Available online at www.sciencedirect.com
ScienceDirect
Procedia Environmental Sciences 25 (2015) 183 – 190
Procedia Environmental Sciences

7th Groundwater Symposium of the
International Association for Hydro-Environment Engineering and Research (IAHR)

Assessment of the nexus between groundwater extraction and greenhouse gas emissions employing aquifer modelling

S. Nazari[a]*, T. Ebadi[a] and T. Khaleghi[b]

[a]*Department of Civil and Environmental Engineering, Amirkabir University of Technology (Tehran Polytechnic), Tehran, Iran*
[b]*Department of Industrial and Systems Engineering, Wayne State University, Detroit, Michigan, United States of America*

Abstract

One of the main sources of Greenhouse Gas Emissions (GHG) is electricity consumption which is getting used for different purposes..Water pumping, especially, pumping from deep groundwater resources consumes a lot of energy. In arid and semi-arid areas, in which groundwater is the only source of water, water pumping is done for different purposes such as agricultural, industrial and urban uses. Kerman plain is one of these arid and semi-arid areas which is located in South East of Iran. Groundwater reliance and aquifer decline are the most prominent challenges that this area is faced with in recent years. This challenges increase the demand for more electricity consumption to pump water from the aquifer so that CO_2 emissions will be increased. A large percentage of water extraction from the aquifer is used for agricultural purposes. In this paper, by modelling Kerman plain aquifer with MODFLOW software by using Geographical Information System (GIS) database and also studying height of groundwater table from 1999 to 2012, electricity energy consumption of groundwater extraction for agricultural, industrial and urban water supply is calculated and the CO_2 emissions trends resulted from electricity energy consumption is evaluated. Then model results are examined for a business as usual (BAU) scenario of changes in water resources. As a result the amount of CO_2 emitted from groundwater abstraction by three mentioned sectors is calculated for specified time horizon. Finally, some suggestions are presented for reducing greenhouse gas emissions for the time horizon.

Peer-review under responsibility of the Scientific Committee of the IAHR Groundwater Symposium 2014

Keywords: Greenhouse gas emissions (GHG), Electricity Energy, Groundwater, Water pumping, MODFLOW, GIS

---

*Corresponding author. Tel.: +98-930-832-9590
E-mail address: s-nazari@aut.ac.ir

Peer-review under responsibility of the Scientific Committee of the IAHR Groundwater Symposium 2014
doi:10.1016/j.proenv.2015.04.025

1. Introduction

During the last decade, an unprecedented state of global warming has been witnessed. Many of scientists have argued that increasing levels of carbon dioxide (CO2) emissions as a greenhouse gas, significantly contribute to the warming of global temperatures and climatic instability (IPCC [1]). During recent decades, development in industrial, agricultural and domestic water consumption has intensified the pressure on the water resources in order to satisfy the water demands. Water availability for the above mentioned purposes has become increasingly important topic of international and interdisciplinary research in response to major water challenges which are the main concerns in certain parts of the world. Water supplies for different activities generally require high energy consumption and have contributed to increase in energy use in many parts of the world (Curlee et al. 2008 [2], Goldestein et al. 2002 [3]). A systematic review of energy used in the water industry is often considered within life-cycle assessments (LCAs) (Sabrina et al. 2011 nature climate change [4]). Also a review of LCAs of water industry found that energy use carries the highest environmental burden (e.g. GHG emissions) in most cases consumed as electricity for pumping (Friedrich et al. 2007 [5]).

Growing populations are creating a higher water demand, and in areas where water is already scarce accelerated research will be required to help develop sustainable mitigation and adaptation scenarios to climate change will still be meeting demand (Blickenstaff et al. 2013 [6]). In the areas which groundwater is considered as the only source of water supply, pumping water from regional aquifers is an energy consuming process especially when the aquifer has a declining trend because of overexploitation. In these areas electricity consumption intensifies the production of large amounts of greenhouse gases. In order to manage groundwater resources it’s essential to provide aquifer models by which water management options can be applied.

