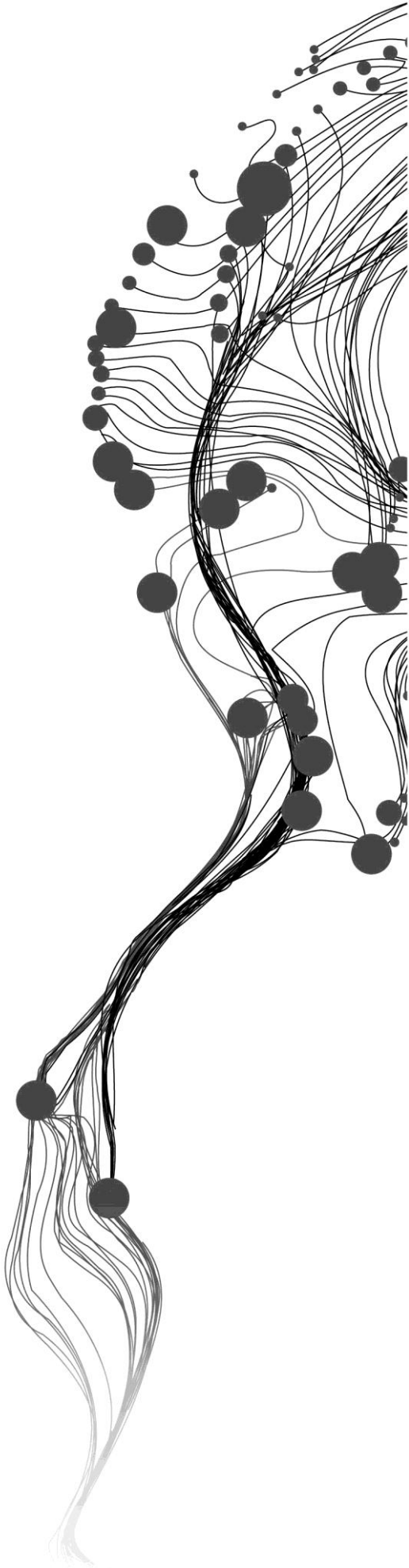# ESTIMATION OF TERRESTRIAL WATER STORAGE IN THE UPPER REACH OF YELLOW RIVER

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March, 2011

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ABSTRACT

Terrestrial Water Storage (TWS) in the Upper Reach of Yellow River (URYR) area is an important hydrologic component for the Yellow River. Improved estimation of TWS in the URYR is crucial for water resource management for China. Despite its importance, storage and change of TWS in the area has not been well studied at a larger scale. In this research, TWS and its change (TWSC) is estimated in the URYR during the period of 2003 to 2009. TWS is calculated from two methods: the first method employs the GRACE remote sensing satellite while the second employs estimation by use of GLDAS land surface state variables. TWSC is estimated from the TWS by subtraction of two consecutive monthly values. In addition, TWSC is also estimated from a water balance approach using a combination of river discharge measurements and GLDAS land surface flux variables. The spatial average values of GRACE and GLDAS from 1-degree-by-1-degree spatial resolution is extracted using a watershed mask derived from the DEM of the study area. The TWS result from the GRACE and GLDAS show an increase in TWS of 0.8 cm/year and 0.6 cm/year, respectively due to an increased precipitation of the area. The TWS and TWSC are qualitatively evaluated using hydrological and meteorological data. During the study period, the discharge of Yellow River increased by $13*10^8$ m³/year due to the increased TWS. In addition, the TWS and TWSC indicate a high water storage loss in 2006. This is associated with a low precipitation, a high evaporation and a high discharge from the river. All the results indicate the great potential of GRACE and GLDAS providing hydrological information to water resource management in URYR.

Key words: Yellow River, Terrestrial Water Storage, GRACE satellite, GLDAS, Tibetan Plateau

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LIST OF ACRONYMS

CLM	Community Land Model
CWS	Canopy Water Storage
DEM	Digital Elevation Map
DISC	Data and Information Services Center
DLR	Deutsches zentrum für Luft- und Raumfahrt
ET	Evapotranspiration
GES	Goddard Earth Sciences
GLDAS	Global Land Data Assimilation System
GRACE	Gravity Recovery and Climate Experiment
LSM	Land surface model
NASA	The National Aeronautics and Space Administration
netCDF	Network Common Data Format
P	Precipitation
R	River Discharge
SM	Soil Moisture
SRTM	Shuttle Radar Topography Mission
SWE	Snow Water Equivalent
TWS	Terrestrial Water Storage
TWSC	Terrestrial Water Storage Change
URYR	Upper Reach of Yellow River
VIC	Variable Infiltration Capacity model
WGS84	World Geodetic System 1984

1.   INTRODUCTION

Land surface processes on the Northeast Qinghai-Tibetan Plateau have a great effect on hydrologic, climate, and socioeconomic aspects in China. In hydrological terms, this region is a source area for many rivers like the Yellow, Yangtze and Mekong. The discharge of these rivers is controlled mainly by terrestrial water storage and permafrost of the Tibetan Plateau. In climatic terms the Tibetan plateau also plays a crucial role, through the energy and water cycles over this area. This energy balance of the region is largely controlled by soil moisture of the Tibetan Plateau. Consequently soil moisture in the Tibetan plateau plays a major role in global climate change in terms of the energy and water cycles. Both the hydrologic and climate impacts affect greatly the socioeconomics of China (Sheng & Yao, 2009).

Previous studies have shown that the Tibetan Plateau is highly sensitive to climate change. This is mostly caused due to its high altitude, its freezing land surface temperatures, and the presence of permafrost and glaciers. A permafrost degradation has been observed(Sheng & Yao, 2009), which is caused by the warming of the Tibetan Plateau (due to climate change) and human activities. This degradation in effect causes dropping water tables, shrinking lakes and wetlands, and noticeable surface cover change. Grassland ecosystems and alpine meadows at the source areas of the Yangtze River and Yellow River have turned into steppes (Cheng & Wu, 2007; Jin et al., 2009). These changes will affect the discharge of the rivers. As the Yellow River is very important for the socioeconomic development in China, changes in the river discharge will cause noticeable impacts in China.

China has been a country with limited land water resources for the past 30 years. The over-usage of water has increased along with the rapid economic development in China (Zhong et al., 2009). The Yellow River basin in China is one of its most important basins, directly supporting a population of 500 million people living in China (McVicar et al., 2007). The river is important for food production and socioeconomic development for China (Zheng et al., 2009).

Changes in the hydrological processes in the Northeast Qinghai-Tibetan Plateau will affect the Yellow River discharge and hence create significant socioeconomic impacts in the river basin. Water shortage in the Yellow River has resulted in economic losses to industry, domestic life, and agriculture(Xu et al., 2002). The Yellow River discharge has reduced to zero many times since 1960, which has left a huge impact on water resources and ecosystems downstream (Liang et al., 2010). For example the duration of drying-up per year in the downstream sections of the main river have increased significantly (Jia et al., 2006). It has been recognised that the water resource issue is one of the most significant problems that the Yellow River basin will face this century. Water authorities will face great challenge in satisfying the stream flow requirements and providing more water for growing populations, industry and agriculture.(Xu et al., 2002).

Improved estimation of Terrestrial Water Storage (TWS) and its Change (TWSC) in Upper Reach of Yellow River (URYR) is crucial for water resource management for China in the river basin. The TWS is a key hydrological part of the entire Yellow River discharge as it controls the Yellow River runoff. In spite of the TWSC importance, its storage change in the area has not been well studied at a larger scale. This is mainly due to the lack of sufficient network of ground based monitoring station. Observation of TWS was not possible from space. However, the Gravity Recovery and Climate Experiment (GRACE) can be used to measure these important variables. Together with the Global Land Data Assimilation System (GLDAS) data from this satellite can be used to estimate TWS and TWSC in areas where ground measurement data

is limited. The main motivation behind this research is to estimate the TWS and its variation in the URYR and characterizing its effect to the Yellow River discharge by using GRACE and GLDAS data.

1.1.   General objective

The general objective of this study is to estimate terrestrial water storage and its change in upper reach of Yellow River from 2003 to 2009.

1.1.1.   Specific objective

In order to achieve the general objective, the following specific objectives are set in this research.

- To estimate the terrestrial water storage and its change in the URYR from GRACE terrestrial water anomalies.
- To estimate the terrestrial water storage and its change in the URYR from GLDAS land surface variables.
- To compare the terrestrial water storage and its change estimated from GRACE and GLDAS data sets for the study area.
- To evaluate the terrestrial water storage and its change with hydrological and meteorological variables.

1.1.2.   Research questions

With each of these objectives, a research question can be defined for the definition of this research.

- How can we observe the TWS and its variation in the URYR from GRACE terrestrial water storage anomalies?
- How can we observe the TWS and its variation in the URYR from GLDAS land surface state variables in the Upper Reach of Yellow River?
- Are GRACE and GLDAS estimates of storage and change of terrestrial water comparable for URYR?
- How can we evaluate GRACE and GLDAS estimates of TWS for the URYR?

1.2.   Structure of the Thesis

This thesis is structured into six chapters. In chapter 2, a theoretical background of TWS measurement using GRACE and GLDAS is discussed. In chapter 3, the research methodology and materials are explained. In chapter 4, the research results and discussion are presented. In chapter 5, the research conclusions are presented.

2. THEORETICAL BACKGROUND

2.1. General

Terrestrial Water Storage (TWS) is the total amount of water stored on surface and subsurface of land. It includes groundwater, soil moisture and permafrost, surface water, snow and ice and wet biomass (Rodell & Famiglietti, 2001). It is a key part of the global hydrological cycles. It exerts important control over the water, energy and biochemical fluxes, thereby playing a major role in Earth's climate system(Yeh et al., 2006a). In addition the terrestrial water is used for agriculture and domestic purposes. However, changes in land surface parameters like, precipitation patterns, evapotranspiration and temperatures will affect water storage (Bovolo et al., 2009; Jin et al., 2009).

Accurate measurement of TWS at large scales is challenging due to limited number of TWS monitoring stations. Common methods of measuring the TWS are boreholes, soil moisture stations, and lake level measurements. Such methods have good accuracy but they are too costly for monitoring a large area with an adequate network of measuring stations. To overcome this problem, a methodology is proposed based on remote sensing and auxiliary data. Application of Gravity Recovery and Climate Experiment (GRACE) data in combination with Global Land Data Assimilation System (GLDAS) is a newly developing method for estimating TWS that is considered as the state of the art. In the next sections the theoretical background and the applicability of the GRACE satellite and GLDAS model for estimation of TWS is presented.

2.2. GRACE Observations of Terrestrial Water Storage.

The GRACE satellite mission, launched by NASA and the German Aerospace Centre (DLR) in 2002, measures temporal variations in the gravity field, which is used to estimate changes in TWS (Tapley et al., 2004). GRACE is the first satellite remote sensing mission, which is directly applicable to the assessment of Terrestrial water storage under all types of terrestrial conditions (Rodell et al., 2004b). Figure 2-1 shows GRACE twin satellites orbiting the earth at an altitude of 500 km and at 220 km distance apart.
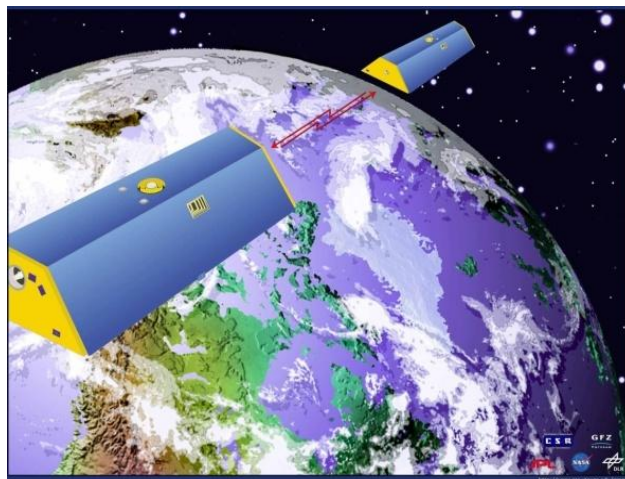
Figure 2-1: The Gravity Recovery and Climate Experiment (GRACE). GRACE twin satellites orbiting the earth at altitude of 500 km and at 220 km distance apart each other. (University of Texas Center for Space Research).

Many satellites provide capabilities of observing global land surface variables and have produced many land surface variable datasets but none of them is able to observe beneath the ground surface. The GRACE satellite can sense the changes deep under the ground surface by measuring the earth's gravity with great accuracy. While most remote sensing satellites use radars or radiometer to measure various wavelength of light, which are reflected or emitted from earth, the GRACE has no sensor to observe the ground (Rodell, 2009). Instead, it measures the distance between two identical satellites orbiting Earth using highly precise K-band microwave system(Tapley et al., 2004). Later on, the distance measurement is used to determine temporal variation of the earth's gravitational field.

