Title

Evaluation of the Safe Yield of Groundwater Production Derived from Wind Energy

Journal

Journal of Energy Engineering, 141(4)

ISSN

0733-9402

Authors

Keshtkar, Hilda
Bozorg-Haddad, Omid
Jalali, Mohammad-Reza
et al.

Publication Date

2015-12-01

DOI

10.1061/(asce)ey.1943-7897.0000240

Peer reviewed

Evaluation of the Safe Yield of Groundwater Production Derived from Wind Energy

Hilda Keshtkar[1]; Omid Bozorg-Haddad[2]; Mohammad-Reza Jalali[3]; and Hugo A. Loáiciga[4]

Abstract: Groundwater aquifers are key sources of water in arid and semiarid regions. Fossil fuels are commonly used to power water-well pumps. The adverse effects of greenhouse gas emissions from fossil fuel use have led to the search for alternative clean energy sources to extract groundwater. A key factor in assessing the viability of wind energy use in groundwater extraction is the safe yield of groundwater production that can be derived by using windmills to power water wells. This paper presents and tests simulation and optimization models developed to estimate the safe yield of groundwater production derivable from the joint application of wind energy to water extraction and water storage for irrigation. **DOI: 10.1061/(ASCE)EY.1943-7897.0000240.** *© 2014 American Society of Civil Engineers.*

Author keywords: Windmill; Safe yield; Groundwater; Water storage.

Introduction

Extraction of groundwater by powering water-well pumps with fossil-fuel energy is perhaps the most common method used to supply groundwater in many regions (Sterret 2007). Using fossil fuels leads to air pollution by the emission of greenhouse gases (Intergovernmental Panel on Climate Change 2014). Desire to avoid such pollution has focused attention on alternative clean energy sources (Loáiciga 2011). Wind energy is a clean, renewable energy source that has few adverse environmental effects and is available in many places. Although wind energy has been used for small-scale hydrologic applications, it is gaining popularity as a clean source of electricity generation to supply water for agricultural and other water-resource uses.

There have been a few studies conducted on the feasibility of using wind energy for water resources applications. Al Suleimani and Rao (2000), for example, investigated the amount of groundwater that can be extracted using wind turbines operating at various speeds. These authors claimed that existing wind resources were enough for groundwater extraction in several rural places in Oman. Valdés and Raniriharinosy (2001) designed three different simple wind pumps for use in Madagascar. Bakos (2002) investigated the feasibility of using a wind-driven water plant system for inexpensive electricity generation. The author concluded that using such system would be feasible and could reduce electrical energy consumption in several Greek islands. Bueno and Carta (2006) recommended wind-powered hydro storage systems in the Canary Islands. Garcia-González et al. (2008) suggested using wind energy in conjunction with hydro pumped-storage units in order to solve the problem of variable wind speed. Vieira and Ramos (2008) reported an optimization model that determines the best operation times of the day for a wind-energy system with pumped storage and defined water inflow and consumption. Vieira and Ramos (2009) reported an optimization model to optimize water supply efficiency. Their results indicate that using wind turbines to provide pumping energy needs would reduce costs significantly. Ramos et al. (2011) proposed three solutions to improve energy management and the efficiency of water supply systems, namely: (1) using water turbines in gravity pipes to control the pressure and electricity generation, (2) optimizing pumping operation rules giving consideration to electricity tariffs and water demand patterns, and (3) using renewable energy tools such as wind turbines in water pumping stations. According to their results, optimization of the operating rules of water supply and electricity production in renewable hybrid systems can minimize water-pumping costs and reduce CO_2 emissions. Sun et al. (2011) found out that wind-wheel and water-pump operations can be matched out at different wind speeds, and that the maximum water discharge can be achieved at different wind speeds if the torque specifications and wind-wheel power generation are matched out correctly and optimized. Notton et al. (2011) investigated the joint application of renewable energy with water storage. Protopapas and Papathanassiou (2012) reported that using hybrid (wind energy and diesel power) stations to provide dispatchable power leads to significant increase in wind energy production. Bekele and Tadesse (2012) studied the feasibility of a small-scale hydropower/photovoltaic/wind-based hybrid electric supply system for six sites. After optimizing the hybrid system, the cost of energy was determined to be less than $0.16 per kWh.

Recently, many techniques have been developed and applied in all aspects of water resources systems such as reservoir operation (Bozorg Haddad et al. 2011a; Fallah-Mehdipour et al. 2011a, 2012a, 2013a), hydrology (Orouji et al. 2013), project management (Bozorg Haddad et al. 2010b; Fallah-Mehdipour et al. 2012b), cultivation rules (Bozorg Haddad et al. 2009; Noory et al. 2012; Fallah-Mehdipour et al. 2013b), pumping scheduling (Bozorg Haddad et al. 2011b), hydraulic structures (Bozorg Haddad et al. 2010a), water distribution networks (Bozorg Haddad et al. 2008; Fallah-Mehdipour et al. 2011b; Seifollahi-Aghmiuni et al. 2011, 2013), operation of aquifer systems (Bozorg Haddad and Mariño

[1]M.Sc. Graduate, Dept. of Irrigation & Reclamation, Faculty of Agricultural Engineering & Technology, College of Agriculture & Natural Resources, Univ. of Tehran, Karaj, Tehran, Iran. E-mail: Keshtkar_H@ut.ac.ir

[2]Associate Professor, Dept. of Irrigation & Reclamation, Faculty of Agricultural Engineering & Technology, College of Agriculture & Natural Resources, Univ. of Tehran, Karaj, Tehran, Iran (corresponding author). E-mail: OBHaddad@ut.ac.ir

[3]Assistant Professor, Dept. of Civil Engineering Iran Univ. of Science and Technology, Tehran, Iran. E-mail: MrJalali@iust.ac.ir

[4]Professor, Dept. of Geography, Univ. of California, Santa Barbara, CA 93106. E-mail: Hugo.Loaiciga@ucsb.edu

Note. This manuscript was submitted on May 9, 2014; approved on August 13, 2014; published online on September 22, 2014. Discussion period open until February 22, 2015; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Energy Engineering***, © ASCE, ISSN 0733-9402/04014045(12)/$25.00.

2011), site selection of infrastructures (Karimi-Hosseini et al. 2011), and algorithmic developments (Shokri et al. 2013). Only a few of these works dealt with the use of wind energy in deriving the safe yield of groundwater production.

As implied by the previously cited studies, using wind energy for extracting groundwater has been assessed to have an economic potential, Yet, recent studies have rarely addressed the safe yield of water production that can achieved by using wind energy to extract groundwater. To ascertain the feasibility of replacing fossil fuel energy with wind energy for groundwater extraction in a specific region, it is necessary to determine the safe yield of groundwater production that can be achieved by using wind energy. The determination of the safe yield of groundwater production depends on several factors, such as the local groundwater conditions, wind conditions at deployment sites, the type and size of windmills deployed, the number of windmills needed to meet water use, and the availability of storage reservoirs for extracted groundwater. This study develops a simulation/optimization model used to determine (1) the safe yield of groundwater production derived from wind energy to drive windmills, and (2) the effect that water storage used in conjunction with wind energy has on the safe yield of groundwater production. The model optimizes the amount of water discharging from a water reservoir so as to maximize safe yield in daily and 10-day periods.

The use of wind energy to extract groundwater takes two forms. The first form relies on wind turbines to produce electricity that powers water-well pumps. The second form of wind energy application relies on simple windmills, which apply wind energy directly to extract groundwater. Electricity generation with wind turbines is relatively expensive. It requires relatively high operation and maintenance costs. In many countries, farms are located in rural areas that are far from urban metropolises, areas where the availability of labor skilled in the repair and service of wind turbines is frequently limited. Therefore, wind energy application by turbines is relatively complex and expensive. In contrast, windmills require neither high operation and maintenance expenditures nor highly skilled personnel. For these reasons, this paper is devoted to assessing the feasibility of using windmills for extracting groundwater. A schematic of a windmill and its components is shown in Fig. 1.

Methods

The performance of wind energy in groundwater extraction can be measured by the amount of water that can be produced over a period of analysis. The maximum discharge that is obtainable from a reservoir (connected to a groundwater extraction system) at all times within each period of analysis is herein defined as the safe yield of groundwater production, and the average excess discharge from the reservoir over the safe yield is called the secondary yield. The first step in determination of the safe yield is to calculate the amount of power, and, thus, the amount of water that can be pumped using wind energy in a region. Thereafter, the safe yield of water in different periods is estimable. If the obtained water is used for agriculture, then a 10-day period seems appropriate for the analysis of supply of irrigation water.

