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Groundwater Resources of Zimbabwe: An Assessment of Fluctuations

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Abstract

The research was aimed at coming up with a method that can be used to assess groundwater levels from a remote sensing platform. Groundwater resources provide the highest potential for coping with, and mitigating the impacts of, climate change and increasing food production. However, in Zimbabwe there is limited information on spatial and temporal variability in groundwater storage due to inadequacy of monitoring stations. The research used monthly Gravity Recovery and Climate Experiment satellite data from 2004- 2010 with a spatial resolution of 20*20km. The data was imported in to a GIS and the statistically analysed to review patterns in the data. The results from the new method revealed that groundwater levels in most parts of Zimbabwe's catchments are in a state of decline. Most of the catchments have average groundwater levels marginally above their long term means except for the Zambezi Valley which now shows a negative longterm trend. All the catchments in Zimbabwe show a great deal of variance from their mean levels, but the coefficient of these variations increase in magnitude as one moves from the southern catchments to the northern catchments.

Keywords: GRACE satellite; Groundwater fluctuations; Remote sensing platform; Zimbabwe

Introduction

Water use in Africa is set to increase markedly over the next few decades as a result of population growth and planned increases in irrigation [1]. Agriculture is at the centre of the Zimbabwe's economy, accounting for millions of dollars in revenue and also a source of livelihoods for millions of people. Despite its importance, agriculture is being threatened by climate change which increases the probability of extreme events like floods and droughts [2]. Groundwater resources provide the highest potential of coping with, and mitigating the impacts of, climate change and increasing food production. Increasing reliable water supplies throughout Africa will depend on the development of groundwater [3,4]. This is because groundwater responds much more slowly to meteorological conditions than surface water and, as such, provides a natural buffer against climate variability, including drought [5,6]. This potentially reliable source of water is not being fully utilised partly because of the lack of proper scientific knowledge of its location and whether it occurs in quantities sufficient for it to be viably used [7]. In addition there is a poorly developed infrastructure that is used for the monitoring and assessment of the long term variability of this important resource [8,9].

The need for monitoring hydrological conditions, such as changes in the levels of groundwater, for developing countries is increasingly becoming important because of climate change. This will enable evidence-based planning for the sustainable use of the water resources. However, technical and human capacities in hydrology are declining as noted by the reduction in the number of meteorological and hydrological stations in Africa during the past 30 years [10,11]. Even if enough funds and human resources were to be made available for the extension of hydrological networks to measure and monitor river discharge and groundwater, it would take between 10-30 years before adequate data is collected [12]. In addition, the equal and spatial distribution of hydrological stations will also be difficult to establish because some of the sites are remote and inaccessible [11,13].

Collecting, processing and analysing groundwater data is thus the first step towards assessment of the current state, anticipating changes and forecasting trends in its quantity and quality due to natural processes and human impacts in time and space, providing information for improvements in the planning, policy and management of groundwater resources [14].

Thus, it is imperative to develop methods for predicting groundwater patterns where they are not directly measured. Furthermore, the need to come up with methods for prediction of ungauged basins has been recognised as a research agenda for the coming decade by the International Association of Hydrological Sciences [15]. Limited knowledge of African groundwater resources is also evident from the paucity of information on groundwater included in the IPCC Fourth Assessment Report and Technical Paper on water [16] which noted major uncertainty in how changes in climate may affect groundwater and what resources are currently available to help support adaptation strategies. Many countries with severe groundwater depletion problems have limited information on spatial and temporal variability in groundwater storage [17], as monitoring networks are generally limited and it is difficult to regionalise point-based measurements. Careful characterization of the groundwater resources is required to guide investments in water supply and to manage the resource to minimize environmental degradation [18] and widespread depletion.

In Zimbabwe, most groundwater measurements are taken from point sources by taking readings of water levels in of wells, trenches and boreholes [19,20]. None of these methods offers a regional/inter-basin perspective to the measurement of groundwater levels at once, yet it is imperative for water managers to understand water consumption over larger basins [14].

Thus this study, aims at coming up with a method that can be used to assess groundwater levels from a remote sensing platform. It also seeks to answer the key question on the state of groundwater fluctuations in Zimbabwe.

Materals and Methods

Remotely sensed data, and in this case the Gravity Recovery and Climate Experiment (GRACE) satellites, have the potential to

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address the observational gap of monitoring regional groundwater storage changes. The GRACE satellites do not measure variations in groundwater storage directly, but instead measure the Earth's gravitational field. Unlike most missions, the satellites themselves act as the measurement devices. The GRACE system consists of two chasing satellites (also called Tom and Jerry). When gravity increases, in this case due to the presence of a mass of ground water, the first satellite to approach this mass will feel a slightly larger gravitational pull than before because of the additional mass of water and the satellite accelerates. As the trailing satellite approaches the same mass of water it also accelerates and catches up with the leading satellite. Then, as the higher-mass region falls behind, each satellite is held back a little again, first the leading, then the trailing satellite. These two satellites will be sending microwaves between themselves hence it is possible to calculate that staggered acceleration, and hence infer the change in the gravitational pull on Earth's surface.

