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New Approach For Prediction Groundwater Depletion

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A R T I C L E I N F O

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A B S T R A C T

Current approaches to quantify groundwater depletion involve water balance and satellite gravity. However, the water balance technique includes uncertain estimation of parameters such as evapotranspiration and runoff. The satellite method consumes time and effort. The work reported in this paper proposes using failure theory in a novel way to predict groundwater saturated thickness depletion. An important issue in the failure theory proposed is to determine the failure point (depletion case). The proposed technique uses depth of water as the net result of recharge/discharge processes in the aquifer to calculate remaining saturated thickness resulting from the applied pumping rates in an area to evaluate the groundwater depletion. Two parameters, the Weibull function and Bayes analysis were used to model and analyze collected data from 1962 to 2009. The proposed methodology was tested in a nonrenewable aquifer, with no recharge. Consequently, the continuous decline in water depth has been the main criterion used to estimate the depletion. The value of the proposed approach is to predict the probable effect of the current applied pumping rates on the saturated thickness based on the remaining saturated thickness data. The limitation of the suggested approach is that it assumes the applied management practices are constant during the prediction period. The study predicted that after 300 years there would be an 80% probability of the saturated aquifer which would be expected to be depleted. Lifetime or failure theory can give a simple alternative way to predict the remaining saturated thickness depletion with no time-consuming processes such as the sophisticated software required.

1. Introduction

1.1. Groundwater depletion

Groundwater depletion is the continuous reduction of groundwater storage volume when groundwater abstraction exceeds aquifer recharge so that in the long term the groundwater cannot sustain development activities. Groundwater depletion represents a great challenge, especially in nonrenewable aquifers such as the Nubian Sandstone aquifer in the Western Desert, Egypt. This aquifer suffers from continuous water level decline as a result of over-pumping during and after the development of El Kharga Oasis (Barber, 1977; Soliman, 2013). Initially, the wells in this region were flowing. However, after nearly 50 years of continuous pumping the head drop in some areas is estimated to be 60 m (Soliman, 2013). The average thickness of the aquifer in the Oasis is around 400 m (Ezzat, 1976,; Himida, 1968).

1.2. Quantifying groundwater depletion

Current approaches for quantification of groundwater depletion are based on the water balance method and volumetric approach such as the temporal gravity method to estimate dynamic storage. McGuire et al. (2003) used integrated measurements of changes in groundwater levels and storativity to estimate groundwater depletion. Kjelstrom (1995) used water balance and pumping tests. Faunt et al. (2009) used deterministic calibrated groundwater flow models to quantify groundwater depletion. David and Allen (2015) used a logistic equation to study changes in groundwater storage. Many researchers such as Rodell and Velicogna (2009) and Famiglietti et al. (2011) quantified groundwater depletion using gravity changes over time by a satellite technique. This work is concerned with exploring lifetime approaches in predicting saturated thickness depletion of the non-renewable aquifer.

1.3. Study site location

The El Kharga Oasis is located in the Western Desert of Egypt along the Nile Valley at longitude 30° 20′ and 30° 40′ east and

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latitude 25° 05′ and 25° 30′ north (CONOCO, 1987) (Fig. 1). This region is characterized by low rainfall estimated to be 2.35 mm/year.

1.4. Geology and hydrogeology

The groundwater aquifer in the study area consists of Nubian Sandstone deposits of Lower Cretaceous age (Fig. 2). The Nubian deposits consist of sandstone intercalated with discontinuous clay lenses (Hermina, 1967; Diab, 1978). The aquifer is underlain by Pre-Cambrian basement rocks and igneous rocks, (Shata, 1961). The thickness of the aquifer is limited in the south of El Kharga Oasis and attains its maximum thickness in the northern part where the average thickness is about 400 m (Himida, 1968). Intercalated discontinuous clay lenses in the Nubian sandstone form confining conditions in some parts of the aquifer and divide the aquifer into shallow and deep levels. However, regionally the whole aquifer could be considered as one hydrogeologic unit (Ezzat, 1974). Many hydrogeological studies (e.g. Thorweihe and Manfred, 2002) indicate that the groundwater in the Nubian aquifer is a nonrenewable resource. Hydraulic conductivity of the aquifer varies spatially and vertically according to clay content within the sandstone beds (Ezzat, 1976). The groundwater in this region was drawn from shallow wells before 1960. In early 1960, a heavy drilling program in the Western Desert was developed to exploit deeper aquifers to expand agricultural activities. Water abstraction approximated fifty million m^3/year from 270 shallow wells. After drilling deep wells, groundwater abstraction approached 117 million m^3/year from 190 deep wells. All wells initially were artesian wells. However, with unmanaged abstraction water depths increased continuously with

Fig. 2. Geological map of Nubian sandstone in the Western Desert (Egypt) and its extension to nearby countries.

