

RESEARCH ARTICLE

ESTIMATION OF CHANGE IN TERRESTRIAL WATER STORAGE FOR ABBAY RIVER BASIN USING OPEN ACCESS SATELLITE DATABASES AND HYDROLOGICAL MODEL

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ABSTRACT

Access to freshwater resources has become more limited. Correspondingly, water monitoring methods in sensitive or critical areas interims of terrestrial water storage are becoming increasingly important. The monitoring of the water storage in this area, using appropriate methods and data sets, is highly effective in preventing possible future water crises. This paper aims to estimate terrestrial water storage of the Abbay river basin with available data and tools where hydro climatological studies are scarce due to limited observation. The data obtained from GLDAS, GRACE and TerraClimate were used for the analysis of terrestrial water storage in the river basin. The result shows that there was a varying trend of terrestrial water storage for the study time. We have observed water shortages during the dry season and surplus water during the wet season. The monitoring of changes in terrestrial water storage is crucial for optimal water resource utilization and our results confirm the major role of such monitoring in decision-making processes and management.

KEYWORDS

GRACE Satellite, Hydrological Model, Terrestrial Water Change, GLDAS, Dry Season, Wet Season, TerraClimate

1. INTRODUCTION

Many areas of the world are facing water scarcity. The water crisis as one of the severe challenges influences different sectors (e.g. energy, food, health, environment and economy). The severity of impact of a water crisis depends on different conditions such as topography, weather pattern, and management plans applied in the area. In addition, different forces such as human activities and climate change can add an extra pressure on water resources. For example, change in temperature, evaporation, precipitation distribution affects the hydrological cycle and thus water resources including surface and groundwater (Moghim, 2018; Liuzzo et al., 2015). World freshwater accounts for less than 3% of the total amount of the water on the Earth and is mainly stored in polar glaciers or underground (Chao et al., 2018). For the sustainable management of water, it is essential to assess changes in terrestrial water storage (Hoekstra, 2014). River basins require effective and compressive water management and planning for optimization of the basin water resources (Ferguson et al., 1981). The long term water balance assessment provides improved knowledge of regional and global climatic change and identifies the effect of human beings on water resources (Cretaux & Birkett, 2006; Velpuri et al., 2012; Bracht-Flyr et al., 2013; Mahe et al., 2013; Sutcliffe & Petersen, 2007; Xianghong et al., 2019). Climatic change and anthropogenic modification was due to change in river flow during wet and dry season and is the witness of climate change (Mahe et al., 2013) and more researcher was warranted to understand, simulate and predict the hydrological regimes of the water bodies (Wagner et al., 2010). According to (Ram Karan Singh and Post Doc., 2008), knowing water balance is an essential component of water management and water management is understanding the hydrologic cycle of the river basin.

For water balance estimation, in-situ measurement of each element of water balance gives a completed understanding of the water in the basin ideally. But, in reality, direct measurement of all components of the water balance was not done at all. In-situ data is inadequate and incomplete to indicate the water balance of the water bodies. In recent decades, different researchers have investigated changes in water resources for different regions using satellite, ancillary, and hydrological models for water resource optimization and mentoring. Satellite images were used to analyze the distribution of surface water in the river basin as static and as binary variable (Haas et al., 2009; Kuenzer et al., 2013; Kuenzer et al., 2015; Feng et al., 2014; Ogilvie et al., 2015). Due to a very Advanced High Resolution Radiometer, Moderate resolution Imaging Spectro-radiometer and Visible Infrared Imaging Radiometry Suite, Optimal sensors with coarse spatial resolution and daily orbit were detecting water changes at high temporal resolution. From MODIS data, water surface change was estimated across lakes in China from 2000 to 2010 using 8-day MODIS data (Sun et al., 2014). The monthly extent of inland water bodies from 1986 to 2012 in central Asia was estimated using MODIS and Advanced High Resolution Radiometer data was estimated (Klein et al. 2014). Rodell and Farmiglietti (2001) used the Gravity Recovery Climate Experiment to assess terrestrial water in Illinois. Their results show soil moisture and groundwater changes caused the largest water storage changes. Tiwari et al. 2011 estimated changes in water changes in southern India using GRACE. They showed hydrological changes having strong impacts on changes measured by the GRACE. Moiwo et al., 2011 used GRACE and an empirical model to evaluate water storage changes in the Himayas and Tibetan Plateau, and their results detect storage variation with small random errors. Nie et al., 2018 evaluated terrestrial water storage from GRACE to show global drought index (TSDI), which was correlated with

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other drought indicators, and their result indicates TSDI can be used to monitor drought globally. Chinnasamy and Agoramoorthy 2015 estimated changes in groundwater using Global Land Data Assimilation System and GRACE dataset in Tamil Nadu. Their result is mainly used for agriculture in Tamil Nadu (India) and confirmed a remarkable depletion rate that is higher than the recharge rate. Syed et al. 2008 indicates that the simulations of TWS from GLDAS are consistent with corresponding TWS from GRACE. All these studies confirm that dataset used from GLDAS and GRACE can be important to estimate water resource variations and hazards like droughts, floods etc.

Few studies indicate the seasonal change of water resources in Ethiopia, mainly focusing on characterization and forecasting of seasonal precipitation and meteorological drought analysis. In the present study area, due to changing topography, terrestrial water storage estimation is a challenging task because of the complexity of water balance components and to date, there is no explicit information on the GRACE and GLDAS databases for the estimation of terrestrial water storage that exists for the Abbay river basin, although these data products are very important for local, regional water resource managements. Considering the lack of high-precision, reliable water balance components, hydrological data, insufficient knowledge of terrestrial water balance and limited technologies, our research concentrated mainly on estimating terrestrial water storage based on GRACE, TerraClimate, GLDAS dataset and, for the first time, produces a continuous yearly, monthly and seasonal terrestrial water storage change and liquid equivalent water thickness for the Abbay river basin using machine-learning methods. So, the general objective of this study was to estimate changes in terrestrial water storage in the Abbay river basin using Open Access Satellite Databases and Hydrological Model. Unlike the other studies described here, the emphasis of this work is towards understanding the temporal and spatial changes of different hydrologic fluxes to estimate terrestrial water storage of the study area.

The specific objective of this study to propose ways to process NASA's GRACE and GLDAS satellite mission data to monitor dynamic changes in the terrestrial water storage in the abbey river basin. To estimate liquid

equivalent water thickness for the Abbay river basin using GRACE dataset during the study time To integrate GLDASE with other hydrological and geospatial variables to estimate TWS for the study area To assess trend variability and slopes of TWS and LWE for the Abbay river basin using Mann-Kendall trend test and Theil-Sen's estimate

2. MATERIAL AND METHODS

2.1 Study Area

The study was located in the northeastern parts of Ethiopia at $7^{\circ}40'N$ and $12^{\circ}51'N$ latitude and $34^{\circ}25'E$ and $39^{\circ}49'E$ longitude with an area of approximately 176,200 km² and an elevation difference from 483 to 4266 m AMSL. Ethiopia have 12 river basin and this study was focused on Abbay river basin. Abbay river basin was one of the tributaries of the Nile River, the world's longest river (Cherinet et al., 2019). The first world civilization in the art of irrigation and cultivation of crops was around the Nile River (Woodward et al., 2007). The river is a transboundary river which covers the drainage basin of 11 countries, such as the Democratic Republic of the Congo, Tanzania, Burundi, Rwanda, Kenya, Ethiopia, Eritrea, South Sudan and Egypt flow to Mediterranean Sea (Oloo and Adams, 2007). The Abbay River is an essential river for Ethiopia, and the Grand Renaissance Dam of Ethiopia was constructed on it. The river starts in the high mountainous part of Ethiopia and serves as a contributor to the Nile River. It is located in an area where water is a critical resource for domestic use and irrigation agriculture. The upstream part of the river basin is dominated by mountainous landscapes and most of the downstream areas are relatively flat or gently undulating. There are varying climatic zones in the river basin due to environmental conditions. The maximum temperature of the river basin ranges from 28 °C to 38 °C and the minimum temperature is 15 °C to 20 °C downstream. Generally, rainfall in the study area ranges between 787 mm and 2200 mm per year and the lowest rainfall recorded was less than 100 mm per year. The wet season in Ethiopia begins in April and ends in September. The dry season was from November up to February (Getashaw and Mark, 2020).

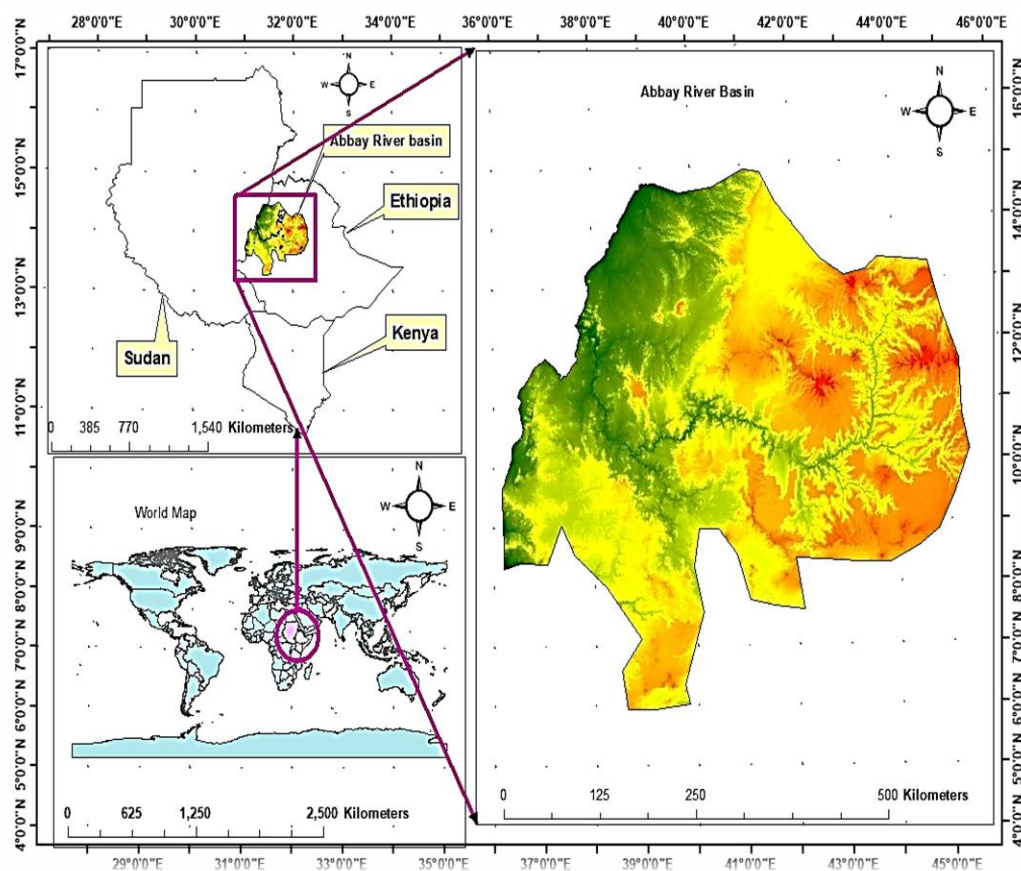


Figure 1: Location map of the study are

2.2 Data Collection

To estimate terrestrial water storage in the Abbay river basin, different datasets were used, such as Surface soil moisture(SMS), profile soil moisture(PR), root zone soil moisture(RZSM), surface runoff (Qs), canopy water storage (CWS), Temperature (T), evapotranspiration (ET) from

