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An Open-Source Web-Application for Regional Analysis of GRACE Groundwater
Data and Engaging Stakeholders in Groundwater Management

Travis Clinton McStraw

A thesis submitted to the faculty of
Brigham Young University
in partial fulfillment of the requirements for the degree of
Master of Science

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ABSTRACT

An Open-Source Web-Application for Regional Analysis of GRACE Groundwater Data and Engaging Stakeholders in Groundwater Management

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Since 2002, NASA's GRACE Satellite mission has allowed scientists of various disciplines to analyze and map the changes in Earth's total water storage on a global scale. Although the raw data is available to the public, the process of viewing, manipulating, and analyzing the GRACE data can be difficult for those without strong technological backgrounds in programming or geospatial software. This is particularly true for water managers in developing countries, where GRACE data could be a valuable asset for sustainable water resource management. To address this problem, I have developed a utility for subsetting GRACE data to particular regions of interest and I have packaged that utility in a web app that allows water managers to quickly and easily visualize GRACE data these regions. Using the GLDAS-Noah Land Surface Model, the total water storage for the regions derived from the raw GRACE data is decomposed into surface water, soil moisture, and groundwater components. The GRACE Groundwater Subsetting Tool is easily deployed, open-source, and provides access to all of the major signal processing solutions available for the total water storage data. The application has been successfully applied to both developed and developing countries in various parts of the world, including the Central Valley region in California, Bangladesh, the La Plata River Basin in South America, and the SERVIR Hindu Kush Himalaya region. The groundwater data in this application has proven capable of monitoring groundwater use based on drought trends as well as agricultural demand in a number of locations and can assist in uniting decision makers and water users in the mission of sustainably managing the world's groundwater resources.

Keywords: GRACE mission, GRACE-FO mission, earth observations, tethys platform, groundwater, water resources, groundwater sustainability, transboundary aquifer.

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I'd like to express appreciation to each of my committee members. I'd like to thank Dr. Jones for guiding this research effort, for his friendship, and for teaching me the basics of groundwater modeling. I'd also like to thank Dr. Nelson for helping me to see how our work as researchers and engineers can positively impact the lives of others and for helping me understand the true definition of success in my life. I'd also like to thank Dr. Ames for teaching me the most practical and useful technical skills I have ever learned in his GIS and GIS programming classes. Your teachings have given me a leg up in my career and have allowed me to contribute to my company's success within weeks of being hired.

I'd also like to acknowledge Sarva Pulla for his work in developing the original version of the GRACE Groundwater Subsetting Tool which provided a framework and a strong starting point for this research. Most of all, I want to acknowledge the constant support of my wife Melissa, my parents Bill and Shari and all members of my family who have helped me get to this point in my education and in my career.

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1 INTRODUCTION

Comprising just over 30 percent of the world's fresh water supply (Shiklomanov, 1993), groundwater is one of the most life-giving natural resources on the planet. It is estimated that nearly 2 billion people throughout the world rely on it as their primary water source (Alley, Healy, LaBaugh, & Reilly, 2002). Groundwater is also a fundamental part of the global agricultural industry as at least half of the world's food is grown using irrigation water extracted from subsurface sources (Siebert et al., 2010). This is especially true in dry, arid regions of the world that are most significantly impacted by drought. Developing countries located in these regions are even more dependent on groundwater as their economies are often maintained by the production of cash crops and a large percent of their populations depend on their own agricultural efforts for food.

Although groundwater is one of the most important natural resources on the planet, it is ironically one of the most mismanaged. Typically, monitoring the health of an underground aquifer system requires drilling multiple wells to consistently record water level and water quality data. Even in more developed parts of the world where monitoring wells have been installed, it is common to see large temporal gaps in groundwater data spanning years or even decades due to a lack of maintenance performed on the monitoring equipment or a lack of effort in consistently recording data. In developing countries, the situation is often far worse.

