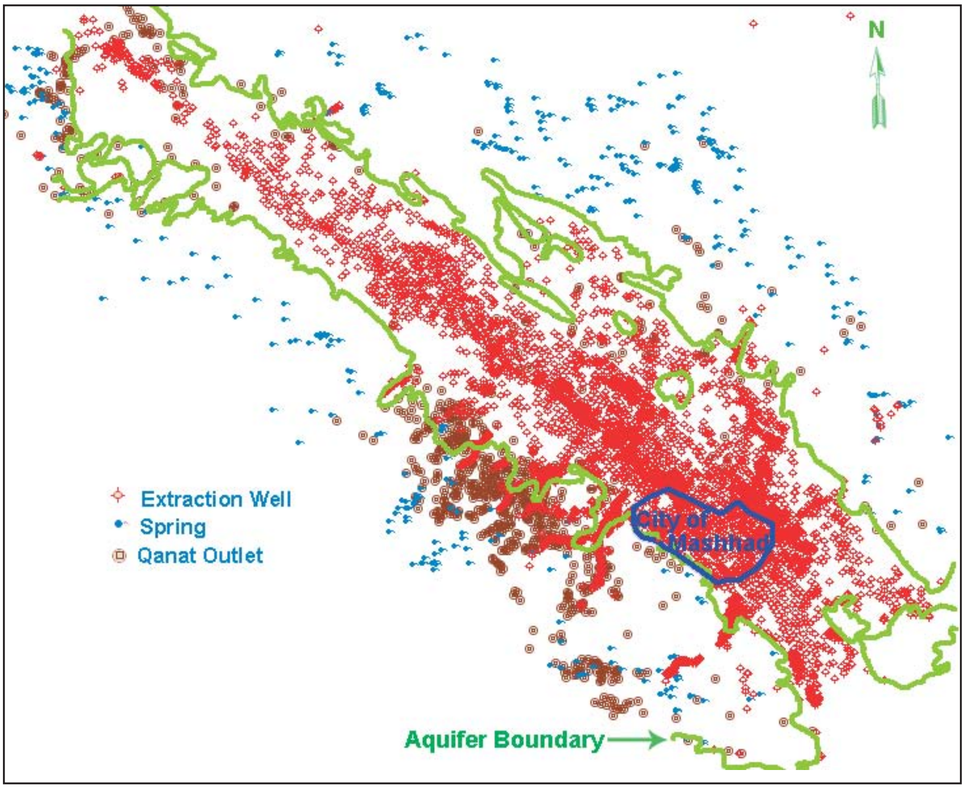

Figure 11. Distribution of groundwater extraction points in Mashhad aquifer

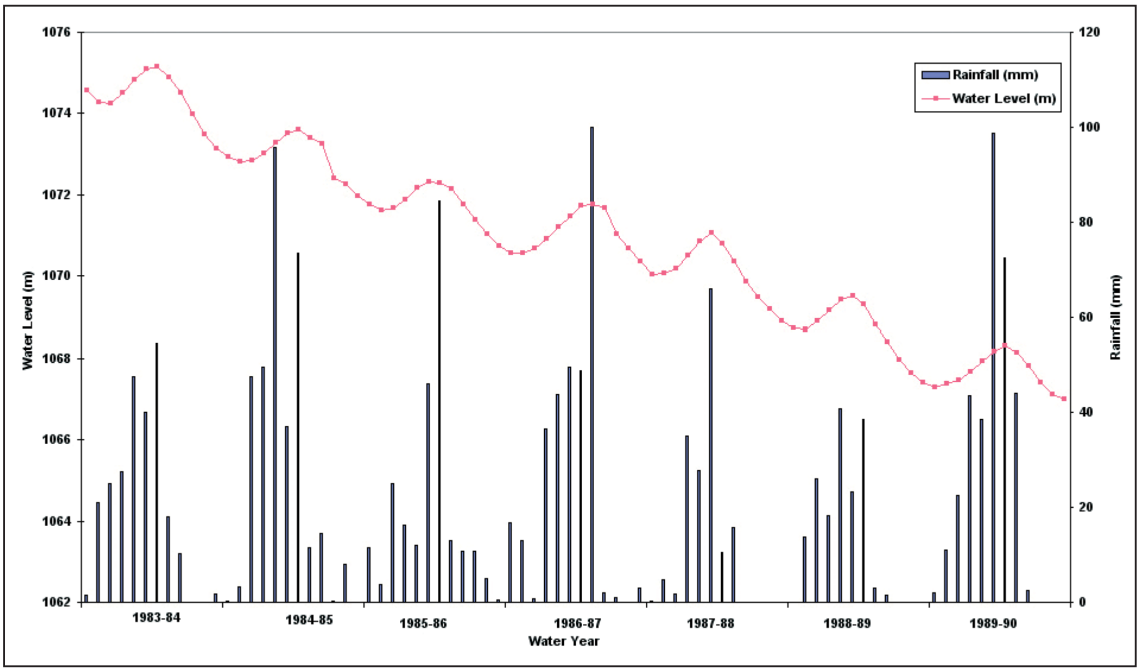

Figure 12. Unit hydrograph of the aquifer between 1983-84 to 1989-90

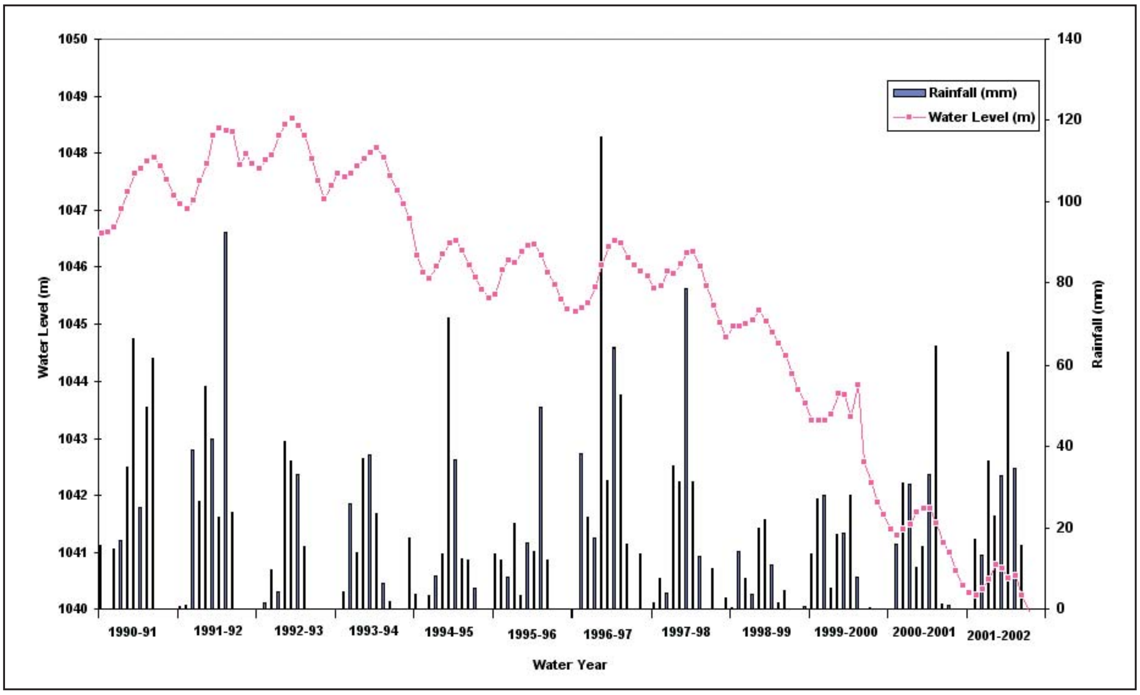

Figure 13. Unit hydrograph of the aquifer from 1990 to 2002

From the first measured data in 1983–84 to 1989–90 groundwater level dropped gradually (Fig. 12). During this period, water table fluctuations within each year demonstrate the role of precipitation and aquifer recharge. Precipitation has resulted in small upward movements of water level.

General trend of the hydrograph shows a huge reduction in aquifer reserves. During this period aquifer has experienced a decline of 7.5 m in water level. Such a falling reflects the impacts of the 1981–89 drought episodes.

From 1990 up to present time water table has fluctuated disorderly demonstrating three distinct parts. Between 1990 and 1994 increasing in water level is observed as a result of 6 wet years between 1988 and 1994. Average rising in this period was about 2 m.

After a period of rising, water table again started to decline gradually for another four years. At the end of this period there was a 1.45 m decline in water level.

Third part of the hydrograph shows a drastic water table plummet, with a minor recovery. The last drought phenomenon caused 5.2 m falling in water table and the threat to the aquifer is still prevailing.

Groundwater quality and pollution

Geological formation in the north and south of the plain are composed of sedimentary and igneous – metamorphic rock respectively. Marl, shale and gypsiferous sandstone of some geological formations in the north have negative effect on groundwater quality. In the northwest of the aquifer, electrical conductivities are slightly high, due to fine alluvium and shallow bedrock effect. Figure 14 shows the monitoring network for water quality assessment and iso-Ec map of the aquifer in 2004.water quality parameters are taken in these points at least once a year. Considering the groundwater electric conductivity (EC) map, in Figure 15, there are 3 separate zones in the aquifer;

- Central part having EC of 250–1,000 (μ S/Cm).
- North-west parts having EC of 1,000–2,250 (μS/Cm).
- South-east parts having EC of more than 2,250 (μS/Cm).

Figure 14 and 15 show that the groundwater quality reduction from the center of the plain to the west and also east. Therefore, over extraction of groundwater will cause expansion of low quality ground waters towards the central parts of the aquifer, particularly where recharge of the aquifer is improper. Mashhad groundwater also exposed to pollution from wastewater disposal through wet wells due to non-completion of sewer collection networks.

Figure 16 shows the amount and pattern of distribution of nitrates in the aquifer of city of Mashhad and its suburb in the year 2003. The average concentration of nitrates in the aquifer was about 65 Mg/l in 2003, which is 1.5 times higher than the permitted amount. Nitrate pollution is mostly concentrated in highly populated and old residential regions.

Consuming nitrated waters for long time periods will increase the possibility of suffering gastric cancer and respiratory system diseases in infants.