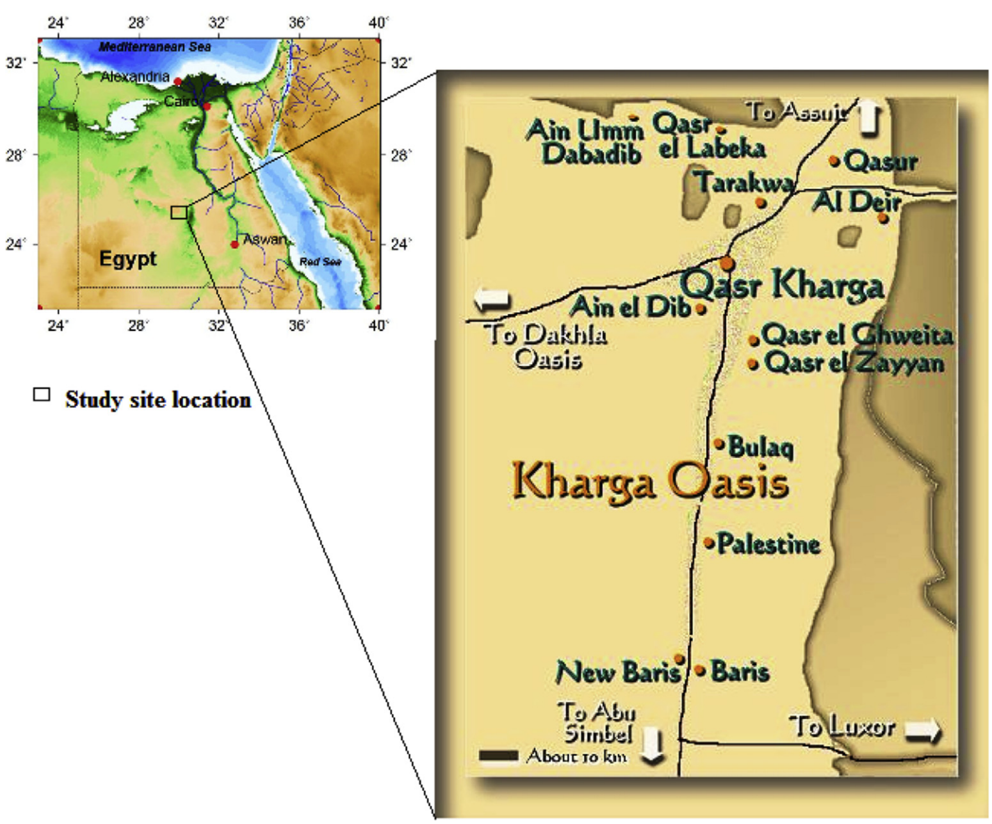

Fig. 1. Map showing the location of study area.

time.

2. Method

2.1. Lifetime approach (failure theory)

In the present study, lifetime or Survival approach is proposed to estimate the lifetime of the saturated thickness of the aquifer. Survival data analysis is used when it is desirable to study the time elapsed from some particular starting point to the occurrence of an event; this time is called *survival time* or *failure time* (Kalbfleisch and Prentice, 1980; Kececioglu, 1991). Survival analysis is used in many fields of study, e.g., time to relapse of cancer or duration of strikes in economics (Abernethy, 2000). Data that measure the length of time until the occurrence of an event are called lifetime and failure time data. Originally the event of interest was death, hence the term ‘survival analyses’. The analysis consisted of following the subject to death. Since time is a common measure of life, life data points are often called 'time to failure'. There are different types of life data:

- *Complete data*, the exact time-to-failure for the unit is known (e.g. the tested unit failed at x hours of operation).
- *Suspended or 'right' censored data*, the tested unit still works for an unknown period (e.g. the tested unit was still working during and after the test time).
- *Interval censored data*, the exact time-to-failure is unknown, but it falls within a known time range.

