An Investigation into Control of Saltwater Intrusion Considering the Effects of Climate Change and Sea Level Rise

H. F. Abd-Elhamid and *A.A. Javadi*
School of Engineering, Computing and Mathematics, University of Exeter, Exeter, UK

ABSTRACT
A large number of coastal aquifers are threatened by saltwater intrusion. Saltwater intrusion may occure due to human activities and by natural events such as climate change and sea leael rise. In coastal aquifers, overabstraction due to high demands for domestic water supply is the main cause of saltwater intruson. Also the rise in sea level due to the climate change accelerates the saltwater intrusion into the aquifers which reduces the fresh groundwater resources. With the impact of sea level rise and overpumping combined together the problem becomes even more serious and requires fast solutions. Coastal aquifers are affected by the rise in the sea level due to climate change and global warming. It is estimated that the mean sea level will rise in a range between 20 to 88 cm during the current century. The rise in sea level will shift the saltwater interface further inland. As a result, the extraction wells that were originally in fresh groundwater, may then be located in brackish water or saline water and upconing may occur. Consequently, the abstraction rates of these wells may have to be reduced or the wells abandoned. This is considered one of the most serious impacts of sea level rise. Therefore, saltwater intrusion due to sea level rise should be predicted and prevented (or at least controlled) to protect groundwater resources. This paper presents a review of the mathematical models developed to study the impacts of climate change and sea level rise on saltwater intrusion in coastal aquifers and the measures that caould be taken to reduce the impact. The impact of climate change and sea level rise on saltwater intrusion is discussed and analyzed. A new method is proposed to control saltwater intrusion considering the impact of climate change and sea level rise. The main benefits of the proposed methodology are discussed. It is shown that the proposed method is economical, has less environmental impact and could be used for sustainable development of water resources in coastal areas.

Keywords: climate change, sea level rise, saltwater intrusion, groundwater protection.

INTRODUCTION
Throughout the world, the areas with arid and semi-arid climate are suffering from water shortage problem. Population growth and continuous development require larger quantities of water, especially in the coastal regions where about 70% of the world population dowel. It is a great challenge to supply the required water, while the available water resources are nearly constant. This requires practical measures to protect the available resources from pollution, saltwater intrusion and other contaminants that deplete the current resources. Saltwater intrusion is a major problem in coastal regions all over the world. In coastal areas the aquifers are in hydraulic contact with the sea. Under normal conditions the freshwater flows into the sea. However, over-pumping may result in inversion of the groundwater flow from the sea towards the inland causing saltwater intrusion. Also the rise in sea level will accelerate the saltwater intrusion. Salinization of groundwater is considered a special category of pollution that threatens groundwater resources, because mixing a small quantity (2 percent) of saltwater with groundwater makes freshwater unsuitable and can result in abandonment of freshwater supply.

Therefore, saltwater intrusion should be prevented or at least controlled to protect groundwater resources. Recently, considerable attention has been focused on models to study the control of

saltwater intrusion in order to protect local groundwater. Various models have been developed to investigate saltwater intrusion. However, only few models have been developed to study the control of saltwater intrusion in coastal aquifers. This paper will discuss and analyze the models that have been developed to study the control of saltwater intrusion to highlight their benefits and limitations and will suggest a new methodology to control saltwater intrusion. Also the study will be used to analyze the position and movement of the fresh water/salt water interface to determine the response of the interface to the rise in sea level.

THE IMPACTS OF CLIMATE CHANGE AND SEA LEVEL RISE

Climate change is a result of natural and/or man-made activities. Due to climate changes the sea water level will rise for several reasons including oceans and seas thermal expansion, glaciers and ice caps melting and Greenland and Antarctic ice sheets melting. Sea level rise has many effects on coastal regions on the long term such as increase in coastal erosion and sea water intrusion. Climatic change has already caused changes in the sea level during the last decade. Global mean sea-level rise has been ranged from (10-20 mm/yr) during the last century IPCC (1996). Future sea-level rise due to climate change is expected to occur at a rate greatly exceeding that of the recent past; for example during the next 100 years, sea-levels are expected to rise at a rate between 20–88 mm/yr (IPCC 2001). In recent years a numbers of models have been developed to investigate the effect of climate change and sea level rise on saltwater intrusion in coastal aquifers (e.g. Sherif, and Singh 1999).

MEASURES TO CONTROL SALTWATER INTRUSION

A number of different measures have been used to control seawater intrusion and to protect the groundwater resources. The main principle of protection is to increase the volume of fresh groundwater and reduce the volume of saltwater. Todd (1974) discussed various means of preventing saltwater from contaminating groundwater sources including: (1) reduction of the abstraction rates, (2) relocation of abstraction wells, (3) subsurface barriers, (4) natural recharge, (5) artificial recharge, (6) abstraction of saline water, and (7) combination of injection and abstraction systems. Extensive research has been carried out to investigate saltwater intrusion in coastal aquifers. However, only few models have been developed to study the control of saltwater intrusion. These models use one or more of the previous measures to study the control of saltwater intrusion. The reduction of abstraction rates aims to reduce the pumping rates and use other water resources (Scholze et al. 2002). The relocation of abstraction well aims to move the wells further inland (Sherif and Al-Rashed 2001). Subsurface barriers aim to prevent the inflow of seawater into the basin (Harne et al. 2006). Natural recharge aims to recharge aquifers with additional surface water (Ru et al. 2001). Artificial recharge aims to increase the groundwater levels, using surface spread for unconfined aquifers and recharge wells for confined aquifers. The sources of water for injection may be surface water, groundwater, treated wastewater or desalinated water (Papadopoulou et al. 2005). The abstraction of saline water aims to reduce the volume of saltwater by extracting brackish water from the aquifer (Sherif and Hamza 2001). The combination of injection of freshwater and extraction of saline water can reduce the volume of saltwater and increase the volume of freshwater (Rastogi et al. 2004).

