Remote Sensing Based Unravelling of Landcover and Groundwater Scenarios Relationships for the Middle Save Sub Catchment of South Eastern Zimbabwe

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Abstract   The impact of landcover/landuse type on the groundwater scenarios has not been investigated extensively in Zimbabwe due to lack of groundwater observation data. The research was aimed at using remote sensing to unravel the groundwater scenarios under different landcover/landuse types in the middle Save catchment of Zimbabwe. The research used the gravity recovery and climate experiment (GRACE) satellite to measure regional groundwater fluctuations from 2004-2010. Landsat satellite images were also used to classify the study area into three landcover/landuse types: grasslands, forests and shrublands. The results showed that grasslands occupy 59% of the land area, forests occupy 22% of the place and shrublands cover19% of the study area. On seasonal groundwater scenarios, areas under forests had the highest magnitude of groundwater recharge (up to 20cm) and also the highest levels of groundwater lose (up to -20cm). Shrublands had recharge levels of up 13cm and loses of about -14cm. Grasslands had the least recharge of about 6cm at peak and the lowest magnitude of groundwater loses of about -7cm. The research also showed that from 2004- 2010 groundwater levels have been in a state of decline in the study area. The research concluded that landcover/landuse affects only seasonal not year on groundwater fluctuations. Geographical information systems and remote sensing were shown to be capable of producing groundwater scenarios of the study area in the absence of systematic ground based groundwater observations.

Keywords: Grace satellite, remote sensing, middle Save, groundwater scenarios

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1. Introduction

Groundwater level is the level of the water table, the upper surface or top of the saturated portion of the soil or bedrock layer that indicates the uppermost extent of groundwater [1]. Groundwater is considered to be one of the most important natural resources and sources of fresh water, especially in many semi-arid areas. It supports human health, economic development and ecological diversity. In Zimbabwe, groundwater is a highly valuable resource as it finds use among a majority of the agricultural, domestic and industrial applications.

Measurement and analysis of groundwater level is needed for maintaining and managing groundwater availability. Groundwater is monitored in many parts of the world mainly by measuring groundwater level fluctuations. This is a direct indicator of groundwater supply and withdrawal rates [2]. Water level measurements of groundwater fluctuations from observation boreholes and remote sensing are the principal source of information about the hydrologic stresses acting on aquifers and how these stresses affect ground-water recharge, storage, and discharge. Long-term, systematic measurements of water levels provide essential data needed to evaluate changes in the resource over time, to develop ground-water models and forecast trends, and to design, implement, and monitor the effectiveness of ground-water management and protection programs [2,3].

Land cover is one of the major factors affecting the groundwater system [4,5]. Studying the effect of cover changes on groundwater is a key issue in setting up a sound landuse/landcover planning project because land-use planning is important for protection of ecologically valuable areas. Landuse/landcover changes in a catchment can impact on groundwater supply by altering hydrological processes such as infiltration, groundwater recharge, baseflow and runoff [5].

There are various methods that can be used in the collection of land use/ landcover data but the use of satellite remote sensing technologies can greatly facilitate the process [6]. Satellite observations are also playing an increasingly important role in regional groundwater resources assessment and groundwater storage change. Compared with traditional ground based surveys, satellite remote sensing provides greater amounts of information on the geographic distribution of land use/landcover and groundwater in a relatively cost and time saving way for assessments on a regional scale [7,8,9,10]. Space borne

remotely sensed data are particularly useful in developing countries where recent and reliable spatial information is lacking [11]. Remote sensing technology and geographic information systems (GIS) also provide efficient methods for analysis of land use/landcover; groundwater issues and tools for land use planning and modelling [12,13].

The behaviour on groundwater under different landcover/ landuse types has received considerable attention the world over [14,15,16,17,18]. None of these researches have been conducted in Zimbabwe and there have been limited attempts to check validity of these results in the country because of limited data availability of groundwater data on a regional scale. The impact of landcover/landuse type on the groundwater scenarios has therefore not been investigated extensively in Zimbabwe. The research therefore aims at using remote sensing to unravel the groundwater scenarios under different landcover/landuse types in the middle Save catchment of Zimbabwe over time in order to determine the most suitable landuse/ landcover type for groundwater conservation.