The GRACE satellites measure variations in water storage indirectly, by measuring temporal variation of gravity field of the earth (Strassberg et al., 2009; Wahr et al., 1998). Unlike most missions, the satellites act as the measurement devices. The GRACE system consists of two chasing satellites (also called Tom and Jerry). When gravity increases, the leading satellite accelerates before the second accelerates and catches up, see Figure 2-2. In short, gravity variations induces distance variations between the satellites (Strassberg et al., 2009). The satellite use microwaves to continually measure their separation distance. After removing the effect of non-gravitational acceleration as detected by on-board accelerometers, the measurements are used to solve for the gravity field (Tapley et al., 2004).
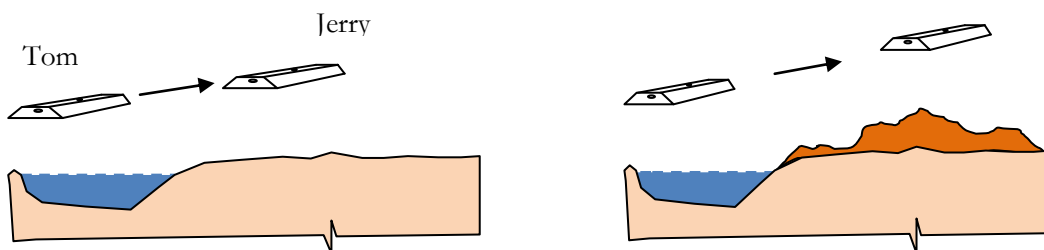
Figure 2-2: GRACE twin satellites passing over different gravity field of the earth surface. When the GRACE satellites passes over the earth surface (left). When the gravity increases below the leading satellite, the satellite will accelerate. This will create greater distance between the two satellites compared (right). (Adopted from NASA).

The Earth's global gravity field is commonly described in the shape of the geoid and can be expressed numerically as a sum of spherical harmonics (Rodell et al., 2006; Wahr et al., 1998). These gravity filed is produced by GRACE, each represented as a set of spherical harmonic coefficients, complete to degree and order 120 (Crowley et al., 2006). These coefficients are provided as level 2 products. Non-hydrological gravitational contributions are removed from the level 2 products based on numerical models of the underlying processes, including atmospheric and oceanic circulation and solid Earth tides (Rodell et al., 2006).

The gravity fields by GRACE requires spatial smoothing to reduce the effect of errors, which are present in short wavelength components. As the smoothing radius decreases, these errors appear in maps of surface mass variability as stripes (long, linear features generally oriented north to south). This effect is adjusted by post-processing (Swenson & Wahr, 2006). To generate spatial maps of TWS anomalies (deviations from the series mean) in cm of equivalent water height, the spherical harmonic coefficients are smoothed with a Gaussian averaging kernel width, and then expanded to regular grid (Wahr et al., 1998). Often the kernels are applied on scales of 250 km to 1000 km radius. The uncertainty of GRACE measurement after all this processing is about 2.1cm. At resolutions finer than about 200,000 km², the uncertainty in the estimates begins to be large and affect the water storage signal (Rodell & Famiglietti, 1999; Yeh et al., 2006b).

Temporal variation in the gravity (measured by GRACE) is used to study a large variety of problems in a number of disciplines from monitoring change in water storage to snow storage on continents. For example, GRACE is used to estimate groundwater storage change (Rodell & Famiglietti, 2002), terrestrial water storage budget (Landerer et al., 2010), drought monitoring (Yirdaw et al., 2008) and snow mass retrieval (Niu et al., 2007).

2.3.   GLDAS land surface variabels and Terresterial Water Storage.

Understanding of soil water dynamics, plant physiology, micrometeorology, and the controls on atmosphere–biosphere–hydrosphere interactions requires advanced observation and modelling systems. This has led to develop several land surface models (LSMs) in the past two decades with the goal of simulating the transfer of mass, energy, and momentum between the land and the atmosphere. Different LSMs are used in GLDAS. For example, GLDAS Mosaic, Noah, the Community Land Model (CLM), the Variable Infiltration Capacity model (VIC; Liang et al. 1994) and the Catchment Land Surface Model (Koster et al. 2000) are the common ones(Rodell et al., 2004b).

The GLDAS is global, high resolution, offline terrestrial modelling system that incorporates satellite and ground based observation in order to produce optimal fields of land surface states of flux in near real time. GLDAS produces optimal fields of land surface states (e.g., soil moisture (SM), snow water equivalent (SWE), canopy water storage (CWS), surface temperature) and fluxes (e.g., evapotranspiration (ET), ground heat flux) (Rodell et al., 2006; Rodell et al., 2004b). The GLDAS makes use of the new generation of ground and space based observation systems, which provide data to constrain the modelled land surface states. The constraints are applied in two ways. First, by forcing the LSMs with observations based meteorological fields, biases in atmospheric model based forcing can be avoided. Second, by applying data assimilation techniques, observations of land surface states can be used to restrain unrealistic model states (Rodell et al., 2004b).

Advanced LSMs provide detailed estimates of hydrological fluxes and storages. These estimates are valuable for studies of climate and water resources (Zaitchik et al., 2010). The GLDAS data has been used for global and regional hydrological studies. GLDAS soil moisture, snow water equivalent and canopy water storage data has been used to isolate groundwater storage change from the TWS measurement of GRACE data (Rodell et al., 2009). GLDAS data also used by (Syed et al., 2008) to estimate global TWS on major river basin and compared it with GRACE TWS estimate. The GLDAS provides a time series of land surface states and fluxes, which are used to study water storage.
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3. MATERIALS AND METODOLOGY

3.1. Study area discription

The study area for this research is the Upper Reach of Yellow River (URYR) in Northeast Qinghai-Tibetan plateau; see Figure 3-1. It is located between 95°52'00" to 104°21'00" E and 32°21'00" to 38°17'00" N with an approximate area of 225,900 km², which is about 30% of the total area of a Yellow River basin (780,000 km²). The area has an elevation ranging from 1514 m to 6217 m above mean sea level. The area is surrounded by the Bayan Har Mountains in the south, by the Buqing Mountains in the north, and by the Geshigeya Mountains in the west. The area is interspaced with several rugged mountains and hills, valleys and intermontane basins, lakes, rivers and high plains (Jin et al., 2009).
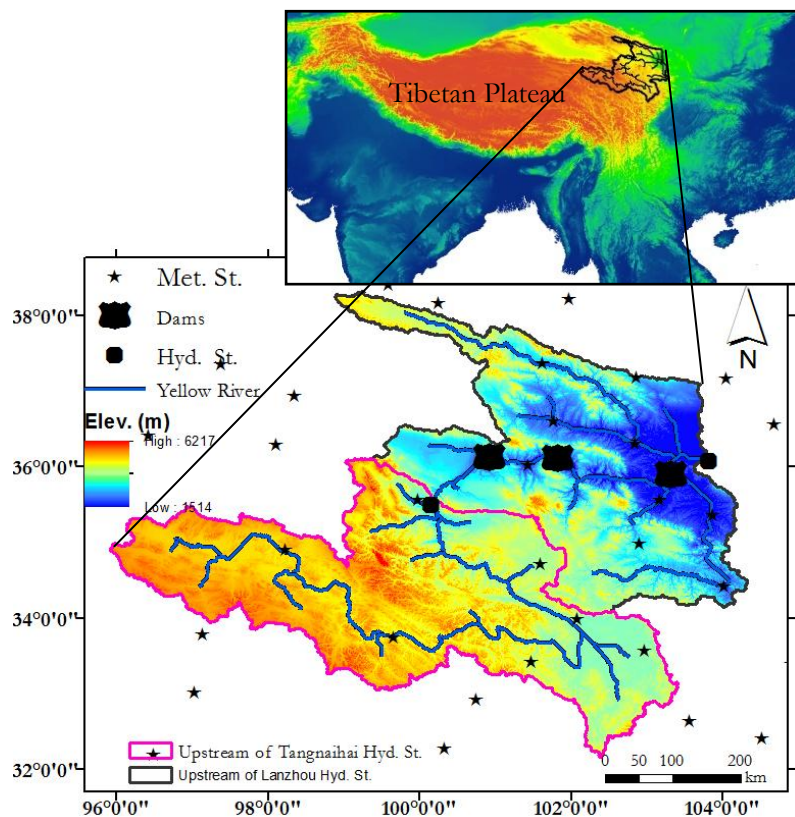
Figure 3-1: Location of the study area (Upper Reach of Yellow River basin in northeast Qinghai-Tibetan plateau.

The study area is one of the main sources for Yellow River discharge. According to hydrological characteristics, the River is divided into three reaches, the upper reach, the middle reach, and the lower reach. The area upstream of Lanzhou station (36°04'12" latitude, 103°49'12" longitude) is called the Upper Reach of Yellow River. Both the middle and the lower reaches are significantly affected by human activities, while the upper reach is much less affected (Xu et al., 2009). The annual river discharge at this station is $316*10^8$ m³ (1956-2001), which is about 50% of the Yellow River discharge. The discharge to this station is controlled by reservoirs, such as Longyangxia, Liujiaxia and Lijuxia (Jia et al., 2006). Another river discharge station is the Tangnaihai hydrological station (35°30'00" latitude, 100°09'00" longitude). This station divides the Upper Reach area of Yellow River equally. The annual average river discharge at

this station is $200*10^8$ m^3 (1956-2001), which is about 63% of the total flow from upper reach of Yellow River.

The climate of the area is long winter and short summer. It displays small annual minimum temperature variation between -7 °C and 4 °C from East to West (Figure 3-2). There is intense solar incoming radiation and long sunshine duration. Furthermore the area is characterised by big windy storm, and short plant growth periods (Zhao et al., 2009). The typical climate in the area above Tangnaihai hydrological station is cold and dry (Feng et al., 2006) and it is covered partly by snow and frozen soil throghout the year (Jia et al., 2006). January is the coldest month and August is relatively the warmest month. The area is considered semi humid region with an annual mean precipitation of 446 mm (increasing from Northwest to Southeast). The precipitation mostly falls between June and September, accounting for 75% of the annual average (Zhao et al., 2009).
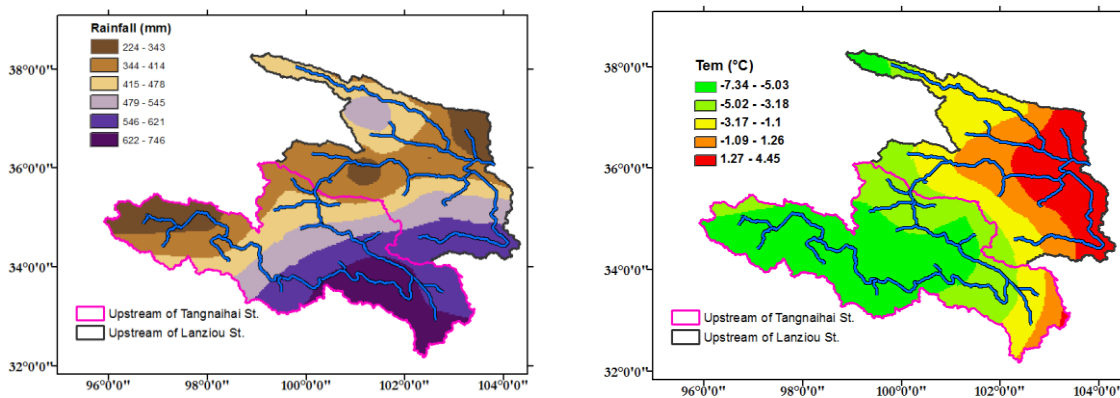
Figure 3-2: Spatial variation of precipitation and temperature in the Upper Reach of Yellow River. Mean annual precipitation pattern from 2003 to 2009 (left). Mean annual maximum temperature pattern (right).

3.2.   Materials

In this research data from remote sensing, large-scale models and ground-based measurements are used. The GRACE satellite provides estimates of TWS from 2003 to 2009. The GLDAS model provides land surface state variables and fluxes. Ground-based measurements of precipitation and temperature are acquired from 41 meteorological stations, see Figure 3-1. Data of the Yellow river discharge is acquired by the Lanzhou hydrological stations. For processing these data, different tools are employed. The details of the data sets and the tools used are described below.