THE LIMITATIONS OF THE PREVIOUS MODELS TO CONTROL SALTWATER INTRUSION

The previous methods for controlling saltwater intrusion have many limitations. Most of these methods are costly and some of them might not be applicable in certain cases. Furthermore, they are generally temporary solutions and with the population growth and increasing demand the intrusion will be increased. The source and the cost of fresh water for injection, especially in

areas that suffer from scarcity of water and the fact that the disposal of the brine into the sea can cause many problems, have usually been ignored. One of the future challenges is the sea level rise due to climatic change and its effects on saltwater intrusion. Climate change has caused changes in the sea level because rising temperature makes the seawater expand and glaciers and ice caps to melt. The effects of climate change and sea level rise on saltwater intrusion in the long term should be considered in the control models. The majority of the previous control models did not consider this point, while few centimetres rise in sea level could have a great effect on saltwater intrusion. This study considers the effect of increase in sea level due to climate change on the fresh water/salt water interface with the focus on determining changes in the position of the interface with time and identifying measures to control such movements.

THE PROPOSED METHODOLOGY TO CONTROL SALTWATER INTRUSION CONSIDERING SEA LEVEL RISE

In this study a new methodology is proposed to study the control of saltwater intrusion. This methodology aims to overcome the limitations of the previous methods. The proposed methodology, Abstraction, Desalination and Recharge (ADR), consists of three steps; abstraction of brackish water from the saltwater zone, desalination of the abstracted brackish water using RO treatment process, and recharge of the treated water into the aquifer. The main benefits of the (ADR) methodology are to return the mixing zone into the original status and to reach a dynamic balance between fresh and saline groundwater through two processes; (1) Abstraction of brackish groundwater to reduce the volume of saline water, and (2) Recharge of treated brackish water to increase the volume of fresh groundwater. The Abstraction-Recharge process helps to move fresh water/salt water interface toward the sea and is considered an efficient method to control saltwater intrusion. This process will continue until a state of dynamic equilibrium is reached with respect to the salinity distribution. Then a suitable quantity of treated brackish water is injected to the aquifer to maintain the balance between fresh and saline groundwater and the excess of the treated brackish water may be used for different purposes or stored in the aquifer. The second step of this methodology, desalination of brackish water using the RO treatment process aims to produce fresh water from the brackish water and use it for recharging the aquifer to overcome the scarcity of water in these areas. It is generally less expensive than other sources of freshwater for injection. For example, desalination of seawater has a lot of problems such as; high cost, high pollution (mainly carbon emission), and disposal of the brine. Desalinating brackish water is an efficient alternative to seawater desalination, because the salinity of brackish water is less than one-third of that of seawater. Therefore, brackish water can be desalinated at a significantly lower cost than sea water. A simulation model is developed for the investigation of saltwater intrusion to analyze the position and movement of the fresh water/salt water interface. The predicted sea-level rise data will be incorporated into the simulation model by specifying an annual increase of 8.8 mm/year as predicted by IPCC (2001) for the current century. Finally the model will study different scenarios to control saltwater intrusion considering the expected rise in sea level for the purpose of determining the optimum locations, depths and rates of abstraction and recharge for the system.

CONCLUSIONS

Over-pumping is considered the main cause of saltwater intrusion into coastal aquifers in many areas of the world and sea level rise accelerates the intrusion. Saltwater intrusion poses a major limitation to utilization of groundwater resources. Groundwater provides about one-third of the total freshwater consumption in the world so saltwater intrusion should be prevented or at least controlled. A number of methods have been used to control saltwater intrusion but they have many limitations. The proposed methodology (ADR) is an attempt to overcome the limitations of

the previous methods. It is considered an economical solution and has less environmental impact because desalinating brackish water using RO treatment process involves lower energy consumption, lower cost and lower pollution and carbon emission as compared with conventional methods of sea water desalination and waste water treatment. It also provides fresh water for recharge using the treated brackish water. The (ADR) technique is considered an efficient method to control saltwater intrusion. It is capable of preventing saltwater intrusion because it increases the volume of fresh groundwater and decreases the volume of saltwater, while considering economical aspects, environmental impact and sustainable development of water resources. Also the effect of sea level rise due to climate change can be considered by varying the seawater level in the numerical model according to the estimated sea levels over the current century as predicted by IPCC (2001).

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Contact Information: H. Abd-Elhamid, Department of Engineering, University of Exeter, Exeter, EX4 4QF, UK, Phone: +44 1392 263909, Fax: +44 1392 217965, Email: hfa201@ex.ac.uk