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Trends in groundwater observation data and implications

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ABSTRACT

The Batinah plain in the North of the Sultanate of Oman is undergoing several severe changes. Growing population, accompanied by urbanization and industrial activities conflict with the traditional agricultural imprint. The development stresses the regional water resources. The vast aquifer, located between the Hajar mountain chain and the Oman Sea, is exploited by increased withdrawal for domestic, agricultural and industrial purposes. Especially in the highly populated coastal region, the reduced pressure due to the decreasing groundwater table leads to enlarged saltwater intrusion from the seaside. We explore time series of water table and salinity from 29 wells in Maawil catchment, South Batinah, some of them recorded for more than 30 years. Typical patterns in the measured data reflect the profound changes of the aquifer, related to saltwater intrusion, extreme rainfall events and dam construction. The analysis confirms the effectiveness of recharge dams for harvesting flash floods and implies the importance of integral management of groundwater resources. The exemplary case study shows trends that can generally be observed in stressed coastal aquifers.

Keywords: Groundwater observation; Seawater intrusion; Time series; South Batinah

1. Introduction

According to the National Centre for Statistics & Information in Oman, the total cultivated area in the Sultanate increased by 2.6% in 2016 when compared with the previous year 2015. During the last 10 years, the cultivated area has been increased by 33% from 150 thousand acres in 2007 to 202 thousand acres in 2016. The annual population growth rate in 2016 increased to 5.9% compared with 4.1% in 2015 basically due to high growth rate of expatriates (NCSI, 2017). The number of water wells used by the Public Authority for Electricity and Water for residential use is 203 wells in North and South Batinah, aside from the wells dedicated for agricultural purposes (PAEW, 2016). This development stresses the water resources especially in the Batinah plain, the most populated area in Oman (Abdallah et al., 2017).

Even though rainfall in the Sultanate of Oman is highly variable, irregular and diversified, 46 recharge dams have been constructed in Oman, eight of them are on Batinah plain, as per 2017 (Kwarteng et al., 2009; MRMWR, 2015; Almanthari, Y., personal communication, October 22, 2018; Fig. 1).

2. Geology of Batinah plain

The Alluvium deposits in Batinah plain were originated from the erosion of Hajar mountain. This mountain is composed of highly fractured siltstone, sandstone and limestone formations, as well as shallow marine carbonate and thin layers of sandstone. The alluvium deposits thickness increased gradually from the mountains foot in the south, and increased gradually towards the coastline (Young et al., 1998).

Two major clastic deposits are distinguished in Batinah plain of late Tertiary – recent age; ancient alluvium, sub-recent/recent alluvium. They are unconformably underlined by consolidated bed rock dipping north and basically composed of tertiary carbonates and marl. Clay and cemented layer might cover the carbonate bedrock as a result of erosion. This clay layer should act as an aquitard. Allochthonous

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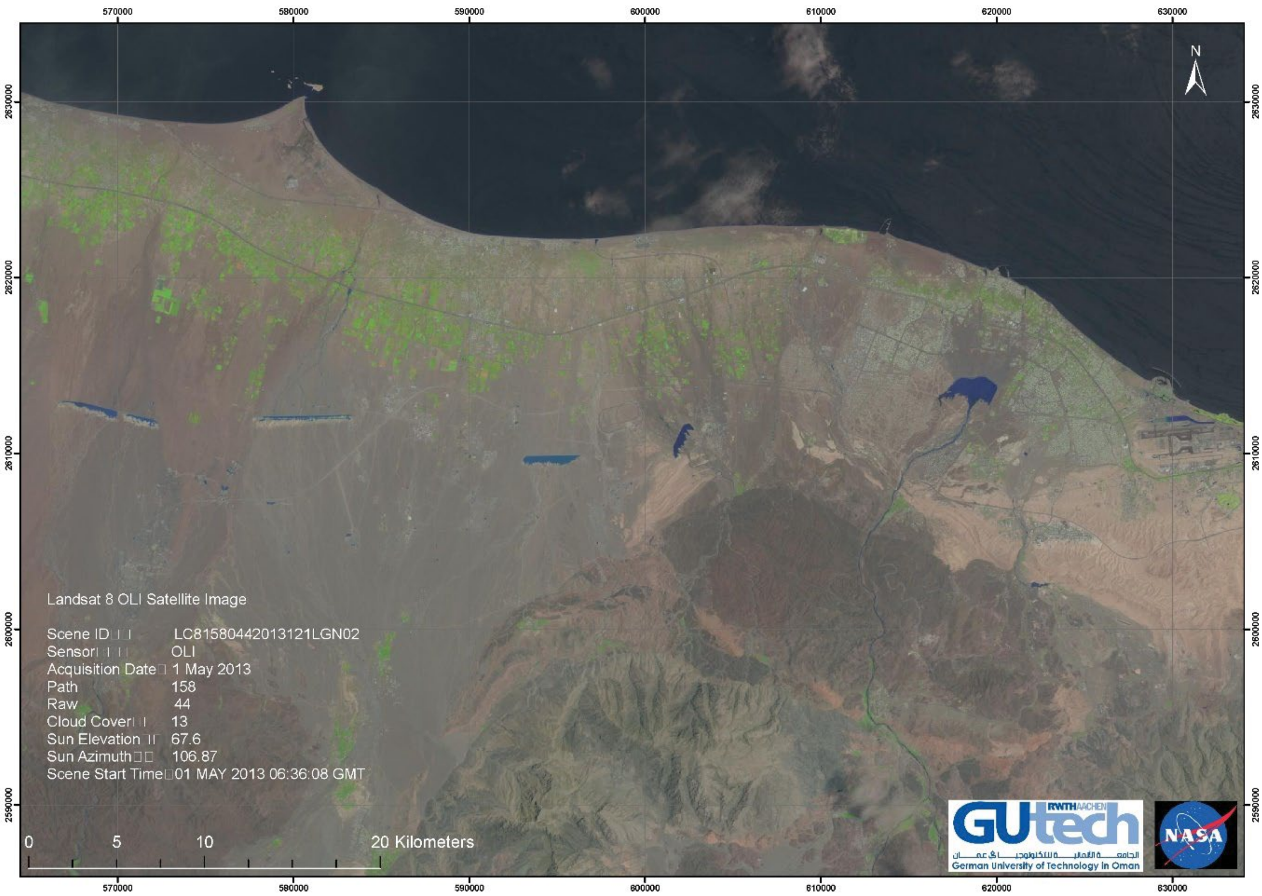

Fig. 1. Recharge dam in South Batinah, Oman. Landsat 8 OLI satellite image acquired 1 May 2013.

Samail Ophiolite is underlining the tertiary (Chitrakar and Sana, 2015).