The GPS location of each satellite is precisely recorded, and a microwave ranging system measures changes in distance between the two satellites to within 10 mm [21,22]. The GRACE project then uses measured variations in the range rate between the two satellites and other tracking data to estimate gravitational coefficients, along with other dynamical orbit parameters, in a least squares estimation to maximize the fit between a modelled orbit (based on gravitational potential) and the measurements [23].

Estimations of the gravity field coefficients are made approximately every month to spherical harmonic degree and order 60. Spherical harmonics are two dimensional basis functions represented by legendre Polynomials and cosine and sine function ns of order times the longitude. Like a fourier series, the sum of the spherical harmonic series represents a sum of sinusoidal functions with wavelengths from the longest (the circumference of the Earth, 40,000 km) to the smallest (40,000 km/maximum degree), which is 600 km in this case [24].

Wahr et al. [25] detailed the methodology for converting time-variable gravity field coefficients to maps of surface mass density (groundwater fluctuations) on the basis of the assumption that for periods less than several hundred years the primary cause of temporal changes in the Earth's gravity field is movement of water mass within the Earth's relatively thin fluid envelope.

The pair of satellites was launched in 2002 and the mission was supposed to have a 5 year lifespan but is still operational on an extended life [26,27].

The area of study includes the whole of Zimbabwe and analysis will be done by catchments because it has been proven that catchment wide analysis of water resources makes more sense than point analysis [14]. This is the reason why Zimbabwe's water resources are managed by catchments. Zimbabwe has got seven major catchments shown on Figure 1 each named after the major river on which most of the rivers drain into. These catchments are: Manyame, Mazowe, Sanyati, Gwayi, Mzingwane, Runde and Save.

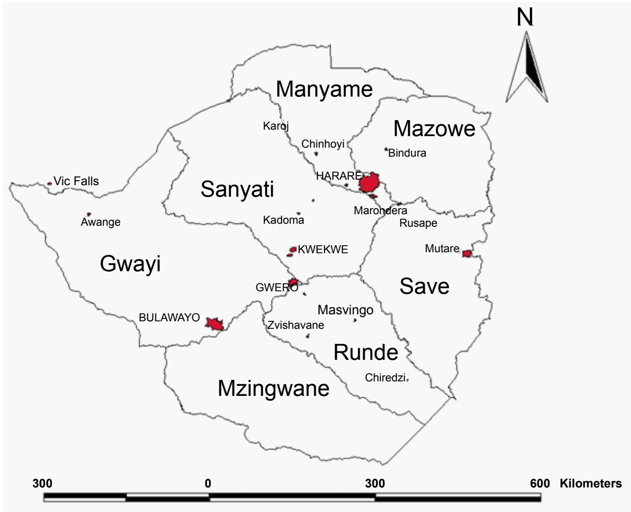

Figure 1: A map of the study area showing the catchments and the major towns and cities in each catchment.

Materials used in the study include the following:

i. Monthly GRACE satellite CSR RL05 data from 2004- 2010 with a spatial resolution of 20Km*20Km, from NASA [28]

ii. ILWIS 3.3 GIS from ITC [29].

Methods

1. The geo-referenced GRACE satellite data was first downloaded from the NASA website. The convenient GRACE data downloading policy ensures that the data is pre-processed and made ready and available for research to anyone in any part of the world (http://www.csr.utexas.edu/grace/gravity/; http://podaac.jpl.nasa.gov/grace/). Therefore in this study there was no need for processing of the data after downloading it from the host website. The geo-referenced satellite data comes in monthly composites and in text format, covering the whole world so we first subsetted the data covering Zimbabwe. These were saved as tables, for further processing in ILWIS GIS. The table data had 84 months data measurements from January 2004-December 2010.

2. The tables were then individually imported into ILWIS GIS using the Import Table fuction. The imported tables were then converted to point maps showing the point fluctuations of groundwater levels. This was done through the Table to Point function of ILWIS GIS.

3. In order to obtaian a map showing the spatial variations of groundwater levels for individual months, we interpolated the point maps using the moving average function. The moving average function assigns, to an output pixel, a weighted average of point values within a defined neighbourhood. The moving average function uses the inverse distance algorithm in order to ensure that points close to an output pixel obtain larger weights than points which are further away from it.

4. Map List function was then used to group images from the same month in one map list from 2004-2010. This therefore means that there was a total of 12 map lists from January to December. Each of the obtained map lists were then averaged out using the Map List Statistics Operation (fn_average function). The resulting raster maps were long-term average levels for each of the 12 months. The average monthly means of groundwater fluctuations were then combined into a map list which was then averaged out to give out final long-term average behaviour of groundwater.