The equations developed in this study are classified in three categories: (1) those for calculation of the extractable power from wind energy, (2) those for converting output of wind power to energy required for pumping groundwater, and (3) those expressing reservoir continuity equations. The simulation model is as follows.

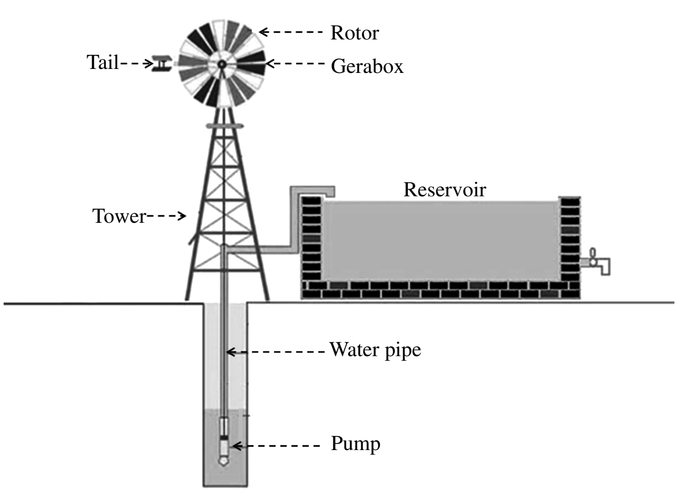

Fig. 1. Schematic of a windmill and its components

Simulation Model

1. Calculation of the extractable power from wind energy:

   The general equation which is used to calculate the power which can be obtained from wind is defined below (Jain 2011):

$$P_t = \frac{1}{2}\rho_a A_r v_t^3 \tag{1}$$

   where P_t = power derived from wind energy at time t (watt); ρ_a = air density (kg/m^3), which is considered to be 1.2 kg/m^3; A_r = rotor area (m^2); and v_t = wind speed in a specified location at time t (m/s). The cut-in and cut-off speed of the windmills are 2.5 and 15 m/s, respectively. Therefore, no power will be extracted in speeds lower than 2.5 m/s or higher than 15 m/s.

2. Converting output power to energy required for pumping groundwater:

   The energy E_t (J) required to lift a rate of water Q_t(m^3/s) with unit weight $\gamma_w(= 9{,}810\ \mathrm{N/m^3})$ a vertical distance HT_t (m) over a period of time Δt (s) when the total efficiency of the powering system is η_t, is given by the following expression:

$$E_t = \gamma_w \times Q_t \times HT_t \times \eta_t \times \Delta t \tag{2}$$

   in which $\gamma_w \times Q_t \times HT_t$ denotes the theoretical power requirement, and the vertical distance is the sum of the depth to groundwater in a well (HG) and the water height in a water reservoir (HR_t), or

$$HT_t = HG + HR_t \tag{3}$$

   The total efficiency η_t is composed of two items: (1) the efficiency of converting wind energy to mechanical energy, and (2) the mechanical efficiency. According to the Betz law, the maximum power that can be achieved by wind turbines in an ideal condition is 59% of the theoretical value. This quantity has been considered to be the windmills' energy conversion efficiency. The mechanical efficiency is calculated by multiplying the windmills components efficiency and it varies with wind speed. Therefore

$$\eta_t = \eta(M)_t \times \eta(E) \tag{4}$$

$$\eta(M)_t = \eta w_t \times \eta b_t \times \eta g_t \times \eta p_t \times \eta r_t \tag{5}$$

J. Energy Eng., 2015, 141(4): 04014045

$$\eta(M)_t = \begin{Bmatrix} 0.25 \text{ if} & 2.5 \le v_t < 4.5 \\ 0.50 \text{ if} & 4.5 \le v_t < 8 \\ 1.00 \text{ if} & 8 \le v_t < 15 \end{Bmatrix} \quad (6)$$

where in Eq. (4), η_t = windmill efficiency at time t; $\eta(M)_t$ = the mechanical efficiency at t; and $\eta(E)$ = energy conversion efficiency. In Eq. (5), ηw_t = rotor efficiency at t; ηb_t = bearing efficiency at t; ηg_t = gear efficiency at t; ηp_t = water pump efficiency at t; and ηr_t = water pipe efficiency at t. v_t is Eq. (6) denotes the wind speed in m/s.

3. Reservoir continuity equations:

The time steps in the reservoir equations of water balance are periodic. The indexes used in the equations of this section are denoted by p. The equations of water balance used in this section are as follows:

$$S_{p+1} = S_p + Q'_p + \mathrm{Pr}_p - \mathrm{Loss}_p - TR_p - Sp_p \quad (7)$$

$$Q'_p = Q_t \times pl \times 86{,}400 \quad (8)$$

where in Eq. (7), S_p = water volume in a reservoir at the beginning of period $p(\mathrm{m}^3)$; S_{p+1} = water volume in reservoir at the beginning of period $p+1(\mathrm{m}^3)$; Q'_p = pumped water volume in period $p(\mathrm{m}^3)$ into the reservoir [calculated with Eq. (8)]; Pr_p = volume of rainfall one reservoir in period $p(\mathrm{m}^3)$; Loss_p = volume of evaporation from the reservoir surface in period $p(\mathrm{m}^3)$; TR_p = outflow volume (outlet) from the reservoir in period $p(\mathrm{m}^3)$; and Sp_p = overflow volume of the reservoir in period $p(\mathrm{m}^3)$. In Eq. (8), Q_t = pumped water discharge rate in period $t(\mathrm{m}^3/\mathrm{s})$; and pl = the period length (day). Due to small reservoir surface, the amount of Pr_p and Loss_p are negligible. Therefore Eq. (7) is simplified to Eq. (9) as follows:

$$S_{p+1} = S_p + Q'_p - TR_p - Sp_p \text{ for all } p \quad (9)$$

The reservoir is considered to be cube- shaped or cylindrical, and its capacity is defined as follows:

$$S_{\max} = AR \times H_{\max} \quad (10)$$

where $S_{\max}$ = reservoir capacity (m^3); AR = reservoir surface area (m^2); and $H_{\max}$ = reservoir height (m).

Optimization Model

The objective of this paper's model is to optimize (maximize) the amount of water that is available in all periods of water use (safe yield). By considering a reservoir with specified capacity of water storage, the safe yield of groundwater is affected by the reservoir capacity. To cope with these conditions, the following objective function of the optimization model is proposed:

$$\text{Maximize } SY \quad (11)$$

where SY = safe yield of groundwater (decision variable). Based on the definitions of safe yield and secondary yield, the resulting continuity equation for the reservoir becomes

$$S_{p+1} = S_p + Q'_p - Y\sec_p - SY \text{ for all } p \quad (12)$$

where $Y\sec_p$ = secondary yield in each period of the optimization model and is equal to the water released from the reservoir in each period. The state variables are: the inflow water quantity to the reservoir (Q_p), the change of water volume in the reservoir, and the secondary yield of water.

The model constraints are as follows:

The water volume in the reservoir must be less than reservoir capacity

$$S_p \le S_{\max} \text{ for all } p \quad (13)$$

The water volume in the reservoir in the last period must be equal to or larger than the water volume in the first period

$$S_{\text{final}} \ge S_1 \quad (14)$$

The capacity of the reservoir is a fixed quantity. A schematic of the variables used in the optimization model is shown in Fig. 2.

Case Study

Iran has several wind-rich regions. Some of these regions have high and steady wind speed that makes them suitable for energy production. In other regions of Iran, adequate wind speed is available only during certain periods. It seems reasonable to choose regions with frequent high wind speed for energy production. However the suitability of such places for wind farms construction has been proven earlier and many projects have been allocated within them. This paper investigates the feasibility of using wind energy in places with average wind potential. Eghlid city in the Fars province of Iran is such a place and has been chosen as a case study in this research.

Case Study Characteristics

Eghlid city has an area of $5{,}956\ \mathrm{km}^2$, which comprises about 5.83% of the Fars province. The city has a population of 96,109. This city is located in a mountainous region and its elevations above sea level at its lowest and highest places are about 2,000 m and 3,943 m, respectively. According to reports from the Fars agricultural agency (2014), the average annual rainfall depth in Eghlid City is about 290 mm. Mean minimum and maximum temperature in this city are 6.3 and 20°C, respectively. Eghlid city is one of the windy places of Fars province, and its wind speed has reached 160 km/h.