Major lithology of quaternary deposits is heterogenic. Clastics with grain size ranging from boulders to silt includes khabra deposits. These are the finest-grained materials accumulated in a vast khabra extending parallel to the coast on the northern side of the Batinah plain. Dune and sand sheets are the best outcrops supporting rainfall infiltration (Bechennec et al., 1986). Anyway, it is not clear if such infiltrated water is recharging the aquifer or not, because of the anisotropy of the unsaturated hydraulic conductivity in vertical and horizontal directions in sand dunes (Hendricks et al., 2003).

3. Hydrogeology of Al Batinah

The estimated hydraulic conductivity of the ancient alluvium ranges between 0.2 and 5 m/d while the sub-recent and recent alluvium show values between 5 and 30 m/d (Chitrakar and Sana, 2015). As an alluvium sediment, clay and silt lenses are sparsely distributed within the Quaternary deposits. These lenses might have restricted horizontal expansion and do support the perched aquifers (Hadidi, 2016).

It is only a small percentage of the rainfall events that take place near the coast (Seeb airport 80 mm/year), while most of the events occur over Northern Oman mountains (330 mm/year) (Kwarteng et al., 2009; Ahmed and Askri, 2016). Due to rapid development associated with increased ground water consumption, sea water intrusion affected wide area next to the Batinah coast (Figs. 2 and 3; Ahmed and Askri, 2016; Al-Awadhi and Mansour, 2015).

4. Methodology

Our data-set consists of water table measurements in 29 water wells in Maawil catchment over the last few decades (Table 1; Fig. 4). The time series was analyzed using the programming language R, a well-established free software environment for statistical computing.

For each time series, the pre-analysis process began with importing the database into R and transforming the original database into a data frame consisting of time and piezometric variables. Then a Tibble object was created that was useful for analysis through the "anomalize" package of R (Dancho and Vaughan, 2018).

After this, the time series data are decomposed into observed, seasonal, trend and remainder components with the anomalize package. Once the components are decomposed, anomalize can detect and flag anomalies in the decomposed data of the reminder component which then are visualized. The method was chosen in order to identify extreme events.

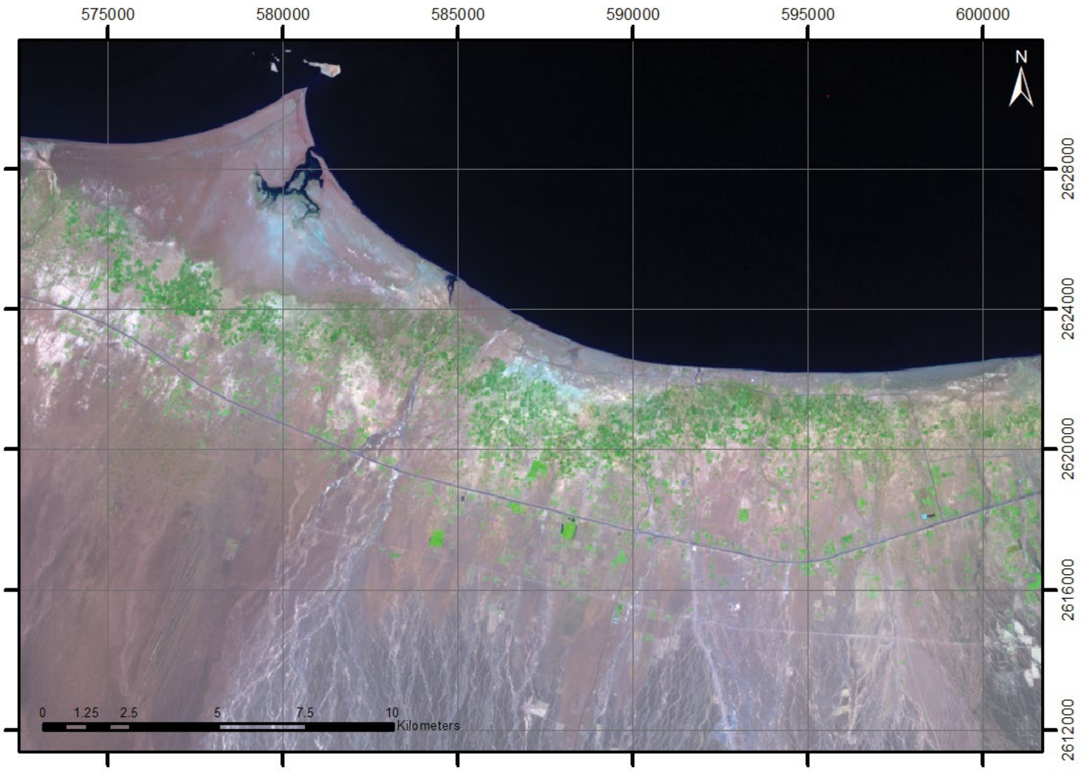

Fig. 2. Landsat satellite imagery for South Al Batinah plain, 23.05.1986.

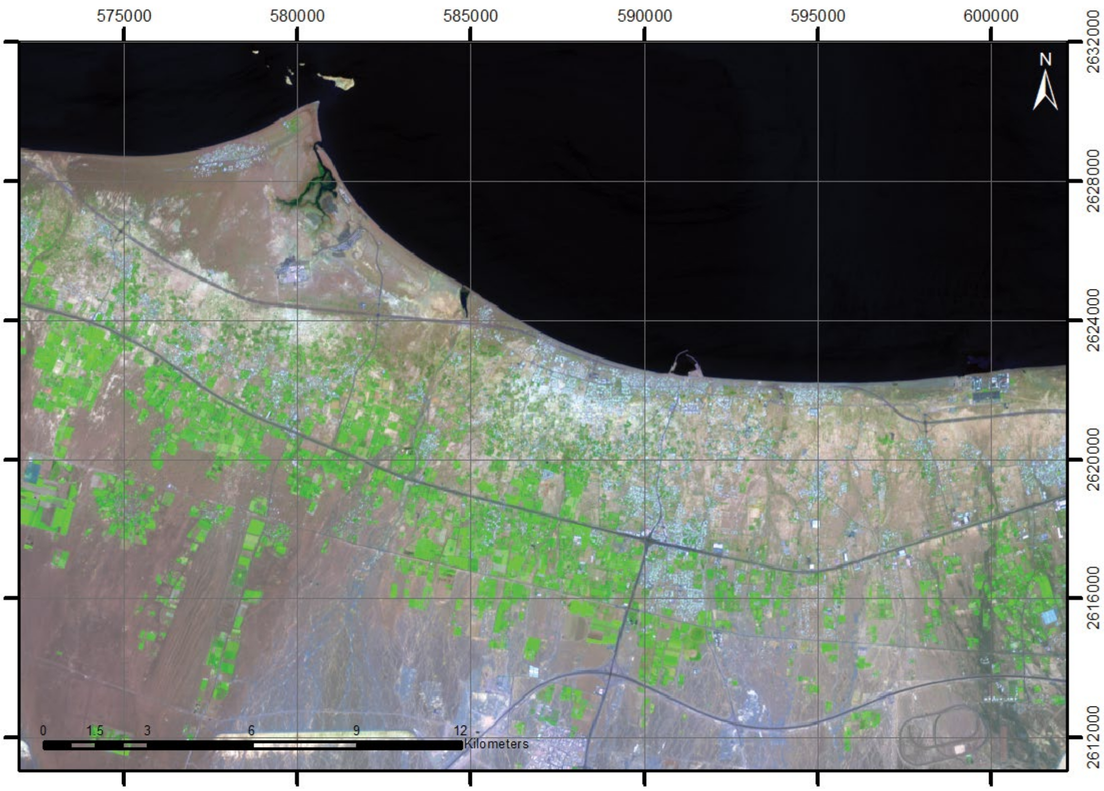

Fig. 3. Landsat satellite imagery for South Al Batinah plain, 10.04.2017.