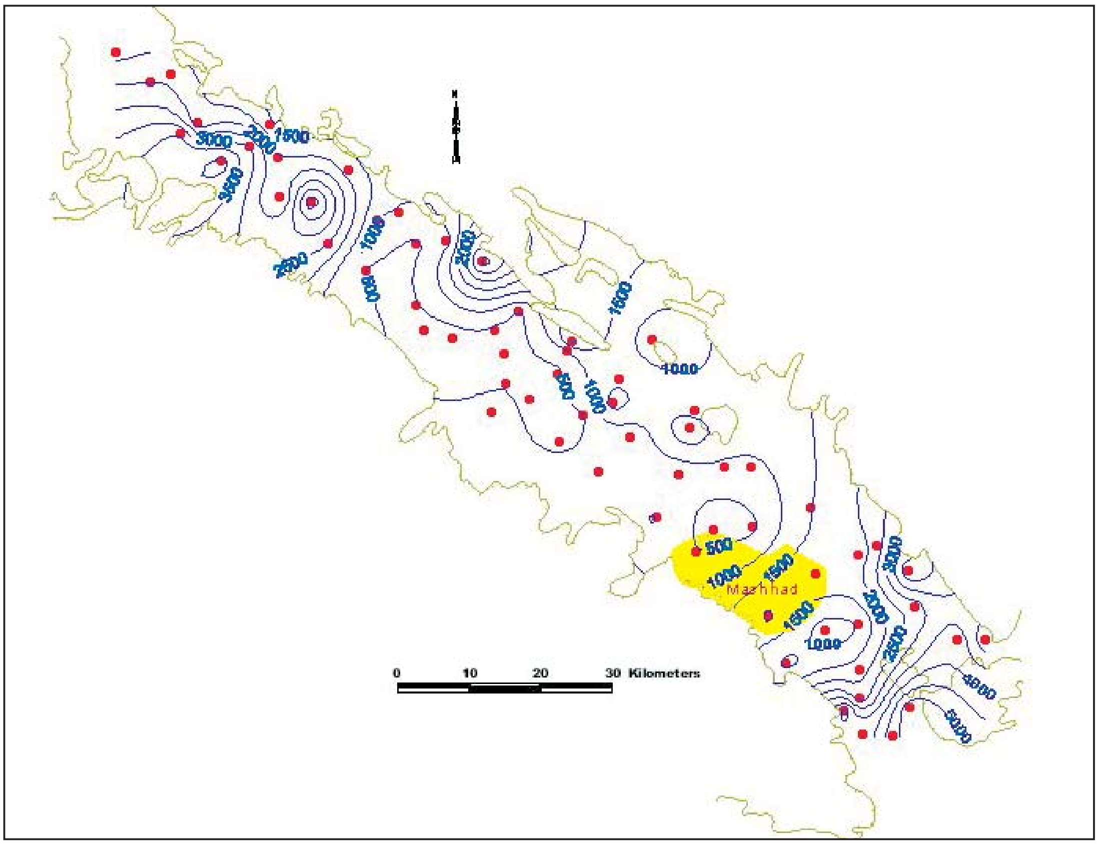

Figure 14. Aquifer quality monitoring network and iso-Ec map in 2004

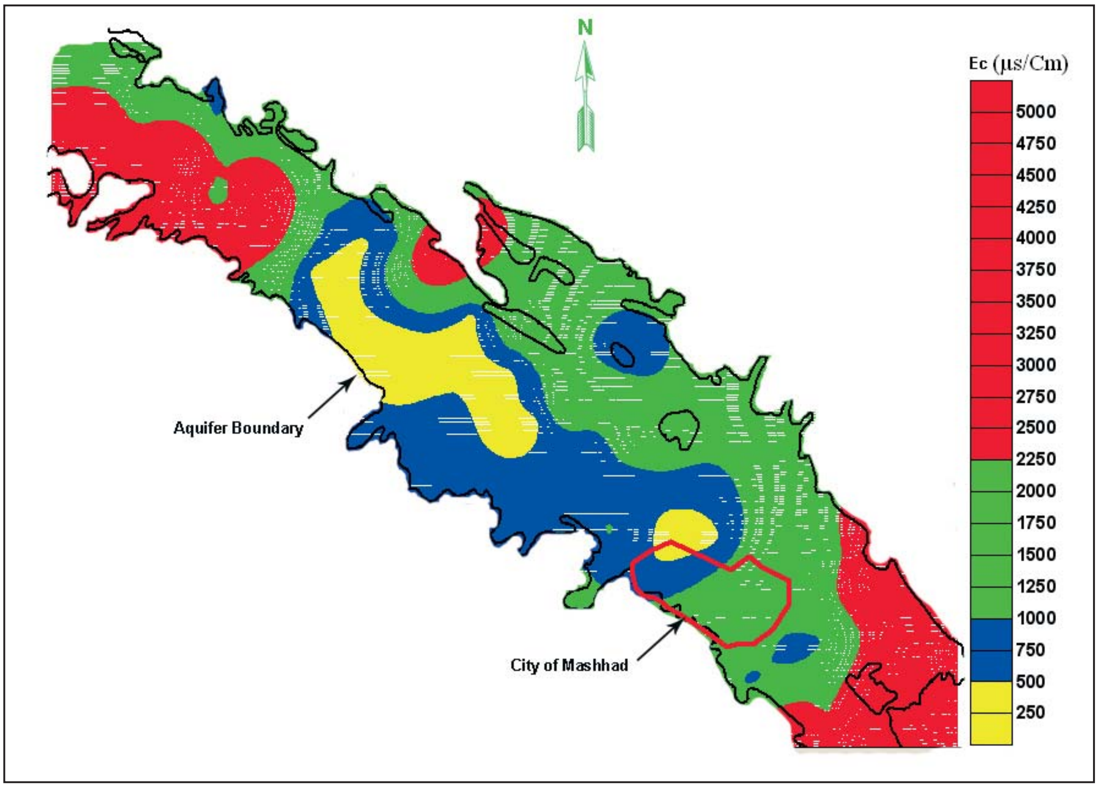

Figure 15. Electric conductivity pattern of the aquifer

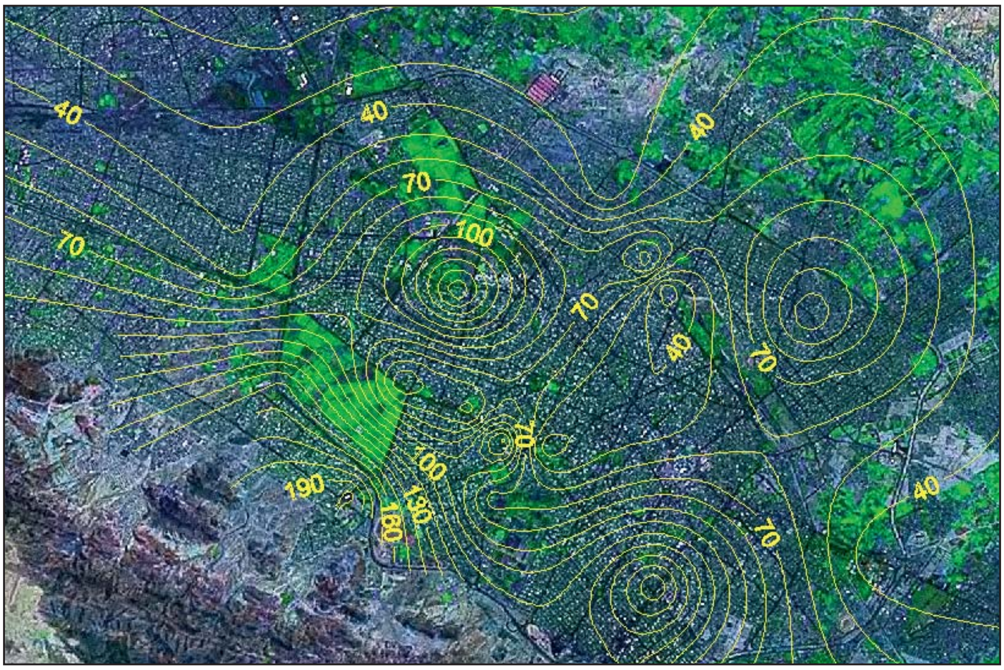

Figure 16. Amount and distribution pattern of Nitrate in the aquifer of Mashhad city

Land subsidence

To record data concerning relative crustal movement within the limits of Mashhad plain, National Surveying Organization has established 4 permanent GPS stations in Tous, Toroq, Kalat and Mashhad, which their positions are illustrated in Figure 17. These stations record in circa-

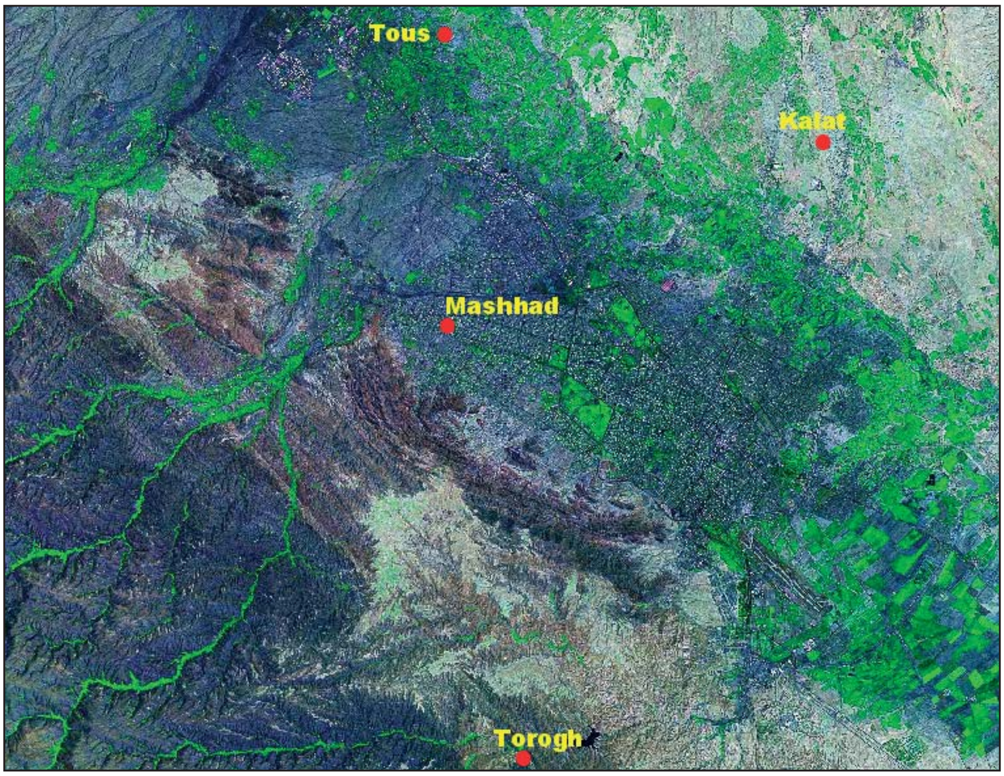

Figure 17. Location of four GPS station in Mashhad plain

dian order the relative crustal movements in North-South, East-west and vertical components. Figure 18, represent the records of Tous station. The other three hasn't shown obvious movement. The amount of vertical variation from January 1st of 2005 to June 2006 was about 30 cm. Although there are various factors contributing on such a sinking phenomena, but the most common factor is the human activities in increasingly over drafting the under ground resources (water, oil and gas). Considering the results, it has been observed that about 80% of subsidence occurrences were due to exploitation of groundwater.

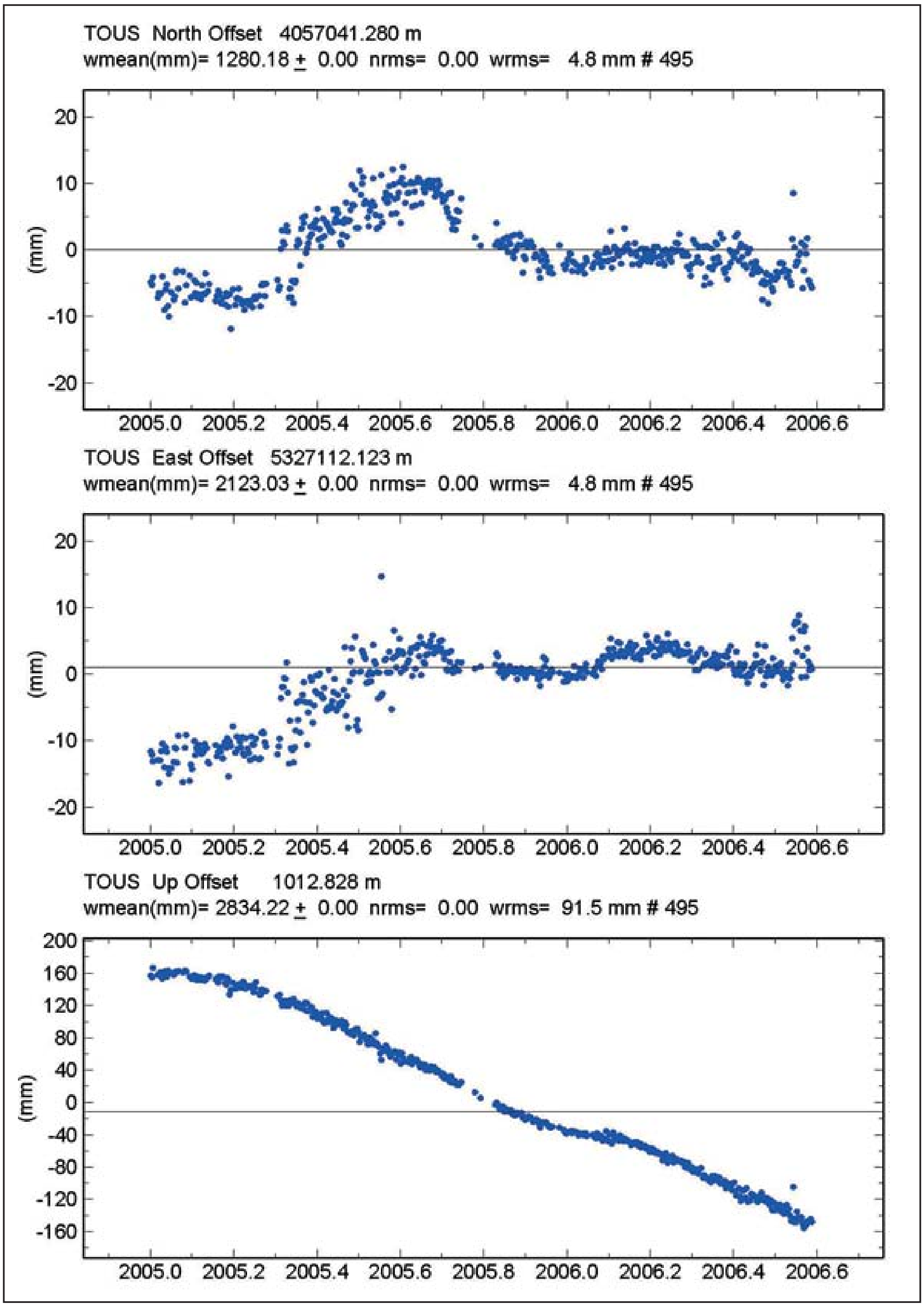

Figure 18. North, East and Up offset of Tous station

Presence of fine grained layers in the water table and loosing their water, cause compaction of the layers and consequently its subsidence. Figures 19 to 22 show subsidence phenomenon in some parts of Mashhad plain.

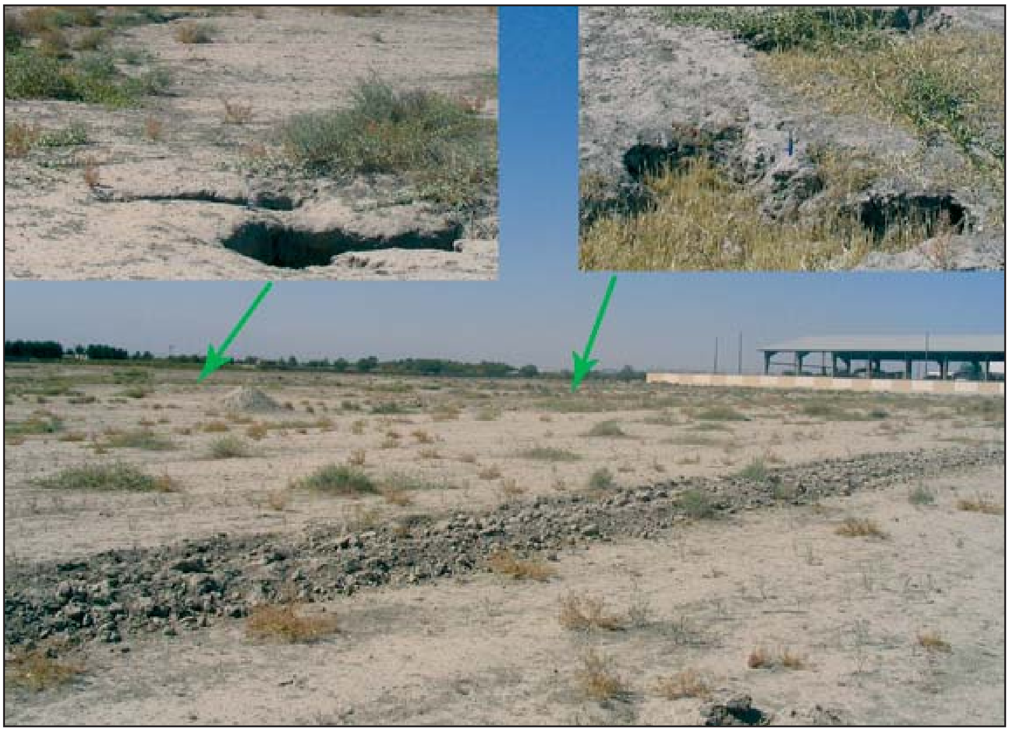

Figure 19. Earth fissures caused by groundwater overdraft

Figure 20. Earth holes occurred due to water table decline

Figure 21. Land subsidence effects under and around elevated water tank

Figure 22. Some subsidence effects in various shapes

Figure 23 shows the position of Tous GPS station and subsidence areas in Mashhad plain. As seen by the figure, subsidence areas are close to GPS station. So, although some farmers try to hide subsidence effects by filling the holes and cracks within their farms, but collected data at Tous GPS station can provide reasonable evidences of subsidence in Mashhad plain. Considering the passage of gas transfer pipelines and presence of thermal and gas power plants in the vicinity of Mashhad, land subsidence would be a great danger to these installations.