For example, the tested unit failed between x hours and y hours (interval censored). This technique of censoring enables researchers to analyze incomplete data due to delayed entry or withdrawal from the test (Mahesh and Machin, 1996). This type of analysis is widely used in reliability engineering studies. Reliability engineering assessment is based on the results of testing from laboratories and data pertaining to the performance results of the product in the field; the data produced by these sources are utilized to measure the reliability of the products being produced. In life data analysis, it is possible to make predictions about the life of the tested unit or product by fitting a statistical distribution function to collected data from a representative sample of the unit under study. The distribution function of the data set can then be used to estimate life characteristics of the product such as reliability or probability of failure at a specific time and the failure rate can be estimated. Life data analysis requires the following:

- Gather life data for the tested unit or object under study.
- Select a lifetime distribution (e.g. Weibull distribution function) that will fit the data.
- Model the failure time or life of the tested unit.
- Generate plots that estimate the life characteristics.

The method of analysis must take the censoring into account and use the censored observations as well as the uncensored observations. The percentiles of population that failed were calculated by the following equation:

$$X_p = \beta[\ln(1-p)]^{1/\eta} \tag{1}$$

where β and ή are scale and shape parameters respectively of the Weibull distribution function.

X is a variable.

p is the probability.

The survival probability function is the probability that a unit survives beyond time (t) and is calculated by

$$R(t) = 1 - f(t) \tag{2}$$

where f (t) is the probability distribution function of a given distribution, the hazard rate is defined as the probability per time unit that a case will fail in a given time interval. It provides a measure of the likelihood of failure as a function of how long a unit has lasted. The failure rate at a particular time (t) is calculated by:

$$h(t) = f(t)/1 - F(t) \tag{3}$$

where f(t) is the PDF (probability distribution function) of the Weibull distribution (Lawless, 1982)

$$f(t) = \beta \Big/ \eta (t/\eta)^{\beta-1} e^{-((t/\eta)\beta)} \tag{4}$$

β = shape parameter, η = scale parameter.

F (t) is the CDF of the given distribution.

$$\mathrm{CDF} = \mathrm{F(t)} = 1 - e^{-(t/\beta)\eta} \tag{5}$$

CDF (cumulative distribution function) is the probability that a random variable has a value less than or equal to x. The hazard rate was estimated according to the following equation (after Lawless, 1982):

$$\text{Failure rate} = \eta/\beta(t/\beta)^{\eta-1} \tag{6}$$

2.2. Main characteristic in applying lifetime approach

An important characteristic of this technique is to determine the failure point. Based on an estimated failure point the collected data classified to censored (failure not happened) or non-censored

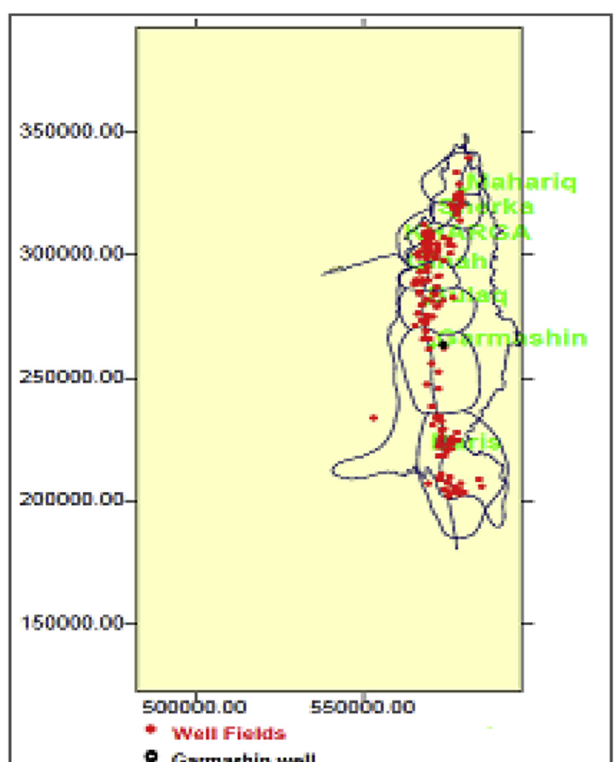

Fig. 3. Map showing the location of wells in Kharga Oasis, Western Desert, Egypt.