Table 1
List of the wells and basic data

Well	Start observation		Start w.t.[a] (m)	End observation		End w.t.[a] (m)	Date to fall below NN	Number of outliers
	Month	Year		Month	Year			
21-2D	03	1993	78.71	10	2016	82.52	–	24
21-3D	04	1993	59.96	10	2016	66.76	24/09/2005	5
ADG17	07	1973	15.95	02	2018	24.54	14/04/1984	3
ADG23	05	1973	13.21	01	2015	25.98	21/01/1984	4
ADW7	01	1976	26.33	03	2018	34.14	04/10/1986	2
BM1	01	1984	4.64	02	2018	9.47	b.o.[b]	13
BM3	04	1984	22.56	03	2018	33.93	07/06/1992	5
DW4	12	1975	12.63	02	2018	25.36	29/06/1987	2
JT5	06	1973	51.05	03	2018	59.88	07/06/1992	9
JT10	04	1973	42.14	03	2018	54.71	16/09/2002	10
JT70	02	1974	2.66	08	2013	9.66	19/06/1982	33
MD1	02	1989	23.88	03	2018	33.80	b.o.[b]	0
MD2	02	1989	28.28	03	2018	39.23	24/10/1992	3
MD3D	02	1989	59.36	01	2018	68.56	25/02/2001	6
MD3S	02	1989	59.29	01	2018	68.60	25/02/2001	11
MD4	02	1989	28.27	03	2018	39.24	15/11/1992	3
MD5	02	1989	59.09	01	2018	68.39	31/03/2001	9
MD6	04	1991	53.24	01	2018	62.66	28/02/1994	3
MD7	10	1991	53.84	01	2018	64.20	29/10/2001	2
MD8	12	1991	33.44	03	2018	42.88	17/01/1993	7
MD10	01	1996	15.55	02	2018	19.36	b.o.[b]	0
MD11	12	1993	19.39	02	2018	27.41	b.o.[b]	3
MD12	04	1996	12.01	02	2018	17.18	b.o.[b]	0
MD13	04	1996	25.37	03	2018	34.32	10/1999[c]	5
NC5	06	1984	15.73	02	2018	23.11	23/04/1986	3
NC6	06	1984	15.18	02	2018	27.20	04/09/1988	5
RE3P	10	1989	87.43	01	2018	95.52	28/10/2002	2
RE4	06	1985	44.40	03	2018	53.53	12/07/1993	7
RE4P	10	1989	45.88	03	2018	53.76	13/06/1993	13

[a]Water table below the ground surface.
[b]Before the starting of observations.
[c]Estimated date.

A time series $Y(t)$ is simply the chronological record of experimental observations of a variable. From this series of data, we want to extract information for the characterization of a given phenomenon under observation. One of the fundamental purposes of the classical analysis of the time series is to break down the series into its components, isolating them in order to study them better. The components of a time series are usually the following: trend, seasonality, error or residual. They can be linked together in an additive way:

$$Y(t) = T(t) + S(t) + E(t) \tag{1}$$

or multiplicative,

$$Y(t) = T(t) \times S(t) \times E(t) \tag{2}$$

The simplest approach to classical decomposition is based on the model:

$$Y(t) = f(t) + E(t) \tag{3}$$

where $f(t)$ is a time function that describes trends and seasonality in a simple way.

In particular, in the case of an additive type model, as in our case:

$$Y(t) = T(t) + S(t) + E(t) \tag{4}$$

where $E(t)$ is independent and identically distributed variables IID (the errors are normally distributed with average zero, constant variance and independent).

