Evaluation of Watershed Scale Changes in Groundwater and Soil Moisture Storage with the application of GRACE Satellite Imagery data

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Abstract

As a hidden resource, our understanding and knowledge on the distribution of groundwater and its quantity is limited. In areas where such data is scarce, geo-observatory products such as the Gravity Recovery and Climate Experiment (GRACE) can provide an accurate estimate of changes in total terrestrial water storage at a coarser, regional resolution. However, in the Lake Tana basin, Ethiopia, groundwater is stored in localized aquifers, and its flow is controlled by physical variables (local geology, soil cover, slope, elevation difference, topographic index and drainage density) and climate (rainfall). The objective of this study is to utilize GRACE (CSR RL05) for the evaluation of spatial and temporal changes of soil moisture and groundwater storage at watershed scale. A geographic information system (GIS) based multi-layer analysis of the physical variables is implemented to delineate aquifer potential zones. The aquifer potential zone of the basin is combined with the GRACE (CSR RL05) based change in total terrestrial water storage data. Accordingly, the very high and high potential aquifer zone classes demarcate hot spots of high groundwater storage fluctuations recorded by the satellite data. The change in storage fluctuation of the 11-year monthly data, from 2003 to 2013, reveals that the total terrestrial water storage of the basin has declined by 18.37 cm. This is equivalent to the loss of 2.21 BCM of water within 11 years. Groundwater and soil moisture gains are a response of recharge, hence it is highly recommended to promote groundwater recharge, soil moisture harvesting, and sustainable use. On the other hand, the study highlights the possibility of application of the regional GRACE (CSR RL05) product for watershed-scale evaluations.

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27 **Key Words:** Gravity Recovery and Climate Experiment (GRACE), Groundwater storage, Soil
28 moisture, Tana basin, Blue Nile River

29 **1. Introduction**

30 In the face of increasing demand for water use (Wade et al., 2010), decision making and
31 sustainable water resources management demands tangible information about the quantity,
32 quality and spatiotemporal distribution of water resources. Groundwater accounts for most of the
33 freshwater resources in many terrestrial river basins (Wade et al., 2010; Famiglietti and Rodell,
34 2013). Although the potential is not yet well defined in the Tana basin, groundwater accounts for
35 most of the water supply in the area (Abiy et al., 2015; Kebede et al., 2006). However, due to the
36 increasing demand for domestic, agricultural and industrial use, groundwater is overexploited,
37 leading to the decline of wells productivity and stream discharge (Nigate et al., 2016; Abiy et al.,
38 2015; Enku et al., 2014). Sound knowledge of the aquifer's flow and storage changes allow
39 dependable water resources management and related decision making. Therefore, reliable
40 information derived from analytical tools and use of emerging technology options, such as
41 remote sensing products, can help in sustainable management and equitable allocation.

42 Recently, the emergence of the Gravity Recovery and Climate Experiment (GRACE) satellite
43 has brought a new dimension to water resources study, regionally (Rodell and Famiglietti, 2001;
44 Famiglietti and Rodell, 2013). After processing at different levels, the Center for Space Research
45 at the University of Texas, Austin, presents the GRACE (CSR RL05) data which indicates
46 monthly anomalies of total terrestrial water storage (Ward, 2004; Long et al., 2013). This data set
47 provides the net change in total territorial water storage (ΔTWS) having calculated the balance
48 between gain and loss terms, such as evapotranspiration (ET). Therefore, ΔTWS represents the
49 sum of the change in storage from aquifers, soil moisture, surface water reservoirs (lakes, ponds)
50 and snow water storage (Ward, 2004; Castle et al., 2014; Scanlon et al., 2016). GRACE

assimilated study has successfully outlined the trend and seasonality of groundwater storage change (Famiglietti et al., 2011), allowed to calculate all terrestrial water balance components (Rodell and Famiglietti 2001; Rodell et al., 2004; Tiwari et al., 2009), and used for evaluation of the impact of climate change and drought (Famiglietti et al., 2011; Castle et al., 2014). This suits the application of GRACE data to groundwater and soil moisture studies, especially in data scarce regions.