5. For the 84 months from January 2004-December 2010 the average maximum, the average minimum and the coefficient of deviation from the mean of groundwater in catchments around Zimbabwe were also calculated in the same way as above but changing the fn map list statistic algorithm to average maximum, average minimum and standard deviation respectively.

6. Previous studies have validated GRACE derived groundwater fluctuations with results from monitoring wells and boreholes. These ground truthing exercises have been done in a variety of environments of the world, namely in humid tropics (Brazil), in monsoon climates (India and Bangladesh), in semi arid regions with the same climate as Zimbabwe (e.g. Australia, Niger and the High Plains aquifer, Central

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United States). All these studies show a good fit between GRACE-derived groundwater fluctuations and in situ borehole records, with discrepancies between the two data sets varying from 2.1-3.5cm [24,30-34]. In this regard, we can conclude that when used to assess groundwater levels over Zimbabwe, GRACE Satellite data will still maintain a comparably reasonable accuracy.

Results

Figure 2 shows the average fluctuations of ground water over Zimbabwe during the 82 months from 2004-2010. From the results, it can be shown that that there are marginally positive fluctuations in the longterm behaviour of groundwater levels for the whole country. Figure 2 also shows that all the catchments in Zimbabwe have average water table fluctuations of less than one cm from its longterm average level. Furthermore, it can be observed that some places within the Gwayi, Sanyati and Manyame catchments are already experiencing slight decline in the level of the groundwater. These are mainly areas to the north-west of the Zambezi valley, towards the border with Zambia.

Figure 3 shows the mean flactuations of the maximun values of the groundwater levels about the longterm average groundwater levels in Zimbabwe. Generally, the maximum values in the rise of the groundwater levels increase as one moves from the western part of the country (25cm) to the eastern part of the country (33cm). This means that catchments on the eastern parts of Zimbabwe are quicker to respond to the input of groundwaterthan those to the west.

Figure 4 shows the mean flactuations of the monthly minimum groundwater levels about the longterm mean groundwater level in Zimbabwe's catchments. As one moves south-north the the magnitude of the minimum values of the groundwater increases. Mzingwane and Runde catchments have the least decline in the levels of their groundwater of about -7cm of their long-term average. Northern Sanyati and Manyame catchments have the largest magnitudes of decline which is -24cm. This essentially means that at one point in time during the year for all the catchments in Zimbabwe, the groundwater levels will be below average. This shows that groundwater in the country is very vulnerable to decline.

Figure 5 shows the coeficient of variation of groundwater from its mean level. The pattern shows a north- south pattern change with catchments in the north deviating almost 13 times from their mean level as compared to about 6 time in catchments to the south.

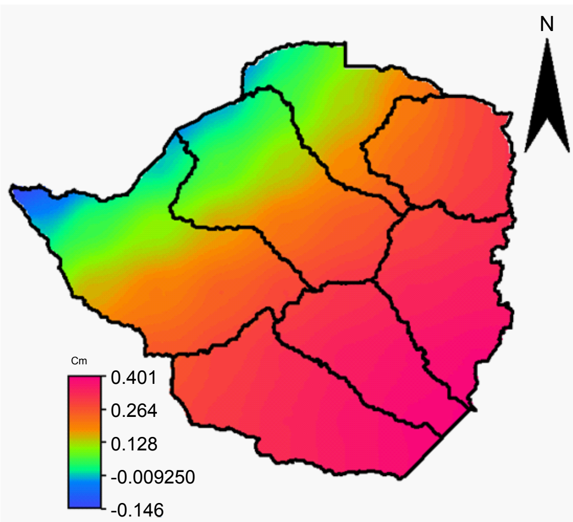

Figure 2: Avererage groundwater flactuations (in cm) about the longterm groundwater mean from 2004-2010 in Zimbabwe.

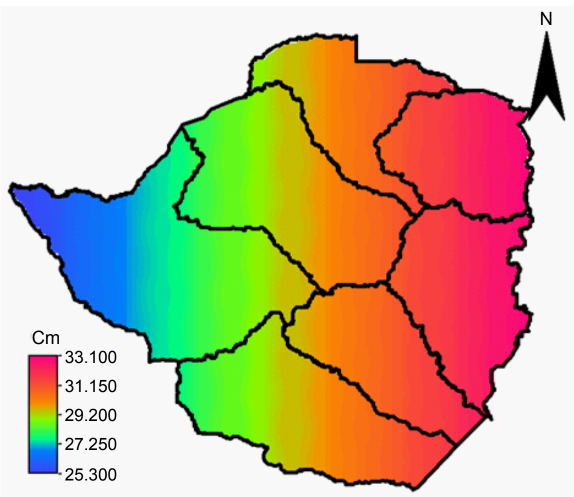

Figure 3: Average Maximum groundwater.