Frequently there are no management plans, regulations, or monitoring systems in place at all

(J. S. Famiglietti & Rodell, 2013; Matthew Rodell, Velicogna, & Famiglietti, 2009) and both government officials and the general public can lack education and understanding regarding the impacts over-pumping has on their groundwater resources (Villholth, 2006). This creates what (J. S. Famiglietti, 2014) refers to as a “free for all” where any property owner who can afford to drill a well essentially has unlimited, unregulated access to groundwater. Local governments have even been known to encourage this harmful practice. In India, for example, the government subsidizes electricity costs to make pumping groundwater more affordable and encourage farmers to irrigate more land to further boost the country’s agricultural production (Shah, Bhatt, Shah, & Talati, 2008). Additionally, in cases where local governments or external personnel are making attempts to better monitor the health of aquifer systems in developing countries, they often fight against theft and vandalism making it difficult to collect data from monitoring equipment (Fell, Pead, & Winter, 2018). This challenge in particular presents a need for a method of monitoring groundwater levels without the use of on-site monitoring equipment.

As populations continue to grow, the demand for groundwater is increasing. A study performed by (Wada, Wisser, & Bierkens, 2014) found that on average global groundwater use increased by 3 percent per year between 1990 and 2010. This was especially true in North and Central America and parts of Asia. With steady population growth and an increase in the demand for food, (J. S. Famiglietti, 2014) suggests that the overuse of groundwater is only going to get worse. He also makes the case that as groundwater levels drop, it will become more and more expensive to drill wells deep enough to reach the water supply. He poses that this has the potential to create an economic division where only wealthy property owners can afford to irrigate their crops. This is of particular concern in developing countries where impending

divisions in social classes could make these already economically stressed societies dangerously unstable.

1.1 NASA Earth Observations and the SERVIR Initiative

Since the late 1950's NASA has used data observed from satellites to better understand the principles that govern the world in which we live. Over the last 70 years, the data collected by satellites has evolved from simple photographs to complex measurements of phenomenon occurring daily within Earth's atmosphere (Council, Studies, Climate, & Space, 2008). Continued advancement in satellite technologies has completely changed how we manage our natural resources and in particular water. One of the more recent developments in satellite technology stems from the Gravity Recover And Climate Experiment (GRACE). The GRACE satellite mission was tasked with mapping earth's gravitational field and in doing so, has uncovered new approaches for monitoring changes in water storage on a global scale (Wahr, Molenaar, & Bryan, 1998). Arguably the most significant breakthrough that has surfaced as a result of this new data, is the ability to monitor changes in groundwater storage without any form of *in situ* monitoring data (M Rodell & Famiglietti, 2002).

One of the principle objectives of this research is to process and deliver data and information from the GRACE mission in a form that is beneficial for stakeholders in developing countries. This motivation is driven by my involvement in the SERVIR initiative. SERVIR (an acronym meaning "to serve" in Spanish) is a joint initiative of the National Aeronautics and Space Administration (NASA) and the United States Agency for International Development (USAID) that seeks to build the capacity of local decision-makers dealing with a wide range of climate-related problems by making global earth observation data and associated tools available

(SERVIR, 2020). The SERVIR model brings together regional hubs supported by USAID grants with scientific experts in the areas of Agriculture and Food Security, Water Resources and Hydroclimatic Disasters, Land Cover and Land Use Change and Ecosystems, and Weather and Climate. For example, the NASA Applied Sciences Program funds scientists from United States (US) institutions with the expectation that technology transfer to the hubs and local stakeholders in their regions occurs by the end of a three-year grant period. The NASA Applied Sciences Program measures research becoming integrated into stakeholder and end-user decision-making using a 9-point Application Readiness Level (ARL) scale where ARL 1 represents basic research and ideas in their infancy to ARL 9 where data, models, and tools are approved, and fully integrated by the stakeholders and have sustained use in making decisions (see Figure 1.1).



Figure 1.1 NASA Application Readiness Level Scale

The GRACE mission has completely changed the way the world is able to monitor groundwater data. As this new data is used in conjunction with the SERVIR program and others

like it, it can open the door for developing countries to bypass many of the social and economic hurdles that are currently preventing them from efficiently managing their groundwater resources.