However, the spatial resolution of GRACE is quite coarse, ~400 km (Landerer et al., 2012. Rodell. et al., 2002), and hence it only helps to evaluate the regional terrestrial water storage changes. This limits the application of GRACE data for water resources allocation and management at small watersheds scale (Moore and Fisher, 2012). In filling the gap between lack of hydrological records and the requirement of sound knowledge-base in local and regional water resources planning and management, downscaling and redistribution of the analysis results to watershed scale is mandatory.

In the Tana basin, Ethiopia, groundwater monitoring system is not established. Hence, any information that would be relevant to groundwater resources study is scarce. Due to lack of information on how the groundwater system behaves, the use of the resources is based on traditional methods. It is observed that the sustained decline of the groundwater table and the decreasing trend of groundwater production wells is a common phenomenon. This calls for an urgent understanding of the groundwater reserve in the area. Therefore, reliable information derived from emerging technology options, such as remote sensing products, is mandatory to evaluate and understand the groundwater distribution in the basin.

Hence, the objective of this study is to evaluate the representativeness of GRACE driven change in total terrestrial water storage at watershed scale in the Tana basin. Further, this study attempted to redistribute the GRACE change in storage record at local scale to identify hotspots of significant storage variability by using aquifer potential zones of the basin.

1.1. Description of Study Area

The Tana basin, Ethiopia, with a catchment area of 15,000 km² and four major tributary rivers (Fig. 1) forms one of the sixteen basins of the Blue Nile River Basin in Ethiopia. Mountainous landscape surrounding flat lowland, the Lake Tana forms the center of the basin. The basin has a unimodal rainfall regime, ranging of from 865 mm 2300 mm per year.

Insert Figure 1 here.

The basin exhibits porous medium fractured unconfined aquifer system where groundwater recharge from mountainous regions flows into the gently laying lowland. The lowland, surrounding by the Lake Tana water body, is a major groundwater reserve zone of the basin (Nigate et al., 2016; Ayenew, et al., 2008). The aquifers are only rarely connected to the Lake Tana water body, and hence aquifers and the lake interaction is only through surface flow (Kebede et al., 2006). Overall, total terrestrial water storage of the basin is dominantly a function of groundwater recharge-discharge relation and soil moisture fluctuation.

2. Dataset and Method

2.1. Dataset

For delineation of aquifer potential zones, the local geological data, soil type, rainfall, and digital elevation model (DEM) were used. Categories in each layer are converted into numerical scales as 'Layer Classes'. These layer classes allow evaluation of the relative internal variations within each layer in the context of groundwater holding and transmission capacity. The details of the description of data are given below.

2.1.1 Geology

The dominant part of the basin is covered by two major geological formations, the Tarmaber Basalts and Basalts related to volcanic center (BECOM, 1998; Chorowiz et al., 1998). The Tarmaber Basalt covers the northern, western part and the southern end of the basin (Fig. 2). The lowland covered by thick Quaternary Alluvial deposit, lacustrine deposits and Colluvium forms the major aquifers zone. Basalts related to volcanic centers predominantly containing scoriaceous basalt covers the southern part of the Tana basin. As indicated on the geological map (Fig. 2), the Amba Aiba Basalts, Lateriteon Amba Alaji Rhyolite and Ashangi Basalts are sparsely distributed in the basin.

Hydrogeologically, there are three major aquifer systems, the Tertiary Volcanic, the Quaternary Fractured Vesicular Basalt and the Quaternary Alluvial deposits (SMEC, 2007; BECOM, 1998, SOGREAH, 2013). The south part with Quaternary Basalt overlain by Alluvial Deposit exhibits the highest productive aquifer. Whereas, the northern, southern and eastern mountainous regions, mostly covered by highly degraded tuff and massive basalt, are characterized by lowest productivity (SOGREAH, 2013).