In order to study the impact of multiple activities carried out simultaneously, there is a need to develop a model which can quantify the response of the groundwater system to changes in surface water management options (irrigation and/or agriculture) and groundwater so that proper measures could be adopted for the sustainable management of groundwater resources (Asaf Sarwar and Helmut Eggers, 2006 [7]).

Groundwater flow models are appropriate tools to assess the effect of foreseen future human activities on groundwater dynamics (Moa et al 2005 [8]; Dawoud et al. 2005 [9]; Mylopoulos et al. 2007 [10]). MODFLOW is one of the most common software for groundwater modelling. When applying MODFLOW it represents a step ahead in recognizing the groundwater behavior since knowing the variation of groundwater depth in time and space is important to support decision making on water management (Xu Xu et al. 2011 [11]). Coupling of MODFLOW with Geographic Information System (GIS) is very helpful to assess the impacts of water abstractions from aquifer by assessing the groundwater table trend.

In this paper Kerman plain aquifer is modelled by an integrated coupling of the MODFLOW with GIS. Then the trend of groundwater table and the unit hydrograph is plotted based on 1999 to 2012 data and the groundwater table is plotted with consideration of the current management policy for 20 years later. Finally, according to the plain water balance information and abstractions, electricity energy used for groundwater abstraction is calculated and the GHG emissions resulted from the electricity energy in this plain is calculated for the above mentioned period.

2. Methodology

The modular-finite difference groundwater flow model MODFLOW-2000 (Harbaugh et al. 2000 [12]) was selected to simulate the behaviour of groundwater flow in the study area because it is welldocumented and extensively tested model, which can be readily incorporated into future studies for optimal water resources management (Xu Xu et al. 2011 [11]).

Data used in MODFLOW consists of the aquifer-system stress factors (i.e. pumping volume, effective recharge, groundwater evaporation and groundwater-surface flow balances), the aquifer system geometry (Using available geological information e.g. boreholes data and cross sections), the hydro-geological parameters (including hydraulic conductivity, specific storage and specific storage yield) of the simulated process, and the main measured variables (i.e. groundwater heads at specified points and different time periods). All related data were collected from Kerman Water and Wastewater Engineering Company (KWWEC). After modelling the aquifer in the MODFLOW environment, the contour layers of simulated model are exported to ArcGIS in order to prepare the maps and evaluation of groundwater table status for the future based on business as usual (BAU) scenario. By obtaining aquifer water balance, annual water abstraction from groundwater and water table, the electricity energy consumed for water abstraction can be calculated. As pumping water can be considered as the most energy-consuming process, we focused on abstraction of water and we used a basic theoretical physical relationship, which prescribes the energy required to lift 1 m3 of water (with a density 1000 kg m-3) through 1 m at 100% efficiency is equal to 0.0027 kWh. Equation (1) shows this relationship:

$$Energy(kWh) = \frac{9.8\left(m\ s^{-2}\right) \times lift\left(m\right) \times mass\left(kg\right)}{3.6 \times 10^{6} \times efficiency\left(\%\right)} \tag{1}$$

Having a lack of detailed knowledge about the efficiency of the individual pumps, (Since some information about the efficiency of the individual pumps is missing) we employed available data on pumping efficiencies, Iran conditions and studies of energy consumption for irrigation pumping in India (where the pumping efficiencies are around 30%)(Nelson et al. 2009 [13], Shah 2009 [14]). We adopted an average of 30% efficiency rate for the case study area. By inefficiencies in the transmission and distribution (T&D) of electricity the overall efficiency of electricity utilization to power pumps is reduced. We also adopted T&D losses (in the range of) 10 to 19%. Using equation (1) and the selected efficiencies, we can estimate the average energy usage required to pump a cubic meter of groundwater (kWh m^{-3}). The rate of GHG emissions resulting from consumption of electricity is calculated according to the following equation:

$$\text{GHG emissions } (KgCO_2) = \text{EC } (KWh/m^3) \times \lambda_1\ (KgCO_2/KWh) \tag{2}$$

Where EC= amount of electricity used per unit volume of water (KWh/m^3); λ_1 = conversion coefficients for GHG emissions per KWh of electricity consumption which is adopted to be 1.69 $KgCO_2$/KWh (Nazari et al. 2014 [15]). Methodological steps of the study are shown in Figure 1.