3.2.1.   Satellite data

GRACE level 3 (equivalent water height) 1 degree by 1 degree data Terrestrial water storage estimate from 2002 to 2010 is used. It was processed by Sean Swenson, supported by the NASA MEASURES Program, and is available at http://grace.jpl.nasa.gov. The data contains monthly TWS anomalies, which are calculated as deviations from the mean value of the period from 2003 to 2007. The data is derived from spherical harmonic data with an order and degree up to 60. These are smoothened by half-width equivalent to 300 km of Gaussian smoothing radius. Figure 3-3 shows the global TWS estimate from GRACE satellite for January 2003.
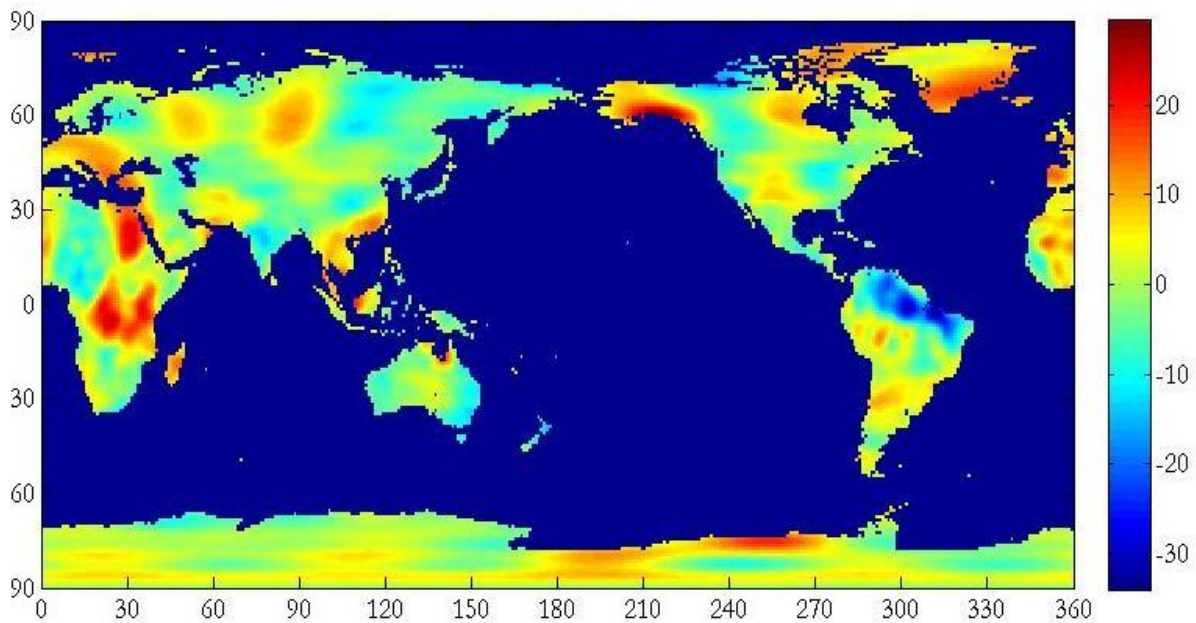
Figure 3-3: GRACE level 3 data of Terrestrial water storage for January 2003.

A Digital Elevation Map (DEM) from the Shuttle Radar Topography Mission (SRTM) is downloaded from http://srtm.csi.cgiar.org/. The data has WGS84-datum geographic coordinate system, with a 1 km resolution in horizontal direction and covers the whole globe. The file is stored in GeoTIFF format and is imported to ArcGIS software for processing. The data in and around the basin area is extracted. ArcHydro-processing extension tool in the ArcGIS platform is used to extract drainage line, watershed area of the Upper Reach of Yellow river. During a fill and sink operation in hydro-processing operation, a mask polygon around Qinghai closed basin lake outside the study area is applied. This is to prevent the lake area from merging with the study area.

3.2.2. GLDAS model data

The GLDAS 1 degree by 1 degree, monthly NOAH land surface model (Ek et al., 2003) from 1979 to 2010 is downloaded from http://mirador.gsfc.nasa.gov/. The data was acquired as part of the mission of NASA's Earth Science Division (ESD) and distributed in Network Common Data Format (netCDF) files by the Goddard Earth Sciences (GES) Data and Information Services Center (DISC). The files are geo-gridded arrays and include information about the data it contains. To download these files, the 'wget' software is used. Preliminary information on the files is extracted using the Panoply netCDF viewer available at http://www.giss.nasa.gov/tools/panoply/.

Each monthly GLDAS data consists of 25 variables. The data set covers from 60° S to 90° N of the world. From these files land surface state variables (soil moisture, snow water equivalent, canopy water storage) and land surface fluxes (precipitation, evapotranspiration) are derived. Finally, the processing of the data is done with MATLAB software. Table 3-1 shows the variables used in this research and Figure 3-4 shows the time series of some of the land surface state variables.

Table 3-1: GLDAS land surface variables used in this research.

It No	GLDAS Variables	unit	Symbol	Sampling
State variables				
1	Four layer Soil Moisture	kg/m	SM	Monthly mean
2	Snow Water Equivalent	kg/m	SWE	Monthly mean
3	Canopy Water storage	kg/m	CWS	Monthly mean
4	Temperature	K	T	Monthly mean
Flux variables				
5	Rainfall	mm/s	RF	Monthly sum
6	Snowfall	mm/s	SF	Monthly sum
7	Snow Melt	mm/s	SM	Monthly sum
8	Evapotranspiration	mm/s	ET	Monthly sum
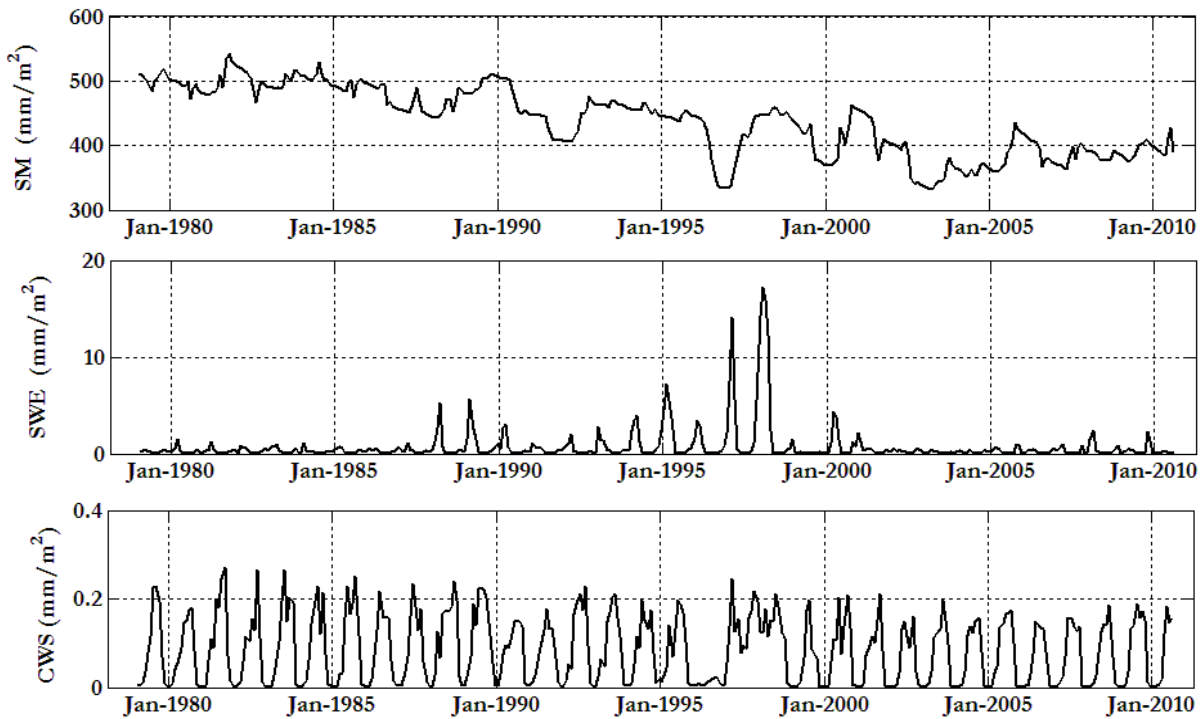
Figure 3-4: GLDAS land surface state variable in the Upper Reach of Yellow river from 1979 to 2010. In the upper panel the soil moisture is shown, in the middle panel the snow water equivalent is shown and in the bottom the Canopy water storage is shown.

3.2.3. Ground observation

There are about 9 hydrological stations in the Upper Reach of Yellow river (Zhao et al., 2009) but, data from the Lanzhou station is used for this research. The data is taken for the period 2003 to 2009. In addition, the daily precipitation and temperature records from 41 meteorological stations were collected. These stations are fairly uniformly distributed inside and outside the study area. Among the station, 18 of them are inside the study area and the remaining are outside but close to the study area. The data is collected for the period from 2003 to 2010. To get the monthly precipitation data for each station, the

sum of the daily precipitation in each month is taken. To get the monthly temperature, the average of the daily temperature of each month is taken.

3.2.4. Tools

- MATLAB
- ArcGIS
- SPSS
- Wget a free network utility to retrieve files from the World Wide Web using HTTP and FTP.
- Panoply netCDF viewer software

3.3. Methodology

3.3.1. General

A common method to measure Terrestrial Water Storage (TWS) and its Change (TWSC) uses in situ measurements like borehole, soil moisture stations, and lake level measurements. These methods have a good accuracy but are costly to employ in a network of measuring stations for the characterisation of large areas. To overcome this, the data from GRACE and GLDAS are used to estimate TWS change for data limited regions of the world.

In order to estimate TWSC in the study area, the GRACE data and GLDAS model output fields are used. The GRACE TWS consists of a combined total of groundwater, soil moisture and permafrost, surface water, snow and ice and wet biomass (Rodell & Famiglietti, 2001). On the other hand, the GLDAS model delivers individual land surface state variables and fluxes. These are used to estimate TWS anomalies and TWSC. In this research, the TWSC results from GRACE and GLADS will be compared. Finally the TWS is characterized with the Yellow River discharge measurement at Lanzhou station. The methodology flowchart is shown in Figure 3-5.

Currently, it is not possible to obtain measurements to validate GRACE and GLDAS data due to large spatial coverage of these data. To compensate this, hydrological and meteorological data are used for a qualitative comparison. Yellow River discharge from Lanzhou station and precipitation and temperature data from 41 meteorological stations are used. From these data, trend and variation in the river discharge is analysed. The mean and variation of the meteorological data are investigated.
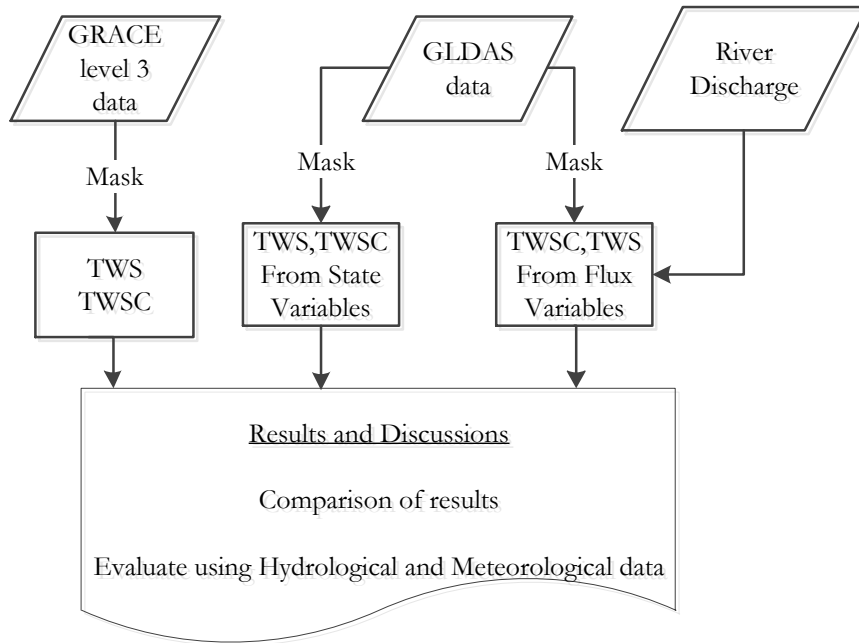
Figure 3-5: A flow chart for TWS and TWSC estimation from GRACE and GLDAS data.

3.3.2. Data masking for the study area.

A mask is extracted from the Digital Elevation Map (DEM), in order to get the GLDAS and GRACE output for the Upper Reach of Yellow River (URYR). The GLDAS and the GRACE data are in 1 degree by 1 degree in regular grid shape. However, the URYR watershed does not have a regular shape that will match with the grids of the GLDAS and the GRACE data. To get the data for the area, the following processing steps are followed:

1. Watershed area is created from DEM of the area.
2. The Watershed area is crossed with grids of GLDAS /GRACE, see Figure 3-6.
3. The ratio of watershed area that lies in the GLDAS/GRACE grid to area of 1-degree grid is taken as mask weight. This amounts the contribution of GLDAS or GRACE value to the watershed.
4. To get the aggregated value for the entire watershed, the mask is used to obtain the weighted average of the GLDAS/GRACE value.
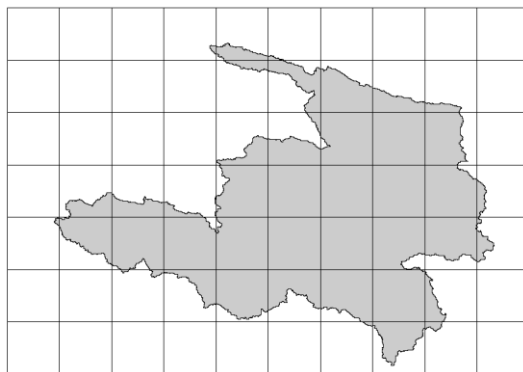
Figure 3-6: Upper Reach of Yellow River area overlaid with GLDAS/GRACE grid cell.

Figure 3-6 shows the Upper Reach of Yellow River area in the GLDAS/GRACE grid cells. The area is extracted from 1km horizontal resolution DEM topographic map in ArcGIS software with ArcHydro extension tool box. The extracted area is overlaid with the GLDAS grid cells as shown in the figure. The area from intersection of the GLDAS/GRACE grid cell with the watershed area is estimated. This intersection area represents the amount of watershed area in the GLDAS grid cell. This will be related to the amount of weight given to the watershed area to mask the GLDAS variable. Equations 3.1 and 3.2 are used to assign the weight and estimate the GLDAS/GRACE value for the area.

$$w_i = \frac{ai}{gi}$$ 3.1

$$V_N = \frac{\sum_{i=1}^{n}(vi \times wi)}{A}$$ 3.2

Where: wi is the weight of grid i, ai is the area of the watershed in the grid i within the GLDAS or GRACE data grid; gi is area of 1 degree by 1 degree GRACE or GLDAS grid cell, V_N, the value of data of month N for the entire watershed, vi is the value the data of grid i, A is total area of the watershed, n is the number of the GRACE/GLDAS grids.

