Groundwater level trend analysis using the statistical auto-regressive HARTT method

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Abstract:

In this study, the Hydrograph Analysis: Rainfall and Time-Trends (HARTT) model was used to determine the contribution of climatic and non-climatic stresses on groundwater levels in the Lake Haramaya well-field, Ethiopia. Monthly precipitation and monitored water-level data were used as explanatory variables of the method. Variability in rainfall explained 81.3% of groundwater levels using 2-month average time-delay. The coefficient of the impact of rainfall on groundwater level ($K_r$) was found to be $0.00562 \pm 0.0007$ mm. This $K_r$ value indicates that a 1 mm increase in rainfall from the annual average rainfall raises the groundwater-level by $0.00562 \pm 0.0007$ mm, while a 1 mm decrease in rainfall causes a $0.00562 \pm 0.0007$ mm drop in groundwater-level in the area. However, the average falling trend of the groundwater level ($K_s$) was 1.51 ± 0.133 m/year, even with rainfall causing water-levels to rise between 1.01 to 3.29 m/year. With decreased rainfall, rainfall accounted for about 19.5% of the total-drawdown, while 80.5% was due to cumulative effects of non-climatic variables. This shows that rainfall inputs are negated by cumulative non-climatic stresses leading to the long-term net decline in groundwater level. Projected water-level results show that groundwater levels will be below pumping positions in <24 years which may have dire consequences for local landowners.

KEYWORDS accumulative residual rainfall; groundwater sustainability; hydrograph; non-climatic variable

INTRODUCTION

Water is the basic constituent for the existence of life on earth. Demand for water is increasing in line with population growth and associated socioeconomic activities including irrigation schemes and industries. Although surface water resources can meet a degree of anthropogenic demands, its high vulnerability to pollution, climate variabilities and manmade stresses have created several inherent uncertainties in meeting the predicted rise in water needs (Shishaye, 2018). In contrast, groundwater can be an advantageous resource with positive attributes including high quality, proximate availability, inexpensive developmental cost and drought buffering capacity (Todd and Mays, 2005). Yet careful management of this finite and consumable resource is very critical (Ponce, 2006). Currently, ~2.5 billion people depend solely on groundwater resources (van der Gun, 2012) and over half the world’s population principally use it (Alabi et al., 2010). In arid countries like Ethiopia, groundwater is the major source of water supply (about 70%) and demand is projected to increase in the coming decades (Kebede, 2013).

The high variability and the complex nature of geomorphological setups, as well as erratic rainfall patterns, have a profound influence on the availability and exploitability of groundwater resources (Gleeson et al., 2016). Anthropogenic disturbances such as over-extraction and a changing climate can also threaten these valuable resources. However, our knowledge of how these factors influence groundwater dynamics remains limited. To enable sustainable long-term management of groundwater resources, understanding the full impact of these factors on long-term groundwater level fluctuations, and downward-upward or cyclic trends is essential.

As groundwater is hidden and slow moving, characterizing groundwater resources can often be left undone. With groundwater extraction taking place in some places unhindered, the full impact of high extraction rates can take many years to come to light (Burazer et al., 2010). Trend analysis for groundwater level is one way of monitoring groundwater level, but complexities arise from sensitivities to multiple climatic and non-climatic factors (Chen et al., 2004). There are however several parametric and non-parametric methods used for trend analysis in groundwater levels. The Hydrograph Analysis: Rainfall and Time-Trends (HARTT) model is reliable in differentiating the contribution of rainfall from the non-climatic events and the lag between rainfall and its impact on groundwater over time (Ferdowsian et al., 2001a). The approach is also effec-
tive at detecting statistically significant trends in ground-water levels.

Groundwater has been the only source of water supply in the Lake Haramaya watershed in Ethiopia since the desiccation of Lake Haramaya in 2006 (Shishaye and Abdi, 2016; Shishaye et al., 2019). Despite the development of many private and public wells for domestic and agricultural purposes, the water supply is still inadequate to meet the needs of the region. Up until 2006, the water table was relatively stable, but since then the groundwater level has been declining unabated (Shishaye and Nagari, 2016). The objective of this study was to conduct a groundwater trend analysis in the Lake Haramaya watershed using the modified HARTT model (Ferdowsian et al., 2001b). In particular, it aims to use the model to determine the contribution of rainfall and non-climatic factors on past and present-day groundwater levels.