Table 1
Lifetime data used in the analysis (first and last column).

Monitoring time	Cumulative drawdown	Remaining saturated thickness	Right censor value (no failure till end of monitoring time)
1962	0.1	399.9	0
1963	0.2	399.8	0
1964	0.33	399.67	0
1965	0.4	399.6	0
1966	0.5	399.5	0
1967	0.6	399.4	0
1968	0.7	399.3	0
1969	0.8	399.2	0
1970	0.9	399.1	0
1971	1	399	0
1972	1.3	398.7	0
1973	1.2	398.8	0
1974	1.5	398.5	0
1975	1.7	398.3	0
1976	1.8	398.2	0
1977	1.9	398.1	0
1978	2.1	397.9	0
1979	2.5	397.5	0
1980	2.8	397.2	0
1981	2.9	397.1	0
1982	3.2	396.8	0
1983	3.5	396.5	0
1984	3.8	396.2	0
1985	4.1	395.9	0
1986	4.5	395.5	0
1987	4.72	395.28	0
1988	6.69	393.31	0
1989	8.44	391.56	0
1990	10.71	389.29	0
1991	12.17	387.83	0
1992	13.57	386.43	0
1993	14.5	385.5	0
2000	24	376	0
2001	26	374	0
2002	29	371	0
2003	34	366	0
2004	36	364	0
2005	40	360	0
2006	45	355	0
2007	50	350	0
2008	55	345	0
2009	60	340	0

(exact failure happened). This work explores parametric lifetime analysis to estimate the probable time for aquifer saturated thickness depletion based on the predefined failure or depletion point, using depth to water as a net result of recharge/discharge process.

2.3. Data needed for the proposed approach

The suggested approach uses depth of water as the net result of the discharge/recharge process in the aquifer. In this case study, the aquifer has no recharge (nonrenewable aquifer). According to lifetime analysis, the tested unit in this study is the saturated thickness of the groundwater aquifer. This tested unit (saturated thickness) is subjected to over-pumping with time. The important point in the lifetime analysis is to determine the failure point or event (when failure happens). In this work if the original saturated thickness (400 m) reaches 1/4 of its original value, it is considered a failure point or depletion event. In a lifetime approach if the tested unit, saturated thickness, has not dropped to 1/4 of its original saturated thickness by the end of test time (monitoring period) then in this case the saturated thickness value called right censored value (i.e. no failure happened until the end of monitoring period) and this value is coded (0) for statistical analysis. If the saturated thickness reaches down to ¼ of the initial value of the saturated thickness,

