

GROUNDWATER MONITORING USING GRACE MISSION

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ABSTRACT:

Since last few decades, India has met to major crises related to groundwater. Major cities, for example, Delhi, Chennai, Bengaluru etc. are facing extreme risk of water crisis. In next few decades, this may lead to a major water crisis when this non-renewable resource is exhausted. Gravity Recovery and Climate Experiment (GRACE) mission, widely used for monitoring of groundwater storage change, could be utilized to get the information of exact amount of water above or below the surface of the earth that may be used to counter act over such situation of water crisis. GRACE mission consists of two earth orbiting satellite vehicles (SVs) separated by 220km with the objective of computing change in gravity by increasing or decreasing distance between both the SVs caused by higher or lower gravity masses. The primary objective of the presented work is to obtain the liquid water equivalent height in a selected area using GRACE mission data with GLDAS soil moisture data. The advantage of using GRACE is that it provides better accuracy (fraction of 1cm) in comparison to traditional methods, therefore, larger extent could be covered. This paper extensively discusses about GRACE application (especially groundwater monitoring), challenges with GRACE missions and about effective methods for groundwater recharge.

1. INTRODUCTION

During the last two-three decades, the water level in the whole world is gradually decreasing, which can cause huge crises all over the world. Major cities, for example, Delhi, Chennai, Bengaluru etc. are facing extreme risk of water crisis which may lead to a major water crisis when this non-renewable resource is exhausted. Various remote sensing techniques are used to locate & monitor water level and recharge them to a possible extinct, such as ERT profiles (using electrical resistance for sub-surface imaging), SD100 Ultrasonic Sensor (measuring water levels remotely), OTT-CBS (a bubbler) etc. Satellite Images used to aid in hydrological interpretation are widely rich in history. Recently, measurements by satellite of temperature, soils, topography, gravity, etc have been collected to detect the presence of groundwater. Satellite imagery is a part of larger probe where critical hydrological parameters have been directly measured from satellite data.

Unfortunately in older times the groundwater monitoring was very difficult globally, but in current scenario, we have enough remote sensing methods and equipment. In remote sensing techniques, GRACE data has been widely used for ground water monitoring purpose, in correcting gravity models and reducing correlation errors between two hydrological datasets (Becker, 2006, Chen et al., 2010; Houborg, 2012; Jiang et al., 2014; Landerer et al., 2013; Skaskevych, 2014; Syed et al., 2008; Tian et al., 2017; Wang et al., 2013; Wouters et al. 2014; Yeh et al., 2006). The GRACE mission, launched in March 2002, consist of two twin satellites measures earth gravity changes with a very high accuracy (Tapley et al., 2004). GRACE tracks the variations in the distance between its twin satellites and combine the measurement with GPS receivers and accelerometers data. Hence, monthly gravity field variations

data are obtained (Almeida et al. 2012). The Grace-based TWS application modifies data based primarily on a combination of hydrological and terrain models. Jiang et al. (2014) provides an extensive review of GRACE mission, its fundamental concept and its application in terrestrial hydrology, for example, terrestrial water storage and drought monitoring. The results of the Grace-based TWS restoration provide a local and temporal distribution of vertically integrated water supplies (surface water, soil, groundwater, and ice) in large river valleys. Thus, due to errors, the use of proxies may be reduced in some hydrological models such as discharge and variability.

Rodell and Famiglietti (2002) shows the application of GRACE data in ground water storage monitoring and concludes to the uncertainty of ~8.7mm in estimates of ground water by GRACE observation for high plains aquifer. Byron et al. (2004) presents the application of GRACE data in measuring temporal variations in geoid and discusses potential factors and possible errors in GRACE estimates. Wahr et al. (2006) presents accuracy assessment of mass variability maps obtained by GRACE by proposed method of estimation of error estimates. Swenson et al. (2006) conducts a study to estimate temporal variations in water storage by using GRACE data and finds the results are congruent with the field observations. Strassberg et al. (2007) presents the potential of GRACE data in monitoring seasonal ground water storage in semiarid regions by comparing ground water results obtained by GRACE and field data. Rodell et al. (2009) shows the efficacy of data obtained by GRACE mission and find ground water to be depleting at rate of 40 ± 10 mm/year (mean value) for Rajasthan, Delhi, Punjab and Haryana states of India.