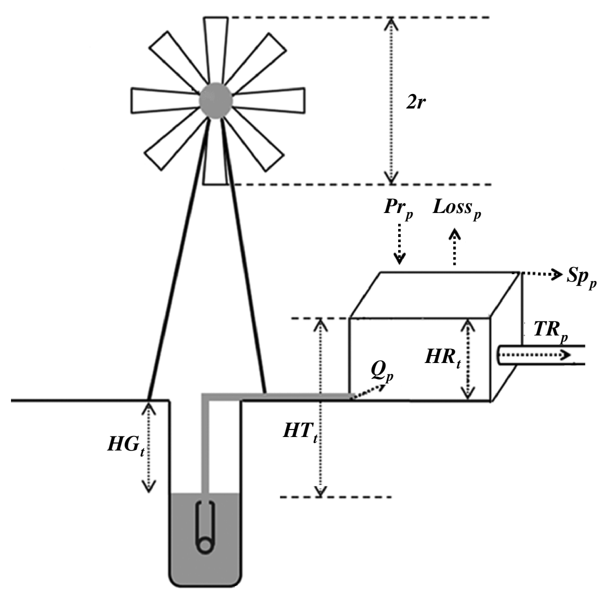

Fig. 2. Schematic of the optimization model

J. Energy Eng., 2015, 141(4): 04014045

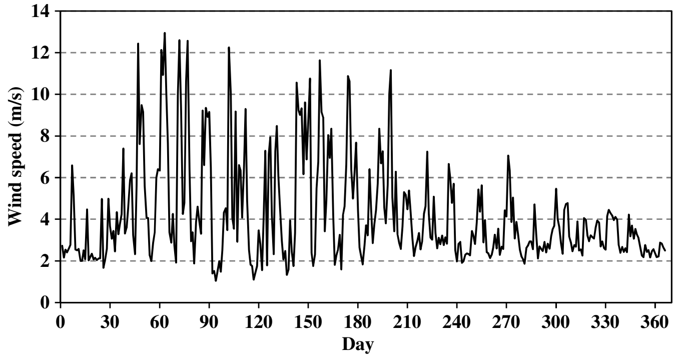

Fig. 3. Average daily wind speed in Eghlid city

Table 1. Average and Maximum Discharge from Wind-Water Pumping Using Different Windmills

Windmill (rotor diameter)	Average discharge (m^3/h)	Average discharge (m^3/day)	Maximum discharge (m^3/h)	Maximum discharge (m^3/day)
2.44 m (8 ft)	3	72	28	662
4.27 m (14 ft)	8	185	71	1,695
610 m (20 ft)	17	416	159	3,815

The 10-min wind speed data for Eghlid city was obtained from the Iranian meteorological agency The wind data was converted to average daily wind power, so that all calculations would be based on a daily time step. The daily average wind speed of Eghlid city is shown in Fig. 3.

In this study, the extractable wind energy is used for pumping groundwater. Therefore the groundwater depth in Eghlid is important. According to the available data, the ground water depth in Eghlid varies between 50 and 70 m (Fars Water Organization 2014). Since the water discharge rates are low in this case study, the groundwater depth changes due to water discharge are negligible. In this research, an average depth of 60 m is assigned to the groundwater level.

Windmill Characteristics

The characteristics of the research's windmills were obtained from the Iranian Isfahan-Talash company (Isfahan, Iran). These windmills are available in different rotor sizes. Windmill specifications are shown in Table 1 for various windmill heights. The extractable power of each turbine is shown in Fig. 4.

Defined Scenarios

The scenarios considered in this study are divided into two general categories as follows:

1. Safe yield of windmills in daily and 10 day periods without water storage.

   In this category, the only factor affecting the safe yield is the windmill capacity to extract wind energy. Therefore there is no optimization model, and a simulation model was implemented to determine the safe yield of groundwater for windmills with different rotor sizes. In this case, the safe yield was determined in two different time periods including: (1) daily periods and (2) 10-day periods. Each 10-day period has 10 possible starting days. Therefore, results differ depending on the starting day of the simulation in each 10-day period, each of which has 10 possible initial states. To determine the safe yield, one must calculate the maximum water discharge that can be maintained within the period of analysis. The overall 10-day safe yield equals the minimum quantity that was calculated among the 10 initial states. This simulation model was implemented in an Excel spreadsheet.
2. Water safe yield determination in daily and 10-day periods considering a reservoir with specified capacity to store water.

The wind speed variability within a day and from day to day introduces restrictions for wind energy applications. Therefore it is rational to store the pumped water in a reservoir and use it at proper times. Without storage a reservoir, the safe yield depends on the wind speed. The water cannot be pumped if the wind speed is lower than the minimum speed needed for windmill operation. In this situation, the daily safe yield equals zero. The use of a reservoir permits saving extracted groundwater and using it for water supply while the wind speed is not sufficient for windmill operation. In this case, the safe yield depends on the water release from the reservoir

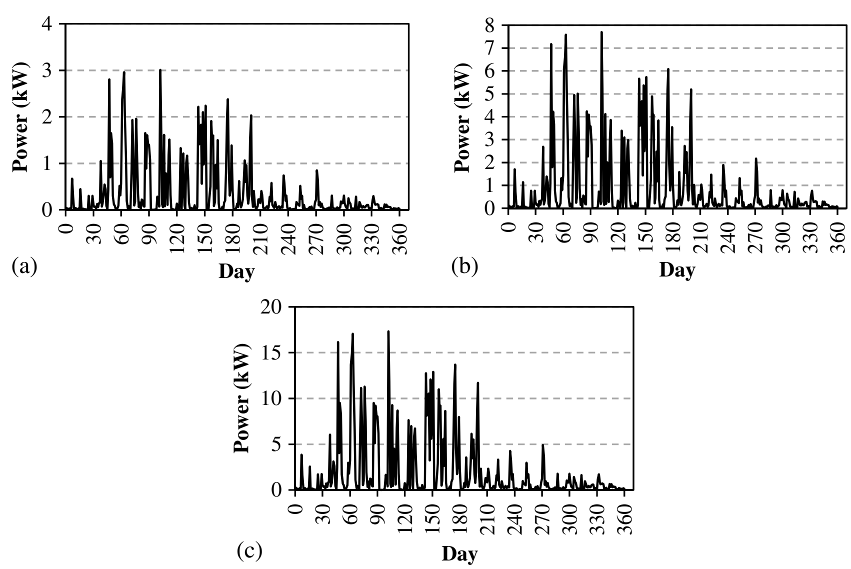

Fig. 4. Achievable power of (a) 2.44 m (8 ft); (b) 4.27 m (14 ft); (c) 6.10 m (20 ft) windmills in Eghlid city

J. Energy Eng., 2015, 141(4): 04014045

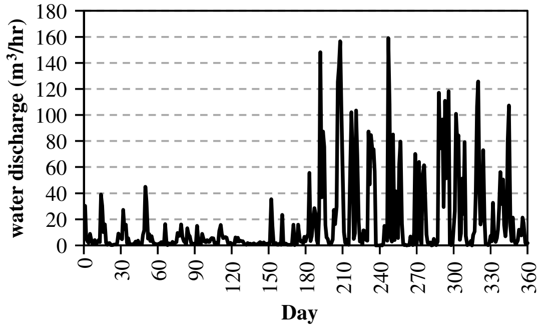

Fig. 5. Average water pumping discharge in m^3/h using a 6.10 m (20 ft) windmill

Table 2. Daily Safe Yield of Groundwater Considering Three Different Reservoir Sizes

	Daily safe yield (m^3)		
Windmill (rotor diameter)	Reservoir capacity = 300 m^3	Reservoir capacity = 3,000 m^3	Reservoir capacity = 30,000 m^3
2.44 m (8 ft)	17	36	72
4.27 m (14 ft)	29	64	181
610 m (20 ft)	47	114	273

in each period of analysis. Therefore, the reservoir release should be determined in a way that maximizes the safe yield. An optimization model was implemented for the purpose of safe yield maximization in which the decision variables are the water releases from the reservoir in each period of analysis. The optimization model is described by Eqs. (11)–(14). The model was applied to three windmill diameters considering three different reservoir capacities. The optimization model calculated the optimized safe yield for daily and 10-day periods. The optimization model was solved with the *LINGO 11* software.

Results and Discussion

The model has been run for the scenarios described in the previous section. Results are as follows.

Daily Safe Yield Determination (without Storage Reservoir)

The simulation model was run in an Excel spreadsheet and the minimum, average, and maximum safe yield of groundwater in one year were calculated for the three considered windmill sizes (Table 1). Since there is no storage reservoir, the available water is determined by the instant wind speed and thus at low wind speeds (less than 2.5 m/s), no groundwater is pumped. Thus the daily safe yield equals zero. The average and maximum water safe yield are shown in Table 1.