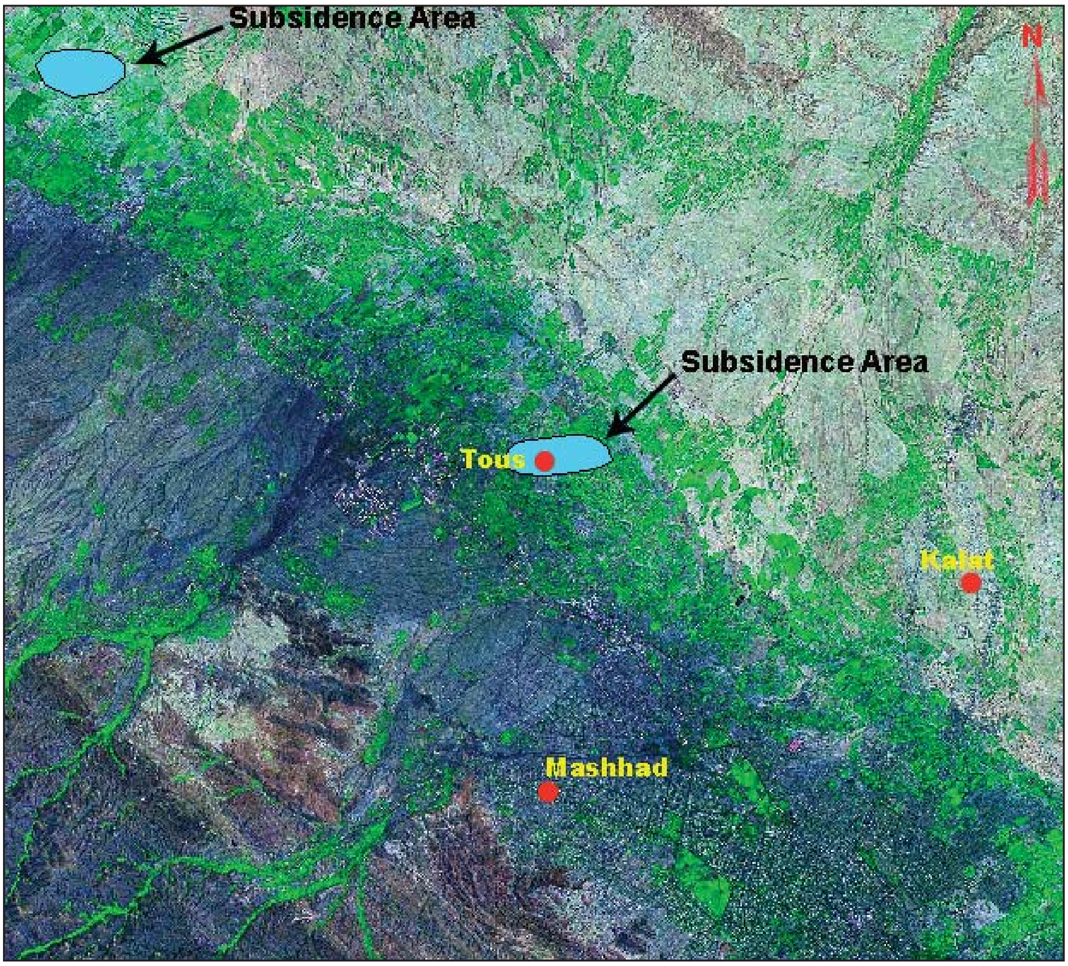

Figure 23. Land subsidence area within Mashhad plain

Ecological impact

From ecological view, drought has led to different negative outcomes within the plain, most important of them are:

- Increasing immigration rate toward cities and consequently unemployment and jobless phenomenon.
- Apparent reduction in agriculture products.
- Vegetation reduction, constant damage of soil layer and composition.
- Decreasing social comfort and increasing social susceptibility.

Water crises mitigation approaches

The most recent droughts in Mashhad plain have forced water authorities to adapt water rationing to the city of Mashhad during the summer. To execute this plan, the city was divided into 7 zones and every day of a week the water was cut to a particular zone.

This periodic rationing of water was executed in May–August 2006, but, due to the further deficit of water resources, the authorities had to divide the city into 2 zones and each zone had access to water only 12 hours per day.

Some other measures taken to mitigate water crisis in the last summer were:

- Boring some new wells in Mashhad plain.
- Displacement and deepening the existing wells to increase their water yield.
- Implementing well development measures using acid wash method.
- Identification of some private wells owned by other organizations and authorities to be connected to the distribution network.
- Distribution network pressure balance.
- To get use of high nitrate water wells by diluting them with other good quality ones. 60 lit/sec of water was added to the network by this way.
- Construction of new water supply transmission lines in some regions to implement periodic water supply.
- Distribution of packed water (bottled) in the city (Mostly for pilgrims and visitors).
- Increasing the public awareness about water saving approaches, utilizing news media (radio, TV, newspapers) and draping placards and posters all over the city.

It is clear that most of these mitigation measures were related to the increase in capacity of groundwater extraction which, by no means, was sustainable solutions for an already over-drawn aquifer bearing so many threats.

Future perspective of drought

It was observed that in Mashhad plain one of the direct drought impaction was sever fall in groundwater table.

If drought pattern continues, it can be anticipated that the groundwater table will further drop by about 12 meters till 2011 with respect to the year 2003.

Figure 24 shows the drawdown pattern in the aquifer from 2003 to 2011. As it is seen, the falling rate increases East-west wards. The highest amount of falling (about 30 to 35 meters) will happen in the West of Mashhad, where there are a number of water supply wells.

Considering the present land subsidence in these regions, it would be obvious that due to the falling of water levels, these subsidences will occur in larger scales. Also, in future the quality of ground water will definitely decrease in these regions.

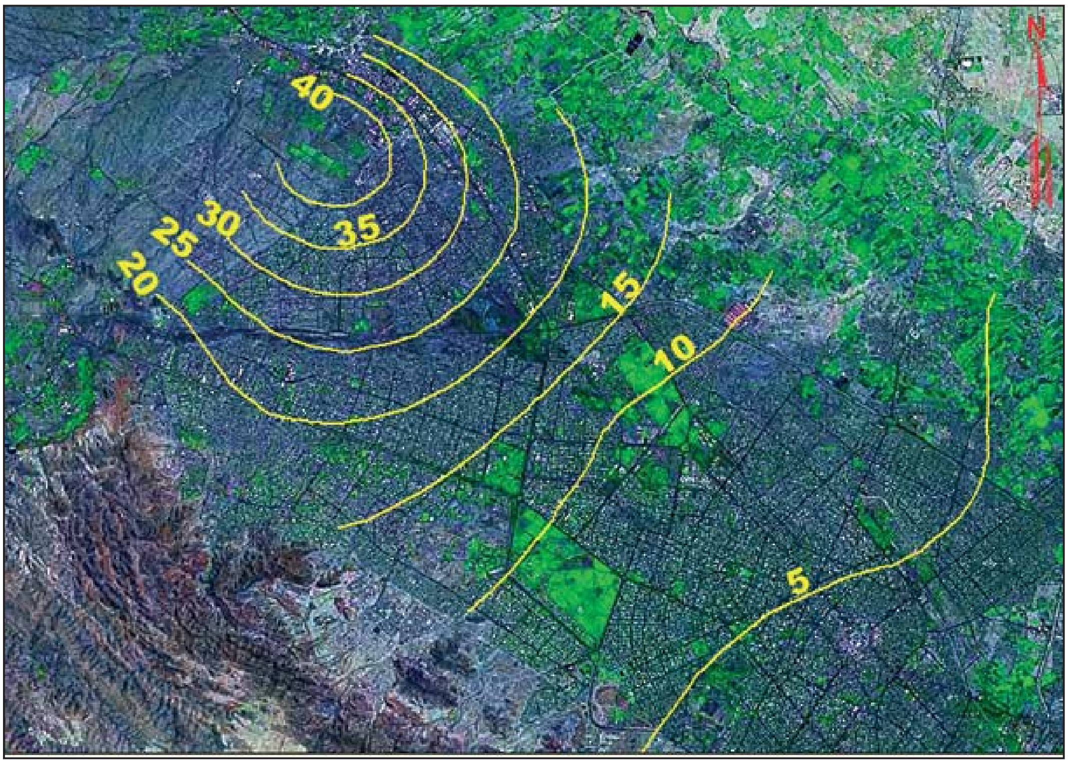

Figure 24. Aquifer drawdown pattern in 2011

Risk Management approach proposal

The importance of livelihood of Mashhad holly city with more than 2.5 million inhabitants which will exceed 4 million in 20 years time and 20 million pilgrims every year and also considering the future development of industry and agriculture in this plain requires an integrated and sustainable water resources planning in the region. Groundwater is the main source of water in this plain; therefore it must be managed with a great care and responsibility. An integrated water management approach should bring about all the stakeholders to the decision processes and provide a platform for execution of water demand management practices. This is not, by any means, an easy task for implementation but it is the only way which should be adopted for the sake of future generation. The following general directions, if implemented properly, will provide a framework for drought risk management in this plain:

- Identification of unauthorized wells in Mashhad plain and closing them down (at the present, there are 1,580 unauthorized water wells in Mashhad plain, which extract annually about 58 MCM of ground water. This is about 1/3 of water deficit of the aquifer).

- Changing the cropping pattern to less water consumed crops and using appropriate irrigation practices to improve the existing low irrigation water productivity.

- Introducing water demand management approaches through media and training programs in training centers (schools, universities …), and also, advertisement and distribution of valves, joints and other accessories to decrease water wastage.

- Adopting heavy penalties for over-user customers or establishing progressive charging rate of water consumption.
- Separation of potable water from other consumptions to get use of low quality water in the system as well.

Artificial recharge is a method to keep the water table balanced. Its efficiency depends upon the factors such as; availability of water, suitable soil grain sizes, thickness of aquifer unsaturated zone, etc …

There are various alluvial fans in Mashhad plain, having coarse grained alluvium deposits with suitable porosity and thickness of unsaturated zones, and can be used for implementation of artificial recharge projects by basin and flood spreading methods.

These alluvial fans are mostly located in the West of Mashhad plain (alluvial fans of Akhlemad, Ferizi, Golmakan, Shandiz and Golestan). The water required for recharge can be supplied from treated wastewaters of Mashhad (amount of 500 MCM/year for the year 2021) or western river floods.

Considering the direction of ground water flow from the west to the east, execution of artificial recharge projects in western regions can be of great help to keep the aquifer balanced.

There are certain places in the city of Mashhad that are suitable for recharge, such as Mellat Park, Holy shrine, and Bassij square, but as the lands are too expensive, well method can be used by injecting treated wastewaters into the wells.

- Artificial recharge of the aquifer

Doosti Dam can supply 150 MCM/Year of water to Mashhad by the year of 2008 that is about 60% of annual water demands. The 170 KM water transmission line project is under construction and will be operative in the year 2008.30

- Water transfer from Doosti Dam to Mashhad

North and North-western carbonaceous rock formations of Mashhad plain (Hezar-masjed mountain ranges) as a karstic region, might be considered to fulfill some fraction of Mashhad's water demands. Although they can not cover all water requirements, but the higher qualities of water may improve the quality of Mashhad's water as a whole.

- Investigation for new water resources development
- Transboundary water transmission to Mashhad.

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PALAEOCHANNELS AS GROUNDWATER STORAGE – A PROMISING OPTION TO COPE UP WITH EMERGENCY SITUATIONS IN RAJSTHAN, WESTERN INDIA

A.K. Sinha[1]

Abstract: Palaeochannels are typical fluvial landforms picked up by remote sensing saellite data in the state of Rajasthan, Western India. This part of globe dominantly falls in arid to semiarid climatic region and is subjected to very frequent spell of droughts. During recent past increasing incidences and intensities of flood and seismicity have also been noticed. Dependency on groundwater is increasing due to growing water demand. The increased frequencies of natural calamities has further stressed the availability of groundwater resource. To meet the resulting emergency situation there is need to augment the ground water resources through the available and innovative technology. The answer to the problem lies in finding ideal and additional subsurface storage/aquifer which may be developed for its groundwater resources and be managed through the management of aquifer recharge(MAR) and subsurface storage (SSS) technology in vogue in many countries. The paper analyzes the role of Palaeochannels with this perspective.

Keywords: Palaeochannel, subsurface storage, groundwater resource, Emergency situations, Remote Sensing, RajasthanWestern India.

Introduction

Natural and/or man made catastrophic events usually causes collapse of existing water supply system. Provision of adequate storage capacity,under growing water demands, increasing climatic variability and varied catastrophic situations is one of the main concerns for water managers in the coming decades. It is expected that a multiple of the present storage capacity may be needed during futures years. Storage of substantial amount of water can either be above ground,in reservoir behind dams or subsurface in aquifers. The subsurface storage is considered to be highly eco friendly and possibly a sustainable means to meet any emergency situation resulting due to enhanced natural and manmade catastrophic events. With increasing frequencies of natural and manmade catastrophic events (Figure 1) the concern is also growing and becoming more widespread. This paper looks into the scope of Palaeochannels as suitable subsurface

1. Dr. A.K. Sinha,Department of Geology, University of Rajasthan, Jaipur 302004, India.
Email: sinhaaa@sancharnet.in

storage/Aquifer/for regulation and withdrawal of groundwater. It is visualized that if the palaeochannel found in this part of globe is subjected to management of aquifer recharge (MAR) and subsurface storage (SSS) technology practices, these landforms of the arid to semiarid regions may meet more than the groundwater requirement poised due to frequent emergency situations in the state of Rajasthan, western India.