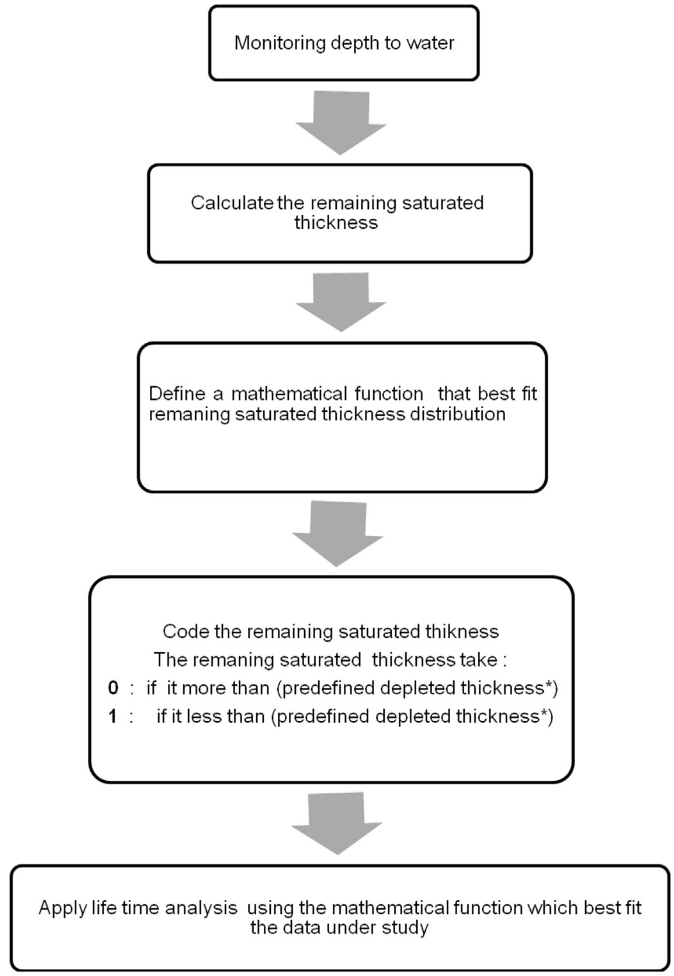

Fig. 4. Flow chart indicates the proposed approach.

then this case is called a failure event (depletion case) and the remaining saturated thickness value is coded (1) for statistical analysis.

Water depth data used in the analysis were collected from 1962 to 2009 in a monitoring well (Garmashin 3) in the Nubian Sandstone aquifer in the El Kharga Oasis region of the Western Desert of Egypt (Fig. 3). The remaining saturated thickness of the aquifer with monitoring time was calculated (Table 1). During the monitoring period, the remaining saturated thickness was coded (0) i.e. no depletion. The flow chart of the proposed methodology is indicated in (Fig. 4).

2.4. Prediction depletion of saturated thickness in the future

To predict the probability of depletion of the remaining aquifer thickness in the future beyond the monitoring period, different distribution functions (Fig. 5a and b) were used to determine the best fit function of the remaining saturated thickness shown in Table 1.

3. Results

Different mathematical distribution functions were fitted to the data collected to choose the best mathematical function that fits and represents the mathematical characteristics of the data collected (Fig. 5a and b). It was found that the two parameters of