2. Material and Methods

2.1. Study Area

Figure 1 shows the study area of the research. The area is part of the Save mega basin and occupies the eastern parts of Zimbabwe. The middle Save sub-catchment covers an area of 1200km^2.
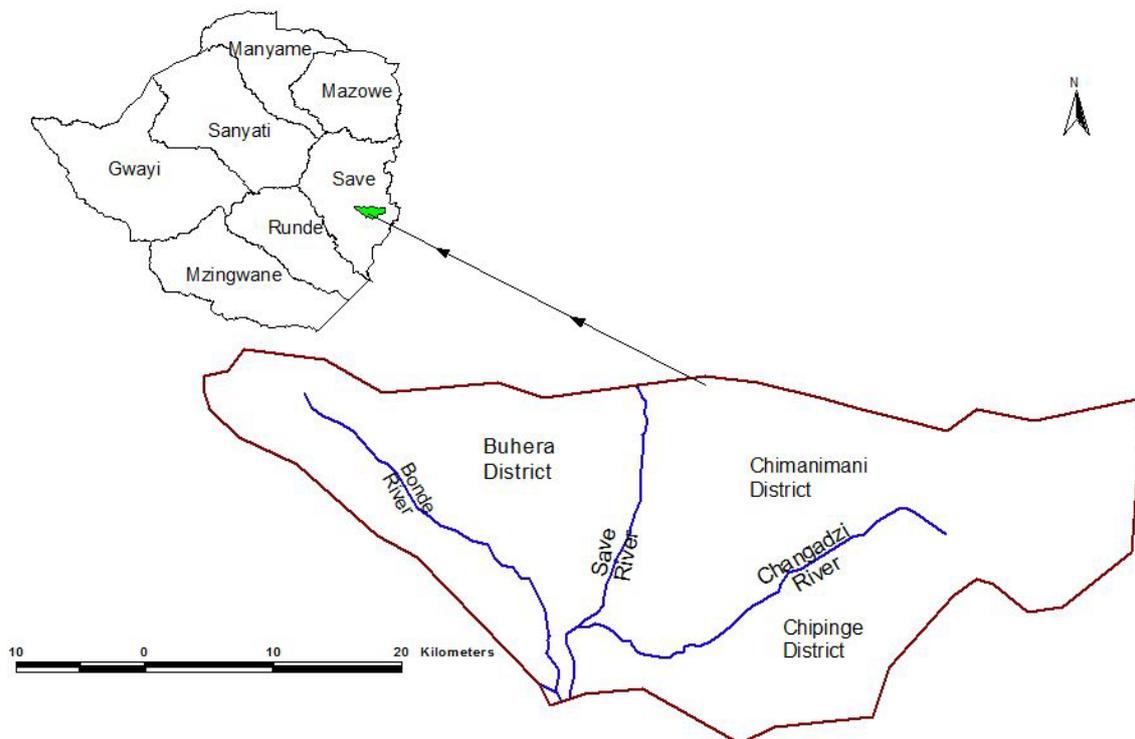
Figure 1. The study area-Middle Save sub-catchment

The area is drained by the Save river and its tributaries, the Changadzi and Bonde rivers. The area is mainly covered by crystalline basement rocks mainly granitoids to the west and central parts, dolerites/gabbros (in large patches in the north and north eastern parts) and the umkhondo group towards the south eastern section. This has led to shallow groundwater depths that are typically between 7-25m. The area receives on average almost 800mm of rainfall to the north eastern parts and about 450mm to the south western portions. Precipitation is received mostly in summer between October and March. The western portions of the sub catchment are fairly flat with slope angles ranging from 1°-4° while as the eastern sections has steep terrain that ranges from 10°-40°.

3. Materials

The study used the following materials:-
- August 2010 landsat satellite images for the study area.

- Integrated land and water resources management systems (ilwis) GIS software [19].
- Gravity Recovery and Climate Experiment (GRACE) satellite data from 2004-2010 obtained from NASA, [20].
- Acview 3.3 GIS software.

4. Methods

Landsat satellite images for the study area were obtained and used in the generation of the classified of the landcover/ landuse map of the study area. The satellite was chosen because of its easy download policy and its reasonably good spatial resolution of 30m*30m. The pseudo natural bands 5, 4, 3 were downloaded and imported into ilwis GIS software. Supervised sampling was then done to select four classes and the final classification then done using the maximum likelihood classifier algorithm. This resulted in a map showing four classes which are: forest, grassland, shrubland and water.