GLDAS processed at NOAA($0.25^{\circ} \times 0.25^{\circ}$) and resample to $1^{\circ} \times 1^{\circ}$ for further hydrological data analysis. Precipitation data from Terra-Climate is at 0.5° resolution and resample to $1^{\circ} \times 1^{\circ}$. The data were collected from January 2010 to December 2020, with monthly temporal resolution and presented in table 1 below.

Table 1: Dataset used for change in groundwater storage for the study area

Parameters	Source and processing	Unite	Converted to
Terra-Climate Precipitation	Precipitation(0.5°x0.5°) Resample to (1°x1°)	mm	mm
GLDAS Soil moisture storage(SM, PR, RSM)	NOAH model SM (0.25°x0.25°) Resample to (1°x1°)	kg/m2	Mm by using conversion factor
GLDAS surface runoff(Qs)	NOAH model SM (0.25°x0.25°) Resample to (1°x1°)	kg/m2/s	Converted into mm
GLDAS canopy water storage(CWS)	NOAH model SM (0.25°x0.25°) Resample to (1°x1°)	kg/m2/s	Converted into mm
Terra-Climate Temperature	Temperature(0.5°x0.5°) Resample to (1°x1°)	°C	
Terra-Climate Evapotranspiration	Evapotranspiration (0.5°x0.5°) Resample to (1°x1°)	Mm	
GRACE (LWE)	GRACE satellite (CSR, JPL, GFZ) at (1°x1°)	Cm	Mm

2.2 Methodology

The inflow and outflow of water in certain river basins can be expressed by using the water balance equation. Water balance estimation is a difficult and complex system due to water balance component uncertainty. An unprecedented opportunity was provided by Open Access Satellite Databases and Hydrological Model (Abatzoglou et al., 2017; Swenson, 2012; Landerer and Swenson, 2012; Swenson, 2006; Li et al., 2019). Water balance estimation consists of four major elements shown in equation 1

below (Zhang et al., 2018; Moghim, 2020).

$$RF - RO - EVT - GW = \Delta WS \tag{1}$$

Where, RF, RO, EVT, GW and ΔWS represents rain fall, runoff, groundwater, evapotranspiration and total water storage changes respectively. We used Open Access Satellite Databases and hydrological models to estimate terrestrial water storage in the Abbay river basin.

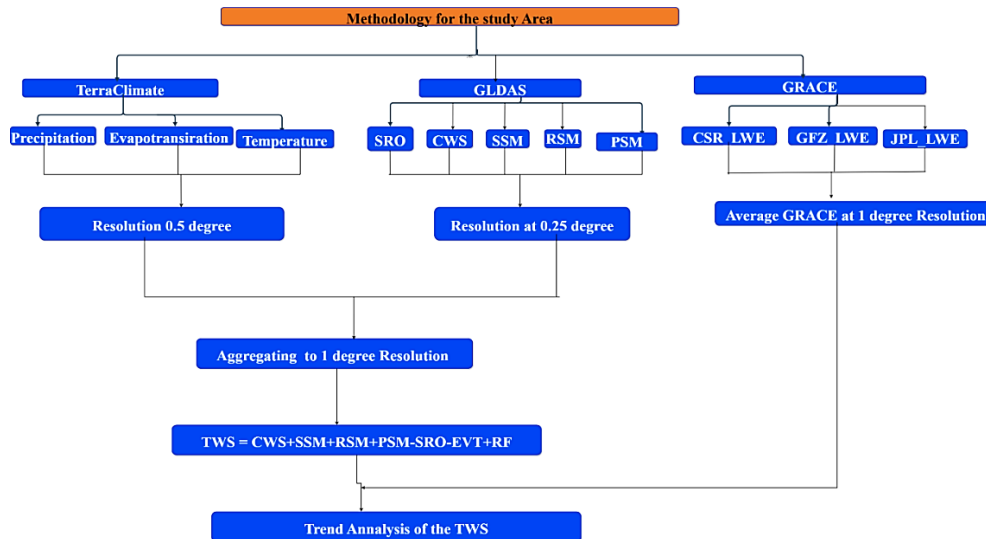


Figure 2: Flow chart for Methodology of terrestrial water storage

2.2.1 Gravity Recovery and Climate Experiment

Spatio temporal change in water storage is not feasible by field measurements in most regions due to the high cost/limited observations. The gridded GRACE satellite data (RL-05, level-3) is processed and provided by three institutions, Centers for Space Research (CSR, the university of Texas), Jet propulsion Laboratory (JPL, Pasadena, CA, USA), and GeoForschungsZentrum Potsdam (GFZ, Potsdam, Germany), respectively (Landerer and Swenson, 2012; Wahr et al., 1998). Thus, satellites are one of the main tools that can be used for data collection in almost all regions. So, GRACE is the widely used satellite that can evaluate global water storage changes which was launched in March 2002 (Wahr et al., 2004; Ramillien et al., 2004; Schmidt et al., 2006). The measurements of GRACE can produce spatio-temporal change of the Earth's gravity field, which shows the water mass change over land (Wahr et al., 1998; Tapley et al., 2004b). GRACE data that were available includes monthly anomalies from 2004-04-01 to 2017-01-07 that are computed relative to a time mean baseline (2004-2009) (Swenson, 2012; Landerer et al., 2012; Swenson et al., 2006). These products have undergone pre-processing, such as de-striping filter, glacier isostatic adjustment, and Gaussian smoothing (Chen et al., 2019). To improve accuracy, the GRACE terrestrial water storage averaging method was used and linear interpolation was used to fill in all missing monthly data (Landerer and Swenson, 2012; Seyoum and Milewski, 2017; Long et al., 2015). The original signal that was lost during data processing was restored by a multiplicative scaling factor that was

introduced to the monthly mass gridded data provided by the GRACE (Seyoum et al. 2019). Scaling factors for GRACE terrestrial water storage are more explained by Landere and Swenson (Landerer and Swenson, 2012).

2.2.2 Global Land Assimilation System(GLDAS)

GLDAS uses data assimilation to incorporate satellite and observation in advanced land surface models including catchment, community land model, the variable infiltration capacity and Noah to provide land surface states and fluxes, which was developed by the Hydrological Science Laboratory, NASA Goddard (Rodell et al., 1999; Rodell et al., 2004a; Rodell et al., 2004b). For the forcing dataset, GLDAS-2.0 uses the Princeton meteorological dataset (Sheffield et al., 2006; Sheffield et al., 2007), GTOPO30 for the elevation, Modified IGBP MODIS 20-category Vegetation, and Hybrid STATSGO/FAO for soil texture. GLDAS provides a global database including radiation, hydrological components, heat fluxes and meteorological variables. This dataset contains a hydro climatological dataset which is widely used in water resources and climatic studies in different areas, where data are temporally and spatially limited (Wang et al., 2011; Mueller et al., 2011). The validation of GLDAS result is confirmed by water resources and climate studies in Iran, where lack of observations inhibits advanced hydro climatological studies and sustainable water resource management (Moghim, 2018). The data is available from 3h to monthly with spatial resolution of one degree (Wang et al., 2016).

Generally, the terrestrial water storage of the aquifer includes surface soil moisture, surface runoff, root zone water storage, profile water storage, canopy water storage, precipitation, evapotranspiration and snow water storage. In this study area, snow water storage was ignored and the terrestrial water storage was estimated by using water balance equation 2 shown below.

$$\Delta TWS = \Delta GWS + \Delta SMS + \Delta SWE + \Delta CWS \quad (2)$$

Where ΔTWS –Change in terrestrial water storage

ΔGWS –Change in groundwater storage

ΔSMS –Change in soil moisture storage

ΔSWE –Change in surface water storage

ΔCWS – Change in canopy water storage

2.3 Terra-Climat

For this study, the climatological dataset was collected from the Terra-Climatic dataset and this dataset was developed from three global gridded climate datasets found at high spatiotemporal resolution and available to the public through an unrestricted data repository of Idaho's Northwest knowledge Network University (Harris et al., 2017). Temporal information is inherited from CRU Ts4.0 for most global land surfaces for temperature, precipitation, vapor pressure. TerraClimate also produces a monthly surface water balance using a water balance model that includes reference evapotranspiration, precipitation, temperature, interpolated plant extractable soil water capacity. The dataset was validated monthly on data obtained from the Global Historical Climatology Network database (Menne et al., 2012). The dataset was available from 1958/01/01 to 2021/12/01 at 0.50 grid. The mean yearly precipitation, temperature from 2003 to 2022 was collected for this study and prepared for further data analysis.

2.4 Statistical Data Analysis

Mann-Kendall Test is a nonparametric statistical test used for the analysis of trend in climatologic and hydrologic time series (Sharma et al. 2019). Mann-kendall test is a rank based method used to analysis the trends in time series. This test has been found to be reliable even for non-normal time series. Further, Mann-kendall test statistics are not significantly affected by presence of outliers. In this test, the null hypothesis H_0 assumes that the realizations are independent that is not trend exists in data series which is tested against the alternative hypothesis H_1 that assumes that the monotonic trend exists in the time series. Assuming X_i and X_j are two subsets of data series where $i=1,2, 3, \dots, n-1$ and $j= i+1, i+2, i+3, \dots, n$.