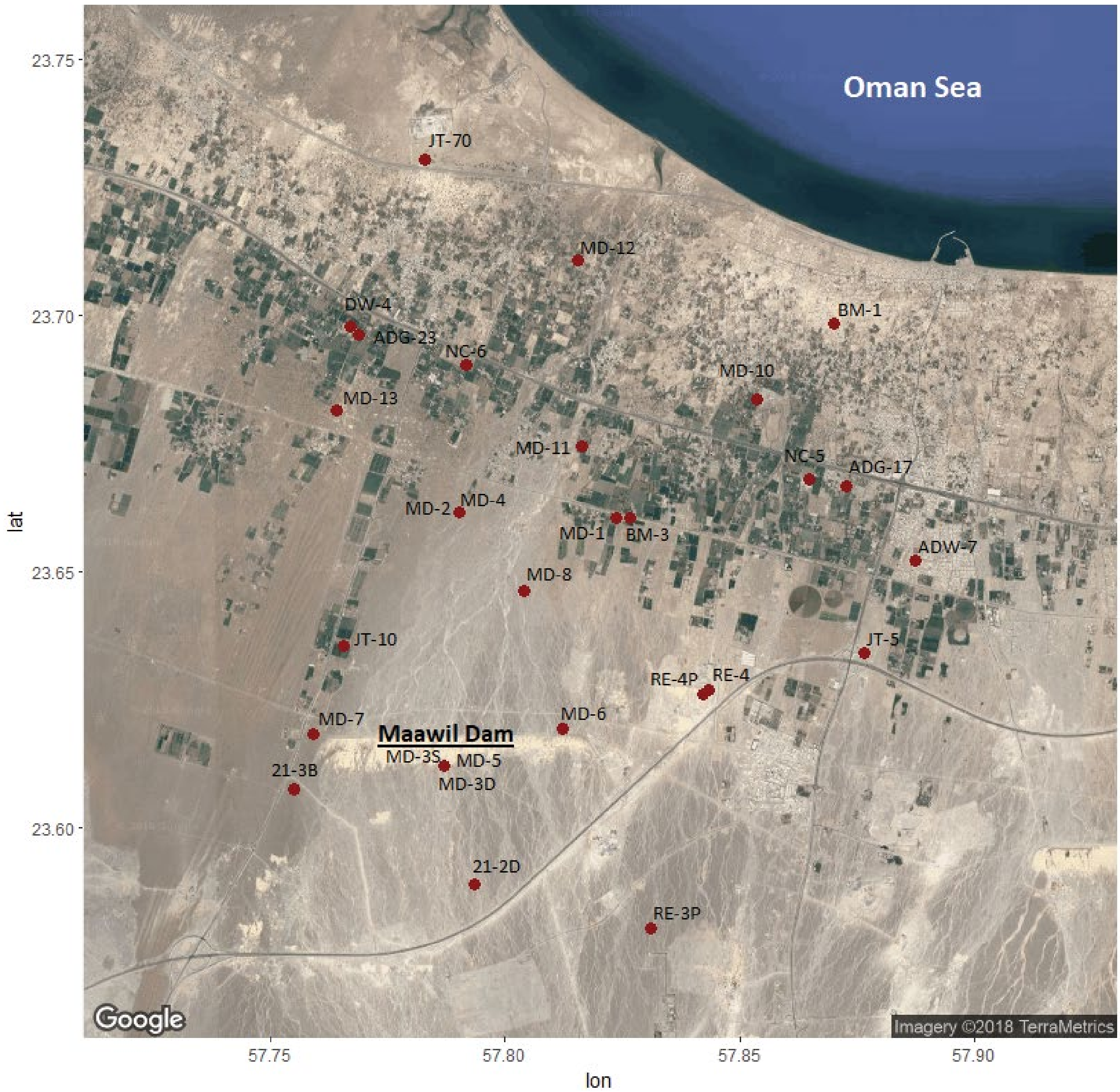

Fig. 4. Overview with observation wells location and Maawil recharge dam.

With R software, it is possible to determine and to extract the three components.

The function STL ("Seasonal decomposition of Time series by Loess") of R uses the method "loess" (local polynomial regression fitting) for the decomposition and applies locally weighted polynomial regressions at each point in the data set (Cleaveland, 1990).

The explanatory variables being the values closest to the point whose response are being estimated. Performs local regression over a sub set of data and repeats the process for the rest of the dataset.

The STL decomposition procedure was chosen because it has important advantages for extensive applications to a large number of time series.

The decomposition separates the "season" and "trend" components from the "observed" values leaving the "remainder" for anomaly detection. Using anomalize, the "IQR" method was chosen for anomaly detection. Anomalies are detected by using the inner quartile range (IQR) method. The IQR takes a distribution and uses the 25% and 75% IQR to establish the distribution of the remainder. Limits are set by default to a factor of 3X above and below the IQR, and any remainders beyond the limits are considered anomalies. The bandwidth control parameter alpha adjusts the 3X factor. Alpha was used with its default value of 0.05. The maximum number of anomalies was set to 20% of the sample.

At the end, the frequency parameter adjusts the "season" component that is removed from the "observed" values, and the trend parameter adjusts the trend window. Both are set in "auto", which predetermines the frequency and/or trend based on the scale of the time series. In the figures below, anomalies are highlighted by red colour.

5. Results

The time-series of groundwater tables of the observation wells owned of the Ministry of Regional Municipality and Water Resources in the downstream watershed of Wadi Maawil shows different characteristics over time. These trends can be classified into six different groups:

5.1. Group 1

JT-5, RE-3P and ADW-7 wells share the fact that they show gradual increase in water table between 1996 and 1998 by 2 m, while the general trend is decreasing (Fig. 5).

5.2. Group 2

This group of wells is located near Maawil dam and share the fact that they have a sudden change in water table during 2007. This group can be subdivided into two subgroups where the trends are more comparable: Group 2/A includes (MD-6 and MD-7), and Group 2/B includes (MD-3D, JT-10, MD-5 and MD3S; Fig. 6).

5.3. Group 3

It consists of ADG-17, NC-5, RE-4P and RE4 wells. They all have in common that their water tables slightly increase between 1996 and 1998, and they show a sudden change in water table (outlier) in 2007 (Fig. 7).

5.4. Group 4

The general trend of this group is the linear decrease in water table over the last three decades and there is no sudden change in trend and there are no outliers. It also can be subdivided into two groups were the trend is more compatible: Group 4/A includes (MD-12 and MD-10), and Group 4/B includes (BM-1, MD-13 and NC-6; Fig. 8).

5.5. Group 5

It shows similarity to Group 4 but there is a stronger decrease in the trend of water table. It includes ADG-23, MD-4, MD-2, DW-4, MD-1, BM-3 and MD-8 (Fig. 9).

5.6. Group 6

This group includes all the wells where no distinguish trend has been comparable to the others. However, they all show decreasing in the groundwater table. This group includes: JT-70, 21-2D, 21-3D and BM-1 (Fig. 10).

6. Discussion

6.1. Group 1

This group of wells is located in dunes and sand sheet according to the geological map. Also, there are no important Wadi routes according to the topographical map. Such type of well are affected to a bigger extent by local rainfall events, and to smaller extent by Wadi runoff which might result from upstream rainfall in the mountain. So, the rainfall event of 1998 affected the water table more than the 2007 and 2010 events (Fig. 11).

6.2. Group 2

This group of wells is located nearby Maawil dam which was constructed by 1991. This group is strongly affected by the 2007 event. 2010 event did not make important impacts

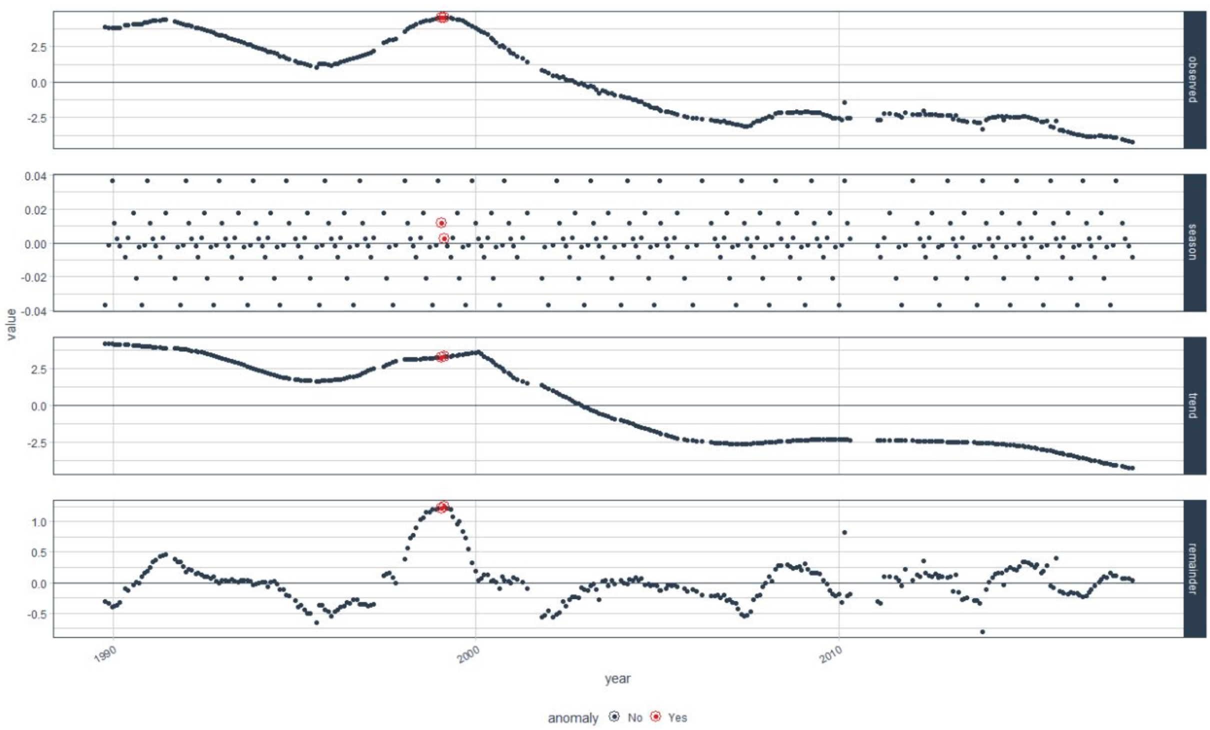

Fig. 5. RE-3P water well time series analysis. An example of group 1 trend.