The daily groundwater discharge obtainable with 6.10 m (20 ft) windmills given average windiness in the study region is shown in Fig. 5. From the graph shown in Fig. 5 and the data in Table 2, it is evident that, in spite of the positive calculated discharges for average windiness in the study region, given the fact that wind speed falls below minimum thresholds frequently, a practically meaningful safe yield cannot be realized without water storage capacity on the surface.

Daily Water Safe Yield Determination (with Reservoir)

In this case, the daily safe yield of groundwater production was determined and compared for the three windmill sizes and reservoir capacities considered in this study. The reservoir capacities were 300, 3,000 and 30,000 m^3. The results are shown in Table 2.

According to Table 2, having a storage reservoir and regulating the reservoir release of water leads to significant increase in water

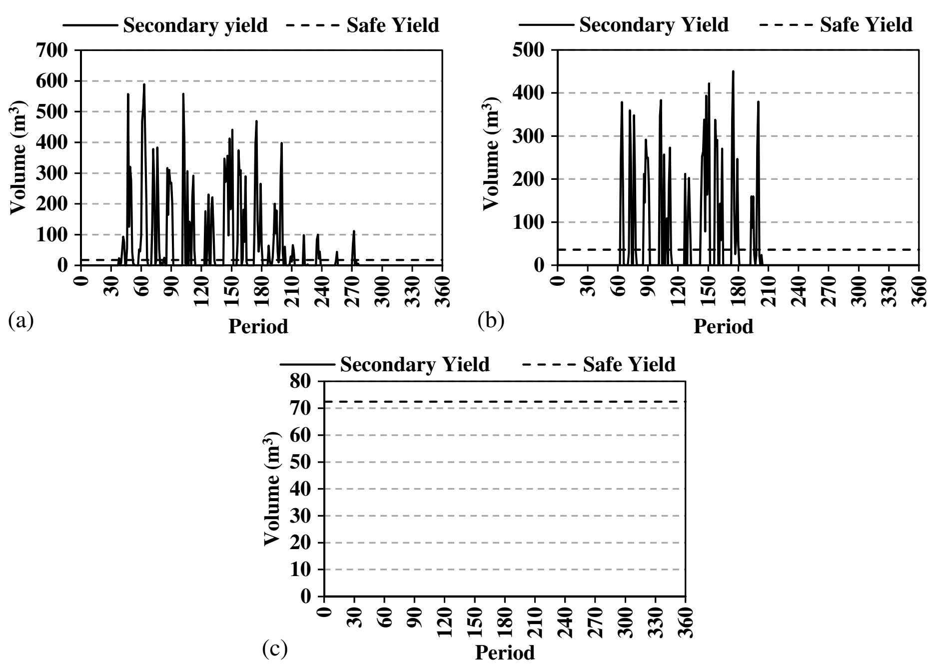

Fig. 6. Daily safe yield and secondary yield considering a (a) 300; (b) 3,000; (c) 30,000 m^3 reservoir, using a 2.44 m (8 ft) windmill

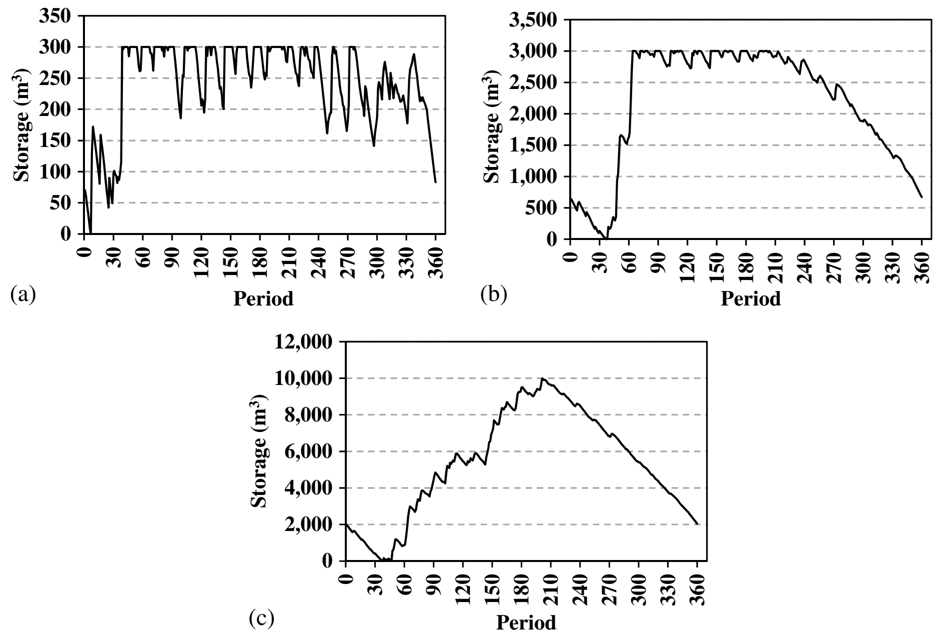

Fig. 7. Daily water storage considering a (a) 300; (b) 3,000; (c) 30,000 m^3 reservoir, using a 2.44 m (8 ft) windmill

safe yield. In this case, the water safe yield varies from 17 m^3/day for an 8-ft (2.44 m) windmill with a 300 m^3 reservoir to 273 m^3/day achieved with a 20-ft (6.10 m) windmill and a 3000 m^3 reservoir.

Figs. 6–11 show the safe yield, secondary yield, and water storage achieved with different windmills and reservoir sizes.

According to Figs. 6–11, having a larger reservoir leads to an increase in the safe yield and a decrease in the secondary yield. This is so because having a larger reservoir permits saving more pumped water. When wind speed is high water is stored to meet water use when wind speed is low. The safe yield and secondary yield comparison shows that when the reservoir capacity equals 300 m^3, most of the time the reservoir is full, and a small fraction of the pumped water is allocated to the safe yield. Therefore most of the pumped water does not become available as secondary yield. Using a 300 m^3 reservoir and 8, 14, and 20 ft (2.44, 4.27, and 6.10 m) windmills, the maximum secondary yield equals 589, 1,548 and 3,501 m^3/day, respectively. Evidently the increase in reservoir storage increases the secondary yield.

According to the parts (c) in Figs. 6–11, all of the pumped water will be assigned to the safe yield for the 8, and 14-ft (2.44 and

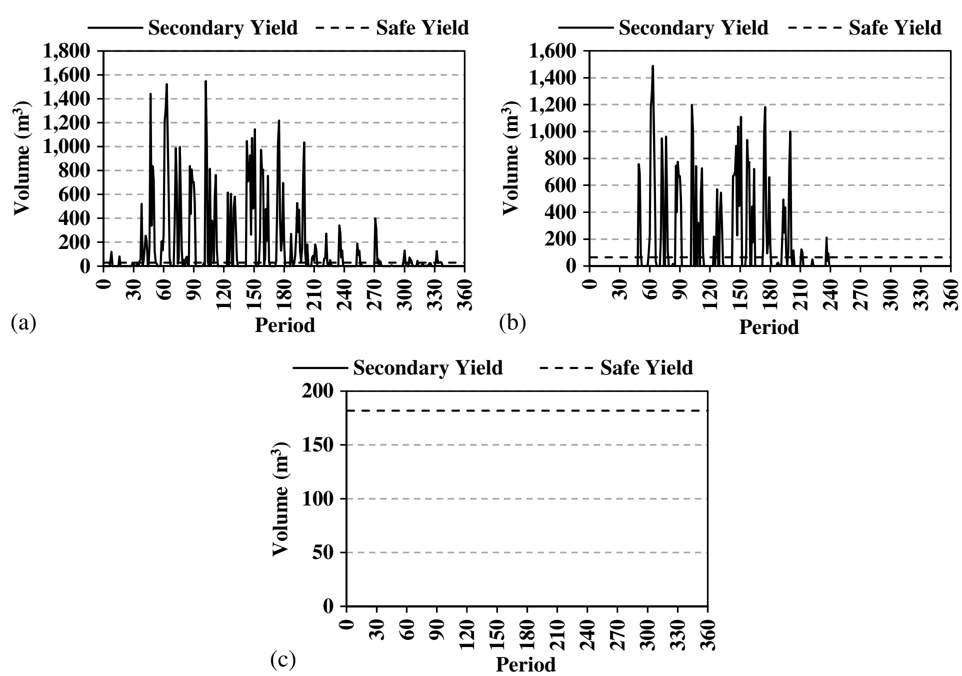

Fig. 8. Daily safe yield and secondary yield considering a (a) 300; (b) 3,000; (c) 30,000 m^3 reservoir, using 4.27 m (14 ft) windmill