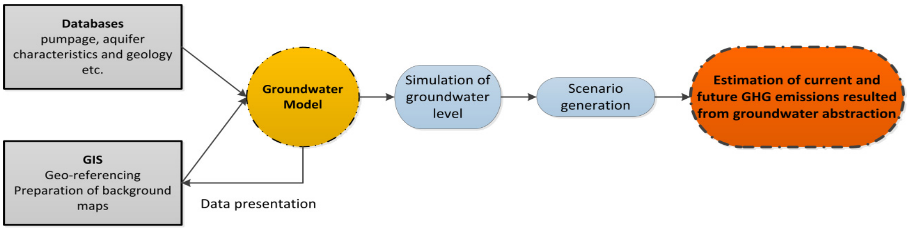

Fig. 1. Methodological steps of the study

3. Case Study

The case study selected is the Kerman plain with an area of 4580 Km^2. The case study is an arid and semi-arid area which is located in South-East of Iran between latitude 29º 50′ to 30º 30′ N and longitude 56º 30′ to 57º 30′ E. Kerman city, with a population of 640,000 and area of 140 Km^2 is located in this plain as shown in Figure 2. This plain is suffering from a decreasing trend of available water due to overexploitation of groundwater resources. Currently, groundwater is the only resource of water supply for domestic, agricultural and industrial demands within this area. An increasing rate of population growth and numerous droughts have been the most important challenges of the plain in recent years. As a result, the aquifer water level has been decreasing because of excessive water withdrawals.

Fig. 2. Location map of Kerman plain as the case study

Mountains comprises 2325 Km^2 area of this plain (51% of total area of plain) which play a dominant role in recharge of the aquifer. The Maximum elevation of the mountains which are located in south and south western of the plain is 4000 meters height from sea level. The average height of the plain is 1830 meters from sea level and general slope of the plain is from south to north western. There are 65 Piezometric boreholes in this plain with defined UTMs, and the historical records from groundwater level of these boreholes are collected from KWWEC.

According to the last statistics (collected from KWWEC) there are 1194 wells with annual discharge of 267.96 million cubic meters (MCM), 27 Aqueducts with annual discharge of 17.7 MCM and 4 water fountains with annual discharge of 7.2 MCM in this plain, so there is a total discharge of 293 million cubic meters from the aquifer in the area. Table 1 displays a summary status of water resources in Kerman plain. 14% of the wells have a depth less than 100 meters, 78% of wells have a depth of 100 to 200 meters and 8% of them have a depth more than 200 meters.

In this plain there is 44344 Hectares of land under cultivation which are irrigated from aquifer by groundwater pumping. 82% of total water discharge is used for agricultural purposes, 15.48% is used for drinking water and 6.67% is used for industrial purposes. So agriculture sector plays the most important role in increasing the rate of groundwater extraction, energy consumption, water pumping and producing GHG emissions.

4. Results and Discussions

Assessing the fluctuation of groundwater level in a limited numbers of wells in the area can't be an accurate and precise representation of aquifer water level. So the aquifer unit hydrograph is prepared for 1999 to 2012 period as shown in Figure 3.