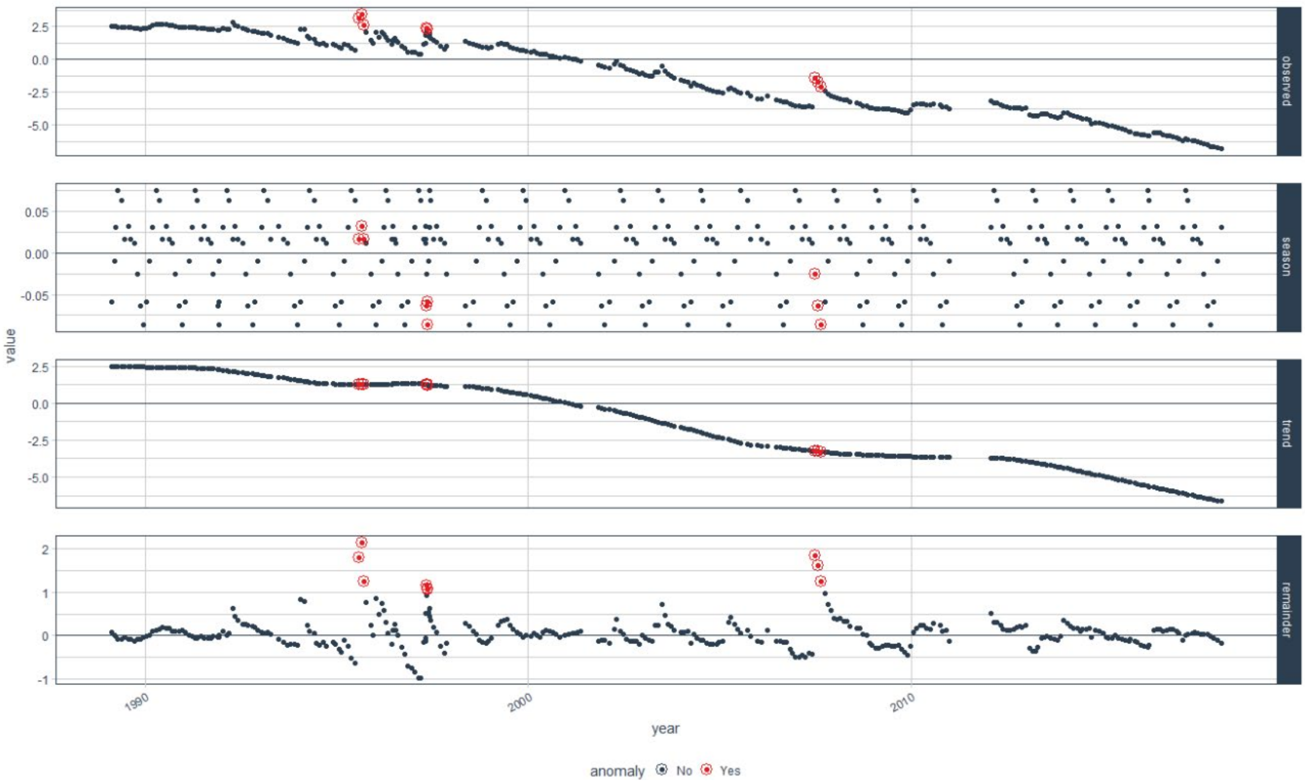

Fig. 6. MD5 water well time series analysis. An example of group 2 trend.

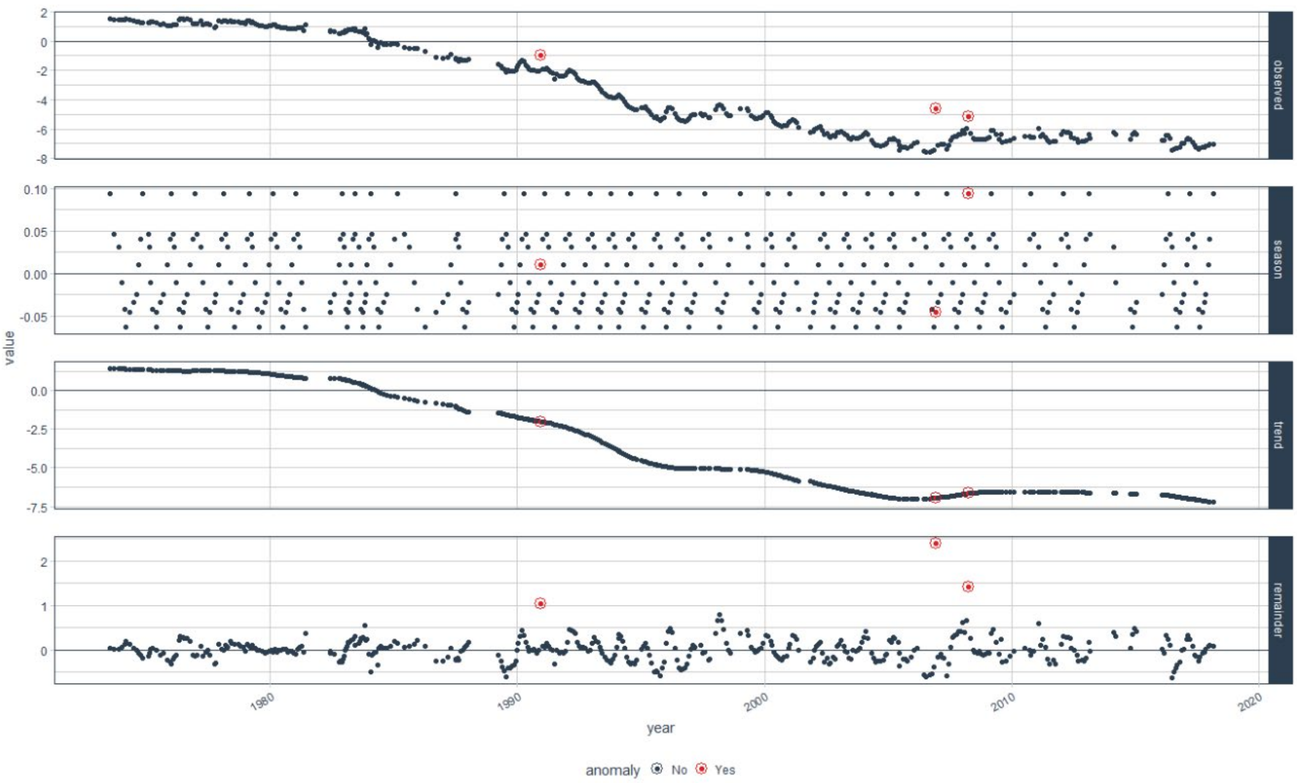

Fig. 7. ADG17 water well time series analysis. An example of group 3 trend.