Chen et al. (2016) quantify change in ground water storage using GRACE data for selected places in the world facing water

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scarcity. Bhanja et al. (2016) validates anomalies in ground water storage obtained by GRACE with observations of more than 15000 wells spread in India. Chen et al. (2019) utilizes GRACE data to obtain variation of ground water storage and analyses its effects on occurrence of flood and drought. Feng (2019) developed a matlab toolbox, named GRAMAT, for dedicated GRACE data processing and generated map of monthly terrestrial water storage change for Amazon river. Singh and Saravanan (2020) presents a study of improving ground water monitoring for various simple and complex aquifers using GRACE data and conducted a correlation analysis between actual and GRACE estimates. The main limitation of GRACE data is availability of data with very low resolution (0.25° and 1°) which limits its application for ground water monitoring at small scale.

The primary objective of the research work is to obtain temporal change in water equivalent height of Allahabad district of India using GRACE mission data with GLDAS soil moisture data.

2. STUDY AREA

The selected study area for this research is Allahabad, a district of Uttar Pradesh state of India (Figure 1). Allahabad is a metropolice city ranking at top in population in Uttar Pradesh. The rapid and unorganized development is forcing the city to face water scarcity in next few decades.

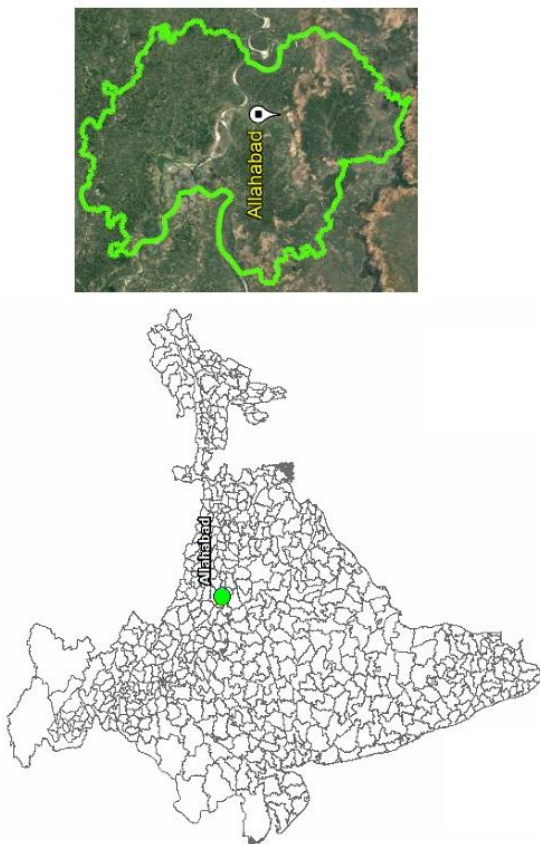


Figure 1. Study Area: Allahabad district (India)

3. METHODOLOGY

GRACE based datasets are available as 1° × 1° grids in ASCII format for the whole world coordinates. Each grid value is the mid-point of average of grid values over the grid, then these grids are masked with the coordinates binding the study area. The purpose of masking is to remove the unwanted data present in the study area and to keep the regular grid shape just over the region of interest.

GRACE data of various versions from JPL, which can be downloaded from grace.jpl.nasa.gov website. To detect monthly changes in groundwater reserves using GRACE, a basic law equation has been developed that describes the components of TWS (Skaskevych et al., 2020):

$$\Delta TWS = \Delta GW + \Delta SM + \Delta SW + \Delta SWE \quad (1)$$

where ΔTWS is change in Terrestrial water storage; ΔGW is change in groundwater data; ΔSM is change in soil moisture data; ΔSW is change in surface water data; ΔSWE is change in snow water equivalent. Assuming ΔSW to be negligible for area where no surface water body exist, then the above equation can be further written as:

$$\Delta GW = \Delta TWS - (\Delta SM + \Delta SWE) \quad (2)$$

The TWS data comes from GRACE data set while SM data is obtained from GLDAS. These terms are generally expressed in volume (km³) or mm of equivalent water height.

A practical analysis of changes in groundwater is carried out using a set of tools which is GRAMAT toolbox (Feng, 2019). It generally focuses on analyzing noise reduction techniques for processing spherical harmonic products of permitting data. The GRAMAT toolbox provides various destripping methods to reduce the errors in the form of noise and to remove the north to south stripes in the GRACE result coefficients. The data used is found on the grace tellus website (<https://jpl.nasa.gov.in>) for the year 2002-2015 by using the GRAMAT toolbox and destripping method proposed by Chamber 2007 was used (see Swenson et al. 2008).