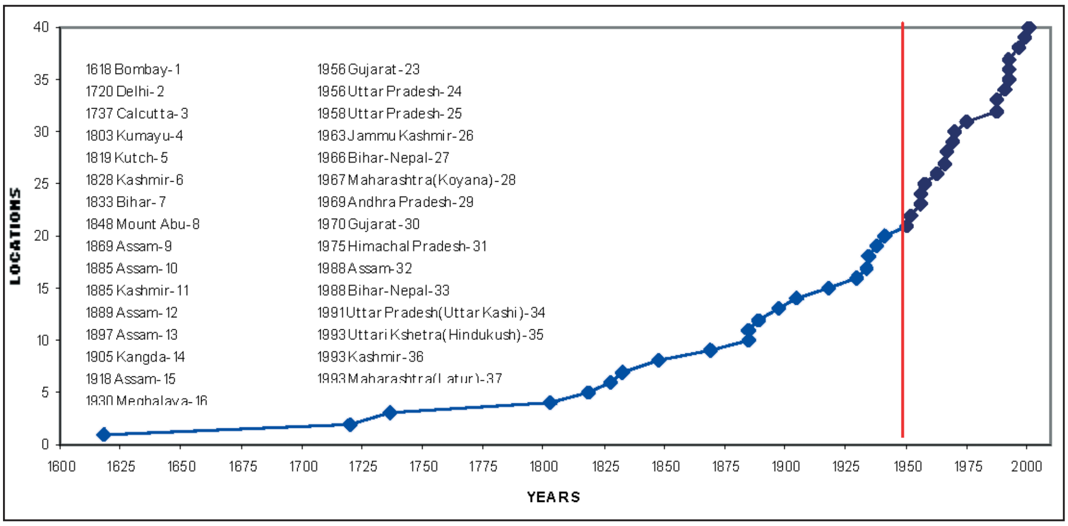


Figure 1. Increasing Frequencies of Earthquake Occurrence in India (Sinha2004)

Palaeochannel as an aquifer

Palaeochannels are typical riverine geomorphic features in a location representing drainage streams, rivers, rivulets which were flowing either during the past time and now stands either buried or lost or shifted due (Figure 2) tectonic, geomorphologic, anthropogenic process/ activities as well as climatic vicissitudes. They appear in plan as linear or curvilinear signature and shape on Remote Sensing data products.. Synonyms for Somewhat similar or related land-forms used in lieu of Palaeochannels are Palaeodrainage, Lost River Buried River, Buried Channel or Buried valley.

Palaeochannels are also identified as remnants of stream channels cut in older rocks/sediments and filled by younger overlying sediments, representing the distribution of valley systems as these existed at a given geological time in the past (Bates & Jackson, 1980). However various definition of Palaeochannel has emerged. Some of which are as follows:

1. Palaeochannels are the drainage/rivers/streams which were flowing either ephemeral or perennial during past but now these are lost due to tectonic activities, climatic changes and geomorphic activities.
2. Palaeochannels are the drainage/rivers/streams which were flowing either ephemeral or perennial during past time but at present time these are lost due to internal (tectonic activities) and external activities (climatic, geomorphic and anthropogenic)
3. Palaeochannels are the older river courses which were buried due to sedimentation.
4. Palaeochannels are the remnant scars of the shifting of the rivers such as Yamuna, Sutluz rivers.

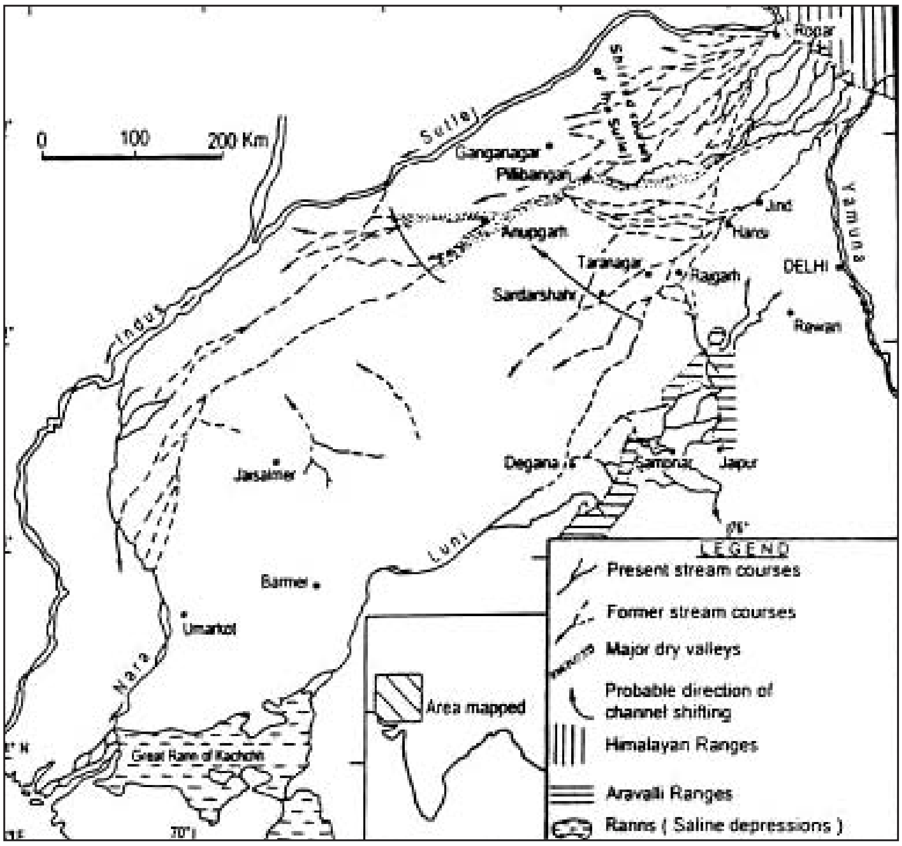


Figure 2. Courses of the present and former streams(palaeochannel) passing through northwest Rajasthan (after Kar 1995).

The palaeochannels have ideal rock strata for storage. According to prospecting data, the water-bearing rock characteristics of these channels are highly porous gravel, coarsemedium sand (in the alluvial fan area), medium fine sand, fine silt (in the river channel zones) and silt (in the delta). The palaeochannels have a relatively convenient source of recharge, as they commonly serve as flood channels or aqueducts and have good paths of infiltration (Table 1, Figure 3). This is because of the fact that on the surface they have usually sandy soil or sandy loam. Some may have even sand dunes or river beaches. Most of the palaeochannels are inter linked with present rivers or canals, which is beneficial to lateral recharge of the groundwater.

Paleochannels can also provide information about the response of catchments and rivers to past climatic changes, with implications for projected changes to climate in the future. Relict fluvial channels that are in filled with high permeability sediments act as preferred pathways for groundwater flow and solute transport. In coastal regions, such paleochannels can provide a hydraulic connection between freshwater aquifers and the sea, facilitating saltwater intrusion landward or freshwater discharge offshore.

Palaeochannels have long attracted scientific and practical interest. Amongst other things, these abandoned channels are economically important because they often contain deposits of Tin, Tungston Gold Silver and diamonds besides permeable fills which form excellent aquifers. Palaeodrainage is an important factor in understanding the full hydrogeological mechanism of the area, as the presence of palaeochannel can pose a serious threat to engineering projects within the region.

As traditional intrusive methods have inherent economic constraints, a large number of geophysical methods – electrical resistivity, electromagnetic potential, seismic refraction and reflection – are being successfully used in delineating and exploiting palaeochannel. The studies and information gained through interdisciplinary sources and techniques have revealed the of palaeochannels in different tectono-climatically dynamic regions of the world.

Table 1. Lithology of Palaeochannel

Units	*Description*
PrePalaeochannel	
Unit 1	Light greyyellow lake marl (maximum thickness >150 cm)
Unit 2	Dark (? Organic) marl (max.20 cm)
Unit 3	Backswamp clay (max. 160 cm)
Channel fill	
Unit 4	Grey clay with manganese staining (max. 30 cm)
Unit 5	Matrix supported gravel, locally part-cemented (max. 30 cm)
Unit 6	Fluvial silts, sands and gravels, coarsening from west to east (max. 220 cm)
Sub-unit 6a	Redbrown silts
Sub-unit 6b	Buff silts
Sub-unit 6c	Grey to orange fluviatile sands containing large freshwater bivalve shells Fluviatile gravels
Sub-unit 6d	
PostPalaeochannel	
Unit 7	Alluvial clay with manganese staining (max. 230 cm)

Figure 3.
Spread of cobbles and gravels at Jayal, near Didwana (District Nagaur,Rajasthan) presumably deposited by the ancient channel.

Palaeochannel in Rajasthan

As the conviction regarding the existence of mighty river called Saraswati through the information derived from literature and archeological finding strengthened, the search of its palaeochannel in the arid regions of Rajasthan and its adjoining states got into momentum. Review of literature reveals that neotectonic activity during the Quaternary period coupled with climate vicissitudes caused disorganization of natural drainage in Rajasthan, which led to disappearance of some of the then existing river and changes in courses of some others.

A large number of investigators have utilized remote sensing techniques to study the arid terrain of Western Rajasthan since last three to four decades. Many palaeochannels were identified through remote sensing techniques (Figure 4). Useful reviews of such works have been made by Sahai (1993). Kar (1993, 1995), Rajawat and Narain (1996), Radhakrishna and Merh (1999), and Valdiya (2002). Ramasamy et al. (1991) have interpreted the palaeochannels of entire Western India using Landsat data, interpreted the same with regional lineament fabric (Bakiliwal & Ramasamy, 1987).

Various agencies also including NRSA, CAZRI, SRSAC(1999) with the help of remote sensing tools have picked up the signatures of the palaeochannels in western India particularly in state of Rajasthan and Gujarat Recharging of palaeochannel has also been considered as drought proofing measures in Rajasthan (Sinha et al 2002).

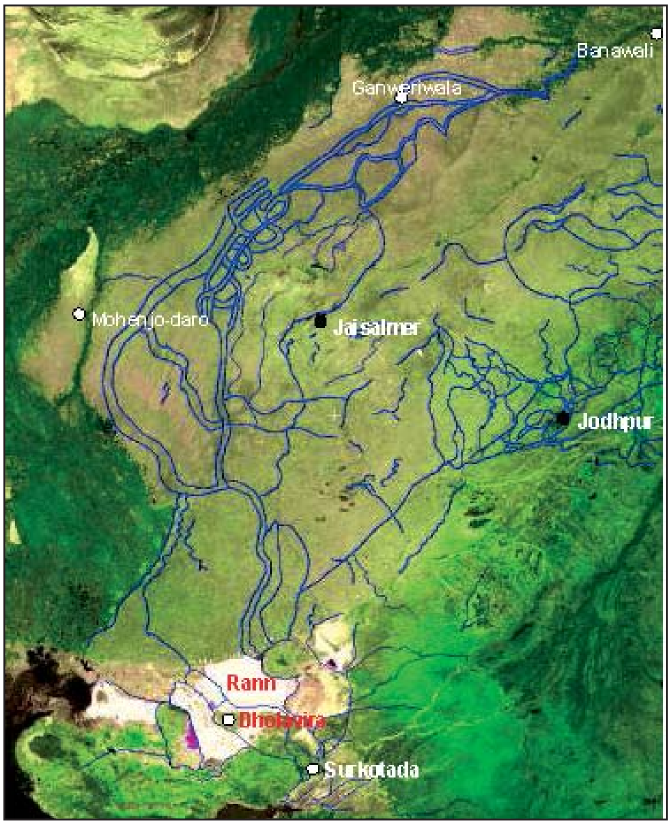


Figure 4. Palaeo Drainage Network Map of The Indian Desert Region IRS P3 WiFS Image (Source: RRSC, Jodhpur, India)

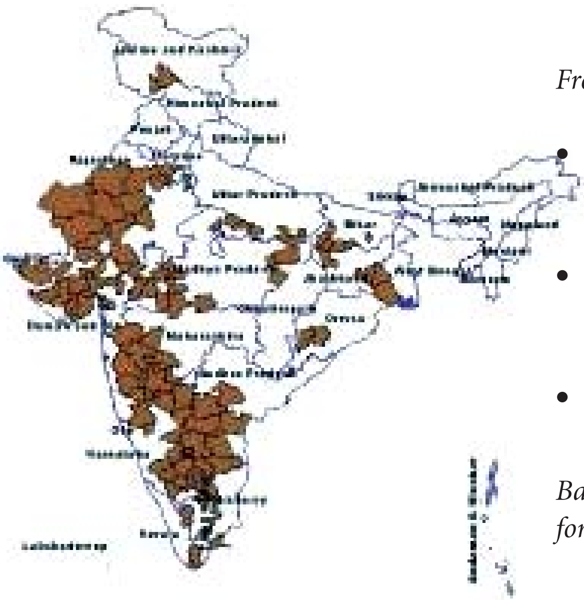
Emergency Situations in Rajasthan

Rajasthan is the most water deficient State of India. It has 10.4% of the country's area but only 1% of its water resources in the form of annual rainfall. There is no perennial river except Chambal and Mahi (AISLUS 1990). The region has to depend upon its share of water from inter state river basin. The rainwater availability is through seasonal rivers during the monsoon.

Deficient rainfall and consequent scarcity of surface water has led to heavy dependence on groundwater, the resources of which are also meager. Rajasthan's economic growth is largely dependent on water, more specifically on groundwater. 71% of the irrigation and 90% of the drinking water supply source is met by groundwater (Rathore 2003).

The state suffers from various natural and manmade calamities such as fast sinking water table; high fluoride, salinity and alkanity in groundwater ; high frequencies and intensities of drough, flood and seismicity.

The groundwater stands overexploited in more than 140 blocks out of the total 237 blocks of the state. Water table is declining at the rate of 10 to 40 cm per year in different parts of the state.The state suffers with drought very frequently. As per one estimate every third year it suffers with drought (Figure 5). Out of thirty two districts thirty one districts suffers with varying intensity of drought.