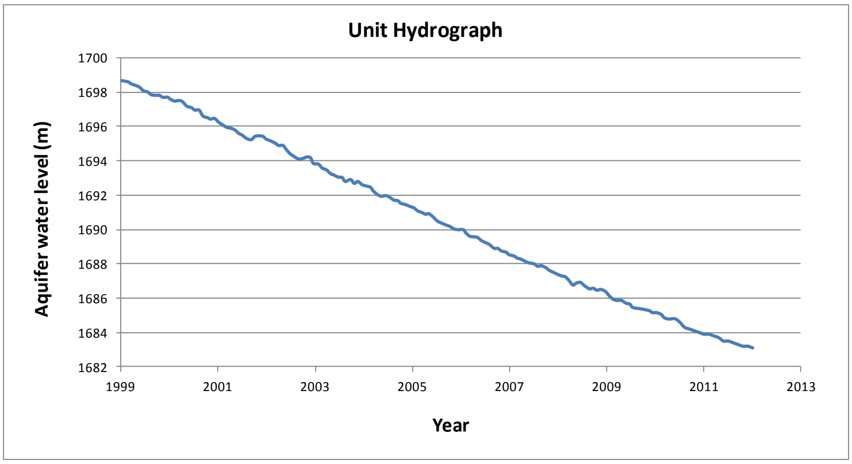

Fig. 3. Unit hydrograph of Kerman plain aquifer from 1999 to 2012 period.

According to Figure 3 there has been a annual reduction in groundwater level of 1.11 meters for the aquifer and a groundwater total reduction of 15.4 meters from 1999 to 2012. The reasons for this decreasing trend are population growth, increasing water demand for agricultural, industrial and domestic use and reduction in precipitation in recent years.

In order to enforce management strategies preparing aquifer models and polygon maps of groundwater table by which the aquifer status can be observed is highly required. . The polygon maps of groundwater table are prepared in ArcGIS environment to see the status of aquifer water table in 2022 based on business as usual (BAU) scenario. Figure 4 and 5 show polygon maps of Kerman plain aquifer water table in 2012 and 2022, respectively. A Comparison between Figure 4 and 5 depicts that we will witness the continuously declining groundwater levels in the future. Also it can be inferred that, generally, the groundwater decline direction is from east toward west and from south eastern toward north western. Most steep decline in water level happens in east because of dense distribution of wells and more overexploitation in this area.

The majority of the wells are categorized as deep wells with an average pump lift of 69 meters. The average depth of the wells which are located in rural area (Kerman city centre) has an increasing trend since the urban wastewater collection system has not completed yet and most of the houses' wastewater is injected into the groundwater surface. . This incident threatens water quality and causes sanitary problems for groundwater.

As long as agricultural lands are located in the same area that most wells are, there will be a high electricity energy consumption rates in this area. With a growing population and rising living standards the water demand for agricultural and animal products is increasing. To meet future demand expansion of agricultural lands is often seen as a necessity and requires more water supply and energy for water abstraction, transportation and application for growing crops.