In first step of GRAMAT, initially, we have to provide the GRACE level-2 data files as input with removing degree 1 and degree 2 harmonic coefficients (Figure 2). For elimination of gravity field correlated error, there are various destripping methods available, therefore, we select the destripping method and removal of GIA signal. In addition to this, we are required to provide Gaussian filter radius for noise reduction in data, the radius might be a few of hundreds kilometre. Further, we complete output settings by providing location of output directory to save estimated spherical harmonic coefficients followed by maximum degree to show the trend map. Then, we provide location of control files to be saved which is used in further steps.

In second step, the output of the first step (sphere harmonic coefficients) is converted in required spatial resolution (1 degree or 0.25 degree) and a grid file is generated (Figure 3). In third step, generated grid file is used as input with boundary file of the study area in .bln format (Figure 4). Further, we provide location of output file and the time-series of mass variation for the study is generated. The fourth step consists of harmonic analysis of generated time-series results in both spatial and temporal manner (Figure 5).

STEP1: Input and Settings (option1)
Select GRACE Level2 GSM/GAD Files:

Replace Degree 1:
☐ Replace
☐ Replace Degree 2:
☐ C20
☐ C21 & S21
☐ C22 & S22
☐ NAN

Disturbing Method:
☐ No disturbing method is applied
☐ Swenson et al. GRL 2006 (described in detail by Duan et al. JGG 2...)
☐ Chambers, 2007 (P3M12 for Released4 GSM files)
☐ Chambers & Bonin, Ocean Science Discussions, 2012 (P4M15 for Released5 GSM files)
☐ Chen et al. GRL 2007 (P3M6 for Sumatra-Andaman earthquake)
☐ Chen et al. Nature Geoscience 2009 (P4M6 for basins and glaciers)
☐ Duan et al. JGG 2009 (unchanged portion depend on degree and order)

GIA effect:
☐ No GIA signal removed
☐ GIA signal removed using Genu A et al. 2012
☐ Gaussian Filter Radius (km): 0

STEP2: Output and Settings
 Directory:
 Maximum Degree:
 Format & File Name:
☒ Option1: Spherical Harmonic Coefficients (*.mat file)
 Name:
☐ Option2: 1 degree Grid (one *.mat file, equivalent water height, meter)
 Name:
☐ Option3: 0.25 degree Grid (one *.mat file, equivalent water height, meter)
 Name:

STEP3/STEP1: Save/Open Control File
 Path:
 Path:

STEP4/STEP2: Calculate

Figure 2. First step in GRAMAT toolbox: Generation of Spherical Harmonic Coefficients

Spherical Harmonic Synthesis (From SH coefficients to Grids)
 Input File (mat/gfc SH coefficients file):
 Output File (mat Grid file):
 Spatial Resolution: ☒ 1 Degree ☐ 0.25 Degree

Spherical Harmonic Analysis (From Grids to SH coefficients)
 Input File (mat Grid file):
 Maximum Degree:
 Output File (mat SH coefficients file):

Figure 3. Second step in GRAMAT toolbox: Grid file generation of required spatial resolution

Input Files
 Grid file:
 Boundary file:
 Mask file:
 Output time series:

Figure 4. Third step in GRAMAT toolbox: Generation of time-series of mass variation

Time series harmonic analysis
 Time series file:
 Output result:
 Annual Amplitude:
 Semi-annual Amplitude:
 Trend:

Spatial harmonic analysis
 Grid file:
 Output results:
 Annual Amplitude Grid:
 Annual Phase Grid:
 Semi-annual Amplitude Grid:
 Semi-annual Phase Grid:
 Trend Grid:

Figure 5. Fourth step in GRAMAT toolbox: Analysis of Generation of time-series results

4. RESULTS AND DISCUSSION

This section includes time series graphs and trend maps for Allahabad region and hence we can see the variation present in the form of EWH (equivalent water height) in cm. The obtained time-series of EWH for Allahabad region covering 2002-2015 is shown in Figure 6. From the results, we can see the periodic changes occurred in the sequential years. Additionally, we see that the equivalent water height thickness is reducing regularly from the year 2002 to 2015 and with reference to this trend of time series plot for further years so we can say the situation becomes very worse.