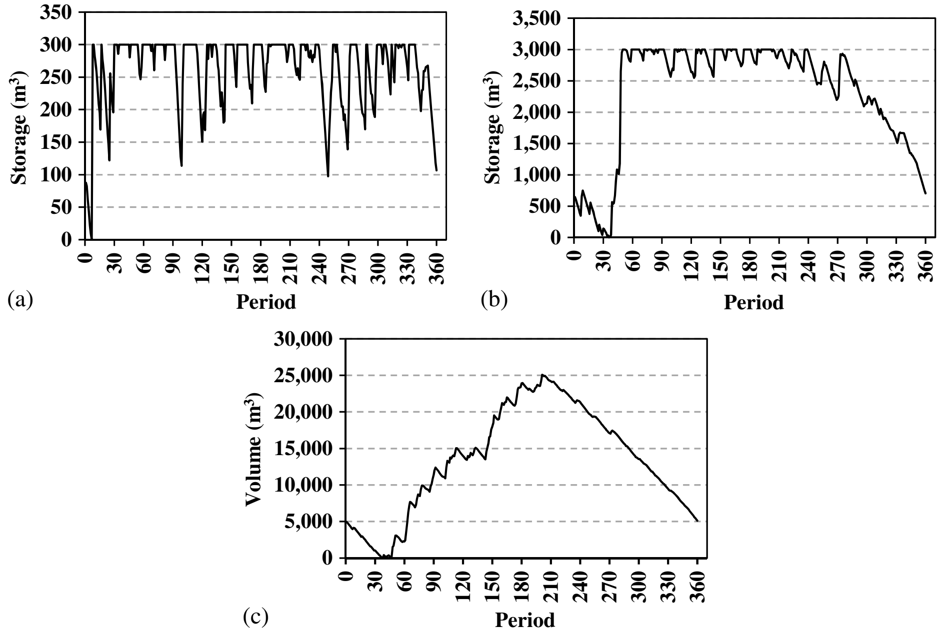

Fig. 9. Daily water storage considering a (a) 300; (b) 3,000; (c) 30,000 m^3 reservoir, using a 4.27 m (14 ft) windmill

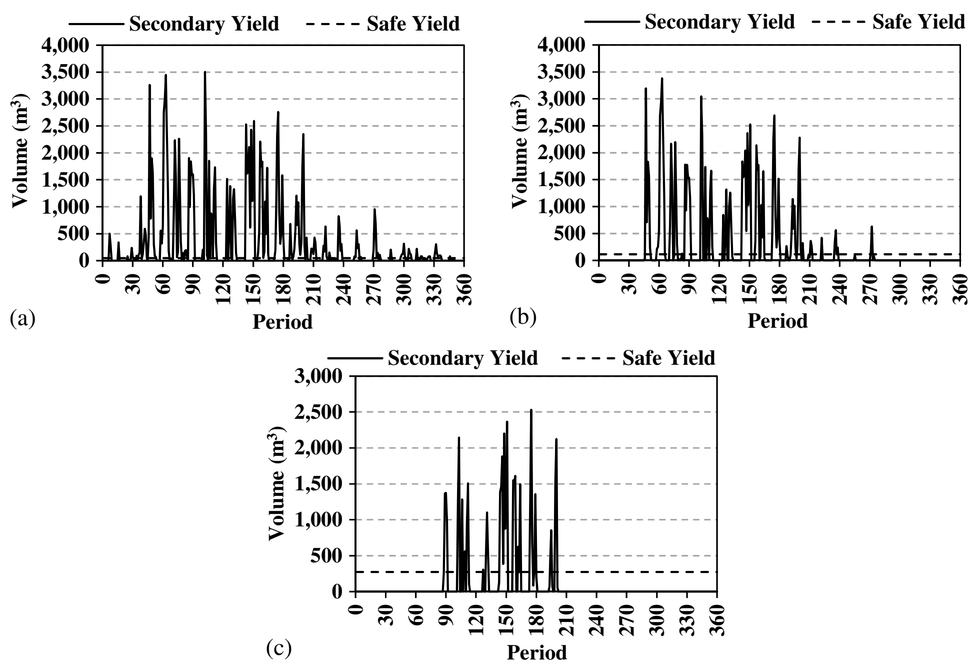

Fig. 10. Daily safe yield and secondary yield considering a (a) 300; (b) 3,000; (c) 30,000 m^3 reservoir, using a 6.10 m (20 ft) windmill

4.27 m) windmills when using a 30,000 m^3 reservoir. Thus, the reservoir capacity in these cases is equal or greater than the capacity to store water in each period of study. Figs. 6–11 also show that the maximum water storage in a reservoir using 8 and 14 ft (3.44 and 4.27 m) windmills are 10,000 and 25,000 m^3, respectively. In fact, the storage capacity of 30,000 m^3 exceeds the storage capacity needed for water release regulation for these windmills. A smaller reservoir with storage capacity equal to the cited maximum storages (10,000 and 25,000 m^3) is enough to store and regulate water optimally. But when using a 20 ft (6.10 m) windmill, the 30,000 m^3 reservoir is not enough for regulating all the available water. Therefore the safe yield could still be increased by increasing the reservoir capacity.

Water Safe Yield Determination in 10- Day Period (with No Reservoir)

In this case, the safe yield depends on the initial state in each period. Therefore, the safe yield was estimated for 10 different states. The minimum safe yield obtained over the 10 states was called the 10-day safe yield. This process was applied to the three sizes of windmills and the 10-day safe yield was determined for them. Results are shown in Table 3.

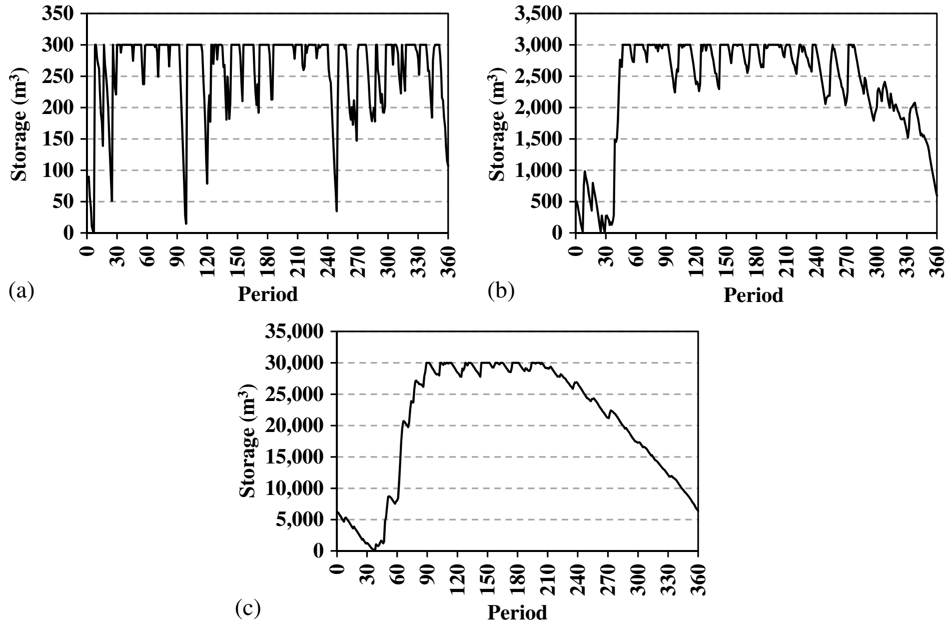

Fig. 11. Daily water storage considering a (a) 300; (b) 3,000; (c) 30,000 m^3 reservoir, using a 6.10 m (20 ft) windmill

Table 3. 10-Day Safe Yield of Groundwater Obtained from Pumping by Different Windmills without Storage Reservoir

Windmill (rotor diameter)	Safe yield (m^3)
2.44 m (8 ft)	38
4.27 m (14 ft)	97
610 m (20 ft)	218

The 10-day safe yields for different initial states and turbines are shown in Fig. 9. According to the graphs in the Figure, it is realized that although the wind speed, and the water pumping rate, may become nil in some days, the total pumped water can be a significant amount in any period. It is observed in Fig. 12 and Table 3 that increasing the windmill size leads to a higher safe yield.