Due to the inadequacy of groundwater monitoring stations in the middle Save sub catchment, remote sensing data in the form of the Gravity Recovery and Climate Experiment (GRACE) satellite was used to come up with the average monthly groundwater fluctuations for the study area. Remote sensed data provides hope where fieldwork-based monitoring techniques of groundwater are difficult and expensive to set up and maintain.

The GRACE satellites do not measure variations in groundwater storage directly, but instead measure the Earth's gravitational field. Unlike in most remote sensing missions, the satellites here act as the measurement devices. The GRACE system consists of two chasing satellites. When gravity increases, e.g if there is a massive flood at an area, the first satellite to approach the flooded region will feel a slightly larger gravitational pull than before because of the mass of all that water and the satellite accelerates, before the second accelerates and catches up. Thus, gravity variations induce distance variations between the satellites [10,21].

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 every month and converting the time-variable gravity field coefficients to maps of surface mass density (groundwater fluctuations) is done 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 [24,25].

Grace satellite data therefore shows monthly groundwater levels of areas around the world when compared to their longterm mean level and in this case it is the average groundwater level from 2004-2010. The Grace groundwater level data is available at at a spatial resolution of 20Km*20Km.

The data for study area was obtained from the NASA Grace website in text format. The data was then imported to ILWIS GIS and converted to point maps showing groundwater levels. These were then interpolated using the moving average function in order to obtain raster data showing spatial distribution of groundwater levels for individual months. The moving average function assigns to pixels weighted averaged point values using the inverse distance to an output pixel in order to ensure that points close to an output pixel obtain larger weights than points which are further away.

The map list function was then used to group images from the same month into one map list. 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 same was also done for the annual average groundwater fluctuations.

Many studies have validated GRACE derived groundwater fluctuations with results from land surface measurements from monitoring well and boreholes. These ground truthing exercises have been done in almost all environments of the world, namely in humid tropics e.g in Brazil, in monsoon climates e.g in India and Bangladesh, in semi arid regions (with the same climate as Zimbabwe) e.g Australia, Niger and the High Plains aquifer, Central United States. All these studies show a good fit between GRACE-derived groundwater fluctuations and recording from in situ borehole records, with estimated uncertainty in the data between 2,1-3.5cm [10,23,26]. Thus there is evidence that GRACE Satellite data can be accurately used over Zimbabwe.

On each landcover type, ten random samples were then generated using the DNR random tools in Arcview GIS. These random points were then used to sample the groundwater fluctuations on different landcover/landuse types at different areas. The time series fluctuations for each landcover/landuse type were then averaged to create the average groundwater scenarios for each class.
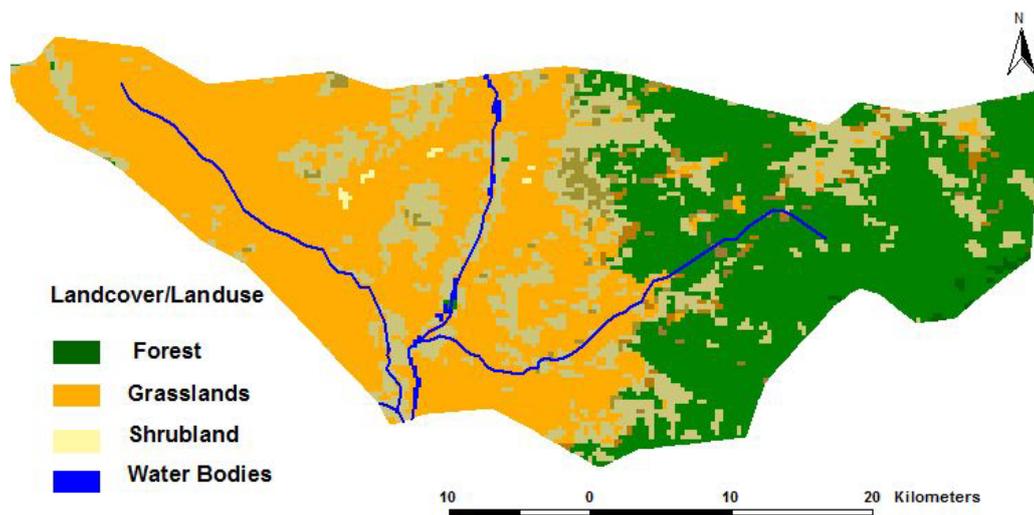
Figure 2. Landcover/landuse map of the middle Save Sub-catchment

5. Results

Figure 2 shows the spatial variations in landcover/landuse on the middle Save Sub-catchment. Grasslands occupy mostly the western parts of the sub catchment and cover 59% of the land area. Forests occupy mostly the eastern portions of the sub catchment and cover 22% of the area. Shrublands occur in patches surrounded by forests and grasslands covering 19% of the land.