MATERIALS AND METHODS

Lake Haramaya watershed (Figure 1) covers an area of 51.1 km² and is located 505 km east of Addis Ababa in Haramaya Woreda, Ethiopia. Topography in the area is rugged with an elevation range between 2005 to 2394 m a.s.l. The area has a subtropical agro-climatic condition with an average annual rainfall of 776 mm and an average temperature of 18°C. The watershed is part of the Harar Plateau, in the upper Wabi-Shebele Basin and is characterized by three major stratigraphic units including the Precambrian crystalline basement, Mesozoic sedimentary rocks and Quaternary sediments (Shishaye et al., 2019). The aquifer system in the area is a single unconfined unit with an average thickness of 55 m (Shishaye et al., 2019).

Monthly rainfall data recorded from 1979–2012 were collected from Haramaya gauging station (Figure 1). Historical groundwater level data measured from nine wells in the area was obtained from the district’s water supply office. The analysis was then conducted using the HARTT model for the time-span of 2005–2012. In the model, rainfall is represented as an accumulation of deviations from average rainfall (ARR) and the lag between deviations from average rainfall and its impact on groundwater levels. The two forms of accumulative residual rainfall, the accumulative monthly residual rainfall (AMRR) and accumulative annual residual rainfall (AARR) were used to compare results. The AMRR was calculated first as the difference between individual events and monthly average rainfall as described by Ferdowsian et al. (2001a):

\[
AMRR_t = \sum_{i=1}^{t} (M_{i,j} - \bar{M})
\]

where \(M_{i,j}\) is rainfall in a month \(i\) (a sequential index of time since the start of the dataset) which corresponds to the \(j\)th month of the year, \(\bar{M}\) is mean monthly rainfall and \(t\) is months since the start of the dataset. The second form of rainfall (AARR) was calculated as the difference between individual monthly mean values and average of the annual mean value of the entire years’ rainfall considered from the relation:

\[
AARR_t = \sum_{i=1}^{t} \left( M_{i,j} - \bar{A} \right)
\]

where \(\bar{A}\) is mean annual rainfall (mm). Further discussion about AMRR and AARR is included in the supplementary material (Text S1).

To separate rainfall impacts and non-climatic stresses (i.e. abstraction) on groundwater level fluctuations, two assumptions were made; 1) land-use change during the period of analysis was not significant and 2) evapotranspiration losses from the water-table was negligible. Using these assumptions, HARTT model was used to determine the long-term fluctuations of groundwater level and to investigate any long-term correlation between climate and groundwater level. The two accumulative residuals of rainfall and the lag between rainfall and groundwater dynamics were used to determine relationships between groundwater trends and rainfall records from the regression using:

\[
Depth_t = K_0 + K_1 \cdot ARR_{t-1} + K_2 t
\]

Figure 1. Location map of the Lake Haramaya watershed
GROUNDWATER TREND ANALYSIS

Table I. Statistical parameters from the HARTT model and the annual rate of groundwater falling heads (ARGF)