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With this information, the geologic units (Fig. 2a) are changed into numerical index values as ‘Geology Class’ (Fig. 2b), following the aquifer medium rating approach of the DRASTIC analysis (Aller et al., 1987). Accordingly, the rating value of 1 corresponds to impervious geologic units and rating of 10 is assigned to highly pervious geologic units. Hence, the geologic class values represent the measure of the degree of geologic units to act as an aquifer; the higher the number, the higher the geologic unit can be a productive zone.

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2.1.2 Soils

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The Tana basin is covered by a wide range of soil types, as indicated in the soil databases of the area (Fig. 3a); originally developed by BECOM (1998). According to the description and hydrological grouping by SMEC (2007), the upslope region is covered by soils with higher infiltration and drainage capacity. The floodplain to the north and east of Lake Tana is covered by thick clay layer, which presents a lowest infiltration capacity. However, the soil in the southern flood plain is covered by rock fragment that has higher infiltration capacity.

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Insert Figure 3 here

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Following the soil hydrological grouping of SMEC (2007), the soil map of the basin (Fig.3a) is changed into numerical index values (Fig. 3b) based on the rating approach proposed by the DRASTIC analysis (Aller et al., 1987). These numerical index values of the Hydrological soil group (HSG) represent the relative rating of soils infiltration and drainage capacity. Soils with high infiltration and drainage capacity receive high rating value and vice versa. As high rating

value represent sites of high infiltration and drainage capacity, it implies high groundwater recharge zones.

2.1. 3 Rainfall Distribution

The Tana basin receives an effective three-month rainfall from June to September and areal distribution varying from 866 mm to 2300 mm (Fig. 4a).

Insert Figure 4 here

The southern parts of the basin have the highest annual precipitation, and the northwest has the lowest. For this study, the rainfall data was scaled from one to hundred, according to Eq. 1; and the scaled rainfall distribution (Fig. 4b) is used as index value to delineate the aquifer potential zone of the basin.

$$X_{normal} = \begin{cases} \frac{X - X_{min}}{X_{max} - X_{min}} & X_{max} - X_{min} > 0 \\ 0 & X_{max} - X_{min} = 0 \end{cases} \quad (1)$$

Where:

- X is the original pixel value
- X_{normal} is the normalized pixel value.
- X_{max} is the maximum pixel value of the layer under consideration for the basin.
- X_{min} is the minimum pixel value of the layer under consideration for the basin.

Accordingly, highest scale values are assigned to the corresponding area with high rainfall distribution. Hence, these areas are associated with high groundwater recharge and high aquifer potential zone.

2.1.4 Digital Elevation Model (DEM)

The 90 m resolution Shuttle Radar Thematic Mapper Digital Elevation Model (SRTM DEM) (USGS-GMTED, 2010) is used to develop elevation difference, drainage density, slope class, and topographic index layers which are further scaled from 1 to 100 (Eq. 1). Each of the scaled layers is reclassified into five classes based on their geometric distribution (Fig. 5).

In the Tana basin, the high topographic elevation zone is a groundwater recharge zone. The lower topographic elevation zone is a groundwater discharge zone that is manifested through seep zones, wetland and springs (Engda et al., 2007; Kebede et al., 2006; Kebede et al., 2005). As a result of these conditions, the lower elevation zone presents a high groundwater potential in the area. This implies that elevation is inversely proportional to groundwater reserve zones, therefore the lowest elevation zones receive higher value of the scaled elevation class and vice versa (Fig. 5a).

Insert Figure 5 here

Given the unconfined nature of the highly fractured medium of the Tana basin, topographic slope controls the rate of groundwater flow in the subsurface (Engda et al., 2007; SMEC, 2007). Steep slope favors runoff and/or an accelerated subsurface flow and gentle slope allows the accumulation of groundwater. Accordingly, the slope is inversely proportional to aquifers

potential and hence the inverse of the normalized slope is (Fig. 5b) deployed to define groundwater potential zone of the area.