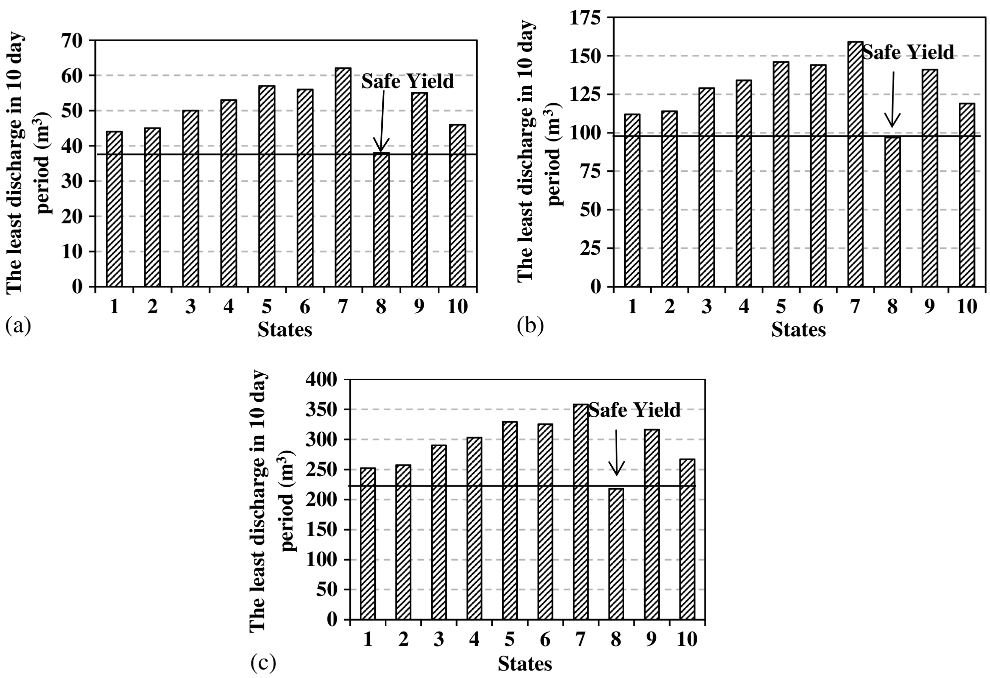

Fig. 12. Smallest discharge among different states (the safe yield for each 10 days) and the 10-day safe yield for (a) 2.44 m (8 ft); (b) 4.27 m (14 ft); (c) 6.10 m (20 ft) windmills

Table 4. 10-Day Safe Yield of Groundwater Considering Three Different Reservoir Sizes

Windmill (rotor diameter)	Safe yield in a 10 day period (m^3) Reservoir capacity = 300 m^3	Reservoir capacity = 3,000 m^3	Reservoir capacity = 30,000 m^3
2.44 m (8 ft)	173	359	722
4.27 m (14 ft)	289	632	1,828
610 m (20 ft)	438	1,131	2,781

Safe Yield Determination in 10-Day Periods (with Reservoir)

The objective of this study is to investigate the feasibility of pumping groundwater water using wind energy for agricultural consumption. According to the results of the previous scenario, the safe yield is equal to the least discharge among all 10-day period states, which is the eighth 10-day period state. In this scenario the pumped water in a 10-day period can be stored in a reservoir to supply the water demand in nonwindy days or in periods with high

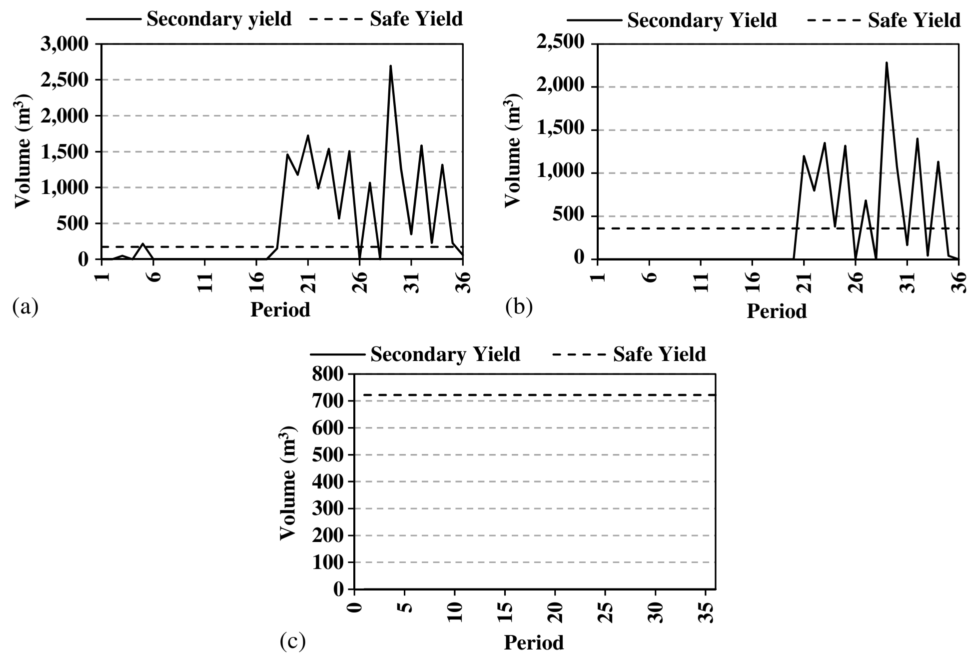

Fig. 13. 10-day safe yield and secondary yield considering a (a) 300; (b) 3,000; (c) 30,000 m^3 reservoir, using 2.44 m (8 ft) windmill

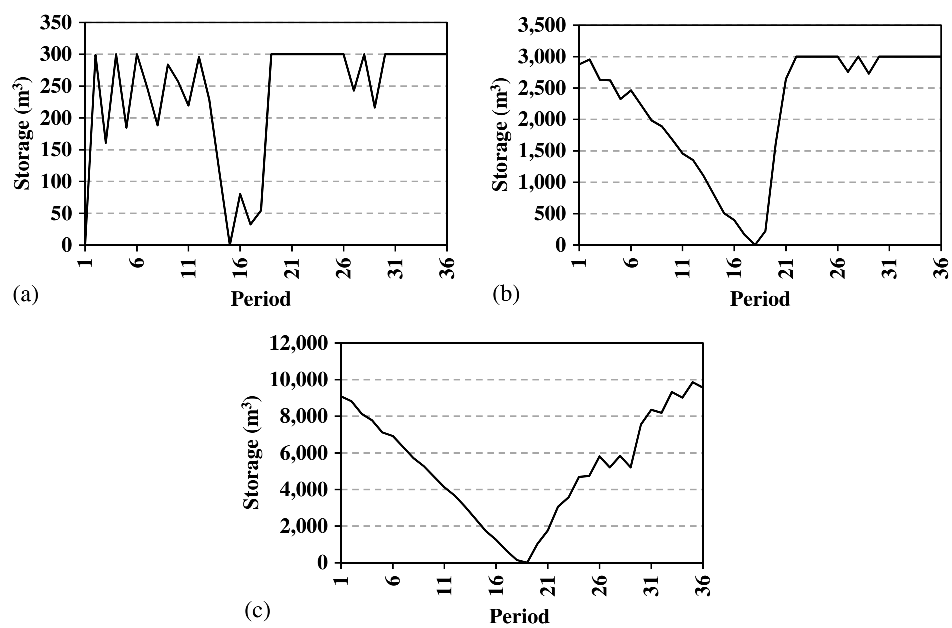

Fig. 14. 10-day water storage considering a (a) 300; (b) 3,000; (c) 30,000 m^3 reservoir, using 2.44 m (8 ft) windmill

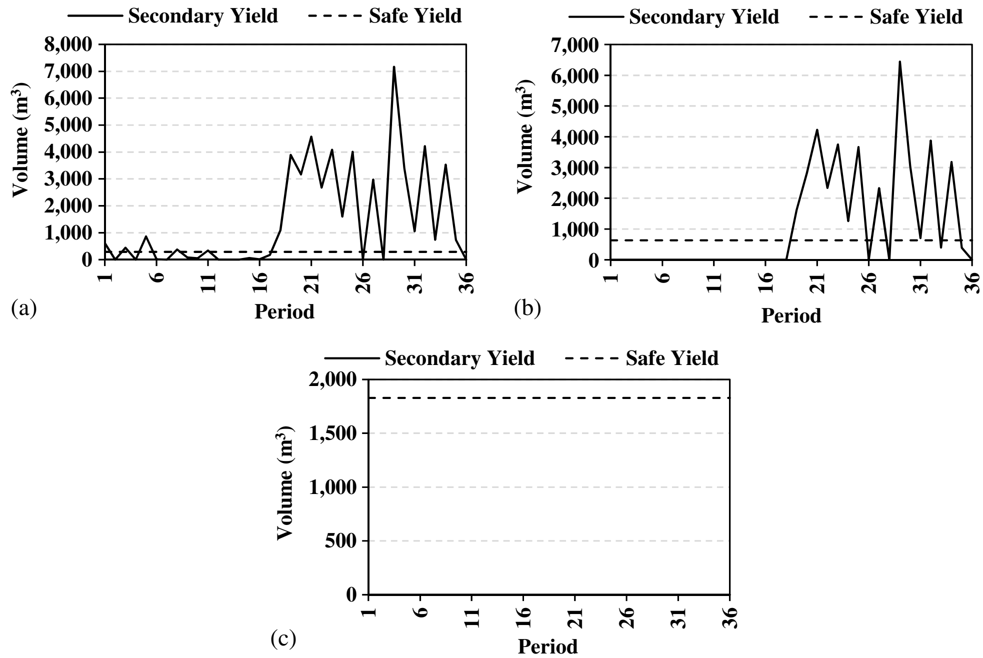

Fig. 15. 10-day safe yield and secondary yield considering a (a) 300; (b) 3,000; (c) 30,000 m^3 reservoir, using 4.27 m (14 ft) windmill