The mann-kendall S_m statistic may be represented as follows:

$$S_m = \sum_{i=1}^{n-1} \sum_{j=i+1}^n (X_j - X_i) \quad (2)$$

$$\text{sign}(X_j - X_i) = \begin{cases} 1 & \text{if } X_j - X_i > 0 \\ 0 & \text{if } X_j - X_i = 0 \\ -1 & \text{if } X_j - X_i < 0 \end{cases} \quad (3)$$

The variance σ^2 for the S_m statistics is defined by

$$\sigma^2 = \left[\frac{n(n-1)(2n+5)}{18} \right] \quad (4)$$

The standard test statistic Z_s is calculated as follows:

$$Z_s = \begin{cases} \frac{S_m - 1}{\sigma} & \text{for } S_m > 0 \\ 0 & \text{for } S_m = 0 \\ \frac{S_m + 1}{\sigma} & \text{for } S_m < 0 \end{cases} \quad (5)$$

If $|Z_s|$ is greater than $Z_{100-\alpha}$ where α represents the chosen significance level at (5% significance level or 95% confidence level with $Z_{95\%}$) then the null hypothesis is invalid implying that the trend is significant. Positive values of Z statistics indicate an increasing trend while negative values of Z statistics represent the negative trend (Timbadiya et al., 2013).

2.6 Sen's Slope Estimator

Sen's slope estimator: The greatness of the pattern was determined by the Sen's slant assessor. The sen's (S) of information pair was determined as:

$$Q_i = \frac{X_j - X_k}{j - k} \quad \text{where: } (j > k) \quad (\text{for } i=1, 2, 3, \dots, N) \quad (6)$$

Where X_k and X_j are the data values in years k and j , for $j > k$. if there are n

value of X_i in time series, one gets as many as $N = n * \frac{n-1}{2}$ to estimate slope Q_i . estimation of Sen's slope is the median of these N values of the slope S_i . The N values of S_i were ranked from the smallest to the largest and Sen's carried out as follows. The median of these N values of T_i is Sen's slope estimator, which is shown as follows:

$$Q_i = \begin{cases} Q_{\left[\frac{(N+1)}{2}\right]} & \text{if } N \text{ is odd} \\ \frac{Q_{\frac{N}{2}} + Q_{\frac{(N+2)}{2}}}{2} & \text{if } N \text{ is even} \end{cases} \quad (7)$$

when N is even number and Sen's slope estimator calculated as $Q_{med} = T * \frac{N+1}{2}$ if N appears odd and it was considered as $Q_{med} = \frac{Q_N + Q_{N+2}}{2}$ if N is even. At last of Q_{med} is calculated by two sided test 100% confidence interval, and then a slope was calculated by non- parametric test. positive value of Q_i represents an increasing trend and negative value shows decreasing trend in the time series.

3. RESULT

3.1 Liquid Water Equivalent Thickness by GRACE

Time-dependent gravity field can be measured by GRACE, which can represent surface mass changes and variations in water storage. The measured temporal variation can represent the liquid equivalent water thickness (LWE). The mass deviation of the LWE from the baseline, can show changes in water storage in the area. Estimation of the data shows that the maximum positive value in liquid water equivalent thickness in the river basin observed by GFZ satellite (Figure 3B), where the minimum observation was by JPL satellite for 2015(Figure 3. C).

For 2016, the maximum positive change in liquid water equivalent thickness was estimated by GFZ satellite (Figure 3E), whereas the minimum positive value was observed by CSR (Figure 3D). Figure 3 indicates the spatial distribution of liquid water equivalent thickness in the Abbay river basin during 2015 and 2016 for the three satellites. The larger negative values indicate the area with a greater decrease in water mass (red color), whereas the positive value indicates an increase in liquid water equivalent thickness (blue color). The western and southwestern parts of the river basin have experienced the most water storage reduction, whereas, the northern and eastern parts of the river basin in Figure 3 show the maximum mass gain for 2015 and 2016. The same area in the river basin experienced both mass loss and mass gain in different years (2002 to 2016, respectively). This change in water storage can be due to changes in surface and groundwater, canopy water storage and soil moisture, which are discussed in the GLDAS section. To manage changes in terrestrial water storage in the Abbay river basin, a time series of average liquid water equivalent thickness for the river basin is presented in Figure 4. The result presented in Figure 4 shows that the maximum change in water storage was observed in 2007 and 2014. This increase in water storage can be caused by the application of irrigation water systems in the country (MoFED. 2006, Awulacchew et al. 2009, Gebremedhin GM 2015), whereas the minimum change in water storage was observed in 2004, 2009-2013. This decline in water storage can be due to droughts experiences (Yimer et al., 2017; Belayneh and Adamowski, 2012; Alem and Getachew, 2012; Viste et al., 2013; Zeleke et al., 2017). Many studies show Ethiopia experienced maximum drought in 2003, 2009, 2011, 2012, 2013, 2014 and 2015(Bayissa et al., 2015; Edossa et al., 2010; Yisehak et al., 2021; Gidey et al., 2018). For the current study, the loss in equivalent water thickness coincides with this drought experience. The average liquid water equivalent thickness shows a downward trend from 2002 to 2004, 2007 to 2009, 2014 to 2015, significant change from 2009 to 2013, and an upward trend from 2004 to 2007, 2013 to 2014. The annual cycle of liquid water equivalent thickness shows that the maximum increase in each year occurs in the Autumn season when remarkable rainfall occurs. While the maximum decrease in liquid water equivalent thickness occurs in the spring season, when decreased precipitation (Ellen et al., 2013). These positive and negative changes in liquid water equivalent thickness reflect wet and dry seasons respectively. Finally, the water storage changes at different times and can be collected from space by the signal of the GRACE. To better understand the time varying water storage, the domain average of the liquid water equivalent thickness is estimated for all months (Figure 5). The analyzed monthly time series shows a decreasing trend of water storage from January to April, whereas, an increasing trend of water storage from May to December (Figure 5). The highest mass loss was observed in March 2012, whereas the highest mass gain was in October 2014(Figure 5). The spatial change in water storage is similar each year and month (figures not presented), with the maximum increases in the northern and eastern part of the river basin and the minimum decreases in the western and southwestern parts of the river basin (Figure 3).

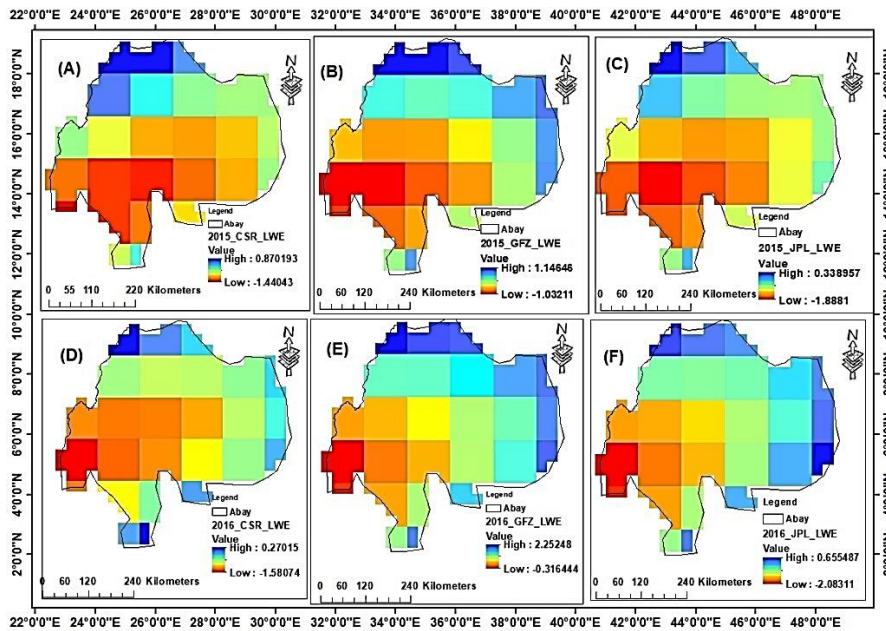


Figure 3: Spatio-temporal variation of Equivalent water thickness of Abbay river basin

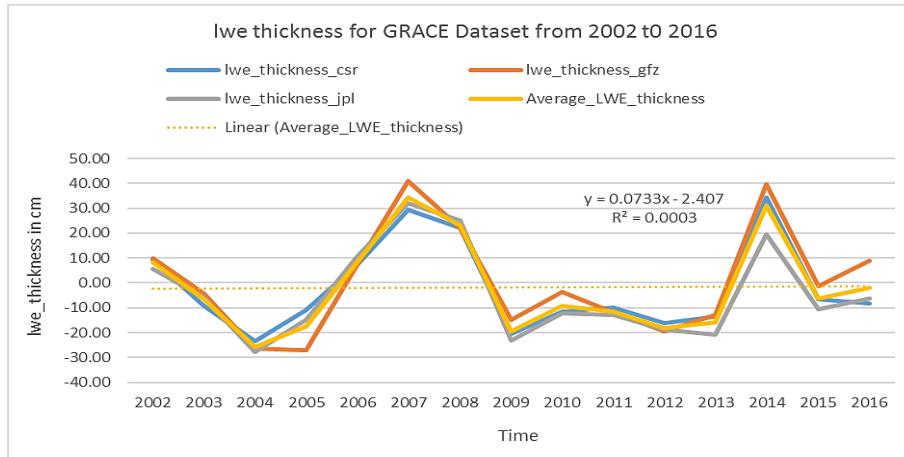
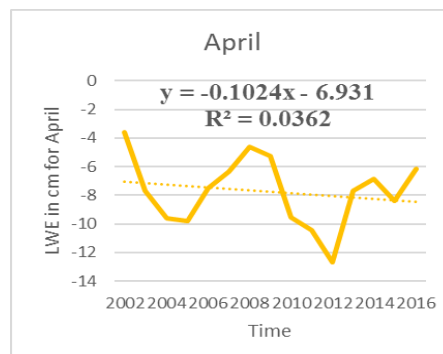
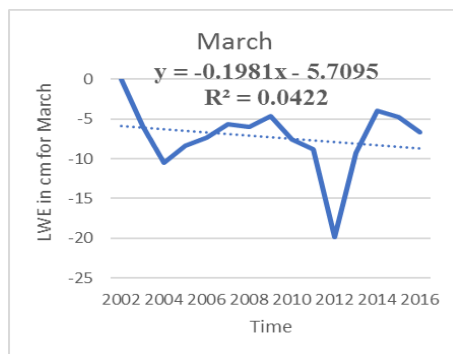
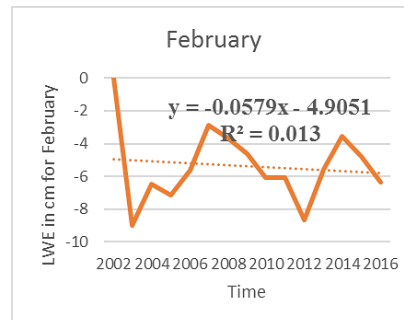
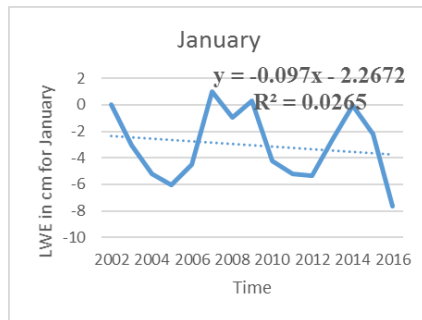