3.3.3.   Terrestrial Water Storage Change from GRACE

GRACE gives indirect estimates of mass anomalies near the Earth's surface by measuring temporal variations in the gravity field, which can be used to estimate changes in TWS. GRACE has delivered more than 100 months of TWS since its mission has started. The GRACE level 3 data provides monthly mean terrestrial water storage anomalies as equivalent water height. These anomalies are the deviation from the mean value averaged of certain period. For example, the data used in this research has an averaging period from January 2003 to December 2007. The signal in this data can be attributed to change in soil moisture, groundwater and surface water. The GRACE data is masked for the Upper reach of Yellow river by the technique shown in section 3.3.2. Later on, the masked data is used to study water storage variation in the area.

The GRACE data is important to study the long-term variation and month-to-month variations of terrestrial water storage. The month to month variations in water are estimated from the GRACE TWS as the difference between two observations with an interval of approximately 30 days. These estimates of TWSC is average change in the TWS from one month to the other consecutive month (Syed et al., 2008). In this research, the TWSC estimate from the GRACE is calculated as shown by equation 3.3. The TWSC helps to understand the short time variation in terrestrial water storage. However, due to subtraction to estimate TWSC from two month of TWS the uncertainty will increase by $\sqrt{2}$ times the uncertainty in the TWS estimate by GRACE (Rodell et al., 2004a).

$$TWSC_N = TWS_N - TWS_{N+1}$$ 3.3

Where: TWS is terrestrial water storage and N indicates the GRACE measurement period or month.

The GRACE measurement is taken almost on monthly interval. However, in some months, measurement is missing. For example, the GRACE data has missing values for June 2003. The GRACE data has also

few days interval of measurements. For example, it has only 12 days interval of measurement for January 2004. These values are linearly interpolated from the previous and next months of the required month as shown by equation 3.4 (Landerer et al., 2010).

$$TWS_N = \frac{1}{2}[TWS_{N+1} + TWS_{N-1}] \qquad\qquad 3.4$$

Where TWS_N is the TWS of month N with measurement missing, TWS_{N-1} is the TWS for the previous month of the measurement missing month, TWS_{N+1} is the TWS for the next month of the measurement missing month.

3.3.4. Terrestrial Water Storage Change from GLDAS

For this research, GLDAS 1 degree by 1 degree, monthly NOAH land surface model are used. From these data TWS anomalies for the Upper Reach of Yellow River are derived. The GLDAS land surface state variables (soil moisture, snow water equivalent and canopy water storage) are used to compute the anomalies and the GLDAS land surface fluxes (rainfall, snowmelt, and evapotranspiration) are used to compute the TWSC for this area. The TWSC is estimated from the land surface fluxes and runoff data taken from the Lanzhou hydrological station.

Terrestrial water storage in the Upper Reach area of Yellow river consists of groundwater, soil moisture and permafrost, surface water, snow and ice and wet biomass variables. The change in TWS is estimated as the sum of the change of aforementioned variables. However, some of the variables have little effect on TWS variation. There is no intense groundwater exploration for domestic or agricultural purpose. The groundwater change in this area is assumed to be not significantly changing. The anomalies corresponding to the major part of signal to TWS can be assumed to arise from change in soil moisture, snow water equivalent and canopy water storage. Hence, the TWSC for the Upper Reach area of Yellow river is calculated as shown by equation 3.5, using the method of Seo et al., (2006).

$$TWSC = \Delta SM + \Delta SWE + \Delta CWS \qquad\qquad 3.5$$

Where, $TWSC$ is the change in total water storage, ΔSM is change in soil moisture, ΔSWE is the change in snow moisture equivalent and ΔCWS is the change in canopy water storage. Note that the changes in surface water (dams, rivers, lakes) are difficult to include in this research and can be a source of error in this estimation.

The TWS anomalies are estimated for the Upper Reach of Yellow River from 2003 to 2009. The TWS anomalies are derived from GLDAS land surface state variables. Two meter depth of four-layer soil moisture, snow water equivalent and canopy water storages are the variables. To estimate TWS anomalies, first all the variables are summed to get terrestrial water storage. Second, the mean value of the aggregate variables is calculated from Jan 2003 to Dec 2007. Finally, the mean value is subtracted from each month's terrestrial water storage to get the anomalies. The averaging period is similar to the averaging period taken in the processing of GRACE level 3 data used for this research. This is to make comparison between GRACE and GLDAS estimate.

GLDAS Noah land surface fluxes are also used to estimate the TWSC for the Upper Reach of Yellow River. GLDAS delivers rainfall, snowfall, snowmelt and evapotranspiration land surface fluxes. The estimation of TWSC from land surface fluxes is calculated using equation 3.6.

$$\mathbf{TWSC = P - ET - R} \hspace{6cm} \mathbf{3.6}$$

Where, P is the precipitation, ET is the Evapotranspiration, R is the River Discharge, $TWSC$ is the change in terrestrial water storage.

Two consecutive months TWSC estimate from this method are averaged to get results comparable with the TWSC estimate of GRACE and GLDAS state variables estimate, see equation 3.7. This is because the two other results are derived from two months difference of TWS. Taking the average of two will account for the difference between the two methods. Using this method, also creates a smoothing effect on the time series of TWSC estimates, that helps to reduce errors (Landerer et al., 2010).

$$TWSC_N = \frac{1}{2}[(P - ET - R)_N + (P - ET - R)_{N-1}] \hspace{3cm} \mathbf{3.7}$$

Where: $TWSC_N$ is the change in storage for the period N, P is total spatially aggregated Rainfall and Snowmelt, ET is total spatially aggregated Evapotranspiration, R is River Discharge.

4.   RESULTS AND DISCUSSIONS

4.1.   Terrestrial water storage and its change from GRACE

Area averaged monthly mean of seven years TWS for Upper Reach of Yellow River from GRACE is plotted in Figure 4-1 below. A linear trend line is fitted to the data by least square estimate method as shown with a straight line. The trend shows that the TWS is increasing (0.8 cm/year) in the area. This result is compared with the Zhong et al., (2009) estimate of (1.1 cm/year) for the study period from 2002 to 2007 in the areas where Qinghai, Sichuan and Gansu provinces meet. These areas include the Upper Reach of Yellow River but with larger areal coverage. The difference in TWS trend between the two can be associated with difference in the study area size and the length of the study periods.
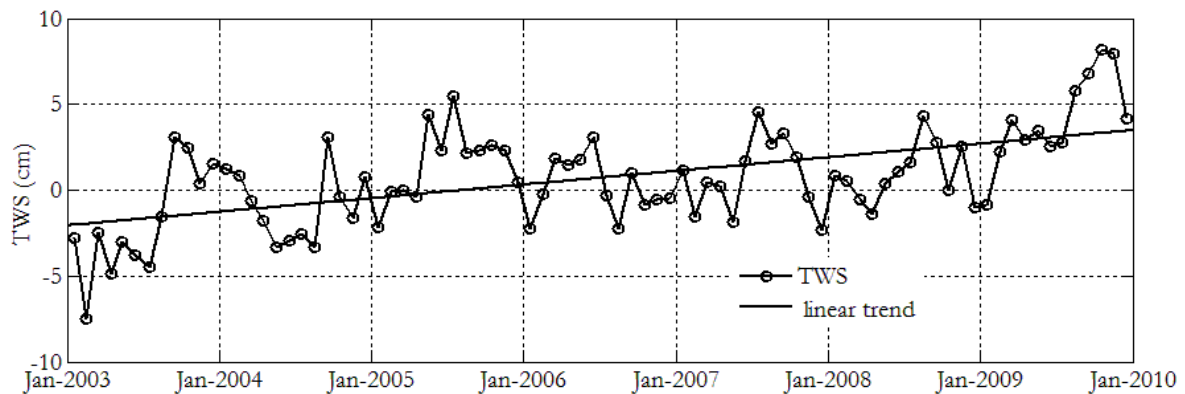
Figure 4-1: Time series of TWS by GRACE of Upper Reach of Yellow River. The circles represent the GRACE observations while the solid line presents the trend (0.8cm/year).

Figure 4-2 shows monthly variation GRACE TWS estimates from 2003 to 2009. The values are calculated from TWS estimate (Figure 4-1). First, the linear trend is removed from the TWS and second, the same months of TWS are selected from the residual. Finally, the mean value of TWS for the selected TWS is calculated. The error bar in the figure stands for the standard deviation of the monthly TWS. The figure shows that the TWS increases mostly during the rainy seasons. The rainy season in this study area starts in May and ends in September. The TWS is estimated the highest in September (mean = 2.3 cm, STD=1.7 cm) and December to Februaryhas the lowest (mean =-1.0 cm, STD=1.9 cm). The difference between these two extremes is close to the uncertainty limit of GRACE measurement (2.1 cm). This indicates that the study area's seasonal hydrological fluxes are low, resulting in low flux variation that cannot be observed by GRACE level 3 data accurately. This means the estimate of TWS from the GRACE data will be dominated by large uncertainty, and consequently will make it difficult to investigate shorter periods or sub basin variations of TWS in the area.

The GRACE data does not show short-term variation of TWS due to low hydrological process in the area. The variation in the area is of the same order as the uncertainty of GRACE measurement. Generally, GRACE data is well suited to hydrological process of large river basins if the amplitude of annual storage reaches well beyond the error range of GRACE (Wahr et al., 2004).   However, the long term variation in TWS from 2003 to 2009 is beyond the uncertainty limit of GRACE estimate. The long term TWS difference reaches from the minimum -7.5 cm to the 8 cm as shown in the Figure 4-1. Consequently, the GRACE data estimated the long-term trend in TWS of the study area.
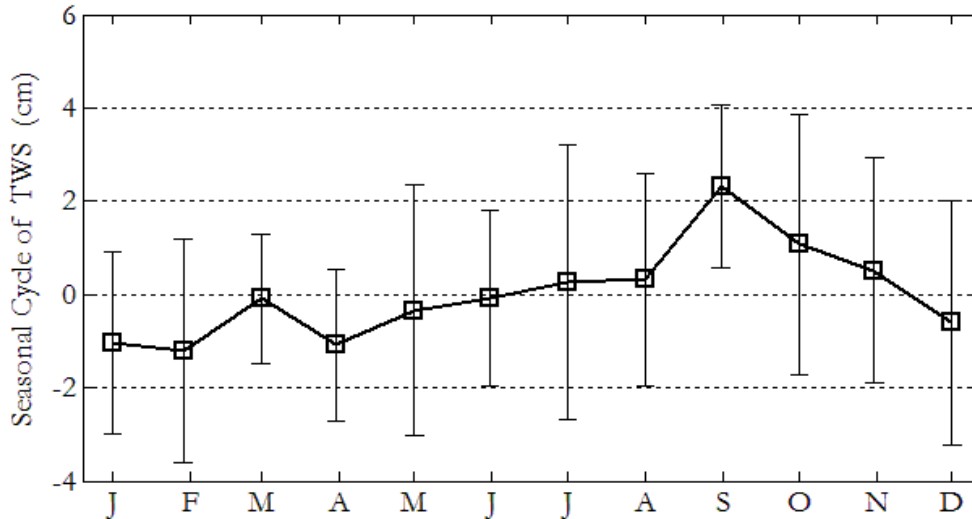
Figure 4-2: Averaged monthly TWS estimate after removing the linear trend from TWS estimate from 2003 to 2009. The error bars represent the standard deviation for the monthly mean values.

Figure 4-3 shows the TWSC from GRACE. The result does not show a distinct pattern in TWSC that reflects the seasonal variations in water storage of the area. This is due to high uncertainties of TWS of GRACE estimate compared to less hydrological process in the study area. If the amplitude of the hydrological variation in the area is smaller than the uncertainty limit of GRACE estimate, the TWS measurement from GRACE will be associated with error. These errors will propagate to the TWSC estimate and will become larger. This is because the uncertainties in TWSC will increase by $\sqrt{2}$ times the uncertainties in TWS (Rodell et al., 2004a).
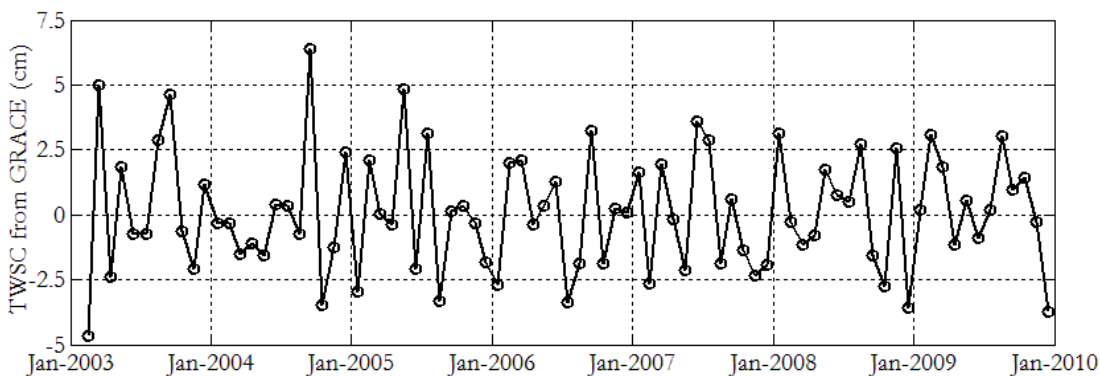
Figure 4-3: Time series of GRACE derived terrestrial water storage change in the Upper Reach of Yellow river from 2003 to 2009.