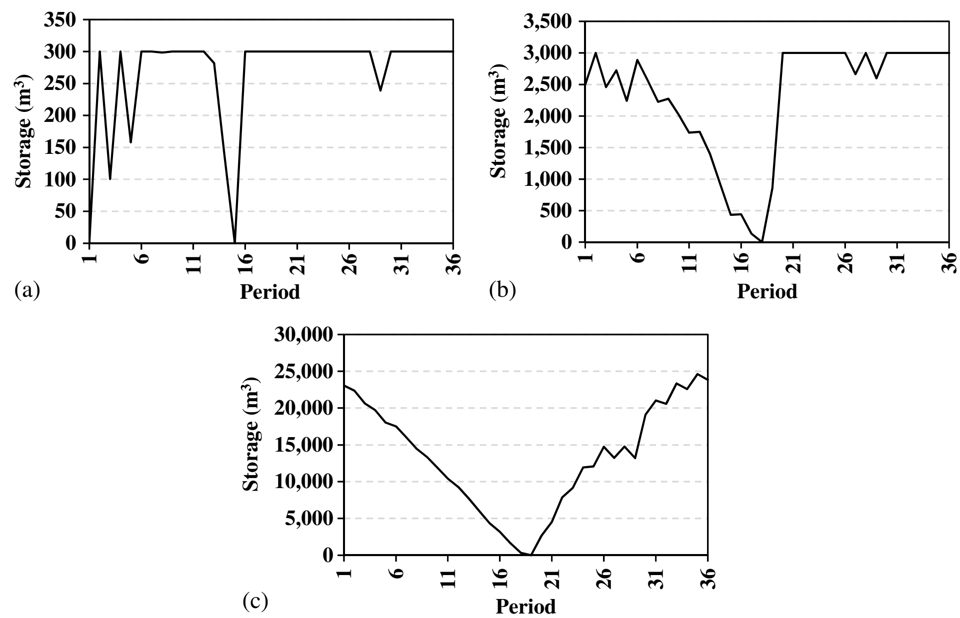

Fig. 16. 10-day water storage considering a (a) 300; (b) 3,000; (c) 30,000 m^3 reservoir, using 4.27 m (14 ft) windmill

water demand, or both. Also, during high wind speed and high pumping rate, water can be stored, or, if the reservoir capacity is exceeded, water can be diverted to nonagricultural functions if possible. Three reservoir capacities were considered under the 10-day scenario for the three windmill sizes. Results are shown in Table 4.

Comparing Tables 2 and 4 reveals that increasing the period length from 1 to 10 days increases the available water. It is clear that using larger reservoirs increases the safe yield.

Curves showing the water safe yield and secondary yield in this scenario are shown in Figs. 13–18.

According to Figs. 13–18, having a 30,000 m^3 reservoir for water storage to regulate storage over 10-day periods provides sufficient storage capacity for all windmill sizes except the 20-ft (9.10 m) windmill.

The optimal reservoir capacity could be deduced by introducing economic criteria involving the cost of groundwater extraction, the cost of reservoir construction, and the benefits from water use. This constitutes a topic for future research.

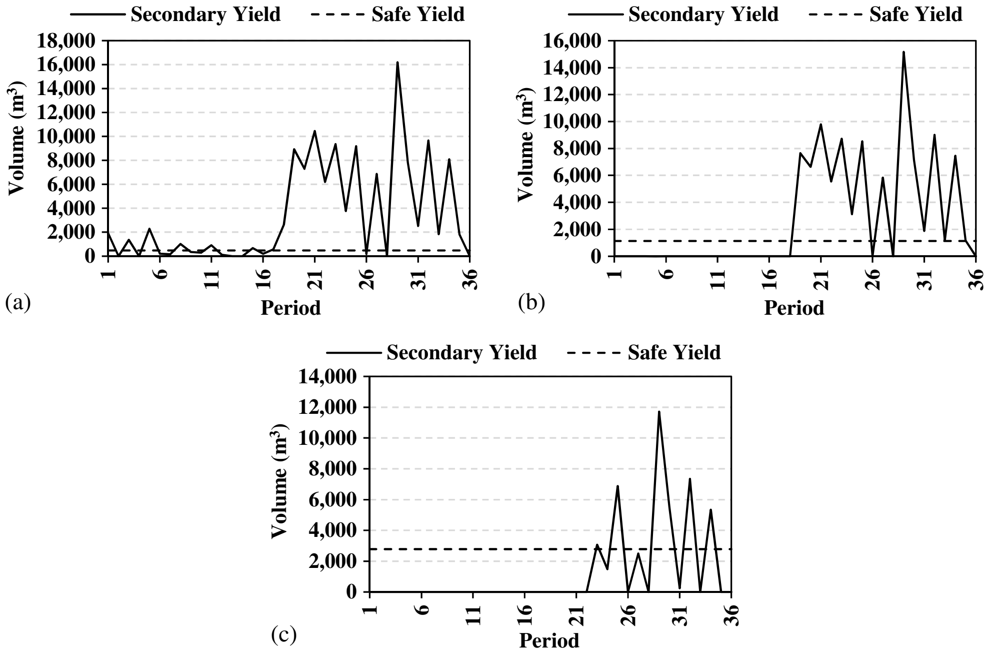

Fig. 17. 10-day safe yield and secondary yield considering a (a) 300; (b) 3,000; (c) 30,000 m^3 reservoir, using 6.10 m (20 ft) windmill

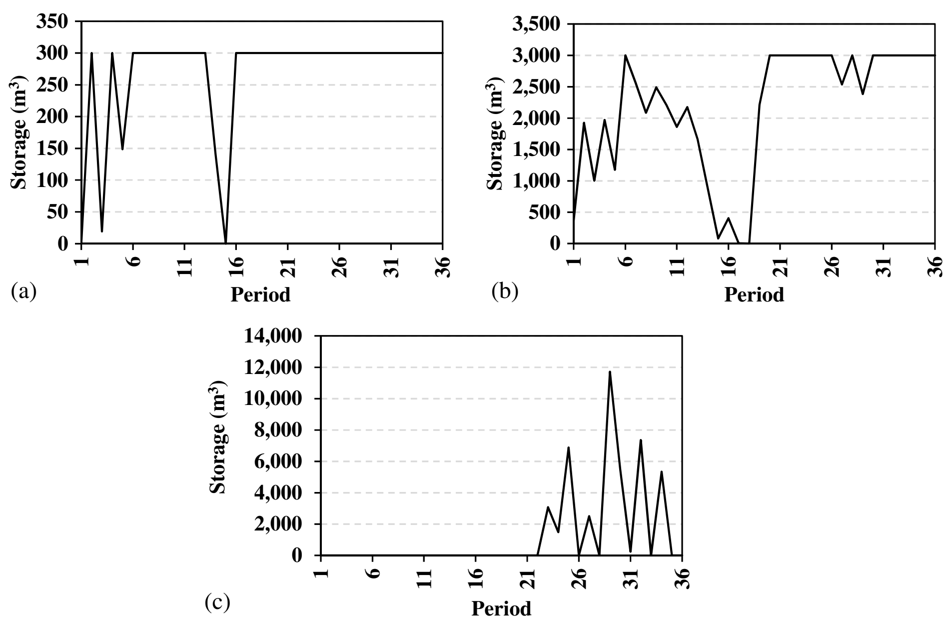

Fig. 18. 10-day water storage considering a (a) 300; (b) 3,000; (c) 30,000 m^3 reservoir, using 6.10 m (20 ft) windmill

Concluding Remark

The capacity of extracting groundwater with windmills was investigated in this work. The safe yield of groundwater production using windmills was calculated for different scenarios with and without a storage reservoir. For this purpose, two simulation and optimization models were developed and run using the *LINGO 11* software.