Figure 4: Time series of liquid water equivalent thickness for each satellites and its average



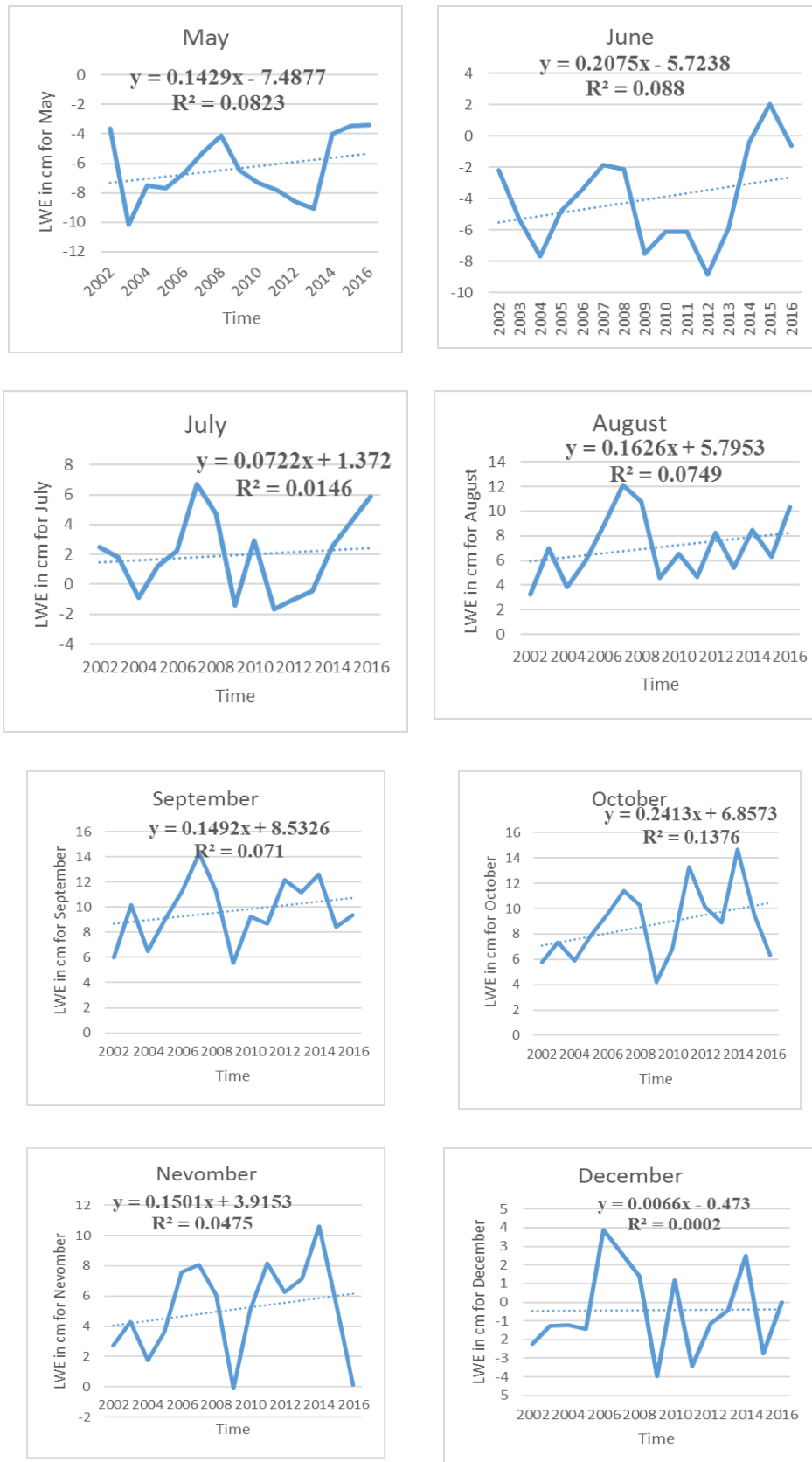


Figure 5: Average liquid water equivalent thickness(LWE) trend in different months

3.2 Characteristics of change in water storage Components for Abbay basin

Change in water storage consists of soil moisture, surface and ground water components for a particular location and is the main input for most hydrological models. Direct measurement of change in terrestrial water storage is challenging, yet there are methods of calculating this water

storage using directly measurable climatic variables such as runoff, precipitation, evapotranspiration, canopy water storage, soil moisture etc. Having uniform and error free spatial and temporal coverage over a chosen study area with minimum temporal coverage of 10 years is the requirement for hydrological characterization of a chosen study area. For this study, changes in terrestrial water storage were carried out using the GLDAS model dataset. These datasets were processed and prepared for

data analysis using the QGIS application tool. The characteristics of water balance components used during the present study to estimate terrestrial water storage include surface runoff, precipitation, canopy water storage, evapotranspiration, surface soil moisture, root zone soil moisture, profile soil moisture, are presented in Figure 6 below and the characteristics of these water balance components are discussed as follows.

3.2.1 Precipitation

The Abbay river basin spans over multiple countries, including Ethiopia, Sudan and Egypt. Precipitation trends within the basin can vary depending on the specific location and time period analyzed. However, here is some general information on precipitation trends in the Abbay river basin. According to a study published in the international journal of climatology in 2021, the upper Blue Nile Basin in Ethiopia has experienced significant increase in precipitation over the past few decades. The study analyzed precipitation data from 1979 to 2018 and found that the trend was particularly pronounced in summer months. The study attributes the increase in precipitation to changes in the Indian ocean sea surface temperature, which can affect the amount of moisture transported to the region. For this study, the spatial distribution of precipitation (Figure 6A) shows that the central and southwestern parts of the river basin experience high rainfall, whereas eastern, northern and western parts of the river basin experience low precipitation. The long term temporal variation of the precipitation (Figure 7C) observed varying trends. The implication of changing rainfall trends is due to changing temperatures (Williams et al., 2011). This observation is consistent with a study published in the journal of hydrology in 2017 found that the lower Blue Nile basin in Sudan has experienced a decrease in precipitation over the past few decades. The study analyzed data from 1961 to 2010 and found that the trend was particularly pronounced in the period from 1981 to 2010. The study attributed the decrease in precipitation to the North Atlantic oscillation, which can affect the amount of moisture transported to the region. Over all, it seems that precipitation trends in the Blue Nile are complex and can vary depending on the specific location and time period.

3.2.2 Evapotranspiration

Estimation of evapotranspiration for a large river basin like Abbay requires complex modeling and data analysis. There are various methods and models to estimate evapotranspiration, including the panman-monotheist methods, the Hargreaves methods, and the Priestley-Taylor method. These methods generally require data on weather variables such as temperature, humidity, wind speed, solar radiation, and atmospheric pressure, as well as data on vegetation cover, soil moisture and other factors. For this study, to estimate evapotranspiration, remote sensing data from satellites was used. This remote sensing can provide information on vegetation cover, land surface temperature, and other variables that are important for estimating evapotranspiration. The moderate resolution imaging Spectroradiometer and Landsat satellites are commonly used for this purpose. The analyzed result for the spatial (Figure 6B) distribution of evapotranspiration experienced increasing trends in eastern, northern and western parts of the river basin, whereas, a few areas in the southern part of the river basin show decreasing trends and temporal (Figure 7B) distribution of evapotranspiration a general decreasing trend for the study period.

3.2.3 Canopy Water Storage

Canopy water storage is a relatively new concept that involves capturing rain water in the canopy of trees and plants, which is then slowly released into the soil and groundwater over time. This technique has been shown to be effective in increasing water availability, especially areas with low rain fall and high evapotranspiration rates. In the Abbay river basin, canopy water storage could be used to improve water availability for agriculture, which is a major source of water for livelihood for many peoples in the region. By planting trees and other vegetation that have high water storage capacities, farmers can capture rain water and reduce runoff, allowing more water to infiltrate into the groundwater and recharge the groundwater aquifer. In addition to improving water availability, canopy water storage can also help to reduce soil erosion, enhance biodiversity, and provide other ecosystem services. However, the success of this technique depends on a range of factors, including the type of vegetation used, the soil conditions, and the hydrological characteristics of the area. Overall, canopy water storage has significant potential as a water management strategy in the Abbay river basin and other regions with similar environmental conditions. The analyzed result shows canopy water storage for the Abbay river basin (Figure 7C) was high in the eastern, western and northern parts of the river basin, whereas the central and southern parts of the river basin experienced low canopy water

storage. Therefore, the canopy water storage result was affected by land use cover and a similar report was confirmed in Osun Basin Naigeria, west Africa (Ashaolu et al., 2019; Pypker et al., 2005). However, further research and testing are needed to determine the most effective approaches and to quantify the benefit of this technique.