<table>
<thead>
<tr>
<th>Well ID</th>
<th>$L_1$</th>
<th>Effect of rainfall (mm)</th>
<th>Time-trend (m)</th>
<th>Total ARGF (m/8-years)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$R^2$</td>
<td>$K_1$</td>
<td>$p$-value</td>
<td>$K_2$ (m/month)</td>
</tr>
<tr>
<td>HW1</td>
<td>1</td>
<td>0.77</td>
<td>0.00302</td>
<td>0.00233</td>
</tr>
<tr>
<td>HW2</td>
<td>0</td>
<td>0.93</td>
<td>0.00815</td>
<td>0.00211</td>
</tr>
<tr>
<td>HW3</td>
<td>1</td>
<td>0.81</td>
<td>0.00423</td>
<td>0.00153</td>
</tr>
<tr>
<td>HW4</td>
<td>7</td>
<td>0.86</td>
<td>0.00333</td>
<td>0.00321</td>
</tr>
<tr>
<td>HW5</td>
<td>3</td>
<td>0.89</td>
<td>0.00821</td>
<td>0.0453</td>
</tr>
<tr>
<td>HW6</td>
<td>0</td>
<td>0.69</td>
<td>0.00518</td>
<td>0.0522</td>
</tr>
<tr>
<td>HW7</td>
<td>2</td>
<td>0.75</td>
<td>0.00724</td>
<td>0.00323</td>
</tr>
<tr>
<td>BH12</td>
<td>8</td>
<td>0.79</td>
<td>0.00421</td>
<td>0.00136</td>
</tr>
<tr>
<td>BH7</td>
<td>4</td>
<td>0.84</td>
<td>0.00700</td>
<td>0.00258</td>
</tr>
<tr>
<td>Avg.</td>
<td>2.8</td>
<td>0.81</td>
<td>0.00562</td>
<td>0.01376</td>
</tr>
<tr>
<td>SE</td>
<td>0.98</td>
<td>0.03</td>
<td>0.00070</td>
<td>0.007</td>
</tr>
</tbody>
</table>

where Depth is the depth of groundwater below the ground surface (m), $t$ is months since observations commenced, and $L_1$ is length of time-lag (months) between rainfall and its impact on groundwater and $K_0$, $K_1$ and $K_2$ are parameters to be estimated (Text S2). The parameter of the regression coefficient $K_0$ is approximately equal to the initial depth to groundwater level, $K_1$ represents the impact of above or below average rainfall on the groundwater level, and $K_2$ is the underlying time-trend of groundwater rise/fall over time. Finally, the coefficient of determination ($R^2$) explained the degree of fit between calculated and recorded water-level curves and the level of statistical significance ($p$-value <0.05) indicates the level of significance of each variable.

**RESULTS AND DISCUSSION**

**Model results**

The Haramaya watershed aquifer system is recharged predominantly from precipitation (Shishaye et al., 2019). Therefore, any significant long-term trend in water-level may not only be due to human interventions but may also be associated with a long-term change in climate variables. Hence, the effect of atypical rainfall was separated from the underlying time-trend using the HARTT model that yielded statistical parameters including coefficient of the impact of rainfall ($K_1$), coefficient of time-trend ($K_2$), and lag-time effect ($L_1$). 95% confidence limits ($p < 0.05$) were used to determine statistically significant relationships. Accordingly, significant relationships for groundwater system dynamics in relation to climate variability were observed (Table I).

Usually, the relative coefficient of determination between the simulated and observed water-levels is a function of input data ranges, model accuracy, data quality, site characteristics, time period and other factors that are difficult to measure (Ferdowsian et al., 2001a). However, it is also important to note that all the wells drilled in the area (Figure 1) are in a similar geologic formation, alluvial deposit (Shishaye et al., 2019). Therefore, it can be concluded that the model results (Table I) represent the cumulative effects of residual rainfall and the underlying time-trend (Figure 2), while other factors (human-induced) are shared by the time-trend (non-climatic variable).

Rainfall explained about 81.3% of the average water-level variations (Table I), implying that rainfall is the main contributor to groundwater water levels. The strongest correlation ($R^2$) highlights the dynamic relationship of groundwater and rainfall variation, highlighting the dependency of the aquifer system on recharge from precipitation events (Figure 2). However, there are situations where the strength of the relationship ($R^2$) varied with sample size. For example, using rainfall data for 1979 to 2012 or 2000 to 2012 varied the fit by 81% and 87%, respectively. The smaller sample size provided a good correlation, but it could mask impacts from events such as long-term drought or excess rainfall events and hence the longer sample is essential to determine how the aquifer system responds to long-term historic events. As the HARTT model requires datasets measured at equal spacing and aggregated to monthly averages rather than higher resolution data (e.g. days) then there is a chance to select points that may not represent the natural conditions and eventually influence the overall model.