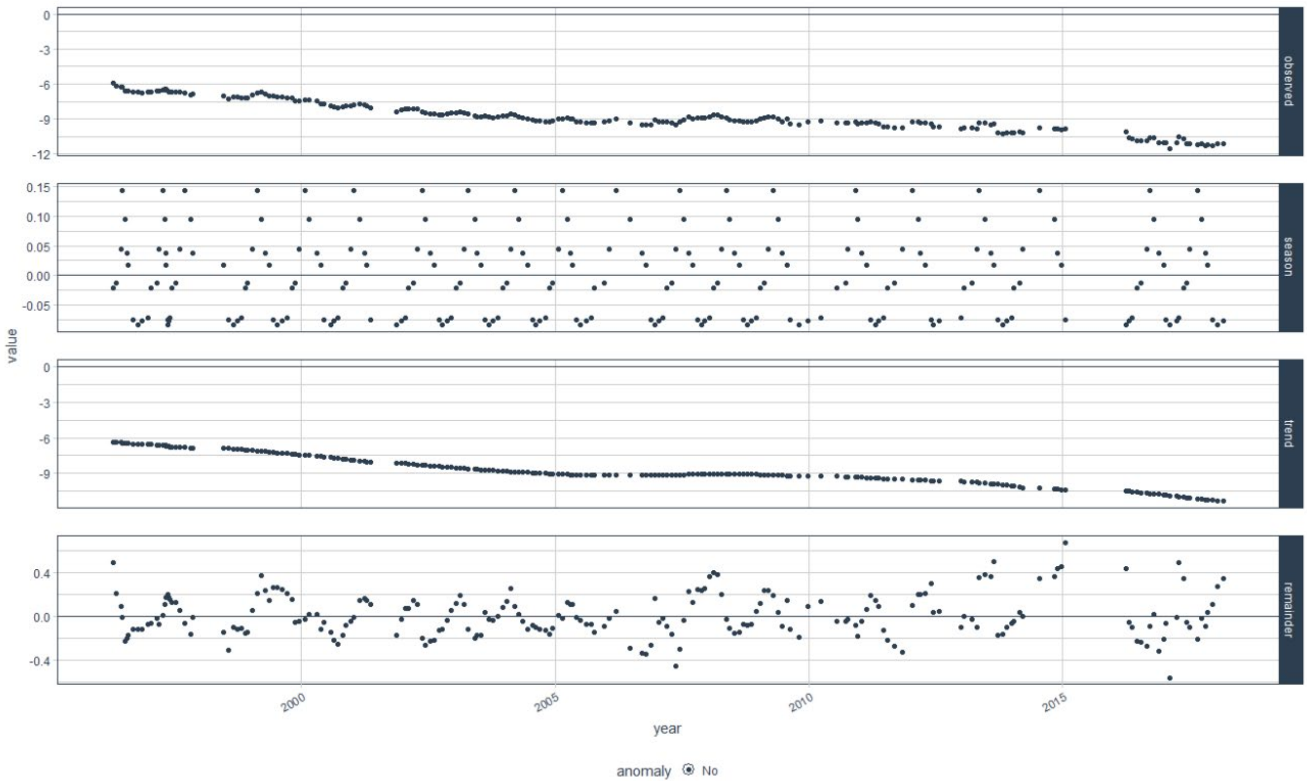

Fig. 8. MD12 water well time series analysis. An example of group 4 trend.

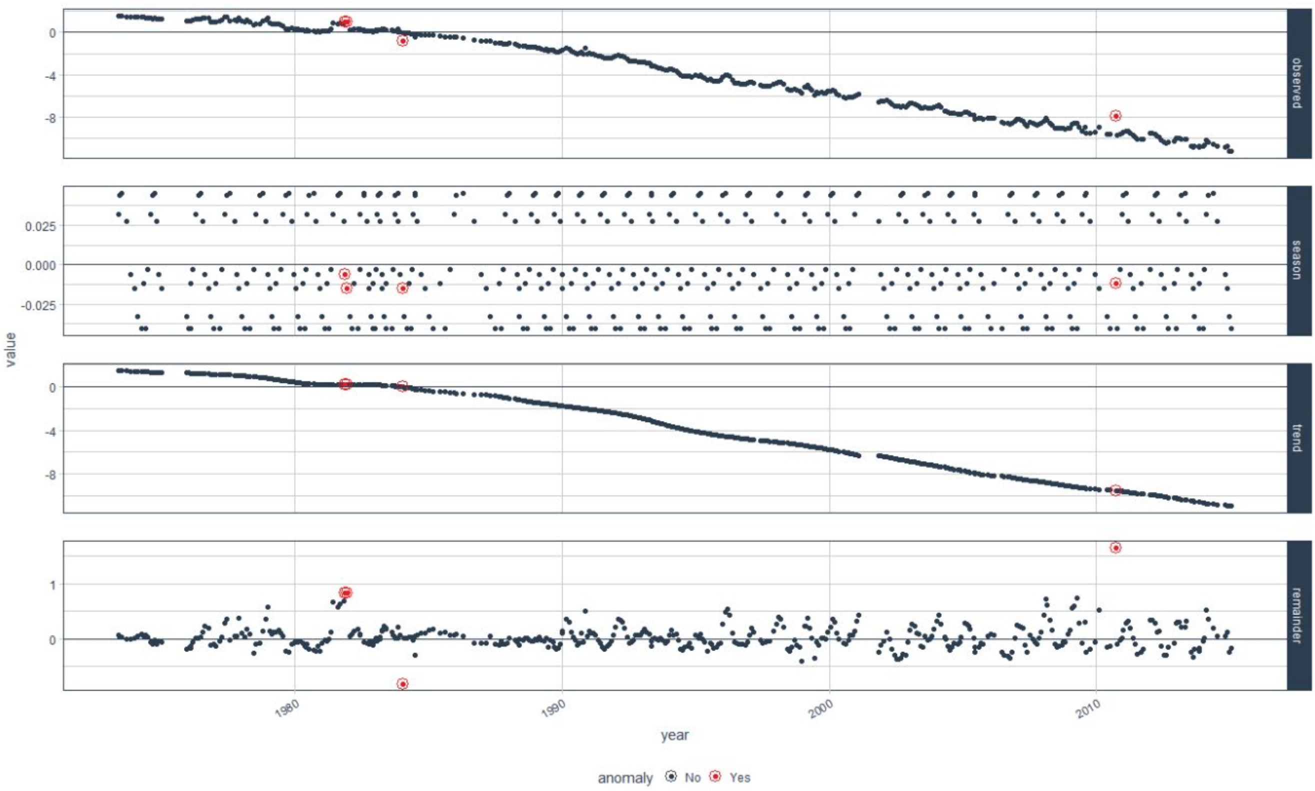

Fig. 9. ADG23 water well time series analysis. An example of group 5 trend.