4.2.   Terrestrial water storage and its change from GLDAS for Upper Reach of Yellow River

Figure 4-4 shows the time series of terrestrial water storage anomalies (TWS) estimated from the GLDAS state variables. The TWS for the period from Jan 2003 to April 2005 is mostly negative. This indicates the storage amount in this period is below the mean value. The TWS from April 2005 to Dec 2009 is mostly positive indicating the storage amount is greater than the mean value. A linear trend fitted to the TWS shows an annual increase of 0.6 cm/year from 2003 to 2009.
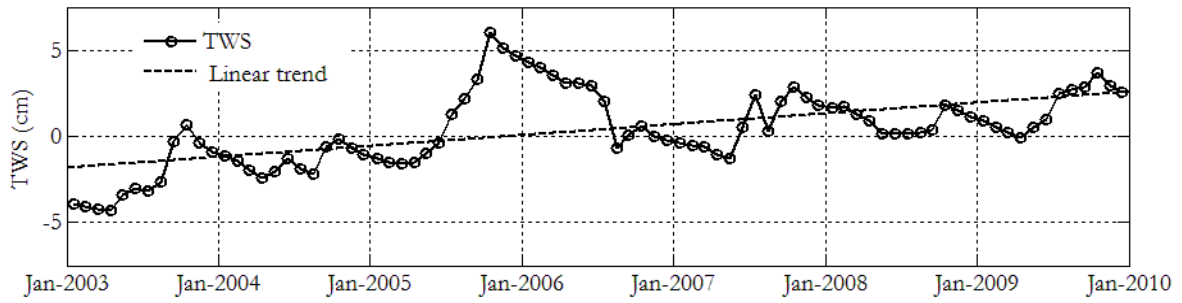
Figure 4-4: Time Series of Monthly TWS from GLDAS Noah Model soil moisture, snow water and canopy water storage.

Figure 4-5 shows TWSC derived from TWS estimate of GLDAS state variables. It is calculated by taking difference from two consecutive months TWS (next month minus the previous month) estimate of GLDAS state variable. As shown in the figure there are variations in TWSC due to seasonal effects. During the rainy seasons, the TWS peaks and during the winter season the TWS is at its lowest point of the year. This indicates that the hydrological variation in the area is captured better by GLDAS state variables in comparison to the GRACE observations.
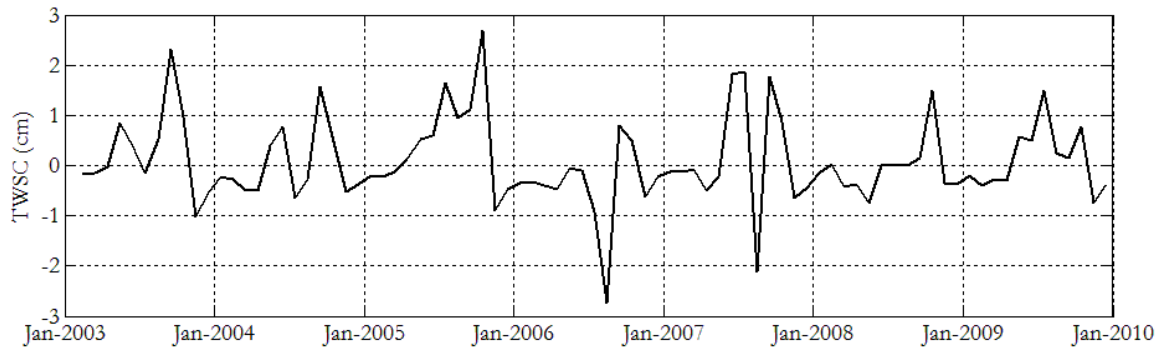
Figure 4-5: Terrestrial Water Storage Change (TWSC) derived from GLDAS state variable.

Figure 4-6 shows TWSC estimates from the water balance approach for the Upper Reach of Yellow River. It is derived from the GLDAS land surface flux variables and hydrological station river discharge. The result shows a seasonal variation in TWSC. A rainy season TWSC peak followed by a wintertime TWSC trough is observed. The hydrological variation in the area is captured better by GLDAS state variables in comparison to the GRACE observations.
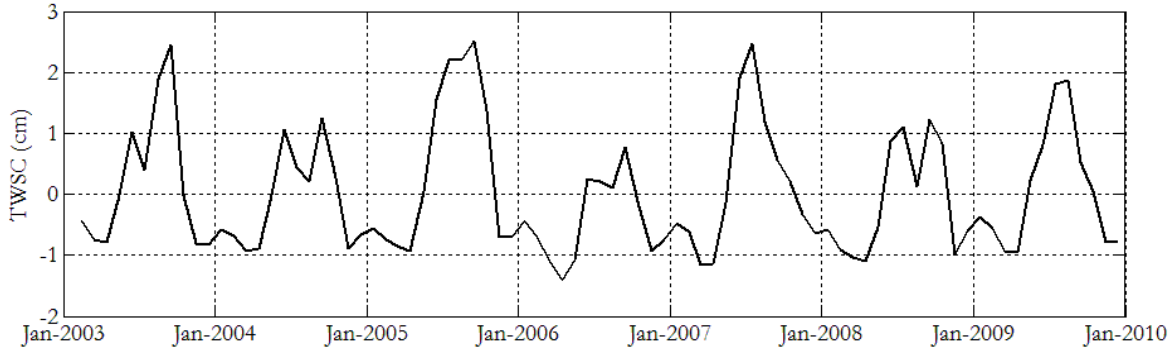
Figure 4-6: Terrestrial water storage change (TWSC) derived from water Balance approach.

The cumulative of TWSC estimated from GLDAS land surface flux variable is shown in Figure 4-7. This cumulative result reproduces TWS to compare with the TWS estimate from GRACE and GLDAS state variables. A linear trend (black line) is fitted to the TWS estimate. Unlike the estimate from GRACE and GLDAS land surface, the trend shows that the TWS exhibits no significant trend. This contradicts the results obtained from GRACE and the GLDAS land surface state variables trend estimates. To examine this, cumulative of the individual water balance terms are plotted in the Figure 4-8.
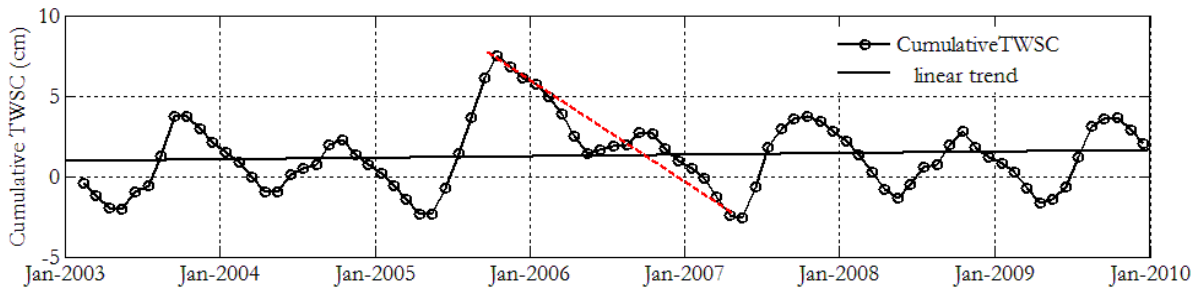
Figure 4-7: Cumulative Terrestrial water storage change (TWSC) in the Upper Reach of Yellow river, from 2003 to 2009, derived from GLDAS land surface flux variables. The broken red line show the continuous decrease in water storage from Oct 2005 to April 2007.

The cumulative of the GLDAS estimates of precipitation, evapotranspiration and Lanzhou hydrological station river discharge are shown in Figure 4-8. In addition the cumulative precipitations minus evapotranspiration (P-ET) are plotted in the same figure. It shows that the cumulative P-ET is below the cumulative of the river discharge. This indicates that GLDAS either underestimates the precipitation or overestimates the evapotranspiration. Generally, the most uncertain term is the evapotranspiration estimate with an uncertainty greater than 25% (Kalma et al., 2008; Swenson & Wahr, 2005), followed by the precipitation estimate with an uncertainty of 10% (Rodell et al., 2004a) and finally the river discharge with an uncertainty of about 5-10% (Zaitchik et al., 2010). Therefore, it may be concluded that the general decrease of the cumulative TWS estimate from the GLDAS flux could be due to overestimated evapotranspiration. When there is over estimation in evapotranspiration in each month, its accumulation will have a lowering effect in the trend, because the evaporation is a sink in the water balance and will create a mathematical artefact due to subtraction of overestimated ET.
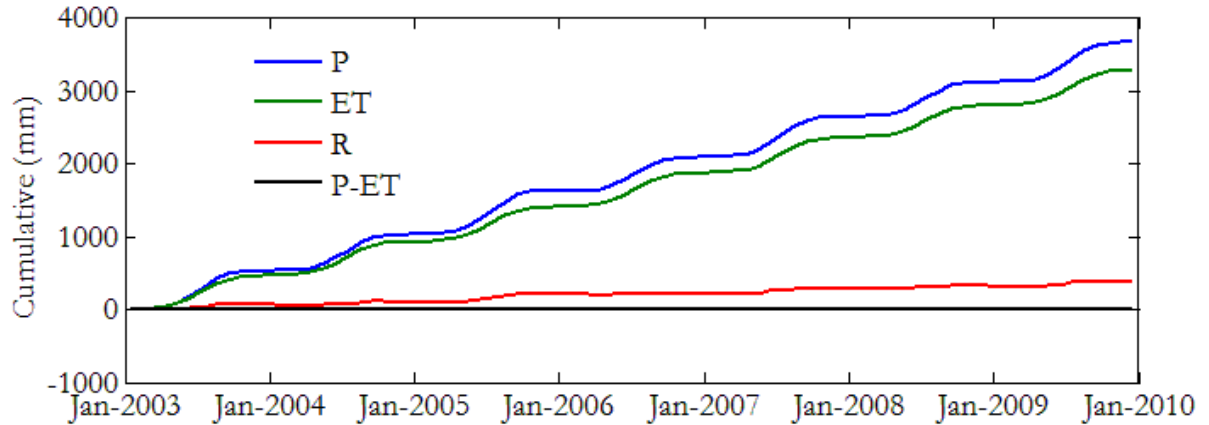
Figure 4-8: Cumulative plot of water balance terms in the GLDAS land surface fluxes. In blue, the precipitation (P) is shown, in green the Evapotranspiration (ET) is shown, in red the Discharge (R) is shown and in black Precipitation minus evapotranspiration.

However, high TWS loss in 2006 matches from all methods. During this year, the GRACE estimated less TWS in the rainy season compared to the winter season (Figure 4-1). The TWS from GLDAS state variables showed a decrease in TWS from Oct 2005 to April 2007) and the TWSC estimated from the GLDAS flux variables also showed continuous decrease as shown in the (Figure 4-7). In short, TWS and TWC from the different methods all indicated that there was a high water storage loss in 2006.

4.2.1.   Comparison of TWSC between GLDAS methods

Figure 4-9 compares the TWSC estimates of the two methods using GLDAS data (land surface state variables and land surface fluxes). It is found that there is an agreement between the two with a correlation coefficient of 0.6. However, significant differences are observed in July 2006 and July 2007. While the GLDAS flux variable method shows negative TWSC in year 2006 and 2007, GLDAS state variable method shows larger (but still negative values of) TWSC. This is associated with a sharp decrease in the GLDAS state variable values in these periods.
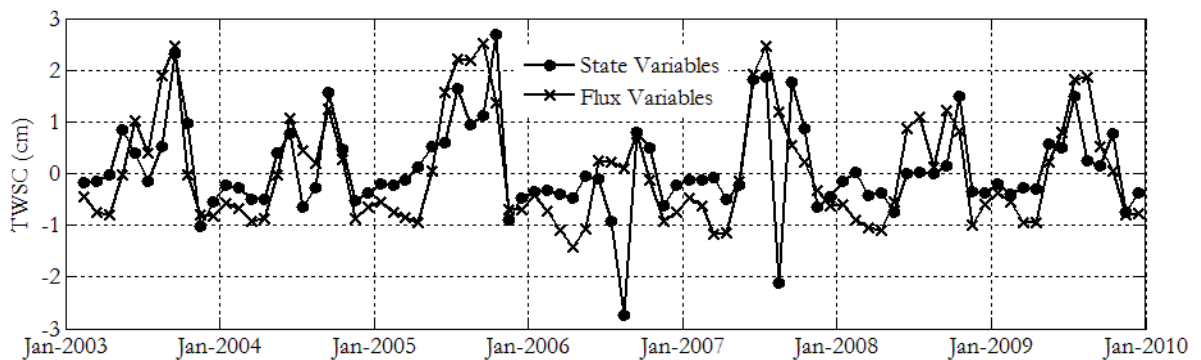
Figure 4-9: Terrestrial Water Storage Change (TWSC) from GLDAS flux and state variables. In this figure the circles denote the TWSC from calculation with state variables and the crosses denote the TWSC from calculation using flux variables.