![Figure 2. Hydrograph of well HW1 at a 0-month time delay](image-url)
The trend in groundwater level

The consistent downward trend in groundwater level was identified by the HARTT model with overall declines observed in all nine monitoring wells over the 89 months (Jan-2005 to May-2012), despite a slightly rising trend in ARR (Figure S1). Statistically, significant falls in $K_t$ were observed and ranged from 0.98 to 2.18 m/year (Table II). The falling trend is consistent with other studies that have reported declining groundwater levels in the area (Shishaye et al., 2019). The rate of decline varied among wells, where the greatest falling trend (> 2 m/year) was recorded in two wells, while a moderate falling trend (1–2 m/year) was recorded in 6 wells and the lowest (< 1 m/year) in one well (Table I).

The annual rate of falling groundwater levels was converted to equivalent total falling heads during the entire period of analysis (2005–2012) with an average value of $1.51 ± 0.133$ m/year and ranging from 7.87 to 16.17 m over the total 8-year simulation period (Table I) which is slightly less than the average observed drop in the water-table in 8-years (14.24 m). Further discussion on the step by step estimations is presented in the supplementary material (Text S3).

Impact of rainfall ($K_1$) on groundwater level

Rainfall data (1979–2012) used in the HARTT model indicated ~27% (202.04 mm) of the average annual rainfall occurs in April-May, while ~48% (356.93 mm) occurs in July-September (Figure 3). The average annual rainfall is 763.85 mm; however, yearly deviations ranged from 418.3 mm (in 1985) to 1018.5 mm (in 2006). Minimum rainfall was recorded between 1984 to 1986 and 1993 to 1998, while the maximum annual rainfall occurred in 2006 in which about 37% of the annual rainfall was above annual average except for 2009 and 2012 which were 13.6% and 31.8% below average, respectively.

Therefore, if there is groundwater level falling at least during the study period owing to the reduction of rainfall patterns, it belongs to these years. The envisaged evidence drawn from the actual and residual rainfall plotted in Figure 3 helps in bridging to assess matching patterns of rainfall and water-level that enables to validate whether the rainfall effect is explained by the HARTT model and broadly outlined the presence of additional drivers other than climate variabilities. Periods where the hydrograph indicates a downward slope (e.g. 1994–1997) suggest a likely decrease in recharge, while any upward slope indicates periods of increased precipitation that led to generating a rise in water-level.

The HARTT model was generally agreeable with the qualitative interpretations of the rainfall variable alone, providing valuable baseline information regarding how the groundwater level responded to rainfall. Statistically significant ($p < 0.05$) values of $K_t$ were determined from the HARTT model (averaged to 0.00562 ± 0.0007 mm). The impacts of rainfall represent water-level rise/falling in mm for 1 mm of rainfall above or below annual average. The statistically significant value of $K_t$ indicates the variation in groundwater level and the time-lag is detected well.

Residual rainfall (ARR, mm) values ranging from −307.56 to −1.04 mm and 8.62 to 400.81 mm were calculated for 2005 to 2012 (no water level data recorded prior to 2005). The extreme negative impact of below average residual rainfall tends to yield falling groundwater levels that appeared in March 2005, while the maximum positive impact (above average residual rainfall) indicates rising groundwater heads as seen in September 2010. Negative and positive effects were articulated separately to quantify the impact of rainfall on groundwater levels in relation to other drivers.

Once $K_t$ was determined, values were multiplied by the anticipated rise/fall in monthly rainfall ($K_t * ARR$) and determine the effect of rainfall on groundwater level rise/fall. The effect of rainfall varied from 0.017 to 4.29 m and the total fall and rise over the study period was from −5.74 to 31.85 m. This implies that groundwater level of the aquifer system declined due to a reduction in rainfall at an average rate of −0.93 m/year, or equivalent to −6.81 m over the 89-month study period. Conversely, positive residual rainfall generated groundwater level rise which was predicted to be 2.87 m/year or 22.81 m during the study period.