Our results have shown that, due to the high variability of wind speed, considering daily time intervals as planning horizons leads to zero safe yield. The reason for this finding is that the minimum wind speed is not enough for pumping groundwater with windmills in many days of the year. Consequently, increasing the length of the simulation period based on the project's objectives improves the water safe yield that can be achieved during the irrigation season. Since the average duration of irrigation in agriculture is 7 to 10 days in the study area, 10-day periods were considered in this research.

It was determined that including a reservoir to store pumped water during periods of high wind speed and using the water during appropriate times increases the safe yield of groundwater production significantly. Our results show that increasing the reservoir capacity would increase the safe yield for as long as there is sufficient groundwater to be stored in the reservoir.

References

Al Suleimani, Z., and Rao, N. R. (2000). "Wind-powered electric water-pumping system installed in a remote location." *Appl. Energy*, 65(1–4), 339–347.

Bakos, G. C. (2002). "Feasibility study of a hybrid wind/hydro power-system for low-cost electricity production." *Appl. Energy*, 72(3–4), 599–608.

Bekele, G., and Tadesse, G. (2012). "Feasibility study of small hydro/PV/wind hybrid system for off-grid rural electrification in Ethiopia." *Appl. Energy*, 97, 5–15.

Bozorg Haddad, O., Adams, B. J., and Mariño, M. A. (2008). "Optimum rehabilitation strategy of water distribution systems using the HBMO algorithm." *J. Water Supply Res. Technol. AQUA*, 57(5), 337–350.

Bozorg Haddad, O., Afshar, A., and Mariño, M. A. (2011a). "Multireservoir optimisation in discrete and continuous domains." *Proc. Inst. Civ. Eng. Water Manage.*, 164(2), 57–72.

Bozorg Haddad, O., and Mariño, M. A. (2011). "Optimum operation of wells in coastal aquifers." *Proc. Inst. Civ. Eng. Water Manage.*, 164(3), 135–146.

Bozorg Haddad, O., Mirmomeni, M., and Mariño, M. A. (2010a). "Optimal design of stepped spillways using the HBMO algorithm." *Civ. Eng. Environ. Syst.*, 27(1), 81–94.

Bozorg Haddad, O., Mirmomeni, M., Zarezadeh Mehrizi, M., and Mariño, M. A. (2010b). "Finding the shortest path with honey-bee mating optimization algorithm in project management problems with constrained/unconstrained resources." *Comput. Optim. Appl.*, 47(1), 97–128.

Bozorg Haddad, O., Moradi-Jalal, M., and Mariño, M. A. (2011b). "Design-operation optimisation of run-of-river power plants." *Proc. Inst. Civ. Eng. Water Manage.*, 164(9), 463–475.

Bozorg Haddad, O., Moradi-Jalal, M., Mirmomeni, M., Kholghi, M. K. H., and Mariño, M. A. (2009). "Optimal cultivation rules in multi-crop irrigation areas." *Irrig. Drain.*, 58(1), 38–49.

Buenoa, C., and Carta, J. A. (2006). "Wind powered pumped hydro storage systems, A means of increasing the penetration of renewable energy in the Canary islands." *Renewable Sustainable Energy Rev.*, 10(4), 312–340.

Fallah-Mehdipour, E., Bozorg Haddad, O., Beygi, S., and Mariño, M. A. (2011a). "Effect of utility function curvature of Young's bargaining method on the design of WDNs." *Water Resour. Manage.*, 25(9), 2197–2218.

Fallah-Mehdipour, E., Bozorg Haddad, O., and Mariño, M. A. (2011b). "MOPSO algorithm and its application in multipurpose multireservoir operations." *J. Hydroinf.*, 13(4), 794–811.

Fallah-Mehdipour, E., Bozorg Haddad, O., and Mariño, M. A. (2012a). "Real-time operation of reservoir system by genetic programming." *Water Resour. Manage.*, 26(14), 4091–4103.

Fallah-Mehdipour, E., Bozorg Haddad, O., and Mariño, M. A. (2013a). "Developing reservoir operational decision rule by genetic programming." *J. Hydroinf.*, 15(1), 103–119.

Fallah-Mehdipour, E., Bozorg Haddad, O., and Mariño, M. A. (2013b). "Extraction of multicrop planning rules in a reservoir system: Application of evolutionary algorithms." *J. Irrig. Drain. Eng.*, 10.1061/(ASCE)IR.1943-4774.0000572, 490–498.

Fallah-Mehdipour, E., Bozorg Haddad, O., Rezapour Tabari, M. M., and Mariño, M. A. (2012b). "Extraction of decision alternatives in construction management projects: Application and adaptation of NSGA-II and MOPSO." *Expert Syst. Appl.*, 39(3), 2794–2803.

Fars Agricultural Agency. (2014). http://www.fars.agri-jahad.ir/portal/home/ (Sep. 5, 2014).

Fars Water Organization. (2014). ⟨http://www.frrw.ir⟩ (Sep. 5, 2014).

Garcia-Gonzalez, J., Moraga, R., Matres, L., and Mateo, A. (2008). "Stochastic joint optimization of wind generation and pumped storage units in an electricity market." *IEEE Trans. Power Syst.*, 23(2), 460–468.

Intergovernmental Panel on Climate Change. (2014). *Climate change 2014: Mitigation of climate change*, Geneva.

Jain, P. (2011). *Wind energy engineering*, McGraw-Hill, New York.

Karimi-Hosseini, A., Bozorg Haddad, O., and Mariño, M. A. (2011). "Site selection of raingauges using entropy methodologies." *Proc. Inst. Civ. Eng. Water Manage.*, 164(7), 321–333.

LINGO 11 [Computer software]. Chicago, IL, Lindo Systems.

Loáiciga, H. A. (2011). "Challenges to phasing out fossil fuels as the major source of the world's energy." *Energy Environ.*, 22(6), 659–680.

Noory, H., Liaghat, A. M., Parsinejad, M., and Bozorg Haddad, O. (2012). "Optimizing irrigation water allocation and multicrop planning using discrete PSO algorithm." *J. Irrig. Drain. Eng.*, 10.1061/(ASCE)IR.1943-4774.0000426, 437–444.

Notton, G., Lazarov, V., and Stoyanov, L. (2011). "Analysis of pumped hydroelectric storage for a wind/pv system for grid integration." *Ecol. Eng. Environ. Prot.*, 1(8), 64–74.

Orouji, H., Bozorg Haddad, O., Fallah-Mehdipour, E., and Mariño, M. A. (2013). "Estimation of Muskingum parameter by meta-heuristic algorithms." *Proc. Inst. Civ. Eng. Water Manage.*, 166(6), 315–324.

Protopapas, K., and Papathanassiou, S. (2012). *Application of pumped storage to increase wind penetration in isolated island grids*, National Technical Univ. of Athens (NTUA), Greece.

Ramos, H. M., Kenov, K. N., and Vieira, F. (2011). "Environmentally friendly hybrid solutions to improve the energy and hydraulic." *Energy Sustainable Dev.*, 15(4), 436–442.

Seifollahi-Aghmiuni, S., Bozorg Haddad, O., Omid, M. H., and Mariño, M. A. (2011). "Long-term efficiency of water networks with demand uncertainty." *Proc. Inst. Civ. Eng. Water Manage.*, 164(3), 147–159.

Seifollahi-Aghmiuni, S., Bozorg Haddad, O., Omid, M. H., and Mariño, M. A. (2013). "Effects of pipe roughness uncertainty on water distribution network performance during its operational period." *Water Resour. Manage.*, 27(5), 1581–1599.

Shokri, A., Bozorg Haddad, O., and Mariño, M. A. (2013). "Algorithm for increasing the speed of evolutionary optimization and its accuracy in multi-objective problems." *Water Resour. Manage.*, 27(7), 2231–2249.

Sterrett, R. J. (2007). *Groundwater and wells*, 3rd Ed., Johnson Screens, New Brighton, MN.

Sun, X., Zhou, W., Huang, D., and Wu, G. (2011). "Preliminary study on the matching characteristics between wind wheel and pump in a wind-powered water pumping system." *J. Renewable Sustainable Energy*, 3(2), 023109.

Valdés, L. C., and Raniriharinosy, K. (2001). "Low technical wind pumping of high efficiency." *Renewable Energy*, 24(2), 275–301.

Vieira, F., and Ramos, H. M. (2008). "Hybrid solution and pump-storage optimization in water supply system efficiency: A case study." *Energy Policy*, 36(11), 4142–4148.

Vieira, F., and Ramos, H. M. (2009). "Optimization of operational planning for wind/hydro hybrid water supply systems." *Renewable Energy*, 34(3), 928–936.

J. Energy Eng., 2015, 141(4): 04014045