3.2.4 Surface Runoff

The surface runoff in the abbay river basin is influenced by various factors such as climate, topography, land use and soil types. The basin receives significant rainfall between June and September, which results in high surface runoff. In addition, the topography of the basin is characterized by steep slopes, which further contribute to high surface runoff. The land use is dominated by agriculture, which also affects the surface runoff by altering the natural vegetation cover. According to the study conducted by the ministry of water research, surface runoff in the Abbay basin is 49.6 billion cubic meters. However, it is important to note that the surface runoff varies greatly depending on the season and year, and is influenced by various factors. Figure 6D shows that the western, eastern and northern parts of the river basin experience low runoff, whereas very few central parts of the river basin experience high runoff and the other part indicates medium runoff. The temporal distribution of surface runoff was evaluated and the result was presented (Figure 7G) and the average minimum yearly surface runoff of 145.71mm/year occurred in 2016, whereas the average maximum runoff of 576.56 mm/year occurred in 2012. The study shows that the Abbay river basin experienced varying runoff during the study time. Based on the study conducted by Yenehun et al. 2020, kahsay et al. 2019 the spatiotemporal variation of surface runoff occurred because of land use land cover, soil type and the intensity of precipitation, and this study was confirmed by those previous studies (Aneseyee et al., 2020; Chaemiso et al., 2021).

3.2.5 Soil Moistures

Soil moisture refers to the amount of water held in the soil particles and the spaces between them. It is an important aspect of the water cycle and plays a crucial role in plant growth, nutrient availability, and ecosystem health. Soil moisture can vary greatly depending on factors such as precipitation, temperature, vegetation cover, soil type and land use. Mentoring soil moisture level is important for agriculture, forestry, water resource management, weather forecasting, as well as for understanding the impacts of climate change on the ecosystem and human activities. For this study to estimate terrestrial water storage, surface soil moisture, root zone soil moisture and profile soil moisture were evaluated and the spatial distribution were presented in Figure 6 (E, F, G), whereas the temporal variations were presented in Figure (7 D, E, F) respectively. Figure 6 (E) shows high surface soil moisture in the central and southern parts of the river basin, whereas a few parts of the northwestern river basin experience low surface soil moisture. The spatial distribution of the surface soil moisture ranges from 3.12 to 8.0 mm. As was presented in Figure(6F), the root zone soil moisture ranges from 154.55 to 405.4 mm, with high concentration in central and southern parts of the river basin. A few areas experienced low root zone soil moisture (red color). Figure 6 (G) presents the profile of soil moisture for the Abbay river basin. The result shows high spatial distribution in the south western parts of the river basin, the north eastern and north western parts experiencing low profile soil moisture, whereas the central parts of the river basin experience medium profile soil moisture. The classification of the soil moisture was based on the Global land data assimilation system (Li et al., 2019). The temporal variation of soil moisture (Figure 7 D, E, F) shows similar variation, except profile soil moisture, which shows an increasing trend for the study time.

3.2.6 Temperature

The Blue Nile basin is the largest watershed in Ethiopia and covers an area of more than 190,000bsquare kilometers. The region is generally characterized by a tropical climate, with temperatures varying based on the time of the year and the altitude of the area. In terms of temperature trends, it is important to note that global warming is having an impact on temperatures worldwide, and Ethiopia is no exception. According to data from the world bank, the annual average temperature in Ethiopia has increased by about 1.3 degrees Celsius since the early 1960s. This increase could have an impact on the Abbay river basin, as rising temperatures could lead to changes in precipitation patterns and river flow, all of which could have significant impacts on the local environment and the people who rely on it. Figure H shows spatial variation of temperature in the Abbay river basin. Higher temperatures occurred in the north western part of the river basin, whereas the rest experienced low to medium temperatures and the temporal variation of the temperature (Figure 7H) shows varying trends, and generally a decreasing trend for the study time.

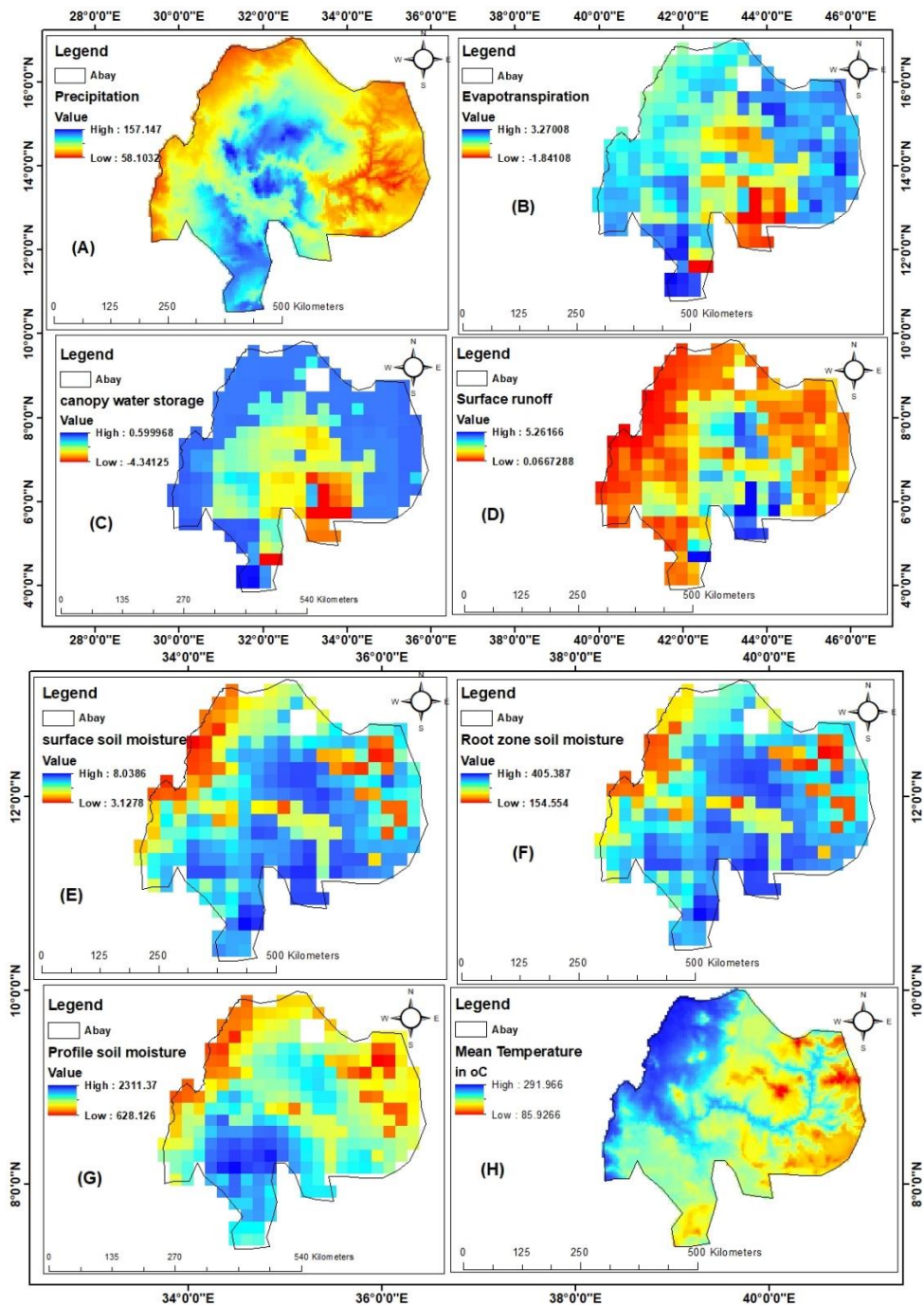
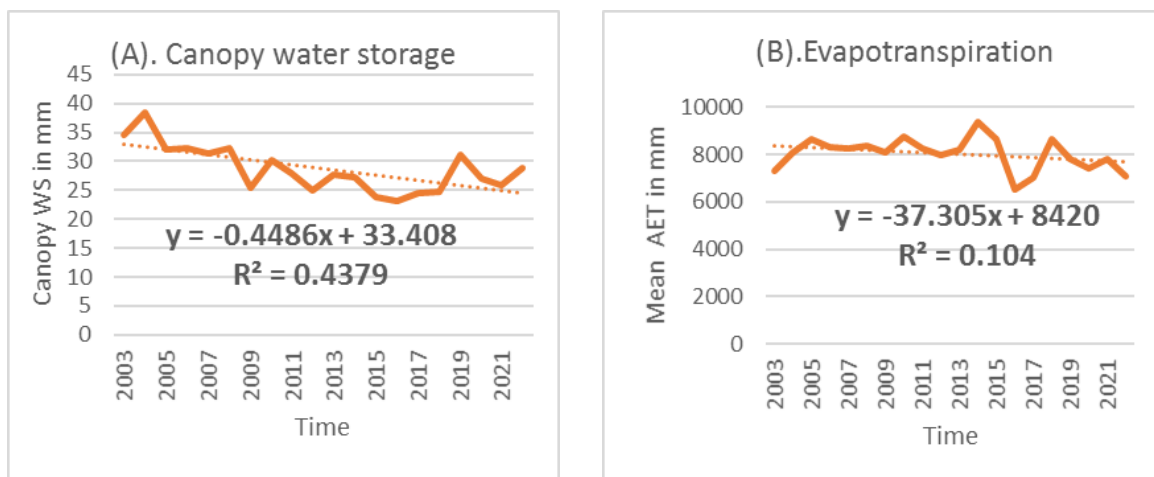


Figure 6: spatial characteristics of water balance components for Abbey river basin