Frequency of droughts

- Tamilnadu, J&K Telangana, West Rajasthan – **every 2.5 years**
- Gujarat, E. Rajasthan & W. Uttarpradesh – **every 3 years**
- Other states – **every 4-5 years**

Based on the rainfall deficiency for the last 100 years

Figure 5. Drought frequency in India and in Rajasthan

Floods often affects very adversely the public drinking water supply. The conventional water supply systems in the affected regions usually collapses and need to be substituted by import of water in bottles and tanks on a large scale to prevent infections diseases. It has been noticed that during recent past ,possibly due to climate change implication , western India is subjected to rising incidences and intensities of flood (Figure 6).

Further, because of the increased overdraft of groundwater from all the potential regions of western Rajasthan, recharge to the aquifer during normal rainfall periods is inadequate, especially because of the sporadic rainfall distribution patterns and the terrain characteristics as well as with a major portion of the precipitation being lost as runoff or through evaporation. It is therefore important to identify the potential aquifers so that the limited surplus rainwater received in the region is conserved efficiently for use during various emergency situations and to meet the ever increasing demands on ground water resources.

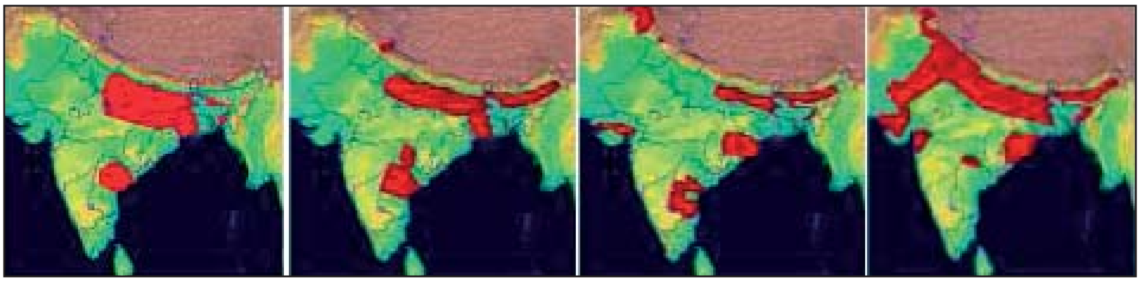


Figure 6. Increasing Incidences of Flood in Western India including Rajasthan – Climate Change dimension (after Das 2005)

Case Study

Introduction

To Identify the palaeochannels for ground water storage and development, a study entitled 'Mapping of Palaeochannel (buried channel) in Mendha river basin of Rajasthan', was carried out on 1:250,000 scale. An integrated approach involving visual interpretation of single band Landsat MSS and TM images, False Colour composite and digital images processing of IRS LISS III data in conjunction with topographical sheets, land use pattern, geomorphologic and geological records was followed to delineate the Anokhi palaeo channel amongst few more in the area.

Objectives

- To assess the groundwater potential in Anokhi palaeo channel with a view to establishing the usefulness of buried channels for groundwater development.
- To locate new aquifers for the development of groundwater resources in Rajasthan.
- To provide suitable locale for groundwater exploration and development.

Study area

The study area is in the north west of Jaipur district of Rajasthan state and extends between north latitudes 27°0' and 27°15' and east longitudes 75°15' and 75°50' and falls in the survey of India toposheet No. 45 M (Figure 7).

The area has scattered hillocks in the northeast. In the western part extensive sand dunes, playas and alluvium exist. The Sambhar salts lake is located in the extreme south west of the area. The general slope of the land is towards southwest. The elevation varies from 380 m above mean sea

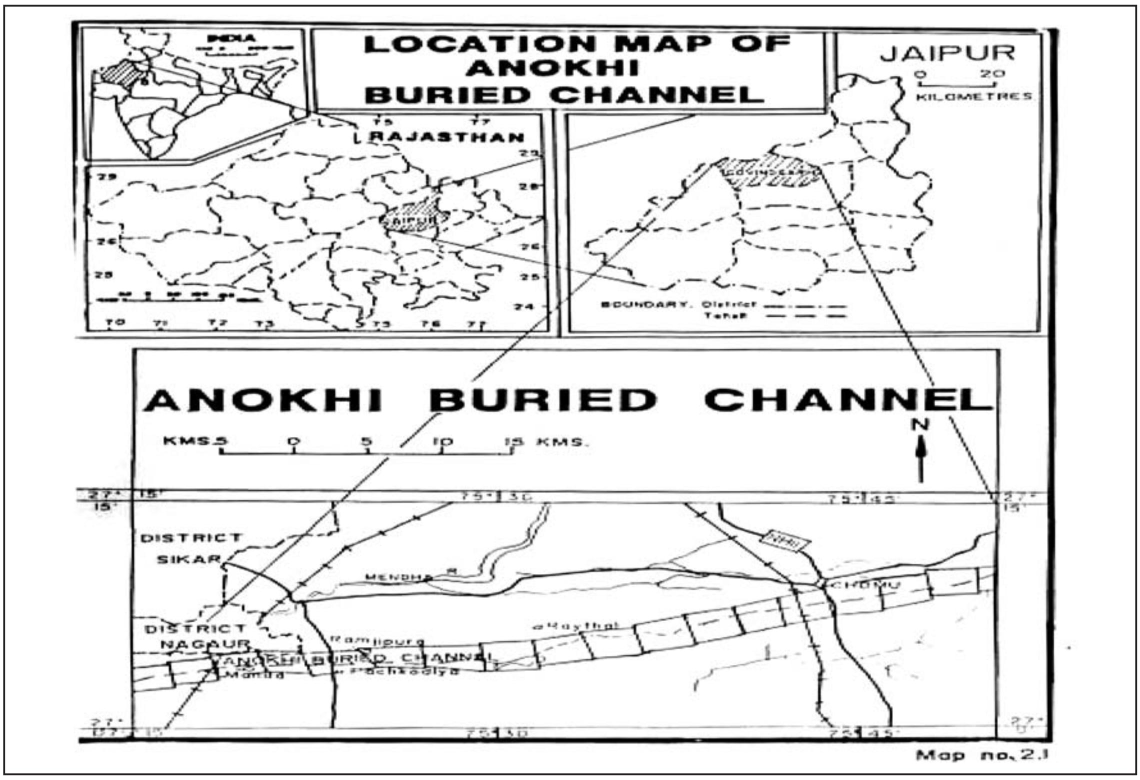


Figure 7. Location map of Anokhi palaeo/buried Channel

level in the southwest to about 520 m above MSL in the northwest. The drainage of the area is associated with inland drainage system that has its natural depression in Sambhar Salt Lake. The main drainage that feeds the Sambhar salt lake is Mendha River and its tributaries flowing from northeast to southwest direction. The study area is an old path of a tributary of Mendha river.

Remote Sensing Data Interpretation

The application of Remote sensing data to palaeochannel delineation is based on three broad principles namely spatial and genetic relationships between surface material and underlying palaeochannel fills; physical and spectral contrasts between palaeochannel fills and surrounding terrain's and the nature of palaeoriver dynamics

The aerial extension of Anokhi palaeo channel was delineated on 1:50,000 scale through digital image processing of remote sensing (IRS IC LISS III) data. The FCC of the area was generated (Figure 8) after applying principal component analysis. The FCC so obtained, was then visually interpreted for precisely delineating the course of Anokhi palaeo channel. Analysis of the FCC reveal existence of a linear feature starting from Jalsu village and converging in Mendha river near village Piprali covering a length of 80 km. with an average width of around 3 km. With a view to narrowing down the target width of buried channel, existing bore holes, hydrographs and meteorological data were also studied in conjunction with the surface data, it was then correlated with other physical features such as old bridges on the roads, railway tracks etc., which indicated the course of earlier river i.e. Anokhi river.

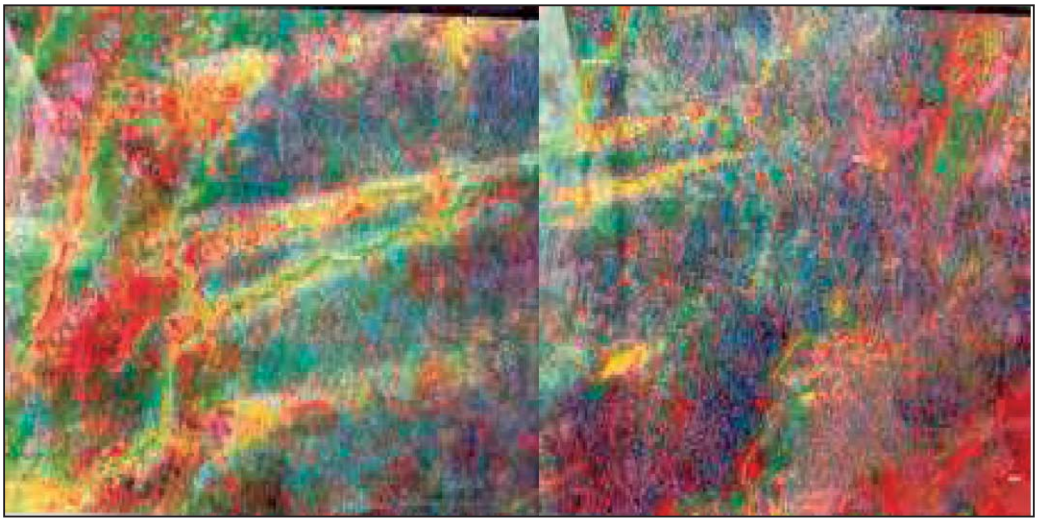


Figure 8. IRS IC FCC showing the existence of a linear feature starting from Jalsu village and converging in Mendha river near village Piprali covering a length of 80 km and an average of 3 km in width

This resulted in further narrowing down the effective target area to a width of around 500 m along the course of channel and it was further reduced up to 100 m after carrying out detailed geophysical survey. Identification of buried channel was verified in the field and the spectral signatures were collected using groundtruth radiometer. The RS data interpretation of the buried channel was correlated with geomorphologic, geohydrological and other related evidences.

Geophysical survey

The geophysical surveys helped in confirming the course of the palaeochannel and also in narrowing down the target area for test drilling (Figure 9). The geophysical survey was carried out in two phases:

Phase 1:

Geoelectric profiling was carried out to ascertain the depth of bed rock across the course of Anokhi palaeo channel along six profile lines with the following specifications:

(i) Length of the profile line	=	500 meter
(ii) Station interval	=	20 meter
(iii) Electrode separation	=	2 meter

Phase II:

Geoelectric sounding (VES) was carried out at eight lines across the course of the channel. At each line three VES points at the interval of 40 m across the expected course of palaeo channel were carried out. There were 24 VES points in all. The specifications for VES were as follows:

(i) Station interval	=	40 meter
(ii) Electrode separation	=	1 meter

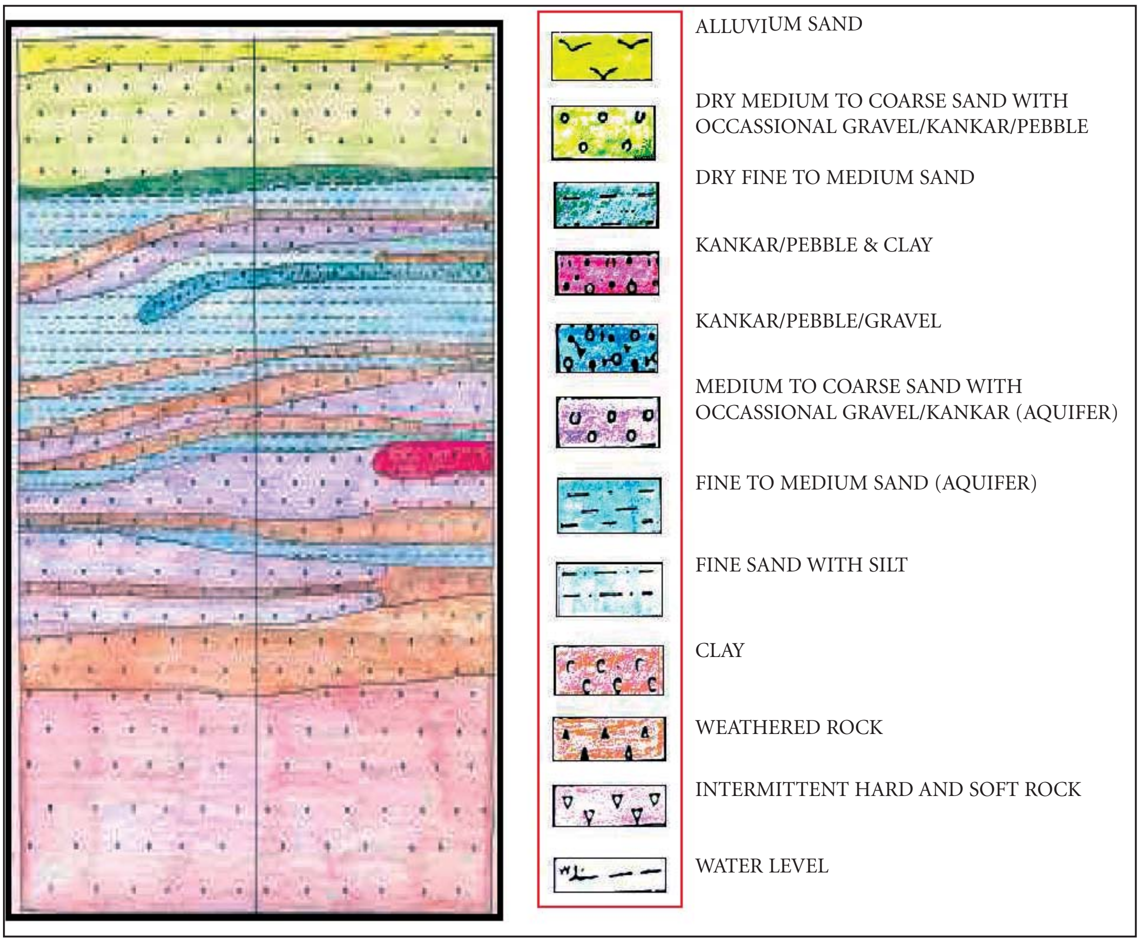


Figure 9. One of the Geoelectric section showing aquifer in the channel

Test drilling

On the basis of the interpretation of the remote sensing data and geophysical survey, locations of 6 bore wells (4 test bore wells and 2 observation bore wells) were finalized for test drilling In all the six bore wells electric logging (both point resistance and SP) was carried out upto the bedrock. To assess aquifer performance on test wells, pumping tests were done for a duration of 72 hours or till the steady state was observed in the bore wells to determine the related parameters viz. transmissivity, hydraulic conductivity, specific yield, storage coefficient, water level, etc.