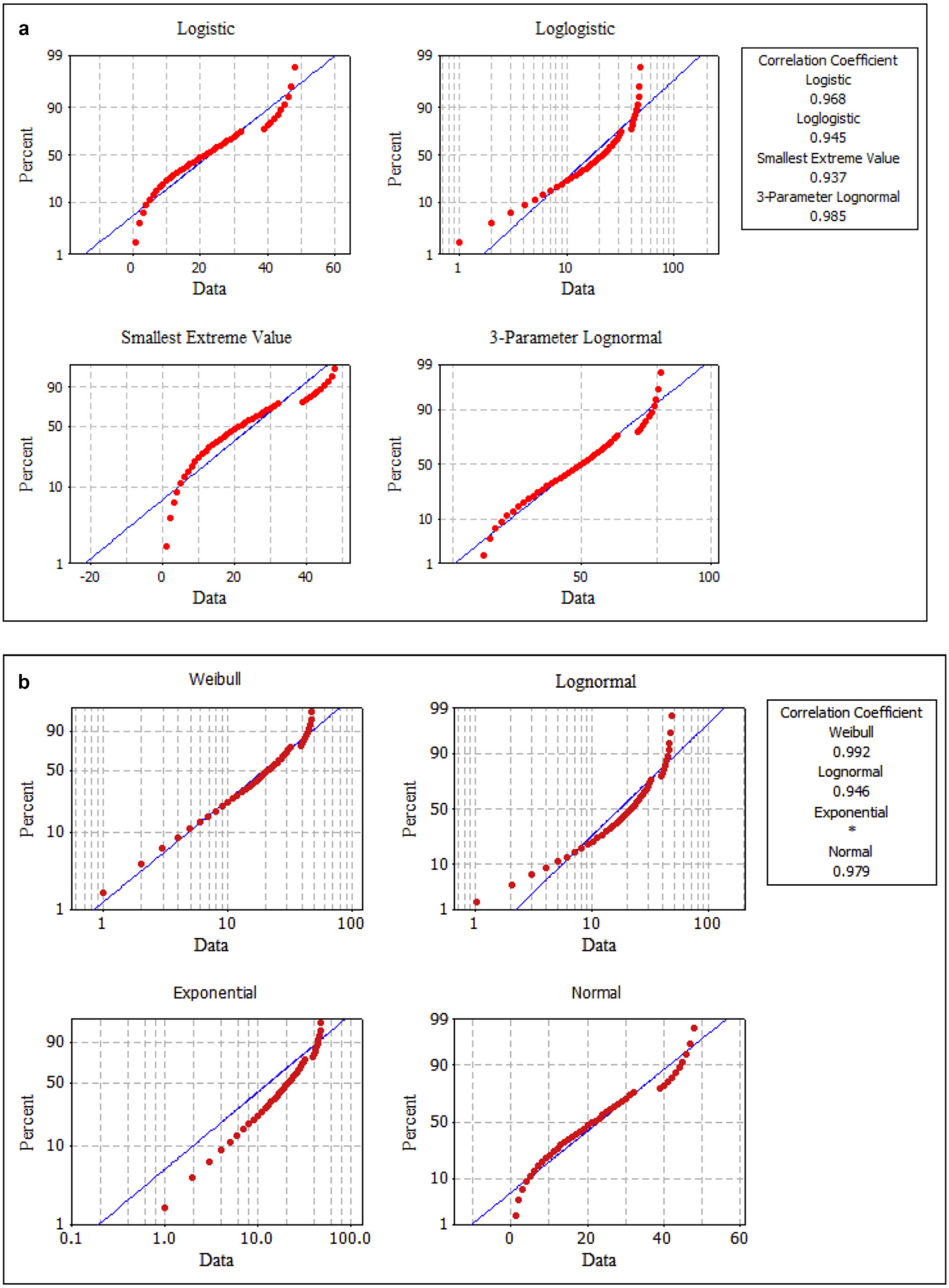

Fig. 5. a Plots of different Probability distribution functions of the test data. b Plots of different Probability distribution functions of the test data.

the Weibull function were the best fits for the data and it was chosen for analysis of the data for two reasons. Firstly, it best fits the data and this appears from the correlation coefficient values. The second reason is that the Weibull function can be used to analyze lifetime data with no failure events (Wayne, 1985). Although they have a high correlation coefficient with the data represented in Fig. 5a and b, the other functions cannot analyze data with no failure event as in this case study. These functions need at least one failure event during the test period (monitoring period) (Wayne, 1985).

Using the Weibull distribution function which best fits the collected data and maximum likelihood estimation method (MLE), the probable percentiles for the saturated thickness depletion and survival (no depletion) were predicted with lower or upper 95% confidence of the prediction (Figs. 6 and 7). Because no failure point is recorded (no depletion) the Bayes analysis is used to give the lower or upper 95% confidence of the prediction of depletion or survival, in the case of no depletion of the saturated thickness (Wayne, 1985).

3.1. Probability of saturated thickness depletion

The probability of failure is the probability of the saturated thickness depletion with time. The probability of the aquifer saturated thickness depletion (Fig. 6) suggests that after 300 years of the exploitation of deep aquifer, there is an 80% probability that the saturated aquifer will be depleted, with the probability that total saturated thickness will be depleted after 400 years since the start of abstraction in 1962.

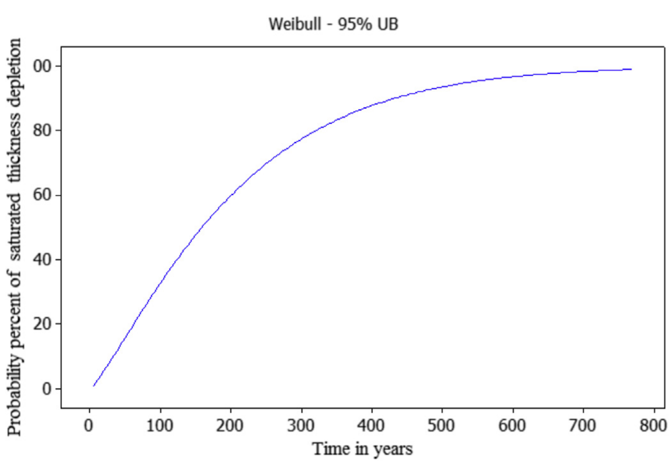

Fig. 6. Probability percent of saturated thickness depletion with time (95% upper confidence (UB).