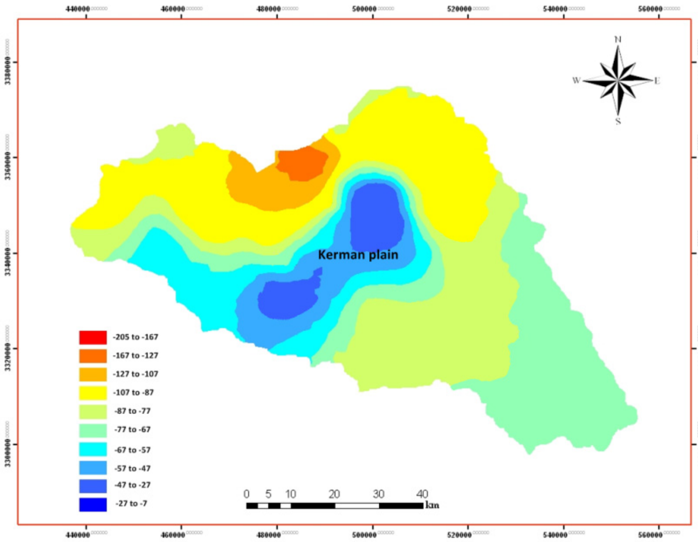

Fig. 4. Kerman plain groundwater table in 2012

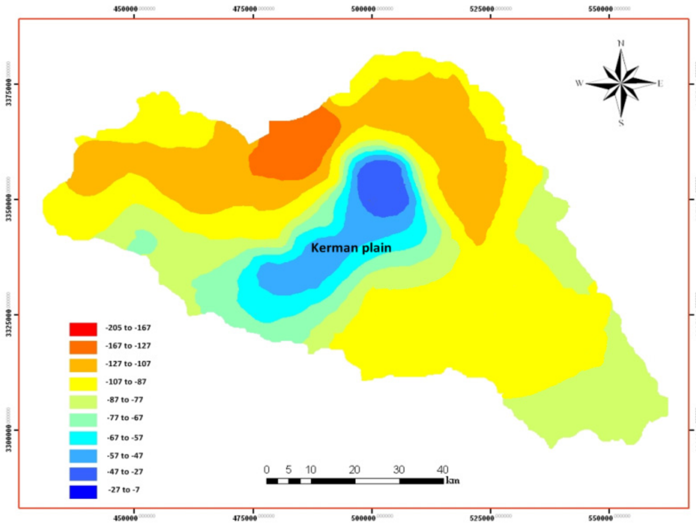

Fig. 5. Kerman plain groundwater table in 2022

Since the water supply is proportional to the lift and distance over which it is pumped, the energy required to irrigate the fields is dependent on the irrigation method/technology. A large portion of agricultural lands in the Kerman plain area use conventional (water logging) systems for irrigation. Using pressurized irrigation systems (e.g. sprinkler, drip) can be an appropriate water conservation policy which provide a larger degree of control and can improve water consumption efficiency and will decrease energy use considerably. Efficiency optimization of electrical pumps is a promising way for decreasing energy use. As the area is mostly sunny, using renewable sources (e.g. solar pumps) for pumping and application of water should also be explored.

Figure 6 shows GHG emissions growth yearly resulted from groundwater abstraction for different purposes in Kerman plain.

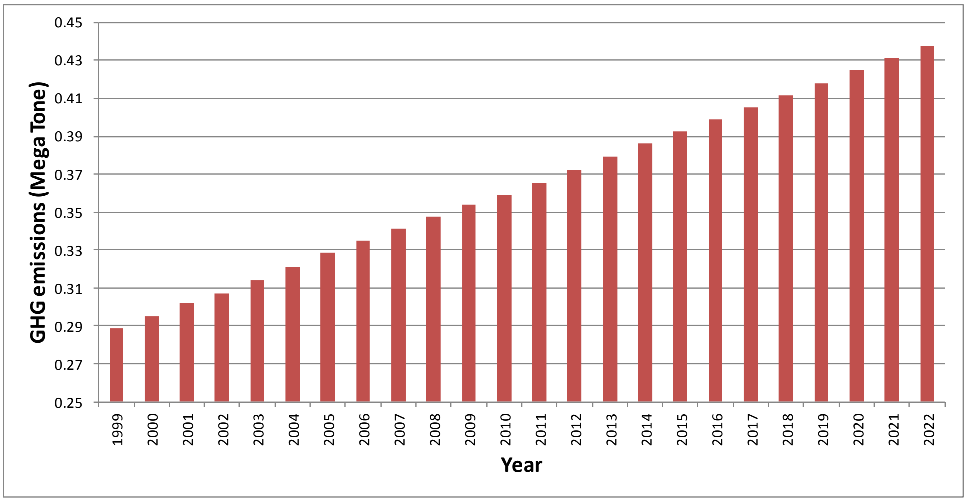

Fig. 6. Amount of GHG emissions resulted from groundwater abstraction from 1999 to 2012

According to Figure 7. total GHG emissions from groundwater use in Kerman plain increases from 0.289 $MtCO_2$ in 1999 to 0.438 $MtCO_2$ in 2022. Applying water conservation policies, water saving and water pumping technologies to this region can reduce electricity energy consumption and GHG emissions in water sector of the case study area.