In addition to topography, the nature of the geologic material determines the type and density of the drainage. In the Tana basin, highland zones have typical box drainage pattern; whereas, streams at the floodplains have meandering pattern. The lowlands are highly characterized by zones of spring emanation, such as the Lomi and Areki springs of the southern part with a discharge of up to 106 l/s to 200 l/s (Nigate et al., 2016). Also, several small streams and gullies are saturated at lowland areas, and these are formed by shallow and saturated subsurface flow of groundwater (Tebebu et al., 2010; Abiy, 2009). Although the drainage density of the basin shows small variation with location, it is considered to be directly proportional to groundwater accumulation. High drainage density is proportional to high groundwater reserve and vice versa. The normalized and geometrically reclassified drainage density map (Fig. 5c) is deployed for aquifer potential zonation of the basin, accordingly.

Evaluation of the distribution of wetness through the Topographic Index (TI) framework (Beven et al., 1984; Beven and Kirkby, 1979) is widely applied to hillslope hydrologic studies (Lyon et al., 2006; Lyon et al., 2004; Schneiderman et al., 2007; Walter et al., 2002). As the TI (Eq. 2) increases with increasing upslope contribution area and decreasing slope, it is known to effectively remarket zones where shallow groundwater accumulates and forms saturation. At soil saturation, runoff and groundwater recharge happen simultaneously. Hence, sites with high TI define shallow groundwater accumulation zones that would lead to runoff and/or groundwater recharged. Implying, TI is directly proportional to groundwater recharge and accumulation.

$$TI = \ln\left(\frac{\alpha}{\tan\beta}\right) \quad (2)$$

Where: TI is the topographic index. α is the upslope contributing area per unit length of contour. β is the topographic slope of every cell. To avoid division by zero, the zero slope areas are changed by 10^{-3} .

For this study, the SRTM 90 DEM is processed in ArcGIS to develop topographic index map of the Tana basins. The result is normalized to a scale of 1 to 100. As a result, the normalized TI map of the area is reclassified into five classes according to its geometric distribution (Fig. 5d) and this is deployed to delineate groundwater potential zones of the area. As a result, high TI is proportional to high groundwater reserve and low TI is proportional to lower groundwater reserve.

2.2. Defining Groundwater Potential Zones

A weighted index map of the seven thematic layers develops the potential groundwater reserve zones within the basin. For an overall summation of the individual layers, the thematic layer's relative weight (W_i) is defined by using pairwise comparison matrix (Satty, 1980). Besides field knowledge of the area, the pairwise comparison is assigned based on similar studies elsewhere (Fenta et al., 2014; Kumar, 2007). Hence, a GIS-based multi-layer analysis, as indicated in the chart (Fig. 6), is applied to define groundwater potential zones within the basin. The overall weighted index map is developed as:

$$APZ = \sum_{i=1}^n (Rc)_i * W_i \quad (3)$$

Where: APZ = Aquifer Potential Zone overall index, Rc = Rate of the classes within every thematic layer, i, W_i = Weight of the thematic layer, i.

Insert Figure 6 here

Furthermore, the overall weighted index is qualitatively interpreted as five classes of groundwater potential zones. This allows scrutinizing the areas with different levels of aquifer potential, where the high groundwater potential zone implies a high capacity of the aquifer to store and transfer water and hence a high change in storage and vice versa.

2.3. Combining GRACE with Local Aquifer Potential Zone

For this study, we have used the GRACE change in total terrestrial water storage (ΔTWS) data from University of Texas Center for Space Research release five (GRACE CSR RL05). GIS-based resampling of this 110 km by 110 km (Fig. 7a) into 90 m x 90m pixel size allows to effectively delineate the GRACE CSR RL05 that is incorporated in the basin (Fig. 7b). The resampling further allows for calculating the total ΔTWS (cm) of the basin. Accordingly, the sum of the GRACE (CSR RL05) pixel values that are included within the basin is the net ΔTWS (cm) of the basin for the corresponding month. The monthly basin's ΔTWS (cm) is calculated for the time period 2004 to 2013. Some missing data within this time range are filled by averaging and/or applying the corresponding month value from other times.