Figure 4-10 shows the yearly TWSC estimated from GLDAS land surface sate variables and from flux variables calculated as the monthly mean value for each year. Both methodologies show similar patterns in

the TWSC with the largest water storage loss in 2006. During this year, the measured precipitation was the lowest from 2003 to 2009, while the temperature was the highest. However, the observed river discharge for this year increased. The discharge was larger than the highest precipitation, which is recorded in 2005. The discharge increased due to the release of stored water in the reservoirs. This all resulted in the highest water storage loss in 2006.
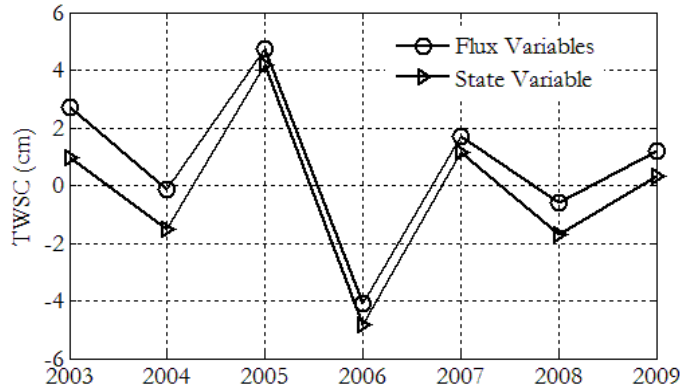
Figure 4-10: Yearly Terrestrial Water Storage Change (TWSC) estimated from GLDAS land surface state variables and flux variable. The circles denote the estimation of TWSC from flux variables, and the triangles denote the estimation of TWSC using state variables.

4.3.   Comparison of GRACE and GLDAS TWS and TWSC.

Figure 4-11 shows a comparison between monthly TWS from GRACE level 3 data and monthly TWS estimated from GLDAS state variables. Overall, TWS estimated by GRACE and TWS estimated from GLDAS state variables agree well in trend, with both methods showing an increase in TWS during the study period. Additionally, seasonal cycles from the two methods show the same behaviours. Especially where there is a qualitative agreement for the yearly peak of TWS. However, the monthly estimate from each result is quite different, as the variation in the GRACE monthly TWS is larger than variation in the GLDAS estimated monthly TWS.
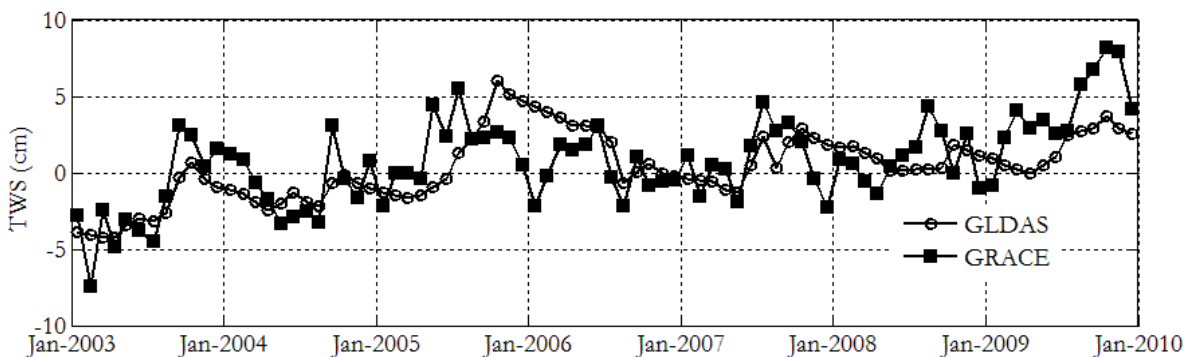
Figure 4-11: Terrestrial water storage anomalies from Jan,2003-Dec,2009 estimated from GRACE satellite gravity level 3 data and GLDAS soil moisture , snow water equivalent and canopy water storage data over Source region of Yellow River. The circles denote GLDAS computations and the squares denote the GRACE observations.

There are large differences in GRACE TWS and GLDAS TWS estimates. For example, in Jan 2006 the GRACE estimate is far below the GLDAS estimate, resulting in a difference of 6.5 cm. The discrepancy between the two is attributed to the difference in measurement techniques. GRACE measures all

terrestrial water storage including the surface water stored by reservoirs and lakes. However, GLDAS does not take such storage into account. If large amount of water is lost or gained from reservoirs, GRACE detects this variation but the GLDAS does not (Krogh et al., 2010). These differences can be also linked to the accuracy of the two measurements.

The increase in TWS estimated from the GRACE data and from GLDAS state variable can be linked to the increase in the amount of precipitation during the study period. The long term GRACE data estimate matched the long term TWS with the GLDAS TWS estimate. However, inter annual variation of TWS for the study area do not match very well. The correlation coefficient between the GRACE and GLDAS product after removing the linear trend from both data set is 0.4. This result is compared with Rowlands et al., (2010) available global comparison of GRACE and GLDAS estimate which is available at http://grace.gsfc.nasa.gov/. In their comparison, the correlation coefficient is between 0.2 to 0.5 for the period between 2003 and 2008.

Although there are differences in GRACE and GLDAS estimates of TWS, both estimates show an increase of TWS from 2003 to 2009. Increases in TWS can be caused by a variety of factors, including an increase in precipitation or a decrease in evapotranspiration. The main source variable for TWS for this study area is precipitation. If the precipitation amount increases, more water will be stored in the area. Decrease in temperature and wind speed will decrease evaporation and consequently result in an increase in TWS. The other reason for the increase in TWS could be a decrease in the runoff from the area. The prime motivation of this research is not the investigation of the cause for TWS in this area. Rather, it is the presentation of the usefulness of GRACE and GLDAS to estimate TWS and its change in the Upper Reach of Yellow River. Exploration of the reason for increase in TWS is a future research question.

Figure 4-12 shows the TWSC by GRACE and TWSC estimated by GLDAS data. The GRACE shows high variation in the TWSC estimates with no clear differences due to seasonal effect on TWS. The two estimates from GLDAS are qualitatively in agreement, with seasonal effects clearly visible. In GLDAS estimates, TWSC increases in rainy season and decreases in winter season. While the two GLDAS estimates clearly peak during the rainy season, the GRACE estimates show large negative values of storage during this period.
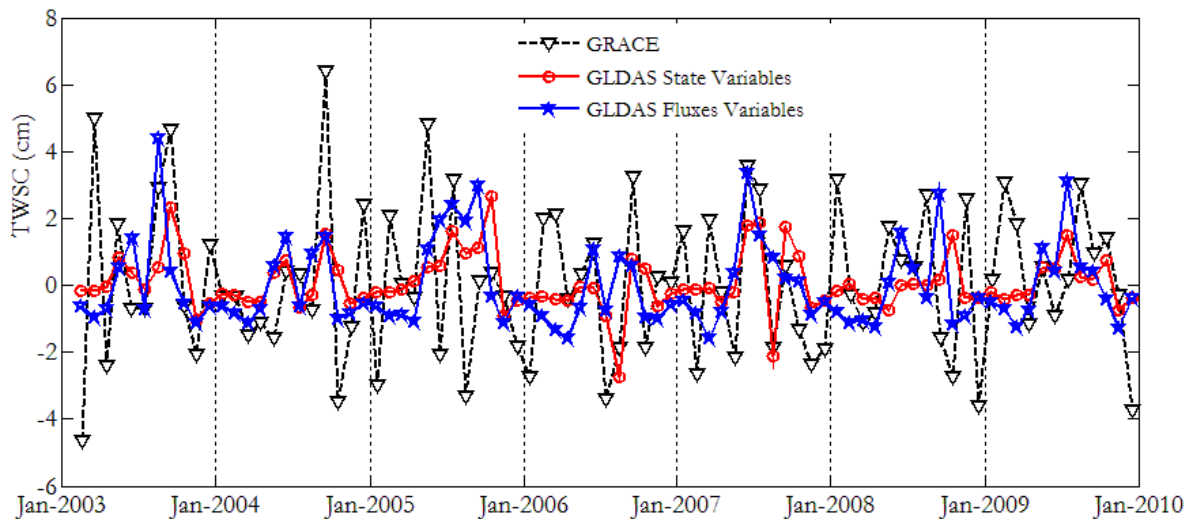

Figure 4-12: Time series of TWSC for the Upper Reach of Yellow River. The triangles denote GRACE observations, the circles denote the computations using GLDAS state variables and the stars denote the estimations from GLDAS flux variables.

4.4.   Evaluation of TWS with Meteorological Variables and River Discharge

4.4.1.   Temperature

Figure 4-13 shows the spatial distribution of the averaged minimum and maximum annual temperature from 2003 to 2009. This is made from 41 meteorological stations data collected from inside and outside the area. The daily temperatures measured by the stations are aggregated into a yearly average temperature. Later on, this average annual temperature is spatially interpolated by ordinary kriging in ArcGIS software. It is shown that the minimum and maximum temperatures in the study area decrease from East (4.45 °C and 16 °C) to West (-7.34 °C and 7.76 °C). The annual minimum and maximum temperatures are calculated for each year and the results are shown in Table 4-1.
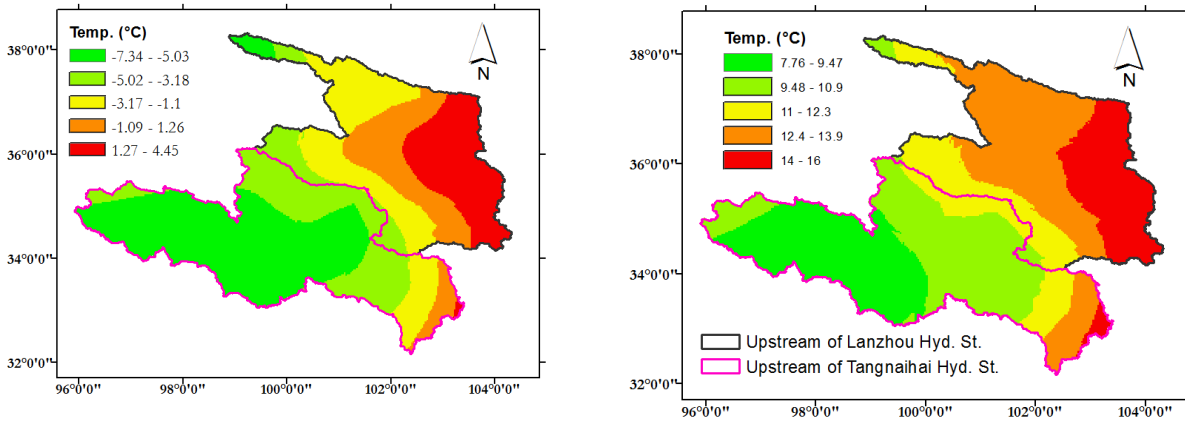
Figure 4-13: Mean of annual minimum (left) and maximum (right) temperature from 2002 to 2009 interpolated from data 41 meteorological stations.

Table 4-1: Annual maximum and minimum air temperature for the Upper Reach of Yellow River

	Annual minimum air temperature				Annual maximum air temperature			
Time	Min.	Max.	Mean	Std.	Min.	Max.	Mean	Std.
(year)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)
2003	-7.96	3.61	-3.21	2.73	8.25	15.64	11.43	1.77
2004	-8.15	3.16	-3.66	2.70	7.55	15.71	11.03	2.02
2005	-7.84	3.70	-2.93	2.64	7.35	15.26	10.83	1.95
2006	-6.93	4.02	-2.76	2.70	8.45	16.46	11.90	1.90
2007	-7.97	3.78	-3.19	2.83	8.34	15.80	11.57	1.77
2008	-7.93	2.93	-3.56	2.61	6.79	15.46	10.74	2.14
2009	-6.21	3.66	-2.52	2.38	8.07	16.02	11.63	1.96

Figure 4-14 shows the result of the mean annual maximum and minimum temperature estimate of the Upper Reach of Yellow river from 2003 to 2009. The figure shows a variation of temparature from year to year. The temperature standard deviations are shown in the Table 4-1. The highest mean maximum temeprature is observed in 2006 compared with other years. The temperature influences the terrestrial water storage of the area, through its effect on evaporation/transpiration rates. Higher temperature means higher evaporation rates if other evaporation factors are set constant. This is one of the reason for the highest TWS loss in 2006
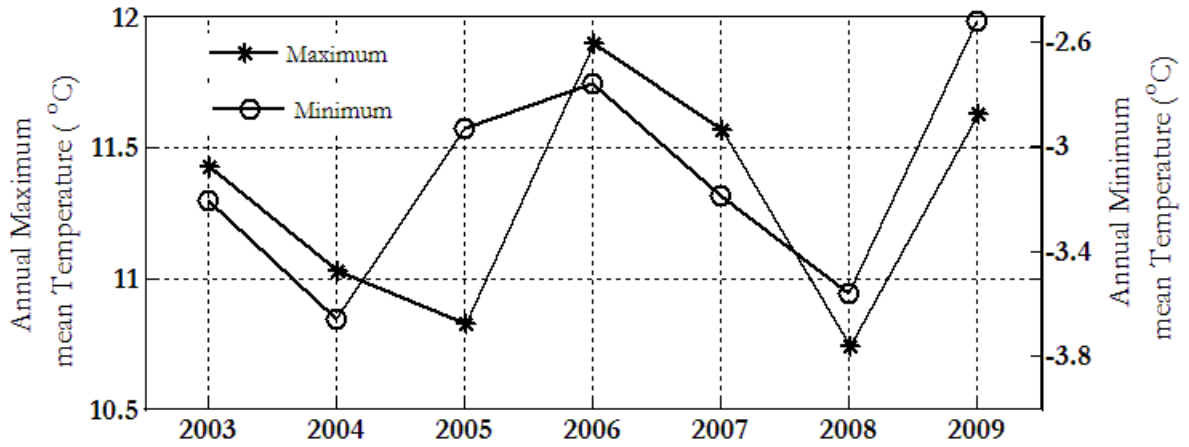
Figure 4-14: Mean annual minimum and maximum temperature from 2003 to 2009. The mean minimum annual temperature (circles) is shown the on right axis of the figure and the mean maximum annual temperature (stars) is shown on the left axis.