Figure 3 shows the average monthly groundwater fluctuations from the mean level for different landcover types of the middle Save sub catchment. From November to around March levels of groundwater on all landcover/landuse types will be on the rise, by April they start falling and in July all landcover/landuse types will be having groundwater levels that are below their average levels. For all landcover/landuse types, October marks the lowest levels of groundwater decline and March marks the highest levels (Figure 3). Areas under forests have the highest magnitude of groundwater recharge (up to 20cm) and also the highest levels of groundwater lose (up to -20cm). Grasslands have the least recharge about 6cm at peak and the lowest magnitude of groundwater loses of about -7cm, shrublands are always in between.
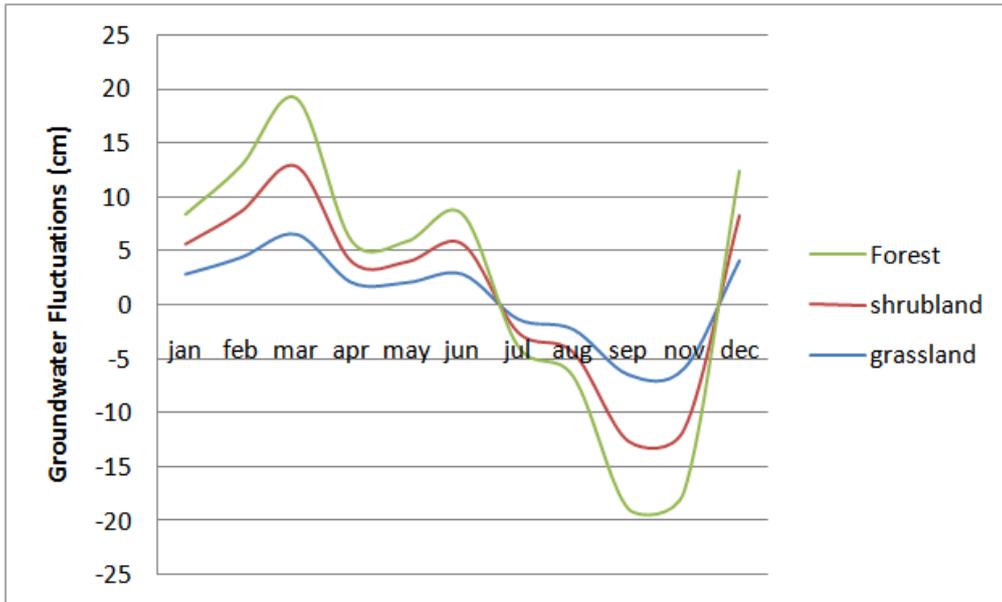
Figure 3. Average monthly groundwater fluctuations from the mean level for different landcover
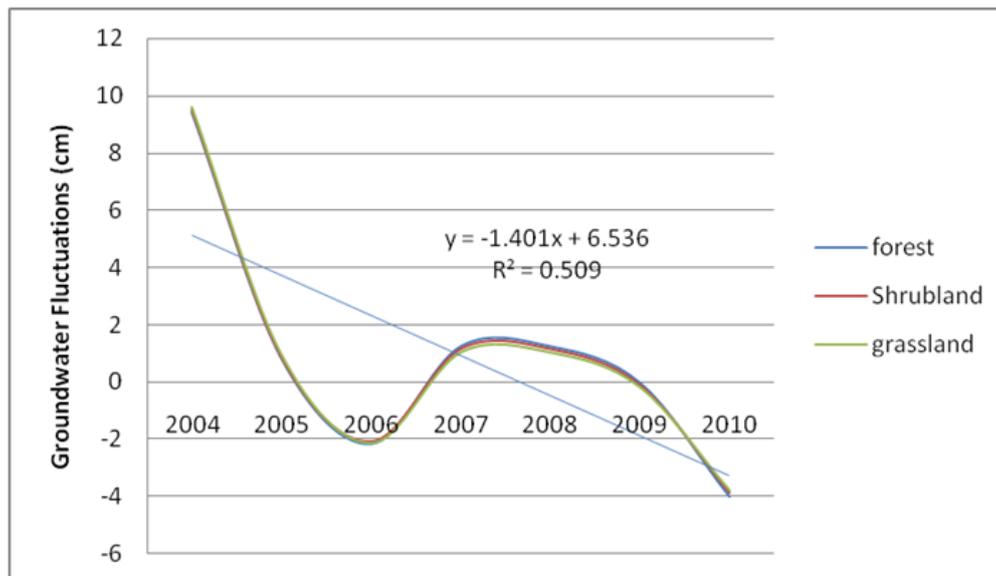
Figure 4. Average annual groundwater fluctuations from the mean level for different landcover