Insert Figure 7 here

In the case of the Tana basin, the total terrestrial water storage is the sum of the change in water storage derived from the groundwater reserve, soil moisture, and surface water bodies. The Lake Tana water body is 3,000 km² area, accounting about 20% of the basin's total area. Hence, the lake level fluctuation is significant in the evaluation of the ΔTWS . Lake level fluctuation data presented in SMEC (2007) and additional data from the Tana Sub-basin office are used to calculate the monthly anomalies of lake stage. The GRACE (CSR RL05) ΔTWS is equal to the

sum of change in groundwater storage (GwS), change in soil moisture (SoM) and change in surface water reserve (SwR) in depth units (cm). Hence, the change in storage of the basin's groundwater and soil moisture is the difference between the GRACE (CSR RL05) Δ TWS and the respective month change surface water storage (SwR, Eq. 4).

$$GwS + SoM = \Delta TWS - SwR \quad (4)$$

The SwR is the sum of the change in storage from stream channels and Lake Tana storage. However, the dominant SwR of the basin is driven from the change in storage of the Lake Tana water body; whereas, the change in storage from stream channels is insignificant. For such analysis, given the time resolution of GRACE (CSR RL05), the SwR has been considered as the change in storage from surface water reservoirs only (Long et al., 2013). Hence, the Lake Tana monthly change in lake level is used in terms of SwR (cm).

Overall, for spatial redistribution of the GRACE (CSR RL05) Δ TWS (cm) at the watershed scale, the following simplified assumptions were made.

- The change in total terrestrial water storage of an area on the ground surface represented by a pixel in GRACE (CSR RL05) Δ TWS (cm) is not uniformly distributed within the area at the ground surface;
- Some part of the area, at the ground, with high aquifer potential can show the larger gain or loss than the change in storage recorded by GRACE (CSR RL05) Δ TWS (cm); whereas, part of the area with limited aquifer potential do not have significant change in storage.

- The monthly GRACE (CSR RL05) ΔTWS of the Tana basin is the sum of the monthly changes in groundwater, soil moisture, and surface water storage changes. Given the duration and scale of observation of the GRACE (CSR RL05) ΔTWS and considering the quick runoff response and size of the basin, the surface water change in storage is defined by the change in stage of the Lake Tana, only.

Accordingly, the overall gain or loss of the groundwater storage from the area is a factor of the relative index value of every pixel as compared to the overall basin's aquifer potential index. Hence, this relative index value of every pixel, for simplicity, is called Fractional Pixel Value (FPV) and was calculated based on Eq. 5 as:

$$FPV = \frac{APZ_i}{\sum_1^n APZ_i} \quad (5)$$

Where: FPV = Fractional Pixel Value is the relative proportion of every pixel to represent the groundwater reserve potential in the defend aquifer zone, and APZ_i = the pixel value of the Overall Aquifer Potential Zone Map.

The fractional pixel value represents the significance of each pixel within the aquifer potential zone layer to behave as a groundwater storage unit. The higher the Fractional Pixel Value the higher a pixel can represent sites that gain or lose water from storage.

3. Results and Discussion

3.1. Aquifer Potential Zoning

In this study, seven thematic layers were developed to delineate aquifers potential in the Tana basin. To designate the internal layers rating, each thematic layer was reclassified into five geometric classes. The relative weight of the individual layers is evaluated using pairwise comparison matrix (Table 1).

Insert Table 1 here

According to this evaluation, the topographic index and elevation difference layers exhibit about 30% of the weight to control the distribution of the groundwater reserve zone in the basin. The Tana basin is predominantly characterized by rolling mountain terrain with numerous local watersheds. With the unconfined shallow nature of the aquifer, it has pockets of aquifer zones which are highly controlled by the upslope contributing area and its relative location with respect to the overall basin. Hence, it is plausible that the topographic index and elevation difference layers receive the higher weight.