Water quality assessment

The quality of water obtained from the above 6 wells were analysed as per the BIS specifications

Observations

The depth of the bedrock from Chomu (90.01m) to PunanakSar (71.12 m) is decreasing gradually over a length of 30 km. Just after the PunanakaSar and towards Sambhar Lake, the depth of bedrock has increased up to 54 m at Manda Bhimsingh.

Water level depth encountered in the bore wells range from 15.19 m (Manda Bhimsingh) to 22.96 (Fatehpura Ki Dhani). The total thickness of aquifer zones varies from 32 m to 59 m. Further, the total thickness of the aquifers in the area is more or less same up to PunanaKaSar. Beyond PunanakaSar toward Sambhar Lake, the aquifer thickness is decreasing.

The aquifer performance test data reveals high transmissivity 378.30 m^2/day to 520.06 m^2/day and hydraulic conductivity 7.26 m/day to 18.51 m/day. The discharge of water in the bore wells in the palaeo channel is ranging from 720 to 800 litre per minute (lpm) between Samod and PunanaKaSar as compared to 68 to 412 lpm in the wells out side the channel zone. Beyond PunanakaSar, however, the discharge is very low, which is an anomaly, presumably due to the presence of a natural barrier. The draw down in the buried channel is ranging from 1.68 m to 8.1 m and the recuperation in the bore wells in the buried channel is higher as compared to the wells outside the buried channel zone.

The quality of water in the channel is potable except in the Manda Bhin Singh where the water is saline, which may be due to its proximity to the Sambhar Salt Lake

The shallow depth of the water table, thickness of the water bearing horizons, fluviatile nature of the sediments, high water yield, low drawdown, high permeability and transmmisivity, indicate the presence of the palaeochannel with good water bearing potential and storage suitable for ground water development. The characteristic of the Anokhi palaeochannel may be summed up as

- Shallow Water Table (15 – 23 m bgl)
- More thickness of Water bearing horizon (15 – 59 m)
- Fluviatile nature of sediments
- High water yield (720 – 800 lpm)
- High permeability
- High transmissivity (378 – 520 m/day)
- Potable water quality.

Conclusion

Palaeochannels are such riverine geospheric features which harbored great human civilization in the past and have potentiality to help survive the present part of human civilization thriving in the arid to semiarid regions all over the globe if this geospheric features are properly identified delineated ,understood and managed Remote Sensing along with surface and subsurface geophysical methods are highly appropriate tools to delineate the geometry of the channel and to assess the groundwater storage potentiality of the palaeochannel.

The Palaeochannels are being convincingly looked upon as possible reservoir of ground water with vast storage capacity. There is need to identify and to establish the storage potentialities of this landforms particularly in such regions where groundwater/water emergency situations are anticipated and/or frequented. The artificial recharge of Palaeochannels to its full capacity may provide adequate long term storage of Groundwater which may be used to mitigate the impact of drought, Flash Flood due to storm water, lean/non supply of water through canal/transboundary aquifer/river and seismicity thus reducing the unsustainability of freshwater supply during emergency situations to the minimum.

We advocate that all of the sand and gravel layers of the alluvial fans and the sand layers of the palaeochannels be used as shallow well extraction zone. Large amounts of shallow freshwater should be extracted to evacuate the storage capacity so that an underground reservoir may be constructed through artificial recharge. This will not only alleviate the problems of drought, flooding and salinity, but also simultaneously make thorough use of our water resources. But there are some critical technical problems in using underground reservoirs for storage. These are:

(1) how to speed up the rate of infiltration, especially that of flood waters (or major amounts of transferredwater);

(2) how to enlarge the storage capacity; that is, how to gradually enlarge the freshwater storage of the palaeo channels while reducing the saltwater storage between channels

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ROLE OF GROUNDWATER IN TEHRAN WATER CRISIS MITIGATION

Hamid R. Jahani[1]
Mansour Reyhani[2]

Abstract: Tehran was faced with a serious threat in available water resources in 2001 as a result of continuous increase in demand for urban water following by drought condition. All three surface water resources (Karaj, Latyan and Lar Dams) together with Tehran aquifer were exploited to much more than their potential to overcome the critical situation. During the history of groundwater exploitation in Tehran, the Tehran aquifer had its highest contribution in 2001 amounting to almost 50 percent of the total supplied water to the city. Result was a considerable decrease in aquifer storage which was ceased but not compensated during the next years. Different scenarios are studied to calculate population growth and future demand for water in Tehran. With regards to estimated figures for population and water demand in coming decade and with respect to inevitable development plans such as Tehran Wastewater Plan, it is emphasized that although Tehran aquifer has played outstanding role in confronting water crisis period, it could no longer be considered as dependable water recourse in probable critical situations in future.

Introduction

Having an average annual precipitation of 250 mm, Iran receives less than one third of global average precipitation. That is why the country is classified as a semi arid country. In addition, the pattern of rainfall distribution over the country is not the same everywhere. The main reason for variability in precipitation amount over the country is variation in physiographic setting and climatic features. The main physiographic features in the country could be mentioned as Zagross and Alborz mountain ranges striking northwest-southeast and west-east respectively, central Kavirs or deserts, Caspian Sea to the north and Urmia Lake to the northwest part of the country. The rainfall amounts from less than 50 mm per year in central deserts and southeast plains to more than 1,900 mm per year in some coastal lands to the south west of Caspian Sea. Different physiographic features affect local climate and produce such variability in precipitation pattern. According to United Nations Sustainable Development Commission index and with regards to water scarcity, Iran is classified as a country with 'severe' situation [Rahimi and Khaledi, 2001].

Geographical setting of Tehran

From north to south, Tehran could be divided into two main geological or geomorphological

1. Dr. Hamid R. Jahani, Member of Scientific Board, Water Research Institute, P.O. Box 16765-313, Tehran, Iran. Email: h.jahani@wri.ac.ir
2. Dr. Mansour Reyhani, Research staff, Water Research Institute, P.O. Box 16765-313, Tehran, Iran. Email: m.barzegar@wri.ac.ir

zones; the piedmont zone to the north of Beheshti St. up to the mountain front, and the Tehran plain to the south of Beheshti St. down to Rey and its suburbs (Figure 1).

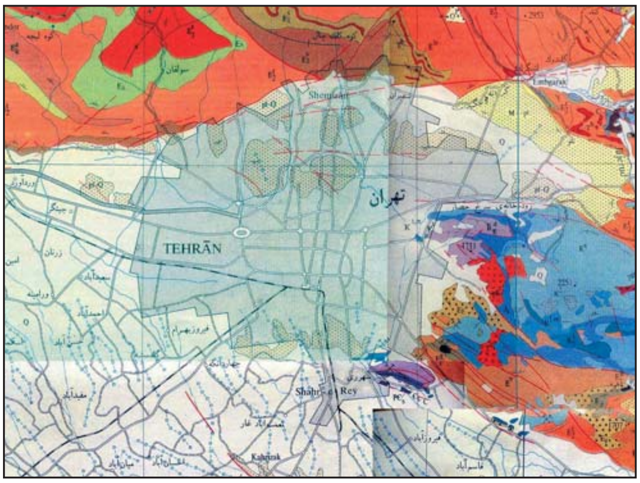


Figure 1. Northern hilly area and Tehran plain on geological map of Tehran [Iran Geological Survey]

There are different hills and valleys in the piedmont zone which are cut and formed by some north-south rivers. These hills and valleys are mainly of conglomerate and alluvial deposits of Hezardarreh and North Tehran Formations.

The plain covers the central and southern parts of the city and is mainly composed of the Tehran Alluvium Formation. The geological material is somehow fine grained especially to the southern parts of the plain and so less favorable regarding surface water percolation.

The city is positioned on the alluvial fans to the southern Alborz mountain range and the general topographic slope is from north to south. The slope is around 3 to 4 percent in the north and 1 percent in the southern parts of the city [JAMAB, 1993].

The north Tehran hilly area is cut by different north-south rivers which have outstanding effect on the geomorphology of the area and also on the Tehran aquifer recharge process. These rivers, together with some old qanats some still yielding enormous amounts of water, have had vital role in providing people with fresh water for drinking and agricultural purposes in the past. They also play important role in converging flood flows originating from upstream mountains and saving people living around, provided that the floodway is not disturbed and changed by people living around.

Background

Tehran plain (Tehran-Karaj area), locates to the southern piedmont zone of Alborz mountain range, in an area of more than 5,000 km^2 bordering to Namak (salt) Lake desert to the south. The average annual precipitation in Tehran is still less than the figure for the country and is about 230 mm. In this regards, Tehran stands among those major cities with almost low rainfall amount in the country.

The Tehran precipitation time series along a 50 year basis shows that amount of annual rainfall over the city fluctuates between a minimum of 100 and a maximum of 400 millimeters (Figure 2). Its pattern follows a cyclic sequence of low water and high water years. The last low flow cycle started in 1997, lasted for almost 5 years and lead to a serious water crisis in Tehran around 2001.

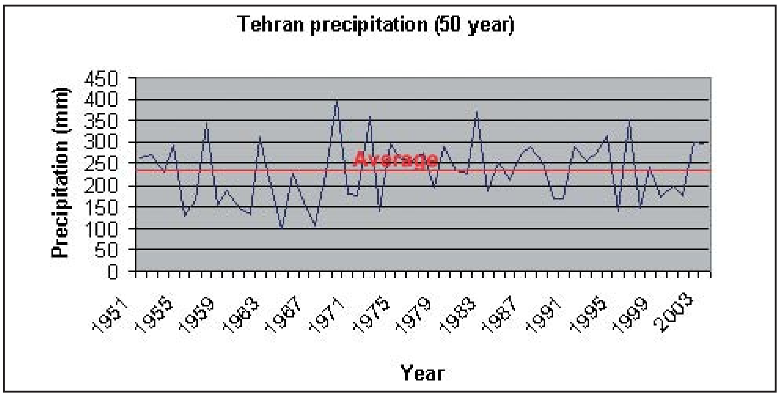


Figure 2. Long-term precipitation in Tehran

There were several factors resulting in water crisis in Tehran in 2001 among which the following could be mentioned:

- Geographical setting of the city and rapid urban development,
- Meteorological setting and low rainfall,
- Population growth,
- Unfavorable public consumption culture,
- Limited available water resources.

Tehran is the 18th most populated city in the world and has accommodated almost 20 percent of the population of the country. The population has changed from around 100,000 in 1891 to more than 8 million in present. The population growth together with the unfavorable water consumption pattern among Tehran citizens (above 300 liters per day which is two times greater than world average), caused a decrease in amount of available water per capita from above 1,000 m^3 in 1956 to almost 500 m^3 in 2001 [Vojdani, 2002]. Result was the critical condition in available water for Tehran citizens in 2001.

Tehran water resources

Water is supplied to Tehran from both surface and groundwater resources. The present surface water resources are:

a. The Lar River, in north-eastern mountains with a capacity to supply 140 MCM per year. The Lar Dam with a total storage of 960 MCM is built on this river.
b. The Jajroud River, in east part of the area, with a capacity to supply 160 MCM per year. The Latyan Dam with a total storage of 95 MCM is built on this river.
c. The Karaj River, in the western mountains, with a capacity to supply 340 MCM per year. The Karaj Dam with a total storage of 205 MCM is built on this river.

Two more water resources of Taleghan Dam on River Shahroud (west of Tehran area) and

Mamlou Dam on River Jajroud (east of Tehran area) are to supply water to Tehran to meet future water requirements of the city amounting to 150 and 80 MCM per year, respectively.

The groundwater is supplied to Tehran in normal situations from almost 300 wells located in north, northwest, west and southwest parts of the city (Table 1). Groundwater exploitation is also for the purpose of water table lowering in some southern parts of the city, as well as providing water to green fields and other parks and public gardens allover the city.

Zone	No. of wells	Range of discharge for each well (liters/sec)	Capacity to supply water (MCM per year)
Western Tehran	85	50-250	100
Eastern Tehran	116	50-250	100
Central Tehran	26	20-80	20
Tehran southern towns	54	30-80	30
Jajroud River	-	Totally 1500	-

Table 1. Zones supplying groundwater to Tehran [Tehran Water and Wastewater Co., 2001]

Tehran aquifer

Groundwater has a big share nowadays in supplying water for different purposes to Tehran. The general direction of groundwater flow in the area is from northern Alborz piedmont zone towards the southern deserts in Varamin area. There are two main water bearing zones in the area; in the north, local perched aquifers are formed in the piedmont zone and in the south, the main Tehran aquifer is formed in the Tehran alluvium Formation as an unconfined aquifer in Tehran plain.

The northern local aquifers are mainly formed in North Tehran Alluvium formation. These are perched shallow aquifers formed in valleys and depressions and are mainly fed by urban returned water.

The main aquifer is bounded from north to Abbasabad northern hills (north to Beheshti St.) and from south to southern parts of Rey. From east it bounds to Sepayeh mounts and from west to Karaj aquifer. The city overlays the main aquifer in an area of about 500 square kilometers [JAMAB, 1993]. The Tehran plain and situation of the main Tehran aquifer is shown in a cross-section through the Alborz mountain range to south Rey plain in Figure 3. The alluvium is almost

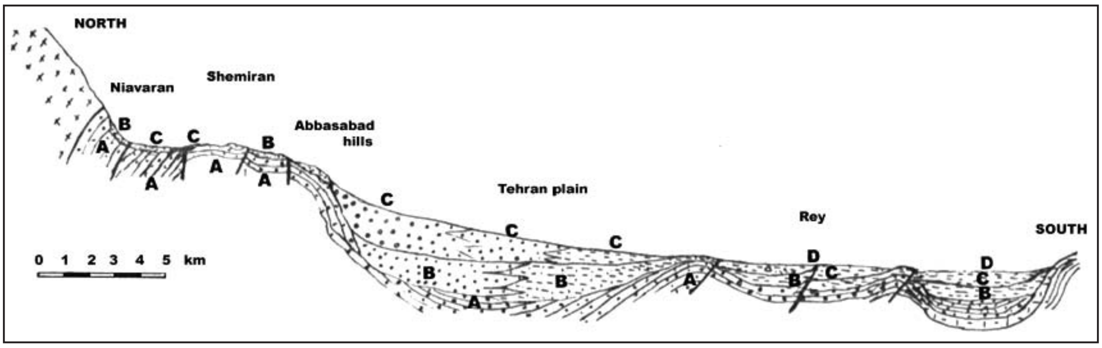


Figure 3. Geological cross section through Alborz Mountain to south Rey area [Berahman, 1993].