4.4.1. Precipitation

The spatial pattern of the average precipitation from 2003 to 2009 is estimated from meteorological data. The annual sum of each station rainfall is calculated from the daily data. The average annual rainfall for each station from 2002 to 2009 is calculated and interpolated by ordinary kriging method in ArcGIS software. Figure 4-15 shows the average annual rainfall for the Upper Reach of Yellow River estimated from daily data of 41 meteorological station from inside and nearby station. The result shows that the annual precipitation decreases from the South-eastern to North-western direction. The average annual precipitation ranges from 200 mm in the North-West to 740 mm in the South-East. Maximum amount of rainfall is observed in upstream area of Tangnaihai hydrological station which is half the total study area.

Figure 4-15: Mean annual rainfall from 2002 to 2003 interpolated from data from 41 meteorological stations.

Table 4-2: Annual minimum, maximum and the mean precipitation from meteorological station over the study area

Time	Annual Precipitation			
Time (year)	Min. (mm)	Max. (mm)	Mean (mm)	Std. (mm)
2003	150	792	499	153
2004	200	773	461	122
2005	167	904	518	132
2006	178	711	434	105
2007	257	702	515	98
2008	208	647	468	99
2009	183	790	485	119

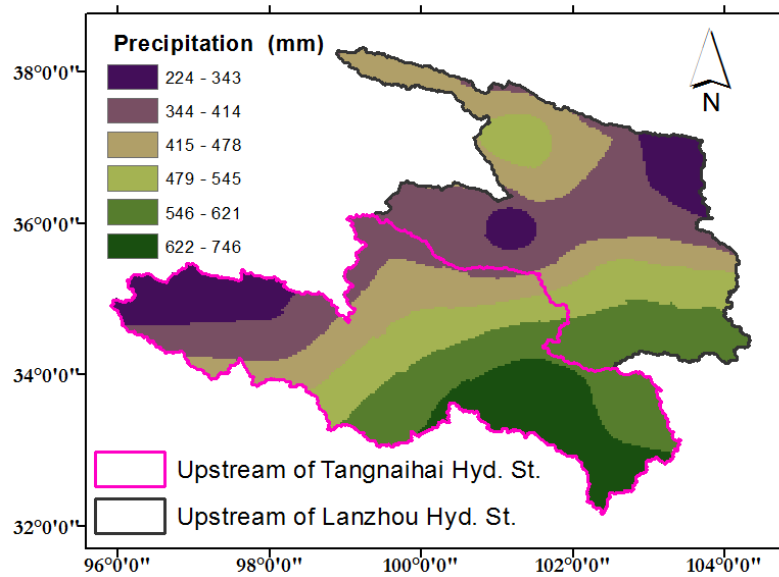The results of the mean annual precipitation from 2003 to 2009 are shown in Table 4-2. The Mean, from 2003 to 2009, of yearly precipitation is about 483 mm. This estimate is greater than the mean, from 1968 to 2000, values estimated by (Zhao et al., 2009) which is about 464 mm. This indicates that the area is receiving higher rainfall than the mean rainfall value of the area. The annual rainfall in 2006 was the lowest during the study period, which is also smaller than the mean rainfall of the study area. In this year, the terrestrial water storage is less than the storage of the other years. The temperature analysis results indicated the highest maximum value in this year. In this case, with less amount of precipitation and higher amount of temperature it would mean higher water storage loss for the area. GRACE and GLDAS estimated the highest of terrestrial water storage loss in 2006.

The precipitation records from meteorological stations are used to evaluate the GLDAS precipitation estimate. There is an agreement between the two estimates with root mean squared error (RMSE) of 19 mm and correlation coefficient of determination (R^2) of 0.89. Except in 2005, the GLDAS estimate is found to be higher than the meteorological station estimate. Both results confirmed that the lowest precipitation is observed in 2006.

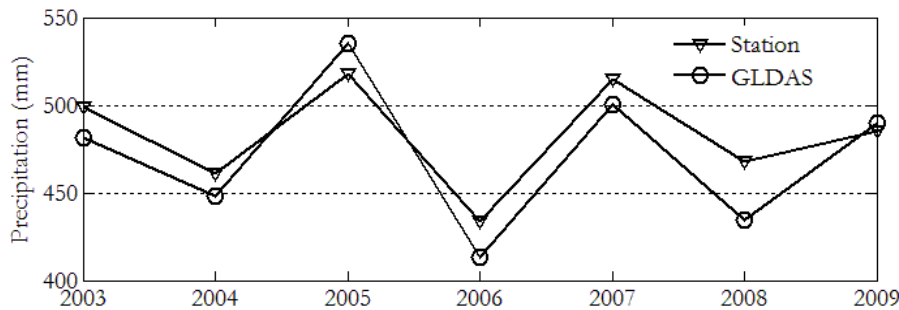**Figure 4-16: Precipitation from meteorological stations and GLDAS output. The triangles denote the measurements by the stations, and the circles denote the GLDAS observations.**

4.4.2. Discharge

Figure 4-17 shows the monthly Yellow River discharge at Lanzhou hydrological station from 2003 to 2009. From the monthly data the annual discharge is calculated. Figure 4-18 shows annual river discharge

of the Yellow River measured at Lanzhou hydrological station. The annual river discharge at this station increased from 2003 to 2009. The linear trend in the figure is fitted by least square method and shows $13*10^8 \, m^3$ increase of discharge per year.
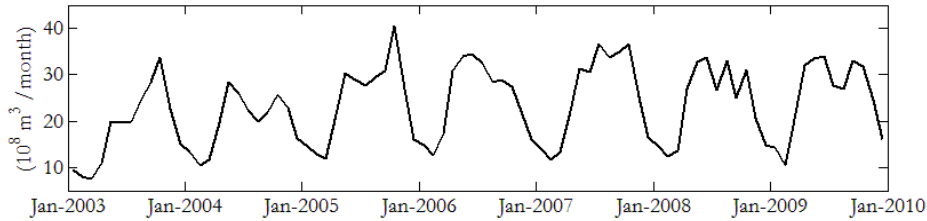
Figure 4-17: Monthly Yellow River discharge at Lanzhou hydrological station.
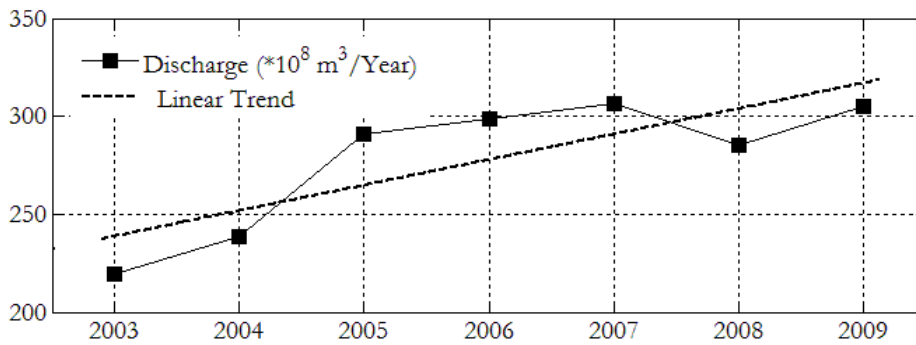
Figure 4-18: Annual discharge at Lanzhou hydrological station from 2003 to 2009. The squares denote the observations by the Lanzhou hydrological station, the dashed line denotes the trend.

Figure 4-19 shows the monthly variation of discharge and precipitation in the study area. Both the discharge and the precipitation are calculated as monthly means from 2003 to 2009. It is observed that the precipitation shows an increase from May to July and a decrease from July to October. While the discharge follows the same trend as the precipitation, it is flattened (with constant discharge values are observed from May to October) due to regulation of discharge from reservoirs. This effect is also confirmed by Figure 4-17. The reservoir effect can clearly be observed in the 2006 monthly discharge, where the shape of the discharge graph is smooth compared to other years. During this period, the precipitation was less than the mean precipitation in the area. The observed discharge at Lanzhou station was released from the reservoirs upstream in this year.

Figure 4-19: Monthly variation of precipitation and discharge The squares denote the precipitation measured by the meteorological stations and the circles denote the measured discharge at the Lanzhou stations.

In the Figure 4-20 the discharge anomalies and the cumulative of discharge are shown. The discharge anomalies are calculated as the deviation of monthly discharge from the mean discharge. Two periods with different trends are identified being, from January 2003 to April 2005 and fro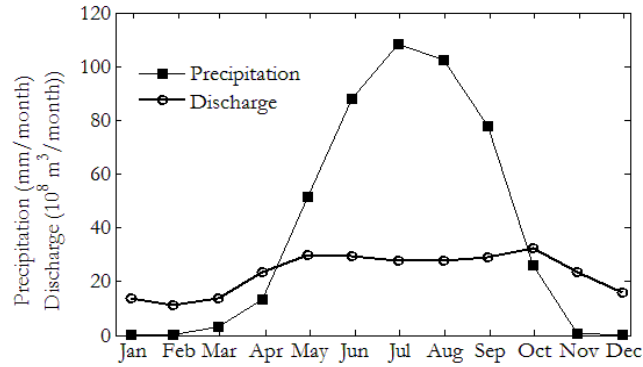m April 2005 to December 2009. In the first period, a negative trend in the cumulative of the discharge anomalies is shown, while in the second period, a positive trend in the cumulative of the discharge anomalies is observed. These results indicate that the discharge is increased from the first period to the second period due to increased TWS in the area. The increase in TWS is observed by the GRACE and GLDAS data and shown in this research.
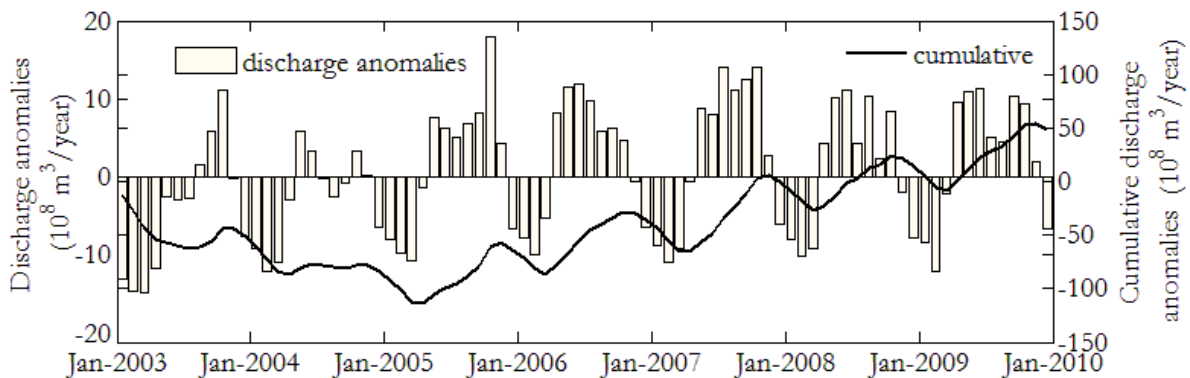
Figure 4-20: Variation discharge anomalies (bar plot, left axis) and cumulative of discharge anomalies (line with circle, right axis).