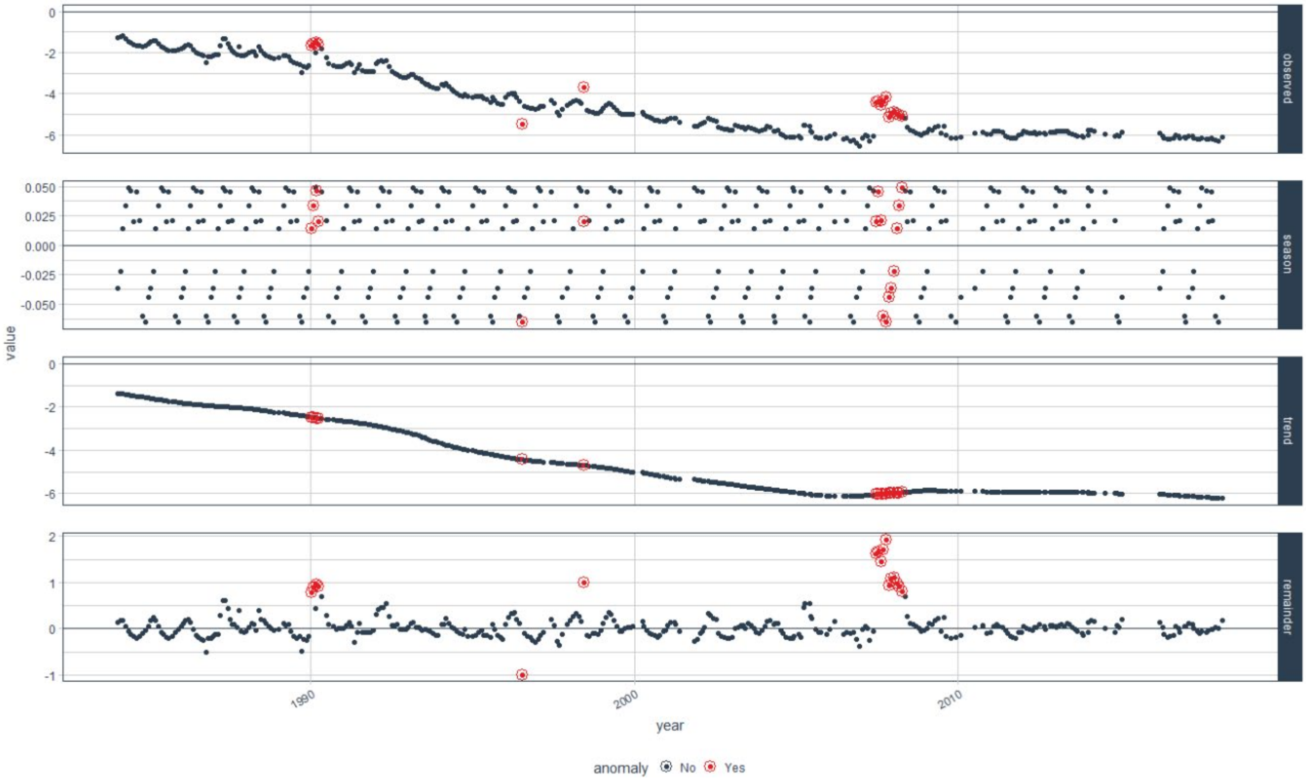

Fig. 10. BM-1 water well time series analysis. An example of group 6 trend.

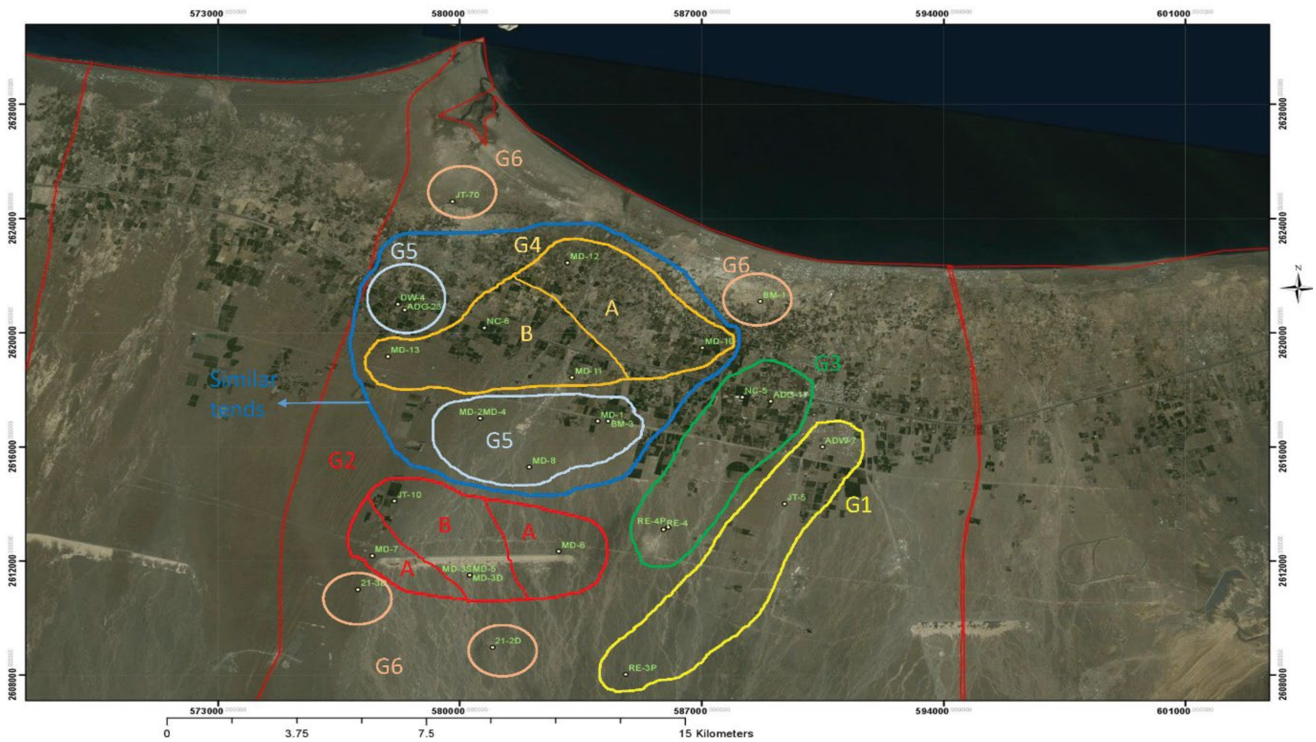

Fig. 11. Water well groups with similarity in trends. Group 1: yellow; Group 2: red; Group 3: green; Group 4: gold; Group 5: light blue; Group 6: rose.