Figure 4 shows the average annual groundwater fluctuations from the mean level for different landcover types. From the year 2004- 2010 groundwater levels have been in a state of decline as shown by the negative trend line equation. The pattern of decline can only be marginally differentiated for all the landcover/landuse types but is more or less the same. The seasons 2005/6 and 2009/10 were years of groundwater drought as shown on Figure 4.

Figure 4 shows the r^2 or the coefficient of determination value of 0.5092. It is a measure of how well the regression line represents the data, this means that close to 51% of the total variation in y can be explained by the linear

relationship between *x* and *y* (as described by the regression equation).

6. Discussions

From the study, it seems that vegetation cover types only affect groundwater scenarios on seasonal bases. This means that different landcover/landuse affects differently the way groundwater is recharged and stored following monthly seasonal cycles. According to experimental research studying paired catchments, a reduction in forest cover causes an increase in groundwater yield, whereas an increase in forest cover causes a decrease in water yield. Forests consume more groundwater than shrublands, and grasslands use less water than forests [14,15]. The study here directly contradicts other studies on the same subject that conclude that forested areas would produce less groundwater recharge than grassland [16,17,18,27]. In the middle Save catchment it is mainly the forests that have the greatest amount of groundwater recharge followed by shrublands and grassland yield the least groundwater (Figure 3).

The reasons for this lack of conformity could be to due to the differences in rainfall amounts received between the eastern sections of the sub catchment that has forest cover and receive more rainfall (about 800mm and on the windward side of the mountain) than the western sections of the sub catchment that receive less rainfall (about 450mm and on the leeward side of the mountains). The situation could also be exacerbated by land degraded that besets the western parts of the sub-catchment. This is where the overcrowded communal lands of Buhera, Birchnough Bridge and Nyanyadzi are located. This land area is characterised by deforestation, gullies, soil erosion, and poor land use practices, overstocking siltation of river beds and overstocking. [28,29,30,31]. When rainfall comes, it will be lost mostly to runoff due the fact that the land surface is almost bare and rainfall comes as violent storms. On the other hand the forested areas are well managed and owned by commercial logging companies hence more water is make available to recharge groundwater.

However the research confirms what most researchers conclude in terms of groundwater loss. Land under forest cover has the greatest groundwater losses followed by shrublands and grasslands have the least amounts of groundwater lose. This is mainly because the area has shallow groundwater depths caused by the underlying basement rock hence groundwater can easily be lost to evapo-transpiration and also the bigger the biome the more water it can transpire into the atmosphere [17,32,33].

On a year on basis, groundwater scenarios do not seem to differ from one form of landcover to another. This may be due to the fact that other factors besides the ones used in the study become more important in influencing groundwater fluctuations. Slope, altitude and rainfall amounts received by the area could be the other important factors. The general decline of rainfall, which is the major input factor in the groundwater system has generally most likely influenced the negative trend of groundwater from 2004-2010. Long-term climatic trends cause changes in ground-water storage [34].

7. Conclusions

The research concludes that landcover/landuse affects seasonal groundwater fluctuations. Areas under forests have the highest magnitude of both recharge and loss of groundwater. Areas under grasslands have the lowest amounts of recharge and loss of groundwater. Shrublands are in between forests and grasslands in terms of ground water loss and recharge.

The research also concludes that there is a general declining trend in groundwater storage for all the landcover/landuse types from 2004-2010. Landcover/landuse types have been determined not to influence groundwater scenarios on a year on basis. GIS and remote sensing have been shown to be capable of producing groundwater scenarios of the study areas even in the absence of systematic groundwater observations. In terms of landuse planning and development of groundwater resources, care must be taken to conserve the resource as it has been show to on the decline.

The results from the research can be used for practical groundwater planning and management in the study area for the purposes of rural water supply and ecological integrity. The research also provides a methodology that can be used for groundwater assessments in places that are data constrained.

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