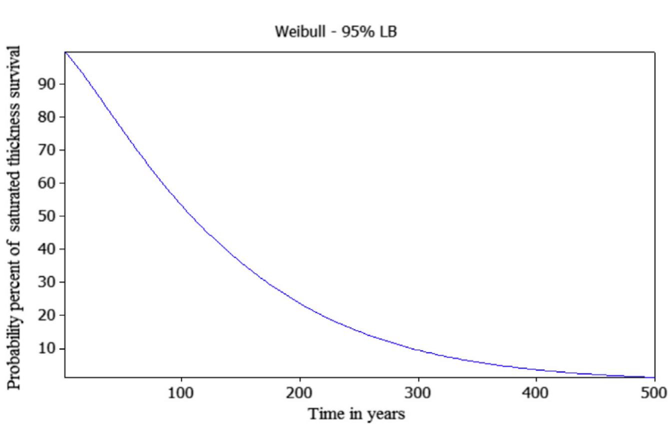

Fig. 7. Probability of survival of aquifer saturated thickness with time.

3.2. Probability of survival (no depletion)

The probability of saturated thickness survival, that is the case of no depletion with time is shown in Fig. 7 which represents the proportion of saturated thickness that survives and has not reached the failure point (i.e. the saturated thickness has value of more than 1/4 of its original saturated thickness). The obtained survival probability of the saturated thickness shown in (Fig. 7) suggests that only 25% of the saturated thickness will remain saturated after 300 years of continuous abstraction since 1962.

4. Discussion

The results are expected since the pumping in this area is increasing continuously due to the expansion of cultivated lands. Increasing the depth of water as a result of excessive pumping suggests a cumulative decrease in the remaining saturated thickness with time. The Predefined depletion thickness is determined by the expert in the field according to the total saturated thickness of the aquifer under study. The predicted results could be changed by reducing the pumping rate and consequently the resulting water depth. Moreover, with changing the two parameters of the Weibull distribution function to best fit the remaining saturated thickness, the failure percentage (depletion) of the remaining saturated thickness will change according to Equation (1). The predicted 80% depletion of saturated thickness is predicted with right censored data (no depletion happened, the saturated thickness of the aquifer has not reached to the predefined depletion saturated thickness). This is one of the advantages of the Weibull functions in failure theory, where it can model the data under study even where there is no failure (complete or predefined level of depletion). The depletion prediction using failure theory is based on real measured values of drawdown as a direct result of pumping rates in the area from 1962 till 2009, which is reflected in the remaining saturated thickness. The predicted depletion using this approach is based on the assumption that pumping policy or rates in the area are constant during prediction time. In addition, the suggested lifetime approach assumes no climate change so there is no major rainfall recharge to the aquifer, which affects the resulting depth to water and consequently the remaining saturated thickness. The failure theory approach could be used to examine the probable effect of currently applied management practices on the remaining saturated thickness in the future. This approach may be somewhat like the flow model (McDonald and Harbaugh, 1988) used in predicting the effect of the groundwater aquifer management strategy on the water depth of an area. Barber (1977) used flow model software to predict ground water depth in the current study area. The predicted water depth was around 80 m in the year 2050 (nearly 90 years after 1962, the year of initial abstraction) at this site (Garmashin 3). It means 320 m of the saturated thickness still remains which is about 75–80% of the original saturated thickness is still undepleted. This agrees with the predicted survival saturated thickness (not depleted) (Fig. 7) determined in this work. Both techniques, flow model and failure theory need water depth history for the system under study, and both can predict the depletion at local (well) and regional scales (whole aquifer). However, the suggested failure theory does not require a lot of data and is not as time consuming as the flow model approach. As noted above, the proposed failure theory can predict depletion at a local scale (well) or the whole aquifer as one pumping unit. However, predicting depletion at the locale scale (well) which services the surrounding area may be more appropriate than a regional scale due to differences in aquifer hydraulic properties and different land uses which are reflected in the abstraction rate from the well and the resulting drawdown.

5. Conclusion

The proposed failure theory described in this paper is a promising as technique for predicting depletion of saturated thickness even where no depletion data are available or has occurred during the monitoring period (test period). The Weibull distribution function used in this approach has the capability to best fit the data better by changing its parameters. The predefined failure point (predefined depletion thickness) is a vital point in lifetime approach results. The proposed approach could be promising in prediction in different aspects of hydrology field if it received more studies and applications.