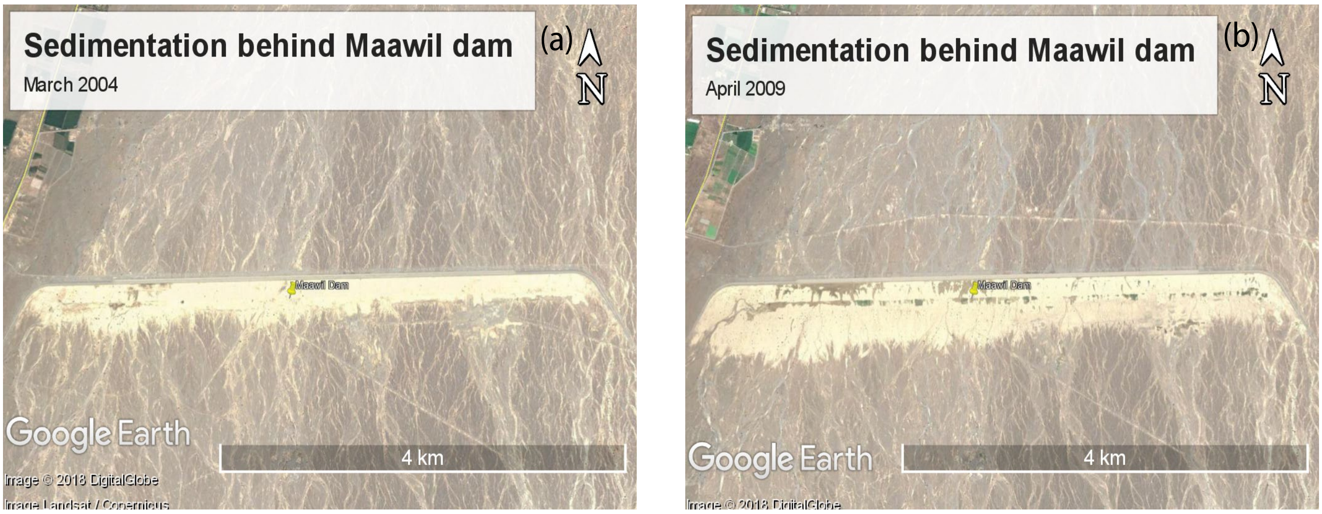

Fig. 12. Sedimentation behind Maawil dam on (a) March 2004 and (b) April 2009.

on the water table. Fig. 12 shows the difference in sedimentation accumulation before 2007 event (Guno), and before 2010 event (Phet). The wide accumulation of sediment with mismanagement of the dam valves during the flood events might cause such results.

6.3. Group 3

This group shows the impact of 2007 event but less than for Group 2, which is closer to the dam.

6.4. Group 4

This group is relatively closer to the saltwater/fresh water boundary, also it has water table close to the sea level. This situation makes the trend without abrupt changes, even that general trend shows linear decrease. The effect of infiltrated irrigation water might affect the water table as well, because it is close to the wider cultivated area. This group is located downstream of Maawil dam.

6.5. Group 5

This group shares similar trend with group 4. It is also located downstream of Maawil dam.

6.6. Group 6

These wells do not show any special trend. Two of the wells are located very close to the sea, and the other two are located upstream Maawil dam.

7. Conclusion

The approach used in this study can provide a quick and independent overview of groundwater trends by simple groundwater water table measurements. Despite the benefits of the proposed method and considering the structure of our dataset, we propose to evaluate this particular case by "time series forecasting method" in order to estimate towards where the system directs and show the usefulness of such methodology for decisions of public interest.

This work shows the possibility of making successful water-table-changes trend analysis of alluvial aquifer in arid region using statistical analysis. The interpretation of these trends for the Batinah region in Oman proves the following: (1) recharge dams with design used in Oman are effective on alluvial fans and it increase storage in the aquifer. (2) Integral management of recharge dam is necessary to improve its efficiency – this includes fine sediments removal: the sediments might be sold as soil enhancement. (3) Local rainfall affects the aquifers where the outcrop is mostly sand dunes and sand sheets.

Acknowledgments

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References

Abdalla, O., Kacimov, A., Chen, M., Al-Maktoumi, A., Al-Hosni, T., Clark, I., 2017, Water resources in arid areas: the way forward. Springer Water.

Ahmed, A. T., Askri, B., 2016, Seawater intrusion impacts on the water quality of the groundwater on the northwest coast of Oman. Water Environment Research, 88: 732–740.

Al-Awadhi, T., Mansour, S., 2015, Spatial assessment of water quantity stress in Sultanate of Oman provinces: A GIS based analysis of water resources variability. Scientific research publication, Journal of Heographic Information System. 7: 565–578.

Bechennec, F., Beurrier, M., Rabu, D., Hutin, G., 1986, Geological map of Barka', Explanatory notes. Sheet NF 40-3B scale 1:100000. Ministry of Petroleum and Minerals.

Chitrakar, P., Sana, A., 2015, Groundwater flow and solute transport simulation in eastern Al Batinah coastal plain, Oman: Case study. Journal of Hydrologic Engineering. 05015020-1-10.

Cleveland, R. B., Cleveland, W. S., McRae, J. E., Terpenning, I. J. (1990). STL: A seasonal-trend decomposition procedure based on loess. Journal of Official Statistics. 6(1): 3–73.

Dancho, M., Vaughan, D., 2018, Anomalize: Tidy Anomaly Detection. R package version 0.1.1., https://CRAN.R-project.org/package=anomalize.
Hadidi, A., 2016, Wadi Bili catchment in the Eastern Desert. PhD thesis, TU Berlin.
Hendrickx, J. M. H., Phillips, F. M., Harrison, J. B. J., 2003, Water flow processes in arid and semi-arid vadose zones. In Simmers, I. (2003) Understanding Water in a Dry Environment. A. A. Balkema Publisher, The Netherland.
Kwarteng, A. Y., Dorvlo, A. S., Vijaya Kumar, G. T., 2009, Analysis of a 27-year rainfall data (1977–2003) in the Sultanate of Oman. International Journal of Climatology. 29: 605–617.
MRMWR (Ministry of Regional Municipalities and Water Resources in Oman), 2015, Water Resources in Oman. Published report.
NCSI (National Center for Statistics & Information), 2017, Statistical Year Book 2017. August 2017. Issue 45.
PAEW (Public Authority for Electricity and Water), 2016, Annual Report 2016. Diam.
Young, M. E., de Bruijn, R. G. M., bin Salim Al-Ismaily A., 1998, Exploration of an Alluvial aquifer in Oman by time-domain electromagnetic sounding. Hydrogeology Journal. 6: 383–393.