There is sufficed amount of rainfall to recharge the aquifer all over the basin. As a result, rainfall is not a limiting factor to define groundwater potential zone. Instead, the groundwater recharge in the area is limited by the combined effects of slope, geology and soil cover. This latest three layers, all together, account for more than 30% of the weight to control aquifer potential zones in the basin.

The sum of the product of the thematic layer's rate with their relative weight (Eq.3) generates a range of index values that imply the local distribution of aquifer potential zones and their total index value (Fig. 8a). The overall index values range from 3 to 380. Smallest values represent areas with limited capacity to reserve groundwater and vice versa. Accordingly, mountainous

regions with steep slope and tuffaceous geologic unit zones have the lowest aquifer potential. Lowlands, with highest flow accumulation zones and covered by pervious soil and geologic units along gentle slope area have the higher aquifer potential. A range of intermediate index values is recorded in western part as a control of the soil type and TI values.

Insert Figure 8 here

The ten class aquifer potential index value (Fig. 8a) is geometrically reclassified into five qualitative aquifer storage potential zones (Fig. 8b). Accordingly, the southern part of the Tana basin, with its higher topographic index, porous vesicular basaltic cover, and low lying flat topography, has the highest aquifer potential. This implies a potential for high change in storage variability over the shallow unconfined aquifer in the locality. The eastern lowland area, despite its highest topographic index, has a thick clay layer which limits its groundwater storage potential. Moreover, the mountain regions, at all sides, have lower groundwater storage potential.

Overall, the aquifer's potential zone delineation result well matches with previous regional studies by Ayenew et al. (2008) and SOGREAH (2013). However, this result has some advantages with a better resolution (90 m), and the fact that it is digitized allowing for further analysis to downscaling of the GRACE data.

3.2. Spatial redistribution of the GRACE Δ TWS

The spatial distribution of the monthly change in total terrestrial water storage (Δ TWS) indicate that the downstream areas, delineated as high and very high Aquifer Potential Zones (Fig. 8b), show most of the monthly total storage changes observed by the GRACE (CSR RL05). The

redistributed monthly change in storage result (Fig. 9²) shows that these sites exhibit the highest gain and loss of the total terrestrial water storage within the basin. These sites are typically characterized by high topographic index and contain porous basalt. Considering the change in groundwater and soil moisture storage is a replica of this ΔTWS , these sites are the hotspots that show the significant change in groundwater and soil moisture storage. Besides that, these sites have a rapidly increasing but slowly decreasing pattern of the monthly ΔTWS . Over all, the area to the south of the Lake Tana is the highest Aquifer Potential Zone of the basin, and this is the hotspot where the storage fluctuation is the highest.

On the other hand, mountain regions show a small range of ΔTWS fluctuations. The impervious nature of the tuffaceous geology, steep slope and limited topographic index has defined this area to be the lowest aquifer potential zone. As a result, despite rainfall availability the aquifer potential is limited and its storage fluctuation is infinitesimal. Further, low fluctuations of storage are also observed in the downstream area of the basin. Areas where the geology is covered by impervious formations, and/or thick clay layer and availability of abrupt change in the topography have triggered poor to low aquifer potential zones within the downstream area of the basin. Over all, these sites, delineated as poor and low aquifer potential zones (Fig. 8b) at mountain regions and lowland areas, show a small range of ΔTWS , and they exhibit quick shift between gain or loss in TWS.

² figures label 'a' refer the original GRACE (CSR RL05) data and the figures label 'b' are the redistribution product of the corresponding month.

351 The GRACE (CSR RL05) is in depth (cm) unit, whereas the numbers on the re-distribution map
352 (Fig. 9³) represent the relative proportion of change in storage. Negative values refer to losing
353 stage, and positive values represent gaining stage of the change in total terrestrial water storage.
354 The magnitude of the numbers represents the level of loss or gain. It doesn't refer to the actual
355 depth of change in storage, however.