References

Abernethy, R.B., 2000. Reliability and Statistical Analysis for Predicting Life, Safety, Survivability, Risk and Warning Claims (North Palm Beach).

Barber, W., 1977. Groundwater Pilot Scheme, New Valley. Egypt. Report for the Government of Egypt, a United Nation Development Program. Food and agriculture organization of the united nation.

Continental Oil Company (CONOCO), 1987. Geological Map of Egypt (Scale 1: 500,000).

David, R.S., Allen, A.J., 2015. Peak groundwater depletion in the high plains aquifer, projections from 1930 to 2110. Agric. Water Manag. http://dx.doi.org/10.1016/j.agwat.2015.10.003 (in press).

Diab, M. Sh, 1978. A Regional Hydrogeological Study of Artesian Water Aquifer in the Western Desert of Egypt: Symposium on the Geology of Middle East. Ankara, Turkey.

Ezzat, A., 1976. Exploitation of Groundwater in El Wadi-el Gedid Project Area, Part IV. Ministry of Desert irrigation.

Ezzat, M.A., 1974. Groundwater Series in the Arab Republic of Egypt Exploitation of Groundwater in El-wadi El-gedid Project Area: General Desert Development Authority. Ministry of Irrigation, Cairo, p. 149.

Famiglietti, J.S., et al., 2011. Satellites measure recent rates of groundwater depletion in California's central valley. Geophys. Res. Lett. 38, L03403. http://dx.doi.org/10.1029/2010GL046442.

Faunt, C.C., et al., 2009. Numerical model of the hydrologic landscape and groundwater flow in California's central valley. In: Faunt, C.C. (Ed.), Groundwater Availability of the Central Valley Aquifer, California, vol. 1766. U.S. Geol. Surv. Prof. Pap, pp. 121–212.

Hermina, M.H., 1967. Geology of the North-Western Approach of Kharga, Egyptian: Geol. Survey, Cairo, p. 88. Paper No. 44.

Himida, I.H., 1968. A Quantitative Study of the Artesian Water Exploitation Resources in Kharga and Dakhla Oases. In: Western Desert of Egypt.

Kalbfleisch, J.D., Prentice, R.L., 1980. The Statistical Analysis of Failure Time Data.

Kececioglu, D., 1991. Reliability Engineering Handbook, vol. 1. Prentice Hall, Inc., Englewood Cliffs, New Jersey.

Kjelstrom, L.C., 1995. Stream flow gains and losses in the Snake river and groundwater budgets for the Snake river plain, Idaho and eastern Oregon, U.S. Geol. Surv. Prof. Pap. 1408C, 47.

Lawless, J.F., 1982. Statistical Models and Methods for Lifetime Data. John Wiley & Sons, New York.

Mahesh, K.B., Machin, D., 1996. Survival Analysis: A Practical Approach. John Wiley and Sons.

McDonald, M.G., Harbaugh, A.W., 1988. A Modular Three-Dimensional Finite-Difference Ground-Water Flow Model (Chapter 6)–A1. USGS TWRI, p. 586.

McGuire, V.L., et al., 2003. Water in storage and approaches to groundwater management, high plains aquifer, 2000, U.S. Geol. Surv. Circ. 1243, 51.

Rodell, M., Velicogna, I.J.S., 2009. Satellite based estimates of groundwater depletion in India. Nature 460, 999–1002. http://dx.doi.org/10.1038/nature 08238.

Shata, A., 1961. Remarks on the geological structure of the groundwater reservoir at El-Kharga and Dakhla Oases (western desert of Egypt). Bull. Soc. Geogr. Egypt 34, 165.

Soliman, S., 2013. Mitigation of excessive drawdowns via rotational groundwater withdrawal (case study: El Kharga Oases, Egypt). N. Y. Sci. J 6 (1).

Thorweihe, U., Manfred, H., 2002. Groundwater Resources of the Nubian Aquifer System NE Africa (Report for Technical University of Berlin).

Wayne, N., 1985. Weibull analysis of reliability data with few or no failures. J. Qual. Tech. 17.