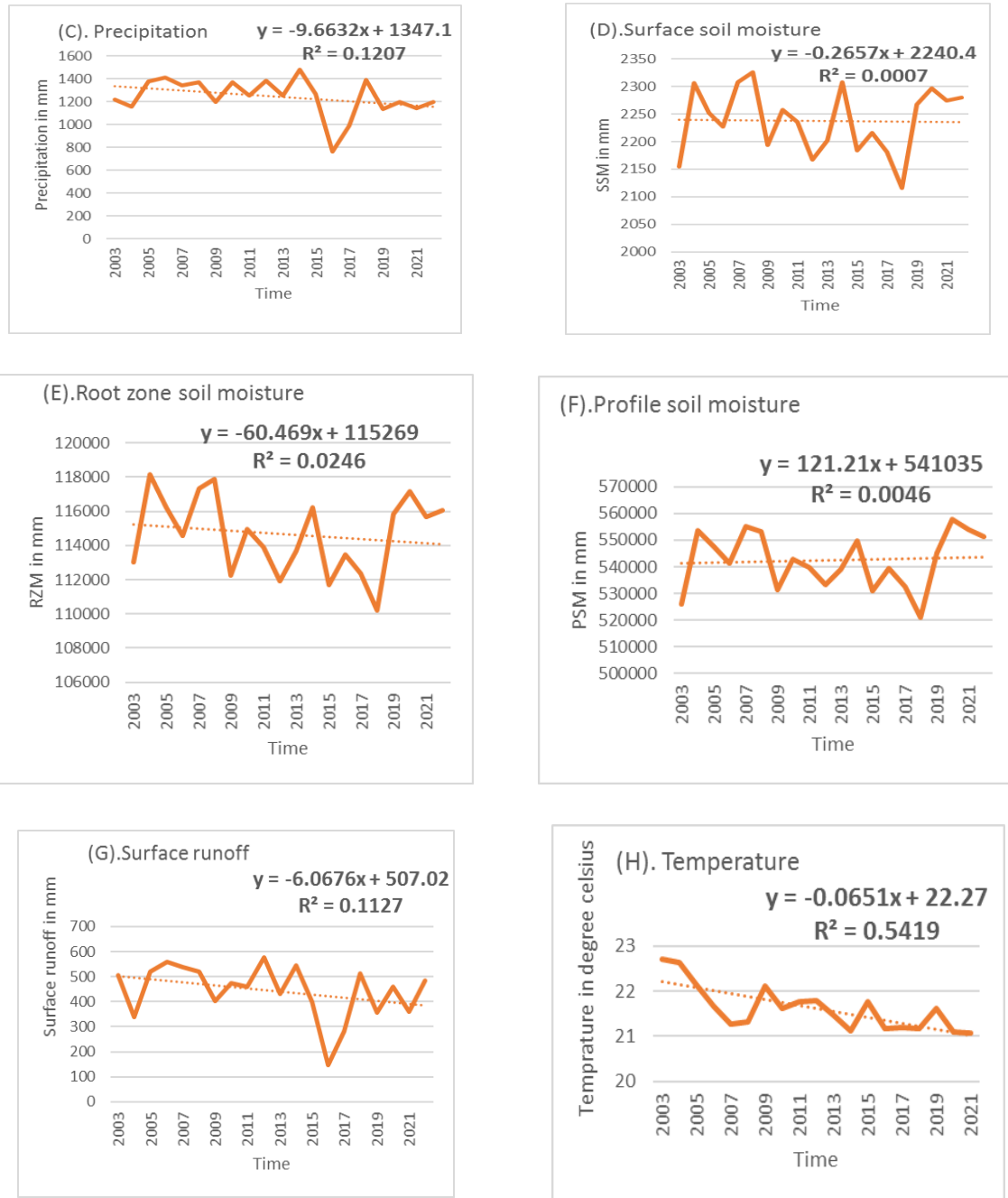


Figure 7: Temporal characteristics of water balance components for Abbay river basin

3.3 The Spatio-Temporal Variation of TWS by GLDAS

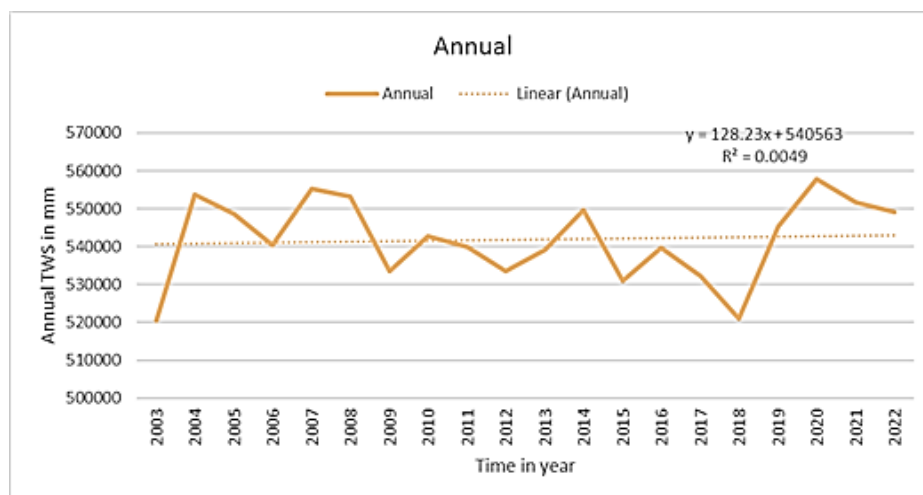


Figure 8: Temporal variation of mean annual change in terrestrial water storage for Abbay river basin

The Abbay river basin is characterized by a range of water storage features, including natural lakes, wetlands, and reservoirs. Additionally, the basin receives seasonal rainfall, which is stored in the soil and groundwater, and contributes to the overall terrestrial water storage. The exact amount of water storage in the basin is dependent on a number of factors, including climate, land use, and human activities such as irrigation, and water withdrawal. For this study, the Spatio-temporal change of TWS for the river basin was evaluated and the result shows high water storage in the southwestern part of the river basin, medium water storage in the central part of the river basin, low water storage in the eastern, northern and northwestern parts of the river basin (Figure 9). Figure 8 illustrates

that the time series of TWS increased from 2003 to 2004, 2006 to 2007, 2009 to 2010, 2012 to 2014, 2015 to 2016, 2019 to 2020, whereas, decreasing from 2004 to 2006, 2007 to 2009, 2010 to 2012, 2014 to 2015, 2016 to 2018 and 2020 to 2022. The maximum increase of TWS was observed in 2020 (557950.03mm), whereas the minimum TWS was observed in 2003 (520385.41mm). For the years 2003, 2004, 2006, 2009, 2011, 2012, 2013, 2014, 2015, 2016, 2018, 2020, a high water loss was observed this due to extreme drought occurrence and different findings confirmed drought experience in the Ethiopian river basin (Bayissa et al., 2015; Edossa et al., 2010; Yisehak et al., 2021; Gebrehiwot et al., 2011; Gidey et al., 2018).

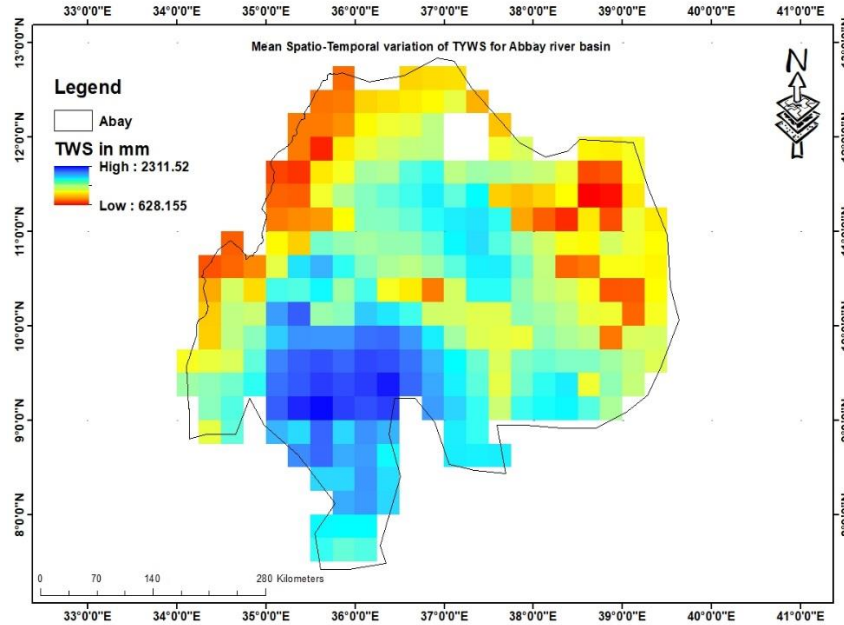
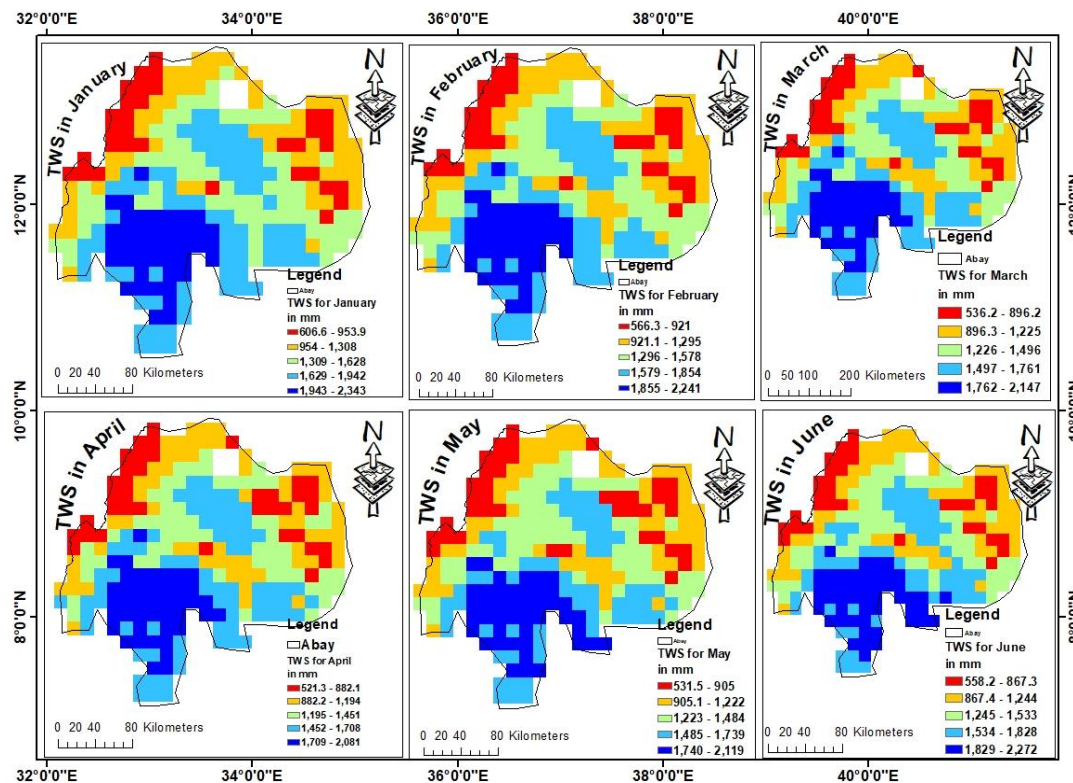


Figure 9: Spatial variation of mean annual change in terrestrial water storage for Abbay river basin

3.3.1 Monthly Time Distribution of TWS

Figure 10 shows monthly variation of terrestrial water storage from the GLDAS dataset; the monthly spatio temporal distribution of TWS shows little variation in water storage (Figure 10). As was presented in Figure 10 for all months, high water storage was experienced in southwestern parts of the river basin. This happened due to reservoir storage of the Grand

Ethiopian Renaissance Dam (Melesse et al., 2021; Belete and Seleshi, 2021). This finding was consistent with study conducted in southern India for land water storage variation (Tiwhar et al., 2011; Yi and Wen, 2016). The red color shows very low terrestrial water storage for each month, whereas the deep blue color indicates very high terrestrial water storage for the study area.