350 m deep (the aquifer 200 to 250 m) at the deepest parts just to the south of Abbasabad hills. The aquifer material is mainly coarse grained and highly productive in these parts. For instance, discharge of deep wells in Kan area located at the alluvial fan, amounts to 200 l/s [Berahman, 1993].

To the south, the aquifer material is fine grained and the wells are less productive. There are clay layers but no confined aquifer is logged yet. Transmissivity amounts to 1,200 square meters per day on average, the lower values belong to southern parts. Storage coefficient or specific yield is reported as 3 to 6 percent [JAMAB 1993].

Aquifer thickness is decreasing from north to south. In the north west it is almost 300 m (in Kan alluvial fan) and in the south (at plain outlet) it is about 50 m. In the central parts (around Enghelab-Azadi Street) the aquifer is almost 250 m thick.

Groundwater recharge and Groundwater balance

Some decades ago, Tehran was very much less expanded and the north parts of the city were covered with coarse grained alluvium cut with numerous perennial and seasonal rivers. This condition provided a big component of surface flow with the opportunity to percolate through the soil and recharge groundwater. Recharge to groundwater was also possible by surface runoff and precipitation penetrating directly from the surface of the Tehran plain. Following to expansion of the city, a big part of surface runoff and precipitation over the city is conducted through urban surface drainage system to the southern deserts, out of the reach of aquifer.

Now, the natural recharge to groundwater is totally changed in Tehran. One source of recharge to the aquifer is the irrigation return water from the fields throughout the plain which amounts to 380 MCM annually. The other source which seems the most important one is urban returned water or the public and industrial wastewater which is continuously leaving the absorption wells towards the deeper parts and the water table. It may also be discharged from industrial units to surface streams, which then percolates to underground. The total volume of returned water amounted to 800 MCM per year at present.

The Tehran aquifer is also recharged through north-south rivers bed percolation, among them the Kan River is the most important one. Finally, the underground waters from the northern hard rock formations recharge the Tehran aquifer southward. The long-term groundwater balance for the entire Tehran-Karaj Study Unit is roughly presented in Table 2.

	Recharge from northern hard rock formations	*Recharge from surface run-off*	*Irrigation return water*	*Industrial and urban return water*	*Total*
Recharge (MCM)	200	350	380	800	1,730
Discharge (MCM)	Groundwater outflow	Discharge from wells and qanats			
	10	1900			1,910

Table 2. Rough groundwater balance

As it could be seen from the table, there is an amount of 180 MCM deficiency for the aquifer storage in the whole area. But for the Tehran city, there is even potential for more groundwater exploitation as a result of excessive recharge from urban return water throughout the city.

The groundwater level and groundwater flow

The general direction of groundwater flow in Tehran area is from north to south (Figure 4). The hydraulic gradient in northwest and northeastern parts is steep, reflecting groundwater recharge from hardrock formations and from Kan River.

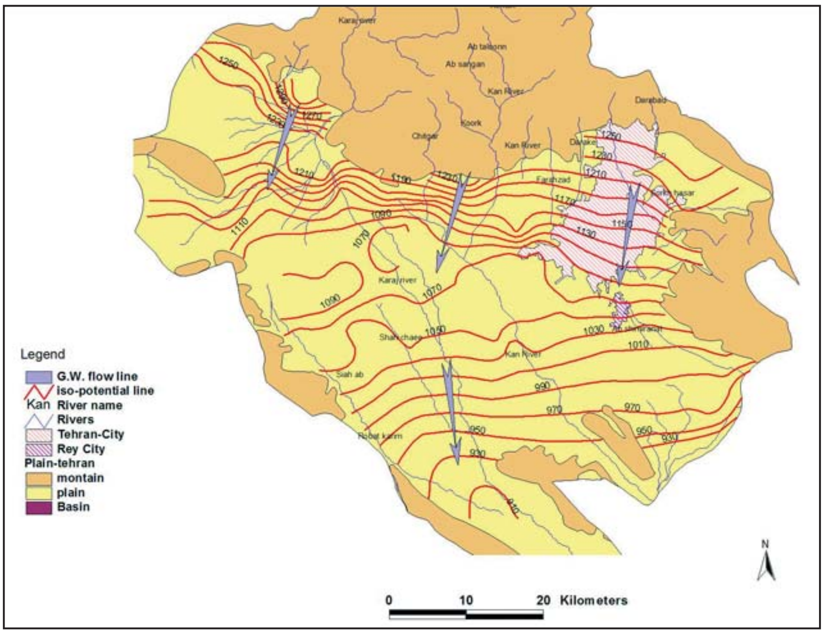


Figure 4. Isopotential map for Tehran aquifer
[based on data from Tehran Water Authority, 2001]

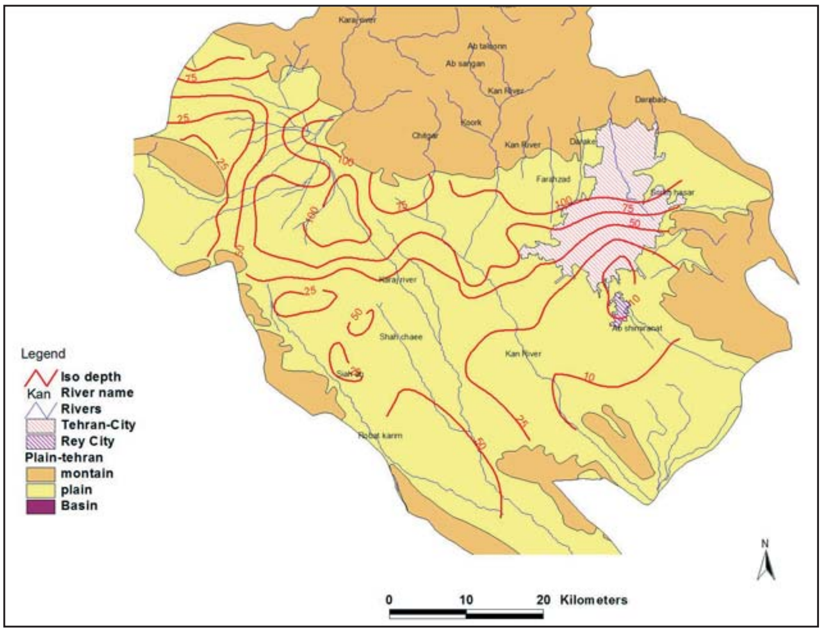


Figure 5. Iso-depth map for Tehran aquifer
[based on data from Tehran Water Authority, 2001]

The depth to water table is less than 100 m in the north and around 5 m in some areas in the south. In the latter case, the water table is influenced by evaporation. As it is shown in Figure 5, in a big part of the city (mainly to the southern part) water table is situated in a depth not more than 30 m. Especially in Rey area, water table is almost close to the surface and continuous pumping operations are performed to make live possible there.

Groundwater quality

According to ground water type maps, the pattern of bicarbonate, sulfate and chloride water types through the plain is not as expected in a plain in a typical situation. In most cases, the bicarbonate water type is the dominant type in upstream areas. Getting farther from recharge source, the sulfate and the chloride water types are expected to be the dominant type, in the mid-basin and in the downstream areas respectively. This pattern is somehow changed in Tehran aquifer (Figure 6). The chloride water type has developed to southern, western and even some central parts of the city, reflecting the effect of industrial and urban wastewater pollution [Haj Hariri et. al, 1995].

According to an assessment on the extent and magnitude of biological and chemical contamination of the Tehran aquifer by the Tehran Water Authority during 1987-1991, the aquifer was divided into two main areas; the highly contaminated and the low contaminated areas. The highly contaminated area was mainly concentrated in the central parts of the aquifer and comparing the extents of this area in 1990 and 1992 showed that this zone was spreading from central parts to other parts of the aquifer [Taher Shamsi, 1999]. Further studies during 1993-1996 indicate more increase in pollutants in the Tehran aquifer. Most of samples taken from the eastern half of the aquifer have shown pollution to microelements such as iron, cadmium, chrome and lead as indicators of industrial wastewater pollution, in 1996 [Haj Hariri et. al, 1995]. Pollution

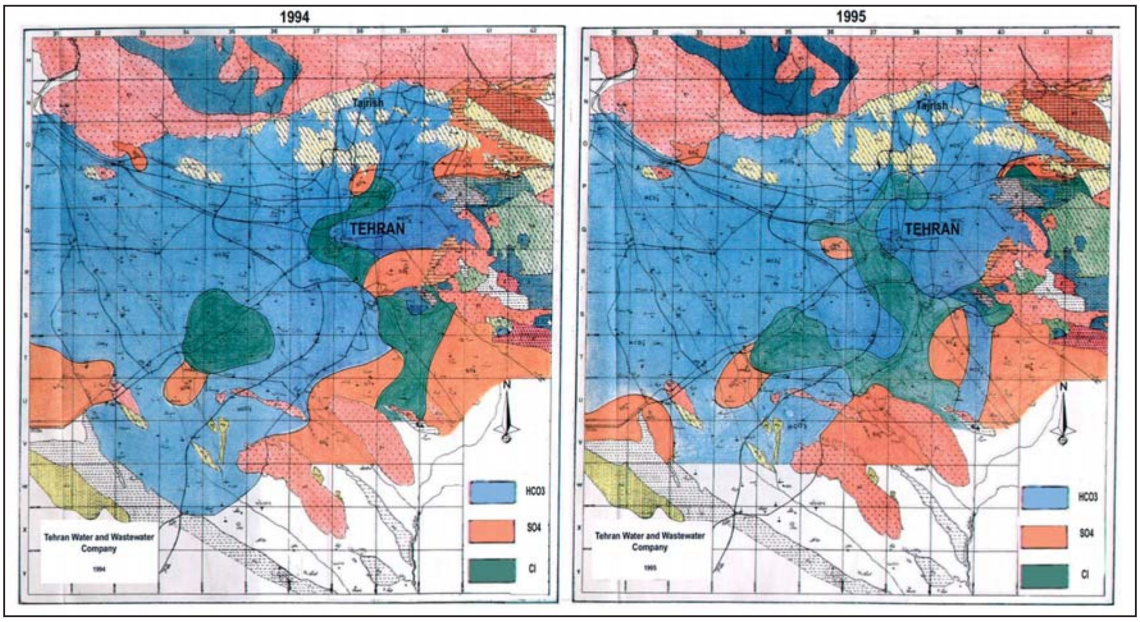


Figure 6. Water type in Tehran aquifer in two successive years 1994 and 1995 [Haj Hariri et. al, 1995]

to E-Coli is documented in the north where the course grain alluvium and the lose cement let pollution reach the aquifer [JAMAB, 1993].

Water consumption in Tehran

Up to the year 1927, water was supplied to Tehran through 26 qanats with a total discharge of 700 l/s. Following to increase in water demand, the construction of a canal, 53 km length, was started in order to convey water from Karaj River to Tehran in this year. In 1950, the construction operation of the first drinking water pipe network was started to supply water to a population of 900,000. After a few years, the Karaj Dam and the Tehran aquifer were added to the Tehran water supply alternatives in 1963. The Latyan (1967), Lar (1981) Taleghan (2006) and Mamlou (to be constructed in 2007) dams were the last solutions to overcome the continuous increase in demand from the ever increasing population. The amount of annual water consumption in Tehran area has increased from 50 MCM equal to 1.6 CMS in 1961 [Berahman, 1993], to almost 900 MCM equal to 28.92 CMS, in 2002 [Tehran Water and Wastewater Co. Website]. Out of these figures, Tehran aquifer has had a very important share in supplying water since 1963. It had over 5 percent share among the total water supplied in the first year of groundwater exploitation. This share increased gradually until the recent years, when it approached almost 50 percent of the total water supplied in 2001. It means the groundwater by itself provided an amount of water to Tehran equal to the water provided by all three dams in this year. Figure 7 shows the share of different water resources in supplying water from the beginning (1955) up to 2002.

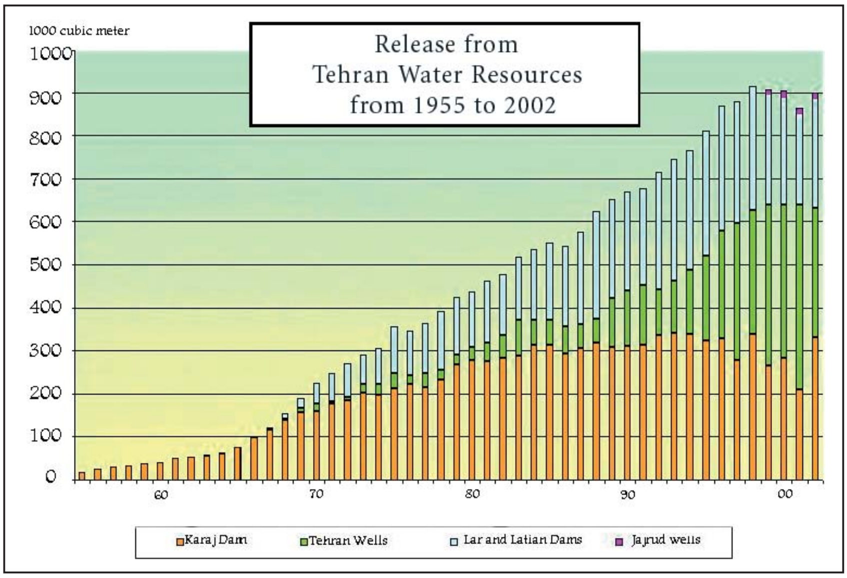


Figure 7. Share of different water resources in supplying water to Tehran [Tehran Water and Wastewater Co. website]

Groundwater in emergency situations in Tehran

Long-term monthly groundwater level fluctuation is presented in Figure 8 as Tehran groundwater unit hydrograph. It shows an almost balanced state in aquifer during 1991-1996 and also 2002-2005. During 1996-2001 the water table is suffering from a continuous decline as a result of the

Figure 8.Tehran aquifer unit hydrograph, data from 1993 through 2004

critical situation in available water resources and low flow condition and drought in Tehran as well as most parts of the country. Amount of decrease in aquifer saturated thickness is reported in the order of 4 meters during this period. The most severe condition is seen in 2001. During 2002-2005, as a result of moderate increase in rainfall and drought mitigation, the decreasing trend in water table level is ceased but not compensated.