356 *Insert Figure 9:*

357 *Insert Figure 10.1 here*

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³ figures label 'a' refer the original GRACE (CSR RL05) data and the figures label 'b' are the redistribution product of the corresponding month.

3.3. Long Term Δ TWS

The total monthly change in soil moisture and groundwater storage shows cyclic gain and loss (Fig. 10), consistent with the seasonal rainfall pattern of the area. The decrease in water storage stage of the basin is consistent with dry season. Studies indicate similar findings, in the Gilgel Abbay catchment of the basin (Enku et al., 2014). They have found a declining stream discharge in dry season and concluded that the dryness of the Gilgel Abbay River is driven by declining groundwater recharge and discharge. Likewise, a GRACE based groundwater study of the Amazon basin (Frappart et al., 2013) indicates cyclic gain and loss of groundwater storage consistent with the rainfall pattern of the area.

Insert Figure 12 here

The watershed changes in soil moisture and groundwater storage lags behind the peak rainfall of the area. The maximum precipitation is in July, while the GRACE change in total water storage rises to the maximum in August to September. After September, the groundwater system gains at a decreasing rate until November. Most of the records indicate that the change in storage becomes zero at November. This reflects that the groundwater system is totally dependent on local recharge. Furthermore, the decreasing trend of the groundwater storage change occurs during the dry season. Likewise, the losing stage of the groundwater reserve drives the low flow condition of the streams. Based on this, it is evident that soil moisture and groundwater storage variability is driven by local precipitation, whereas the dry season environmental flow requirement is dependent change in storage of the aquifers (Enku et al., 2014).

The 11-year monthly change in storage indicates that the basin has a wide range of change in total storage fluctuation (Fig. 11a). This period's total annual storage indicates six out of the 11 observation years exhibit dryness in net soil moisture and groundwater storage (Fig. 11b).

Insert Figure 13 here

Although the annual changes in storage is consistent with the rainfall pattern, the net annual groundwater and soil moisture storage change of the total study period indicates that the Tana basin has an ultimate loss of 18.37 cm within the hydroperiod 2003 to 2013. Considering the basin 15,000 km² area, this is equivalent to a net loss of 2.21 BCM of water. Analysis on the causes of the groundwater and soil moisture storage changes is not considered under this study.

4. Conclusion and Recommendation

4.1. Conclusion

Besides a good agreement with previous studies, the aquifers potential evaluation in this study is made with a better spatial resolution, hence it can be useful for local groundwater investigation, development and management. More importantly, the raster nature of the aquifer potential index map developed in this study is effectively deployed to redistribute the GRACE change in total terrestrial water storage information. As a fact, the study has presented an admonitory approach to refining and extracting groundwater storage changes from the GRACE database.

Based on this, the downscaled GRACE driven change in watershed water storage information has a good agreement and a strong implication to the aquifer system. The increasing groundwater storage is driven by precipitation with some lag time. Hence, the area is predominated by unconfined aquifers that have inter-annual variability of water storage as a reflection of the

rainfall. Likewise, the losing stage of the groundwater reserve drives the low flow condition of the streams. Therefore, it is evident that the streams are highly dependent on the change in groundwater reserve of the area.

4.2. Recommendation

The time series analysis indicates an overall declining trend in soil moisture and groundwater storage change in the basin. Hence the declining groundwater reserve trend is evident. As a fact, a sustainable use of the groundwater resource of the basin should be based upon an informed decision on the overall aquifer storage and productivity. In addition, facilitation of groundwater recharge mechanisms and soil moisture harvesting system are highly recommended.

For further application of the redistribution products to monitoring and evaluation of changes in groundwater resources at local scale, it is recommended to evaluate the results using local ground based information on groundwater and soil moisture. It is recommended to incorporate groundwater and soil moisture monitoring data to the results of redistribution of GRACE (CSR RL05).