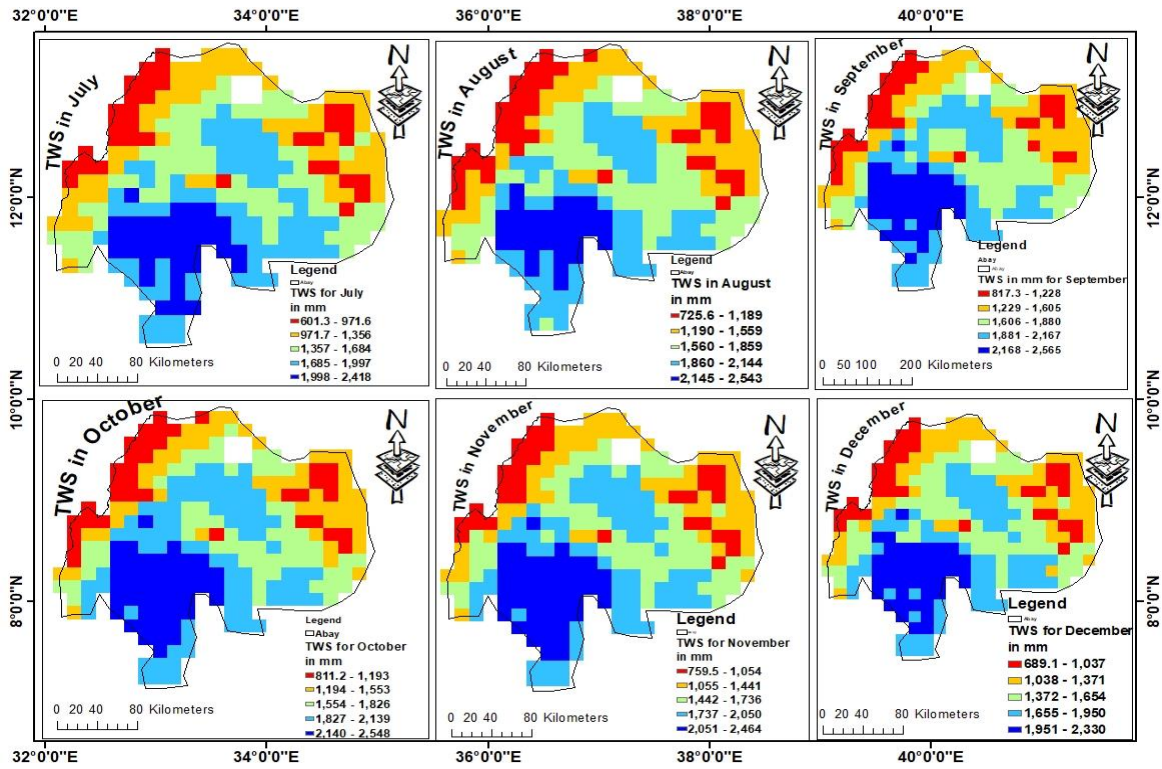
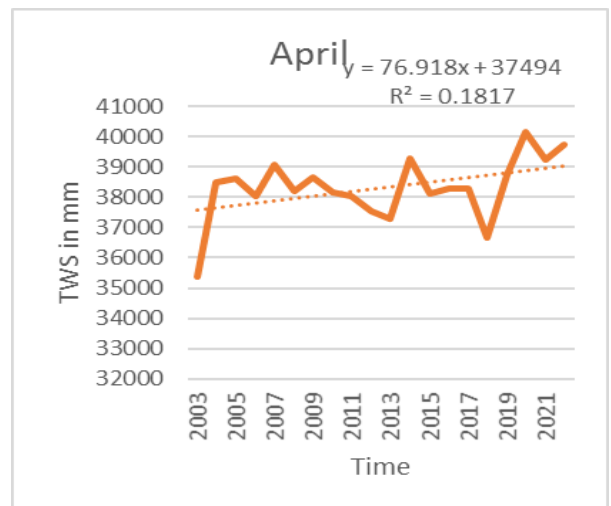
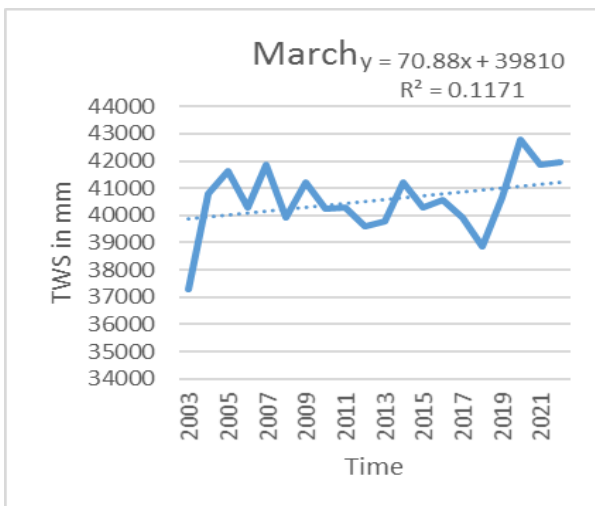
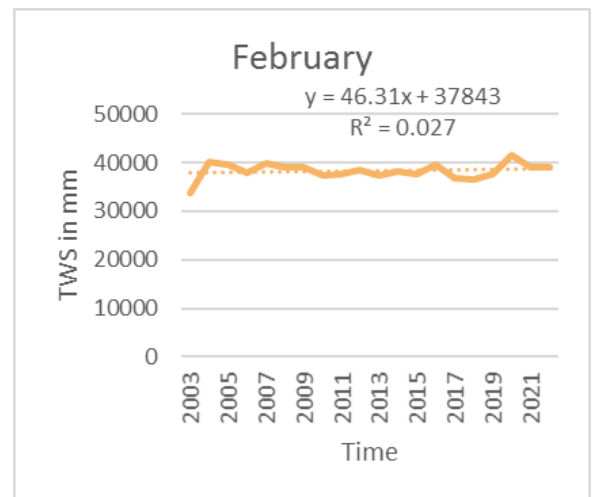
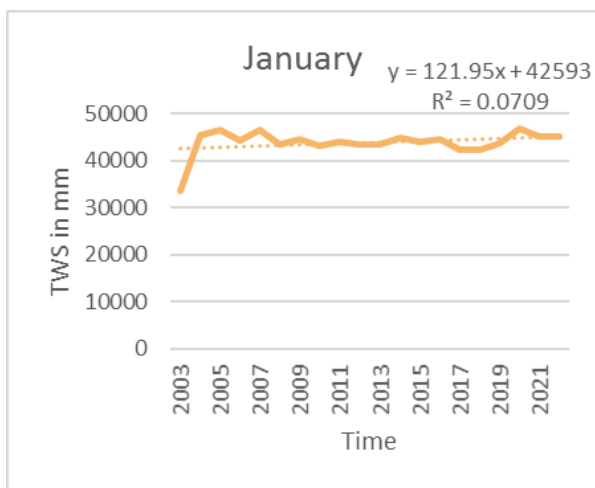


Figure 10: Mean monthly spatio-temporal variation of terrestrial water storage for Abbey river basin