Up to 2001, groundwater was exploited for drinking purpose in Tehran through 260 wells. Due to continuous decline in available water resources during 1996 to 2001 and following to critical situation in 2001, 147 drinking wells were drilled throughout the city in this year. The result was a record of 429.7 MCM of groundwater consumption which is the highest contribution of Tehran aquifer in supplying water.

Outcomes of groundwater over-exploitation in emergency

Tehran is receiving 640 MCM water from surface water resources (Karaj, Latyan and Lar Dams) annually. The resulting returned water recharges Tehran aquifer due to lack of a system of wastewater collection, and it has caused an almost balanced condition among inflow and outflow for the aquifer until the year 1995. According to water balance studies performed for the water year 1993-1994, the aquifer was almost in a balanced condition in that period. Volume of water withdrawal for drinking purpose from the aquifer is less than 200 MCM for the year 1995 while this volume increases to almost 430 MCM for 2001. Such an increase in groundwater withdrawal caused considerable decline in groundwater level in Tehran plain noticeably in drinking water pumping zones. Figure 9 presents long-term hydrograph for some piezometers around Tehran, some of them close to drinking water exploitation zones. As it could be seen, decrease in aquifer saturated thickness is amounted to 30 meters within 1994-2001 in some parts of the aquifer which is an indication of a rapid shrinkage in the volume of aquifer storage. The total decline in groundwater level for 1993 to 2004 has been up to 4 meters. In other words, the aquifer has suffered from a continuous decline in potential during this period. For a Tiessen area of 1226 km^2 (area to the east of Kan River) and considering an average specific yield of 0.06, Tehran aquifer has lost almost 300 MCM in static storage during the mentioned period.

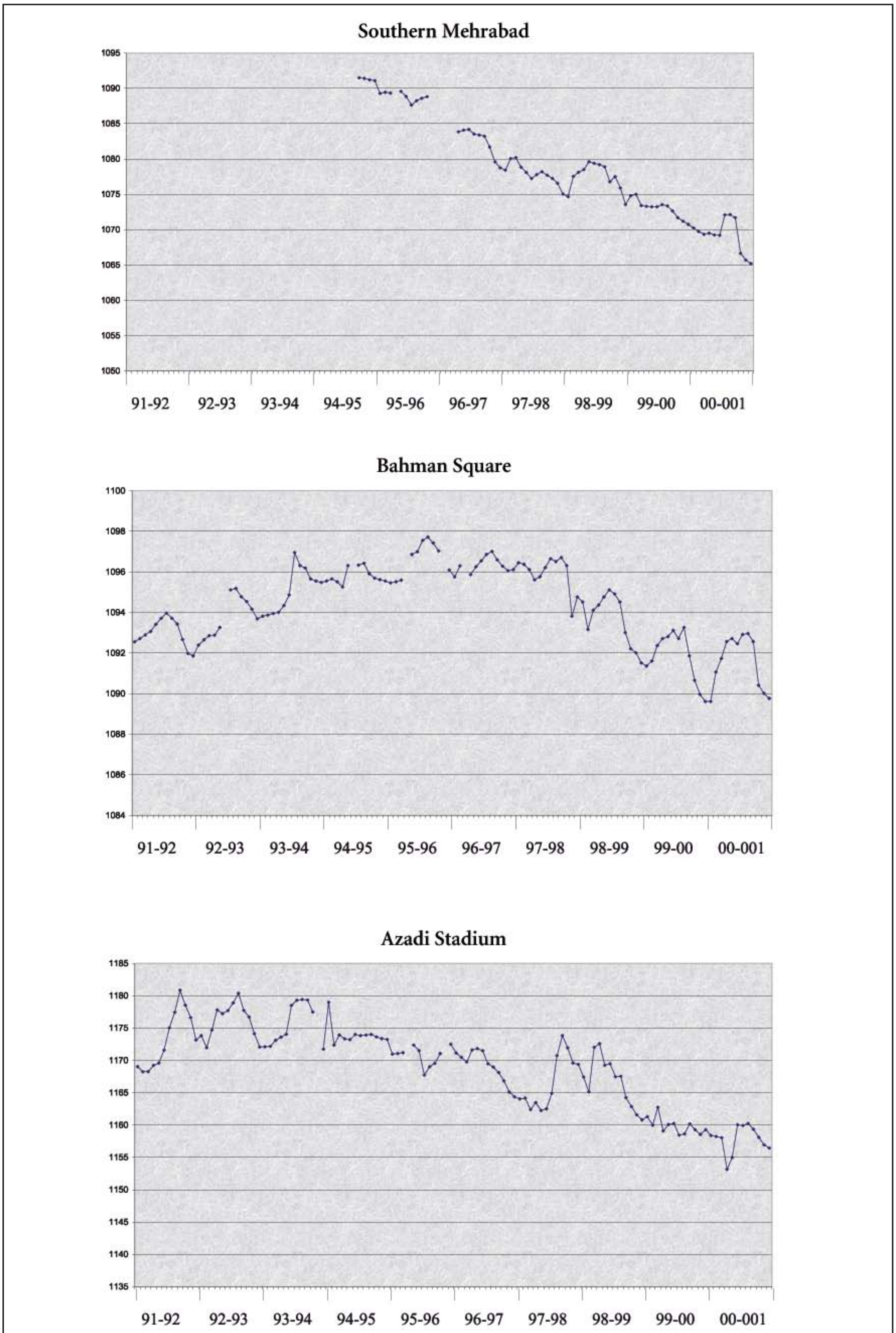
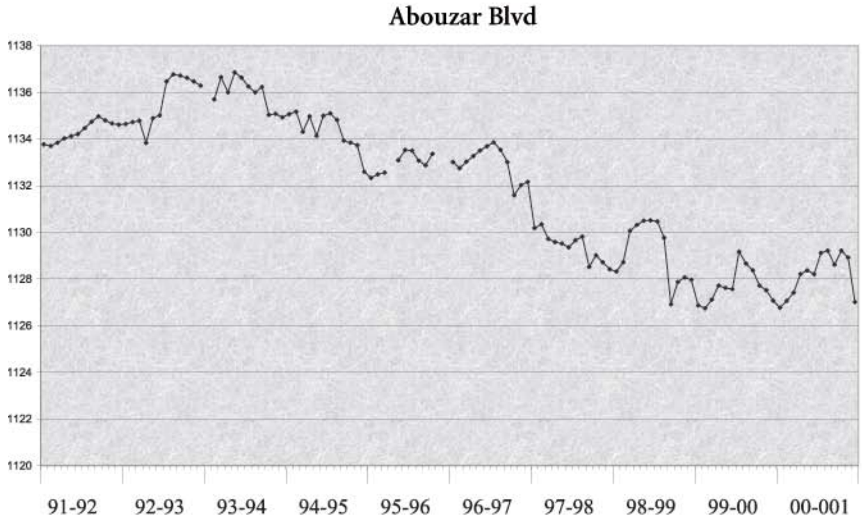
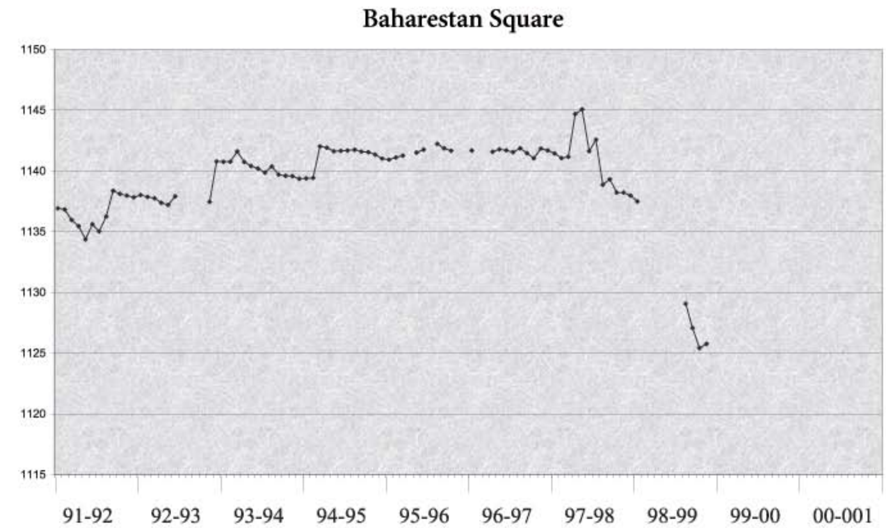


Figure 9. Hydrographs for some piezometers around the city showing decline in groundwater level [based on data from Tehran Water Authority, 2001]





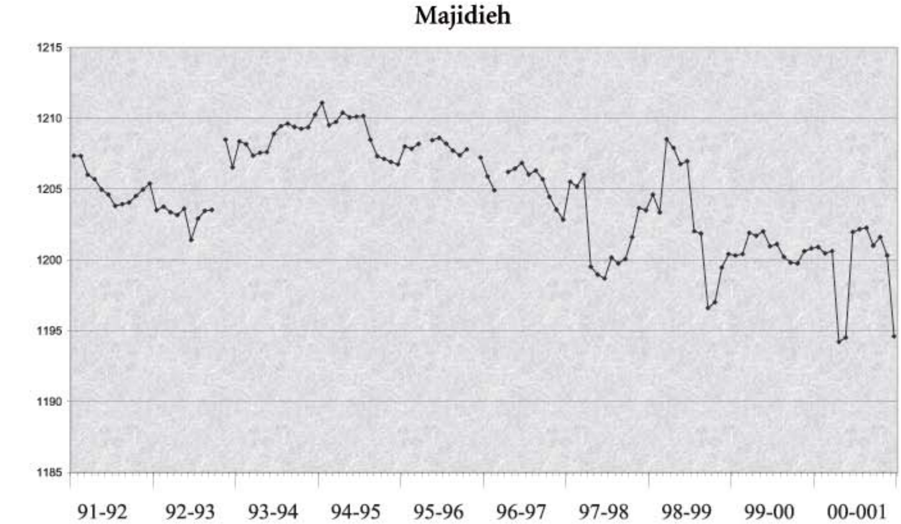


Figure 9. (continued)

Results and discussion

Tehran has faced critical situation regarding available water resources in the last few years in spite of transferring large amounts of water from resources of other areas such as Gilan, Mazandaran, Qazvin and Karaj. Among the main reasons responsible for such crisis, increase in population could be mentioned as the most important one (Table 3).

	1966	1976	1980	1986	1991
population	2720000	4530000	5454000	6027000	6475000
Annual consumption (MCM)	98	346	443	542	681
Per capita consumption (Liters/day)	99	209	222	274	288

Table 3. Increase in Tehran water consumption from 1966 to 1997 [JAMAB, 1992]

According to a study by JAMAB Company in 1992, Tehran population is predicted in three scenarios considering no population control program, population control program run and thorough fulfillment of population and urban planning program respectively. Urban water demand for future is calculated based on the predicted population and per capita demand. According to this study, the variations in urban water demand in Tehran would be a function of predicted population in each scenario only. The total demand for urban water in Tehran is presented in Table 4. The figure given for the years 2001 and 2006 coincide with the real state.

Year	1991	1996	2001	2006	2011	2016
Total demand for water (for different scenarios)	662-697 MCM per year	736-727 MCM per year	818-954 MCM per year	907-110 MCM per year	1005-1262 MCM per year	1108-1430 MCM per year

Table 4. Total demanded water for 1991-2016 [JAMAB 1992]

The existing potential to supply water to Tehran from surface resources is totally almost 640 MCM from Karaj, Latyan and Lar Dams. The surface water resources have been exploited to the highest capacity during the critical period. The groundwater resource has been exploited much higher than its capacity and a decline of up to 4 meters within 6 years was the outcome of this exploitation. From other side, Tehran aquifer is mainly recharged through urban return water. This main source of recharge would no longer exist considering the Tehran Wastewater Plan would be in action in future. Although it means the major source of pollution to the aquifer would be omitted but this will cause a considerable decrease in the aquifer potential as a main water resource for the city.

Conclusion

Tehran aquifer has performed outstanding vital role in supplying water to Tehran during the last four decades, especially in critical situations. Following to increase in groundwater contribution in drinking water supply to the city, decrease in aquifer saturated thickness amounted to 30 meters in some parts of the aquifer within the critical period. This was an indication of a rapid shrinkage in the volume of aquifer storage. Such events if coincide with development plans as

Tehran Waste Water Plan which will result in elimination of the main source of recharge to Tehran aquifer (i.e. urban return water) would cause uncertainty about reliability of the aquifer as a dependable reservoir. From the other side, groundwater quality is threatened by percolating urban returned water while this threat would intensify during the mentioned critical periods as a result of decrease in aquifer storage.

Tehran aquifer supplies between 25 to 50 percent of the total drinking water to Tehran inhabitants in present condition and during critical situations. It shows how vital this resource is to the city. With regards to the fact that immediate utilization of Tehran Wastewater Plan is inevitable, it should be noted that in the future condition, Tehran aquifer could no longer be considered as a potential resource as it is now.

With regards to the fact that an addition of 230 MCM from Taleghan and Mamlou Dams in coming years could not compensate for the slenderized role of groundwater in future condition, focusing on demand management in order to change the consumption pattern and reduce the per capita consumption and going for remedies such as performing adequate artificial groundwater recharge plans seems an obligate in managing Tehran water resources in future.

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