Despite the potential groundwater recharge approximated from $K_t$, the underlying time-trend ($K_2$, m/month) determined from the HARTT model suggested that the rise in groundwater level ranges from 0.98 to 2.02 m/year. Despite the annual rise in water level due to recharge from precipitation (2.87 m/year), groundwater levels were shown to decline at an average rate of 1.51 ± 0.133 m/year.

For example, the negative effect of rainfall on the groundwater-level was pronounced in 2005 (Figure 4). But,
the hydrographs confirmed that changes in water-levels particularly for the time period till July 2005 for individual wells remained relatively stable with some wells showing small rising trends (0–0.1 m/year), where the maximum negative residual rainfall were exhibited. Likewise, the rise in water level is not always a result of precipitation because of delayed residual effects or lateral flow arising due to spatial variations in aquifer properties (Healy and Cook, 2002). Any precipitation event may not provide a linear or uniform rise/fall in the groundwater level. The best example is the rainfall in 2006 which was 33.8% and 15.0% higher than in 2005 and 2009, respectively. However, the rate of fluctuation in 2009 was higher than in 2006, indicating the influence of other drivers. Moreover, a good correlation of water-level between wells was observed between 2008 and 2010, when nearly uniform pumping occurred, and precipitation varied substantially for the period (Figure 3). This reflects that the influence of rainfall on the descending trend in water-level was not as strong as other factors including extraction. Groundwater extraction in the region had risen sharply from 2006 by 17% in 2007–2009 through 21% in 2010 to 24.7% in 2012. The cumulative effects of the non-climatic variables, including pumping on the decline in groundwater level was 80.5%, while only 19.5% was estimated to be at the expense of a reduction in rainfall.

Lag-time effect

The impact of rainfall may not be explained on the water-level instantaneously within the hydrographic records owing to various interacting factors likely ruled by the time needed for recharge and to reach the water-table (Rancic et al., 2009). Some wells responded quickly with a little time delay, while others responded slowly with the time shifting between peak precipitations and difference in groundwater levels varying considerably. Pronounced spatiotemporal variations of calculated rise/fall trend in water-level were observed. Groundwater level attains a maximum at their highest levels approximately 0–8 months following the peak of precipitation then decreases down during the dry period (Figure S2). The variation in lag-times was consistent with other studies, for example, Ferdowsian et al. (2001b) found lag-time ranged from 0 to 17 months, and Yihdeo and Webb (2010) found lag-time ranged from 0 to 11 months. Further discussion about the time-lag is presented in the supplementary material (Text S4). Owing to these factors, substantial spatial and temporal variations in the rate of response and long-term response in water-level were depicted, however, the overall result showed a consistent descending trend in all wells (Figures 2, 4 and S1–S5). The long-term projections of the depth to water-table showed that the groundwater table in the study area will reach below the standard pumping position (7 m above the basement) in less than 24 years. This was calculated by dividing the average saturated aquifer thickness in the area by the average rate of decline depicted from this study (1.51 ± 0.133 m/year). The average saturated aquifer thickness was reported to be 36.5 m (Shishaye et al., 2019).

CONCLUSION

The results show that groundwater extraction was in excess of annual recharge i.e. although the aquifer is recharged and replenished annually, it was found to be counterbalanced by cumulative effects of non-climatic stresses. From the long-term predictions of the groundwater level in the area, the majority of the wells will reach below the standard pumping position on average in less than 24 years. The predictions were made keeping rainfall and pumping patterns constant. Therefore, population growth, industrialization and climate change may exacerbate the situation and may shorten the predicted time period.

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SUPPLEMENTS

Text S1. Further discussion on AMRR and AARR
Text S2. Further discussion on how to estimate $L_0$, $K_0$, $K_1$ and $K_2$
Text S3. Further discussion on how to estimate pumping effects using HARTT model
Text S4. Further discussion on time lags
Figure S1. Hydrograph of HW2 at a 0-month time delay
Figure S2. Hydrograph of HW1 at 3 months delay
Figure S3. Hydrograph of HW4 at a 1-month delay
Figure S4. Hydrograph of HW5 at a 0-month delay
Figure S5. Hydrograph of BH12 at the 8-month delay

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