5. Conclusion

The Kerman plain aquifer was simulated by coupling of MODFLOW model and GIS in which groundwater level was evaluated from 1999 to 2022 based on business as usual (BAU) scenario. Due to severe decline of groundwater table, there has been a high rate of pumping energy consumption for groundwater abstraction in recent years. Increasing rate of groundwater abstractions for fulfilling water demands in different sectors causes GHG emissions which results in emission of 0.438 $MtCO_2$ in 2022 in this plain. Groundwater abstraction is only one of the elements of GHG emissions in water sector. Conveyance and treatment of fresh water and wastewater, which are neglected in this study, are GHG emitting processes which should be considered and understood as the role of water sector as a GHG emitter. The water sector faces different challenges in future. More focus on its energy requirements would be the crucial part of polices for dealing with these challenges.

References

[1] IPCC Second Assessment on climate Change. International panel on climate change. Cambridge University Press, 1996.
[2] Curlee, T. N. & Sale, M. J. in Conf. Water Security in the 21st Century, 22 (Environmental Science Division, 2003).
[3] Goldstein R. & Smith W., Water and Sustainability: Us Electricity Consumption for Water Supply and Treatment: the next half century (Electric Power Research Institute, 2002).

[4] Sabrina G. S., A Rothausen, Delan Conway., “Greenhouse-gas emissions from energy use in water sector”, nature climate change, 2011, 1, 210-219.

[5] Friedrich E, Pillay S, and Buckley C. A., “The use of LCA in the water industry and the case for an environmental performance inidcator.”, Water SA 33, 2007, 443-451.

[6] Blickenstaff K and Condon L., ”Greenhouse Gas Emissions calculator for the water sector: User’s manual”. Reclamation managing in the west, Bureau of reclamation water and environmental resources division (86-68200), Technical memorandum No. (2013), 86-68210-2013-03.

[7] Sarwar A, and Eggers H., “Development of conjunctive use model to evaluate alternative management options for surface and groundwater resources.”, Hydrogeology Journal, 2006, 14, 1676-1687.

[8] Mao XS, Jia JS, Liu CM, Hou ZM., “A simulation and prediction of agricultural irrigation on groundwater in well irrigation area of the piedmont of Mt. Taihang, North China.”, Hydrol Process, 2005, 19(10):2071–2084.

[9] Dawoud M, Darwish M, El-Kady M., “GIS-based groundwater management model for Western Nile Delta. Water Resources Management, 2005, 19(5):585–604.

[10] Mylopoulos N, Mylopoulos Y, Tolikas D, Veranis N., “Groundwater modelling and management in a complex lake–aquifer system.”, Water Resources Management, 2007, 21(2):69–494.

[11] Xu Xu, Guanhua H, Zhongyi Qu, Luis S. P., “ Using MODFLOW and GIS to access changes in groundwater dynamics in response to water saving measures in irrigation districts of the upper yellow river basin.”, Water Resources Management, 2011, 25, pp 2035-2059.

[12] Harbaugh AW, Banta ER, Hill MC, McDonald MG., “MODFLOW-2000, the US Geological Survey modular groundwater mode—user guide to modularization concepts and the groundwater flow process.”, US Geological Survey Open-File Report, 2000, 00-92, Reston, Virginia.

[13] Nelson G C, Roberston R, Msangi S, Zhu T, Liao X and Jawajar P., “Greenhouse Gas mitigation. Issues for Indian agriculture IFPRI discussion paper, 2009, (Washington, DC: International Food Policy Research Institute, Environmental and Production Technology Division).

[14] Shah T ., “ Climate change and groundwater: Indian’s opportunities for mitigation and adaptation”, Environmental Research Letter, 2009, 4 035005.

[15] Nazari S., Mousavi S.J, Behzadian K., and Kapelan Z., “Compromise programming based scenario analysis of urban water systems management options: Case study of Kerman City”, 11th International Conference on Hydroinformatics, HIC 2014, New York City, USA, 2014.