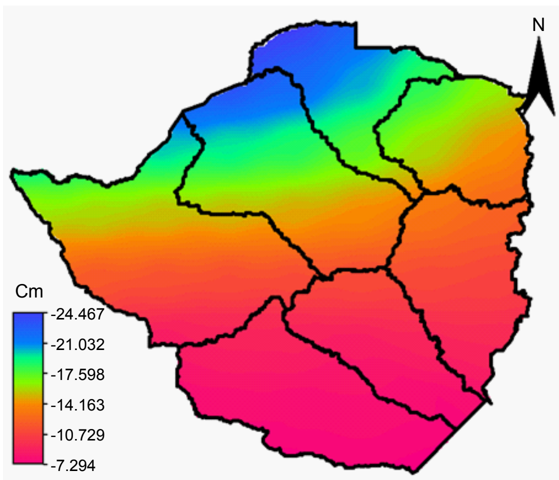

Figure 4: Average minimum groundwater levels.

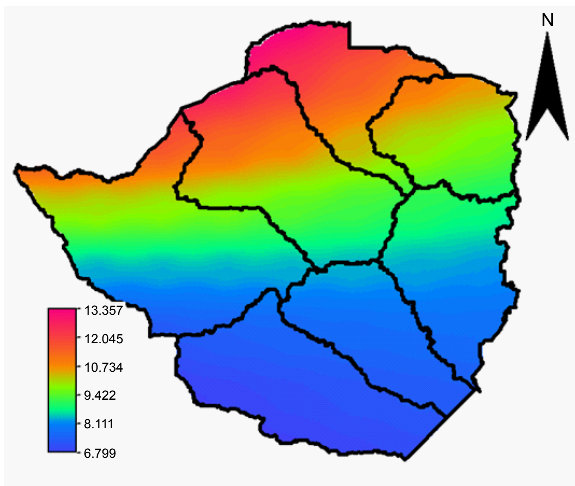

Figure 5: Coeficient of variation from the Mean Groundwater level.

Discussion

Groundwater recharge and fluctuation is a sensitive function of the climatic factors, local geology, topography and land use [35]. The groundwater levels in Zimbabwe are in a state of delicate balance, with one poor rainfall season enough to plunge the whole country into groundwater depletion. This declining trend is most likely linked to the decline in the longterm average rainfall for the country which is a major source of groundwater recharge. Precipitation in Zimbabwe especially the Southern Parts has declined by up to 10% on average over the period 1900 to 1993, which is about 1% per decade [2,36]. Groundwater resources and their long-term replenishment are controlled by long-term climate conditions [37], therefore, climate change will have a negative impact on groundwater resources.

The catchments along the Zambezi valley have started to show signs of longterm depletion of groundwater levels, this has also been proven by Famiglietti [38] who found in his research on the state of major fresh water sources around the world noted that the Congo, Zambezi and the Nile basins were drying up and showing signs of significant groundwater decline.

Groundwater decline in Zimbabwe will most likely affect development in the affected catchments as it provides most of the domestic water in rural areas, supports poverty reduction through irrigation and reliance on it is likely to increase as rainfall becomes more variable and demand for water becomes greater.

This noted decline in groundwater resource recharge have a pottetial to change the aquifer yield or discharge, and also modify the groundwater flow network. Alley et al. [39] and Brekke et al. [40] give examples of gaining streams suddenly becoming losing streams and groundwater divides moving positions.

The depletion of groundwater supplies is not just a concern for Zimbabwe and Africa as studies done by Rodell [41,42] of NASA's Goddard Space Flight Centre prove that it is also a major problem in California, India, Brazil, southern Argentina, western Australia and other countries across the globe, and mainly attributed the decline to expanding agriculture and climate change which reduces the amount of precipitation received at a place. Groundwater is being depleted at a rapid clip in virtually of all of the major aquifers in the world's arid and semiarid regions [38].

The results however must not be a source of panic in Zimbabwe because GRACE Satellite data reveals only changes in groundwater levels from their long-term mean. The results do not divulge how much water is left and do not really tell how stressed the country's aquifers are.

Conclusions

It can therefore be concluded that groundwater levels in most parts of Zimbabwe's catchments are in a state of decline. Most of the catchments are in a state of precarious balance, less than a half a centimeter above longterm average figures except for the Zambezi Valley which now shows a negative longterm trend. This means that groundwater in the Zambezi Valley is more vulnerable than for the rest of the country.

All the catchments in Zimbabwe show a great deal of variance from their mean levels, but the coeficient of these variations increases in maginitude as one moves from the Southern catchments to the Northern catchments.

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