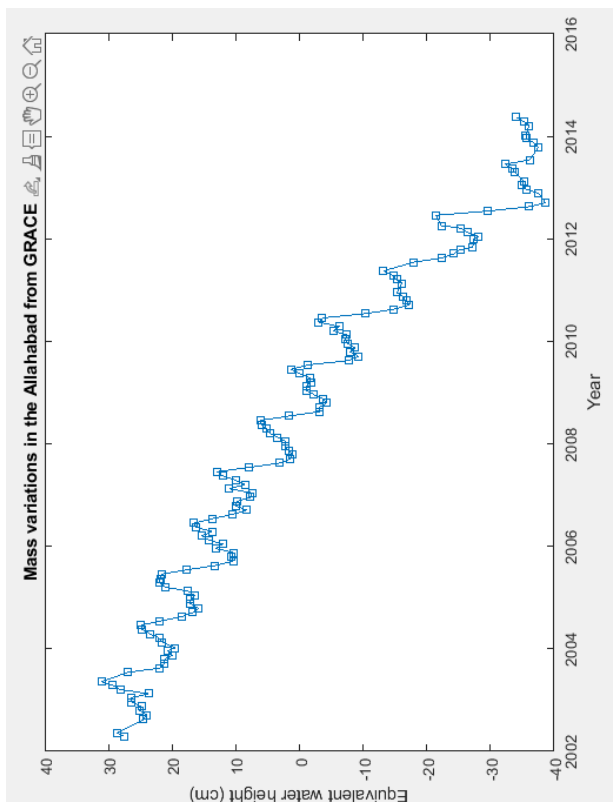


Figure 6. Time series of EWH for Allahabad region from 2002-2015

As a solution of this problem, we are required to identify areas where water level has to be recharged easily. Therefore, we have to use groundwater recharging techniques to conquer the problem such as through induced recharge methods, artificial injecting methods, flooding method, artificial channel method or Basin method. Construction of injection pits of required sizes corresponding to the area of water recharge should be prepared near the recharging area.

Figure 7 displays world trend map of mass variation from GRACE for 2002-2015. The red zone in the plot indicates the regions of water scarcities whereas the blue zone indicates the regions of water availability. From the world trend map, we can observe the current status of water availability among the world which is getting worse. As a result, scarcity of water and rapid increase in depletion of groundwater is observed.

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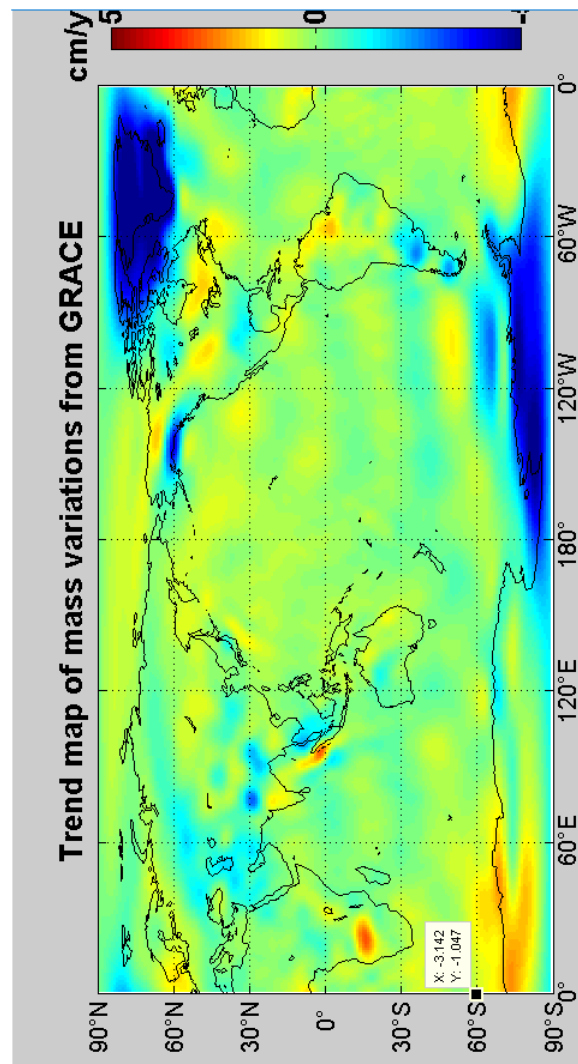


Figure 7. Trend map of mass variation from GRACE covering 2002-2015

5. CONCLUSIONS

In this paper, we present a GRACE Matlab Toolbox (GRAMAT) to process GRACE level-2 data and estimate spatio-temporal mass variations. A case study on TWS variations in the Allahabad region based on the GRACE data and the GRAMAT indicate a decreasing trend in EWH from 2002-2015 which shows the Allahabad city is heading towards water scarcity in next few decades.

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