Figure 4-21 shows the annual discharge (from Lanzhou station), the annual mean precipitation (from meteorological stations) and precipitation (from GLDAS Noah model). The annual precipitation from both data sources shows a yearly variation in precipitation with lowest precipitation in 2006 and highest in 2005. In contrast, the annual discharge mostly increased in this period. The figure shows that the amount annual discharge is not directly related with the amount of precipitation. Especially, in 2006 the precipitation is low compared to other years but the discharge is increased. In this year, annual discharge did not decrease in response to low rainfall.
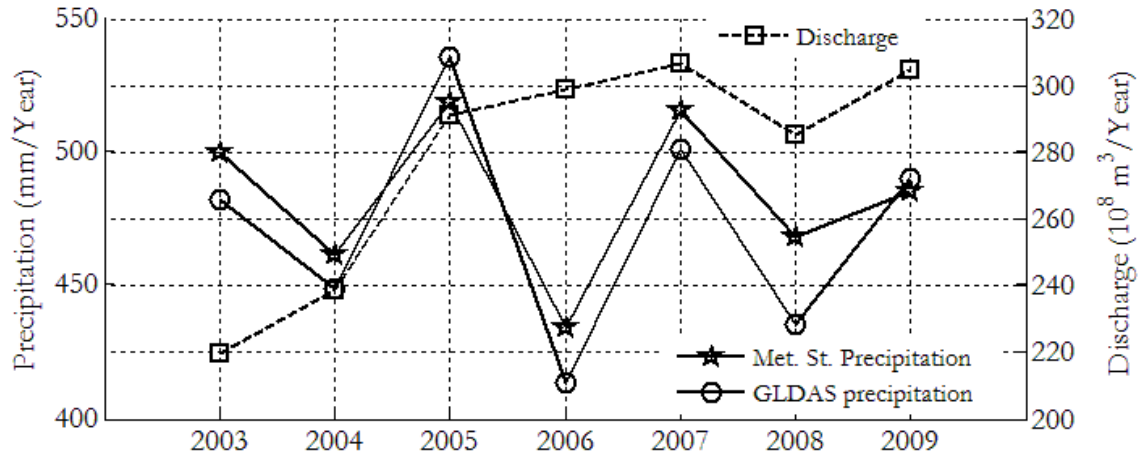
Figure 4-21: Annual precipitation from GLDAS and meteorological station plotted with annual discharge of Yellow River at Lanzhou station.

Figure 4-22 shows the cumulative of discharge anomalies together with the cumulative TWS of GRACE and GLDAS. Both GRACE and GLDAS show similar characteristics, and follow the same pattern as the cumulative of the discharge anomalies. As discussed before in the river discharge anomalies, there are two periods. These two periods are also seen in cumulative of the GRACE/GLDAS TWS estimates as shown in the figure. The cumulative of GRACE/GLDAS TWS shows a negative trend in the first period and positive trend in the second period. The high water storage loss effect in 2006 is seen in the plot. The cumulative plot of GRACE/GLDAS shows constant values from mid of 2006 to mid of 2007.
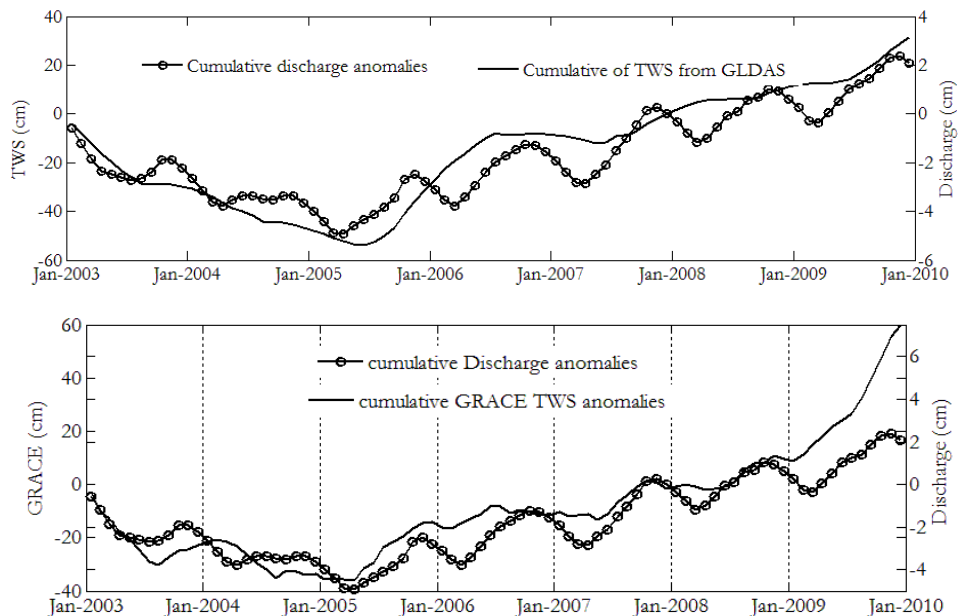
Figure 4-22: Cumulative of discharge anomalies and TWS (right axis) estimate from GRACE observations and GLDAS state variables. In both panels the circles denote the measured discharge by the Lanzhou station, and the solid line denotes the estimates by GRACE/GLDAS. In the top panel the Cumulative TWS anomalies by GLDAS is shown and in the lower graph the Cumulative TWS anomalies by GRACE.

The precipitation spatial variability from the two sources (GLDAS and meteorological stations) are compared qualitatively, in the Figure 4-23. Only a qualititative analysis is performed due to time constraints in this research. There is a general agreement in the spatial pattern between the two

precipitation maps. In both maps, the precipitation increases from south to the north and from west to east direction.
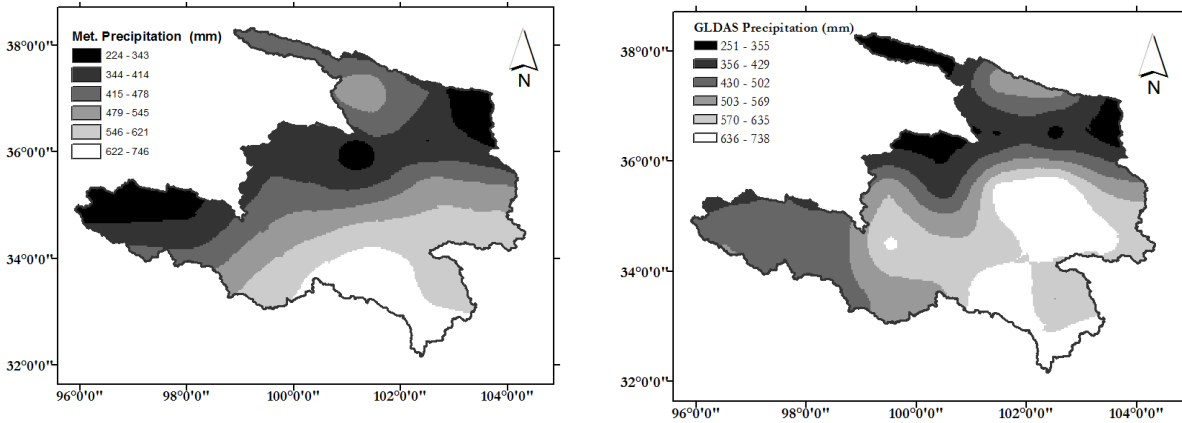
Figure 4-23: Precipitation spatial variation from two sources. In the left panel the precipitation spatial variability is estimated data from meteorological stations. In the right panel the precipitation spatial variability is obtained by GLDAS 1-degree grid data, interpolated to the same resolution as the left panel.
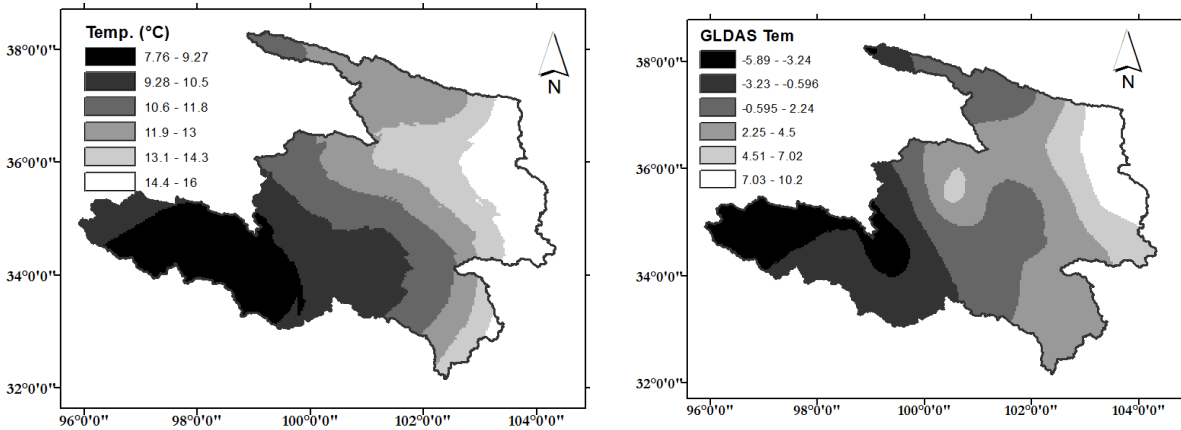
Figure 4-24: Spatial Variation of maximum annual temperature from meteorological station (left) GLDAS mean annual temperature (right).
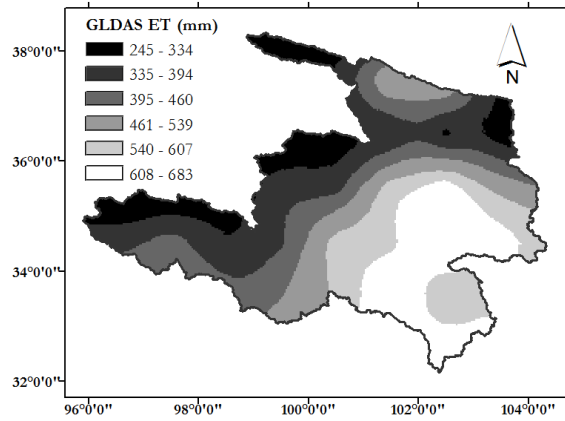
Figure 4-25: Spatial Variation of Evapotranspiration from GLDAS.

Figure 4-25 shows the pattern of the evapotranspiration and behaves similar to the pattern precipitation as shown in the Figure 4-23, which indicates the evaporation is dependent on the available moisture. The evaporation reaches from 245 mm to 683 mm. These values indicate that most of the precipitation in the area is lost by evaporation.

5.   CONCLUSION

In this research Terrestrial Water Storage (TWS) and Terrestrial Water Storage Change (TWSC) are estimated in the Upper Reach of Yellow River. These two variables are important to characterise the discharge of the Yellow River. TWS and TWSC are examined in the area from 2003 to 2009. TWS is calculated from two methods: the first method employs the GRACE remote sensing satellite while the second employs estimation by use of GLDAS land state variables. TWSC is estimated from these TWS by subtraction of two consecutive monthly values. In addition, TWSC is also estimated from a water balance approach using a combination of river discharge measurements and GLDAS flux variables. The spatial average values of GRACE and GLDAS are estimated using a watershed mask derived from the DEM of the study area. This mask is used to extract the values of GRACE and GLDAS from 1-degree-by-1-degree spatial resolution of the two products.

The GRACE–derived TWS anomalies are estimated for the source in the study period. From the estimate seasonal variation in TWS is assessed. TWS get its peak in the rainy season. The maximum and minimum water storages are observed in the September and January respectively. In addition, the overall trend in TWS for the study period is estimated. Annual water storage increase of 0.8 cm/year is observed during the study period. The annual discharge of the Yellow river is increasing during the study period. The increase in discharge rate is associated with increase in TWS of the area.

The TWS is also estimated from monthly GLDAS land state surface variables. Four layers soil moisture, snow water equivalent and canopy water storage are the variables used. Time series of TWS is calculated as the sum of these variables from monthly values. From the series the mean TWS is subtracted to obtain the TWS anomalies. A linear line fitted to the anomalies indicates that the water storage is increasing by 0.6 cm/year in the study area.

The TWS estimate from GRACE and GLDAS is compared. There is a general match in the long term trend between GRACE and GLDAS TWS estimates. There is also a match for seasonal peak and low of TWS. The two data observed the highest TWS loss in 2006. However, inter annual variation show significant difference in some months of the study periods. The correlation coefficient between the GRACE and GLDAS TWS is 0.4.

The TWS from GRACE and GLDAS was evaluated with precipitation, temperature and river discharge of the area. The annual discharge of the river increased from 2003 to 2009 due to increased TWS. On the other hand, the TWS increased due to increased precipitation over the study period. Hence, the TWS estimate from GRACE and GLDAS could be evident. In addition, GRACE and GLDAS have observed the highest water storage loss in 2006 due to increased discharge, less precipitation and high amount of temperature.

TWSC is estimated with three methods. The first is, GRACE estimate of TWS is used to estimate TWSC. The TWSC is estimated by taking the difference of two consecutive months' TWS. The difference is taken as next month TWS minus previous month TWS. The second is from GLDAS TWS estimate for the study area. It is done in the same way as the GRACE TWS used to estimate TWSC. The third is the water balance approach. In the water balance approach, rainfall, evapotranspiration and snow melt from the GLDAS Noah model and river discharge from the out let of the study area is used. The TWSC results show there is a qualitative agreement between the two estimates of GLDAS but the GRACE is not in agreement with any of the two GLDAS results.

In conclusion, the potential of GRACE and GLDAS for monitoring TWS in the Upper Reach of Yellow River area is shown in this research. The results indicate that GRACE can be used for estimating long term trend in TWS and GLDAS can be used to monitor the long term trend and the short term (month to month) variation of TWS for the area of Yellow River. All of these results indicate the great potential of GRACE and GLDAS providing hydrological information to water resource management in URYR.

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