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and opens source information from USGS and Center for Space Research at the University of Texas, Austin. Hence, we are grateful to our data sources.

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Geology

■ Alluvium

▨ Amba Aiba Basalts

▨ Ashangi Basalts

× × Basalts related to Volcanic centers (1)

× × Basalts related to volcanic center (2)

▨ Basalts related to volcanic centers (u)

▨ Basalts related to volcanic center (3)

▨ Coluvium

■ Lacustrine deposits

■ Lake

▨ Laterite on Amba Alaji Rhyolite

■ Marsh soils

▨ Termaber Basalts (2)

Tana Basin Aquifer Potential Index and Aquifer Potential Zone

Change in Storage of the Tana Sub-basin Groundwater and Soil Moisture

Inter Annual Change in Storage Variability

Net Annual Change in Storage

Table 1. Pairwise comparison matrix of the layers used for aquifer potential zonation

Description	TI	Elevation Difference	Slope	Drainage Density	Soil	Geology	Rainfall	Weight
TI	1	3	5	7	6	1	4	0.29
Elevation Difference	0.3	1	7	9	8	4	7	0.28
Slope	0.2	0.1	1	8	2	5	2	0.12
Drainage Density	0.1	0.1	0.1	1	6	8	3	0.11
Soil	0.2	0.1	0.5	0.2	1	7	3	0.08
Geology	1	0.3	0.2	0.1	0.1	1	5	0.09
Rainfall	0.3	0.1	0.5	0.3	0.3	0.2	1	0.03

Figure Captions

Figure 1. Location map of the Tana Basin. The basin located at the north of the Blue Nile River Basin; it is the source of the Blue Nile River.

Figure 2: Geological Map of the Tana basin (a. Source: BECOM, 1998) and Geology Class (b) that represents the corresponding rating of the geologic units changed in to numerical values based the aquifer media classification scheme of the DRASTIC model (Aller et al., 1987).

Figure 3: Tana basin Soil Classification (a. Source: BECOM, 1998) and the Hydrological Soil Grouping (HSG) rate (b).

Figure 4: Rainfall Stations and Areal Distribution of Precipitation in the Tana basin (a), and the Rainfall Class for overlay use (b).

Figure 5. The five class geometric distribution of the four layers developed by using the SRTM 90m DEM of the area and normalized by using Eq. 1: a) Elevation, b) Slope, c) Drainage density, and d) Topographic Index.

Figure 6. Flow chart to delineate Aquifer Potential Zones in the Tana basin and combining GRACE data with Aquifer Potential Zone of the Tana basin.

Figure 7. The Tana basin GRACE (CSR RL05) Δ TWS (cm) data with 110Km pixel size (a) and 90m pixel size (b). Resampling of the GRACE (CSR RL05) allows to clipping by the basins catchment divide, so the net basin Δ TWS (cm) can be defined and the clipped product (b) is used to delineate the define hot spots of change in storage.

Figure 8. Tana basin Distribution of the Aquifer Potential Zone Index and Potential Zone index value (left) and qualitative interpretation of the index values (right).

Figure 9. The GRACE (CSR Release-05) ΔTWS of the Tana basin (a) and the redistributed product (b) is indicated in monthly basis for the year 2006. The distribution of gain and loss sites indicate that the Poor Aquifer Potential zones are the fastest to gain and lose the ΔTWS . The very high and high Aquifer Potential zones show fluctuation of storage for extended period, however these sites remarket the largest range of change in storage fluctuation with time.

Figure 10: Net Change in Groundwater and Soil Moisture Storage of the Tana basin. Subtracting the change in Lake Level of the Lake Tana from GRACE (CSR RL05) generates the net Groundwater and Soil Moisture of the basin.

Figure 11. Inter annual storage variability (a) and the total annual net change in the groundwater and soil moisture storage (b) of the Tana basin.