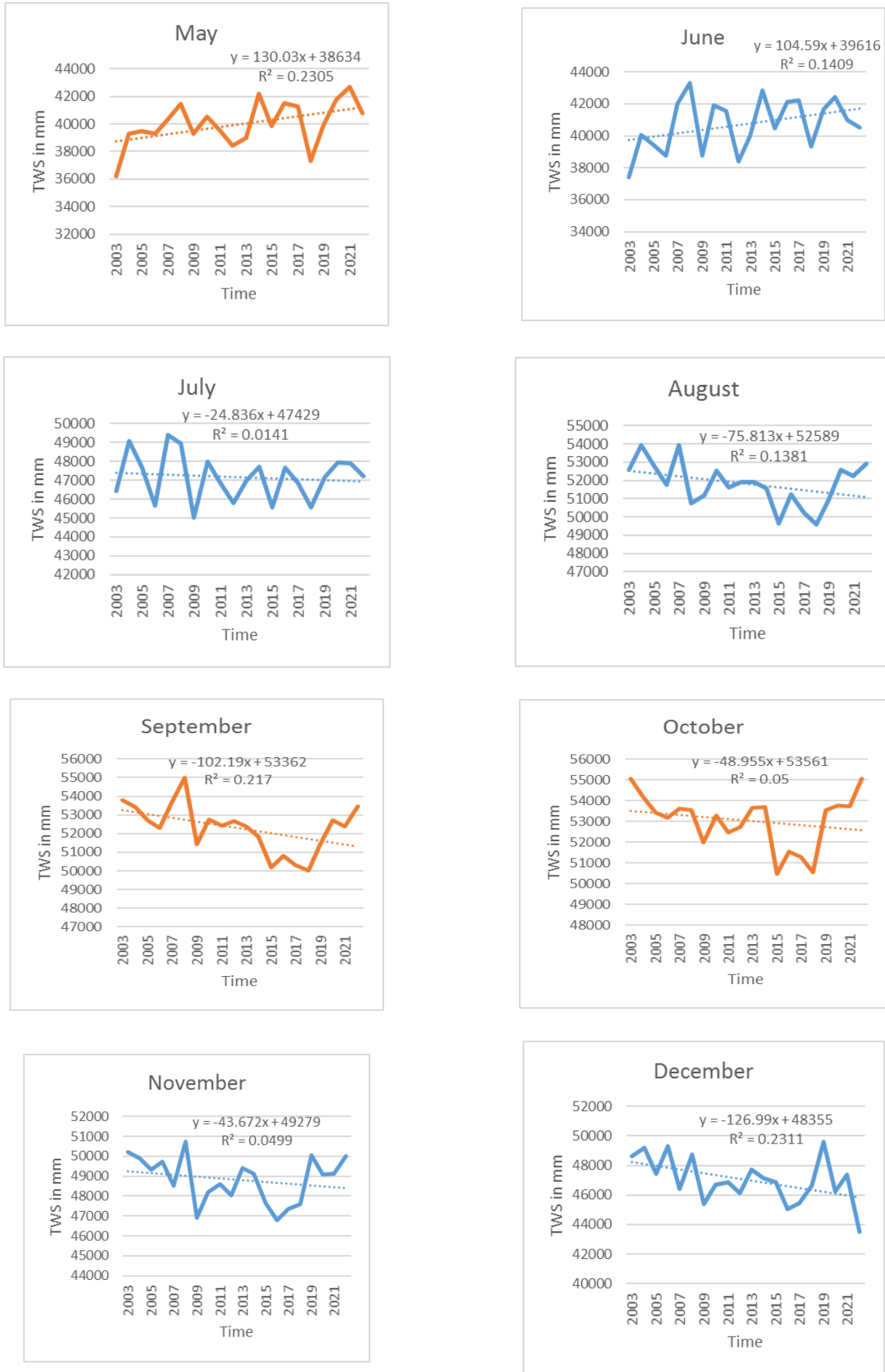


Figure 11: Mean monthly temporal variation of terrestrial water storage for Abbay river basin

Figure 11 shows the mean monthly time series of TWS for the Abbay river basin. The result demonstrated that TWS for the Abbay river basin increased for the months January, February, March, April, May, June and decreased for the months July, August, September, October, November, and December for the study time. The maximum terrestrial water storage is observed all year in August and September. This was due to the rainy season from April to September and it is confirmed by different findings

(Diro et al., 2009; Romilly and Gebremichael, 2011; Seleshi and Zanke, 2004; Gebere et al., 2015), whereas the lowest terrestrial water storage was observed in January and February (Figure 11) and this demonstrates that the area experiencing dry season from November up to February and this is confirmed by previous studies (Funk et al., 2015; Lemma et al., 2017; Suryabhagavan, 2017).

3.3.2 Seasonal Terrestrial Water Storage

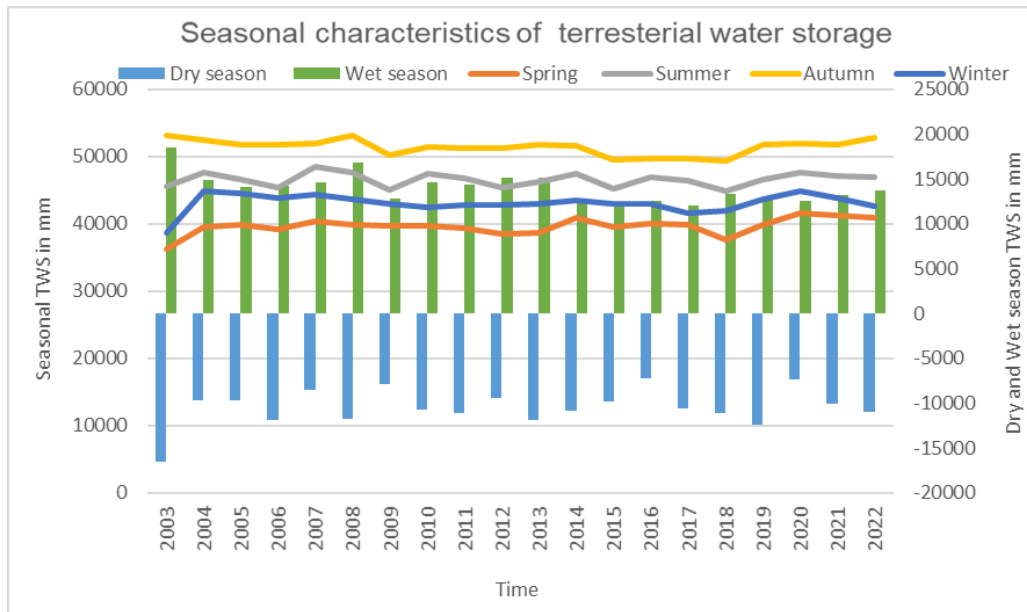


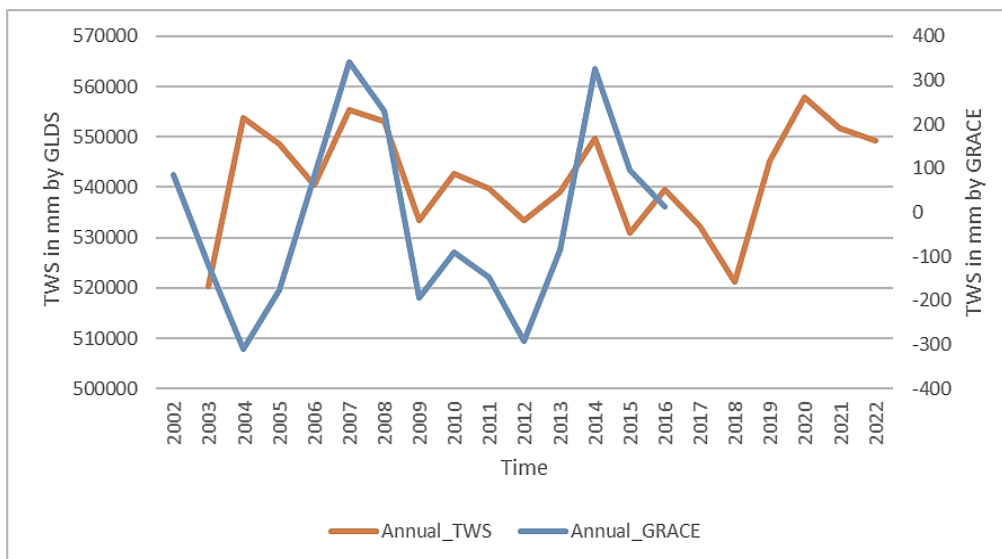
Figure 12: Seasonal characteristics of terrestrial water storage

Figure 12 shows the seasonal characteristics of terrestrial water storage in the Abbay river basin. The estimated result demonstrates very high variation in terrestrial water storage during the study time. The highest terrestrial water storage was observed during the autumn season, high in summer season, medium in winter and low storage during spring season. This difference in terrestrial water storage was due to the rainfall variation for different seasons. The result of this study confirms the previous finding (Conway 2000a; Conway 2000b; Bewket and Conway, 2007; Taye and Zewdu, 2012; Fazzini et al., 2015). The wet season (Figure 12) demonstrates the positive value of terrestrial water storage for the Abbay river basin (surplus of water). This is due to increasing precipitation during the wet season and it is very important to understand extreme hydrological and climatic conditions in the wet season, whereas

the negative value for the dry season indicates water scarcity during the dry season, which leads to drought in the river basin and needs drought monitoring during the dry season.

3.2.3 Relationship between TWS by GLDAS and LWE by GRACE

Figure 13 illustrates the relationship between the mean annual terrestrial water storage evaluated by the GLDAS dataset and the mean annual liquid water equivalent thickness evaluated by the GRACE satellite dataset for the Abbay river basin. The finding shows an increase in TWS, whereas a decrease in LWE from 2003 to 2004, but from 2004 to 2006 TWS shows a decreasing trend and increase in LWE. After 2006, the datasets show similar trends for the Abbay river basin.



4. CONCLUSION

Presently, many regions of the world are concerned about their available water supply, irrigation, and industrial activity. A growing population, human activities and inadequate management make access to clean water increasingly difficult. The shortage of efficient and effective observation in countries, especially in developing countries, results in improper

management. Due to this, the major tasks of the satellite and hydrological model in the analysis of water storage in areas with limited observations are emphasized.

In this paper, the change in terrestrial water storage is estimated using GLDAS dataset, TerraClimate dataset for the Abbay river basins. Additionally, liquid equivalent water thickness using GRACE dataset was

evaluated. The analyzed spatio-temporal variation of the terrestrial water storage was changing based on time and space; this is due to change in precipitation, temperature and other human activities experienced in the river basin. Based on the result, the change in terrestrial water storage shows a varying trend from for the study time. The spatial variation shows decreasing trend in high elevation regions at the upstream of river basin, whereas increasing at the downstream low land area.

The terrestrial water storage was evaluated for the Abbay river basin using GLDAS dataset and TerraClimate. Liquid equivalent water thickness for the river basin was estimated using GRACE dataset. Spatio-temporal variation in the river basin was analyzed and water decline in the upstream of the river basin, and increasing of the terrestrial water storage in the downstream section of the river basin. Seasonality of the terrestrial water storage was evaluated and high water storage observed in the study area for the Autumn season, whereas low water storage was observed in the spring season. Wet and dry season water storage was evaluated for the study area for study duration and the result demonstrates a negative value (water crisis) for the dry season, whereas a positive value (water surplus) for the wet season. The obtained result was essential for drought monitoring during the dry season, flood monitoring during the wet season and for water resource optimization and management.

Climate change and anthropogenic activities largely affect water resources. The result obtained here shows that water storage is easily influenced by climatic variables such as rainfall and temperature, both directly and indirectly. In addition to climate change, there are notable human activities in the study area, such as irrigation, hydroelectric and others that affect water resources.

This study provides evidence that simulated GLDAS and TerraClimate provide valid data even in regions where observation is limited. The observed result shows that long term monitoring of terrestrial water storage is necessary to prevent possible water shortages in the future during the dry season, flood management and to conserve natural resources. Continuous monitoring, which is a requirement of sustainable water management, is also of vital importance in saving freshwater and delivering it to the future generation.

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