1.2 Background on the GRACE Mission

On March 17, 2002, the twin spacecraft for the Gravity Recovery and Climate Experiment (GRACE) mission were launched into orbit and began the task of measuring anomalies in Earth's gravitational field. The two satellites follow the same orbital path, one trailing the other, and are roughly 137 miles apart at any given time (Dunbar, 2014).

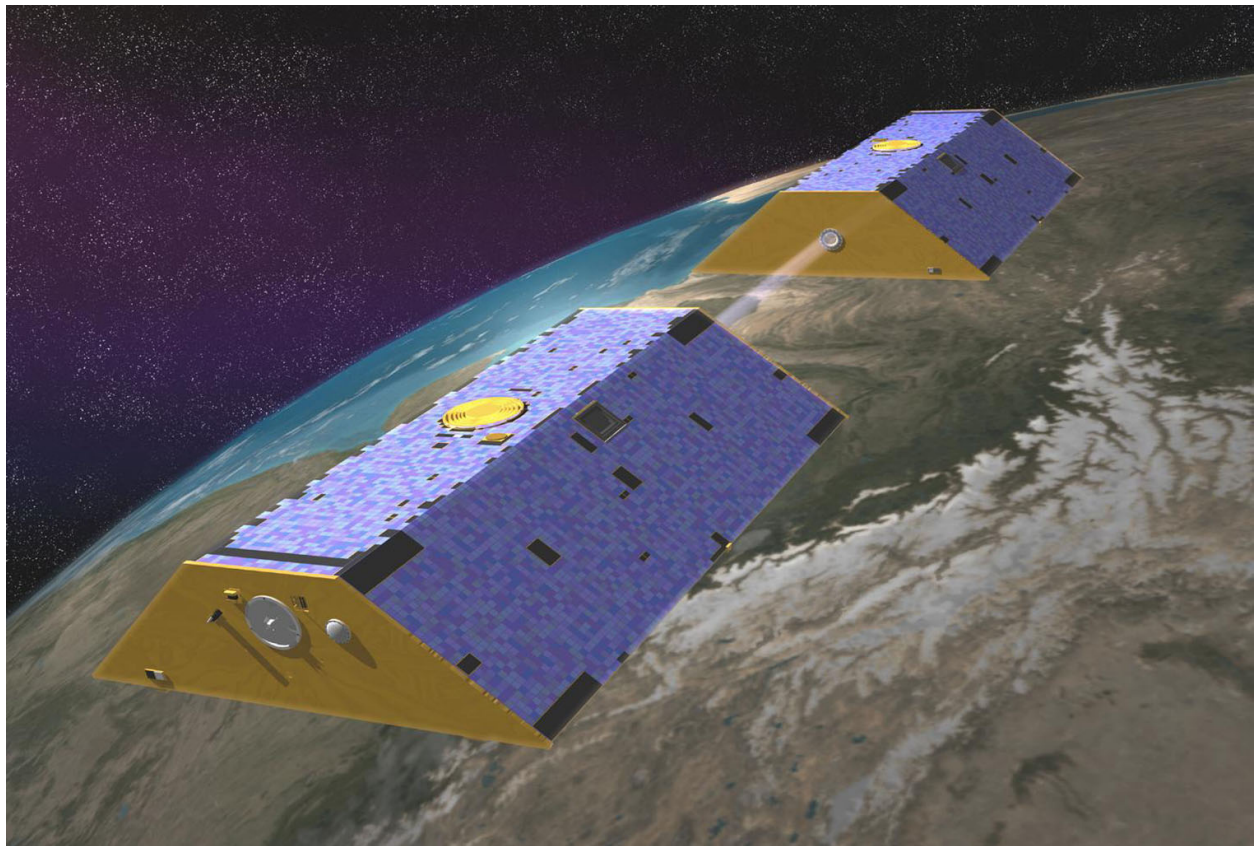


Figure 1.2 Artist's Rendering of GRACE-FO Satellites

As the satellites orbit the earth, locations with higher mass concentration will first pull the lead satellite towards them, temporarily changing the distance between the two spacecraft. The trailing satellite will then feel the effect of the gravitational anomaly created from the source of concentrated mass and the distance between the two satellites normalizes (See Figure 1.3 through Figure 1.5 below).

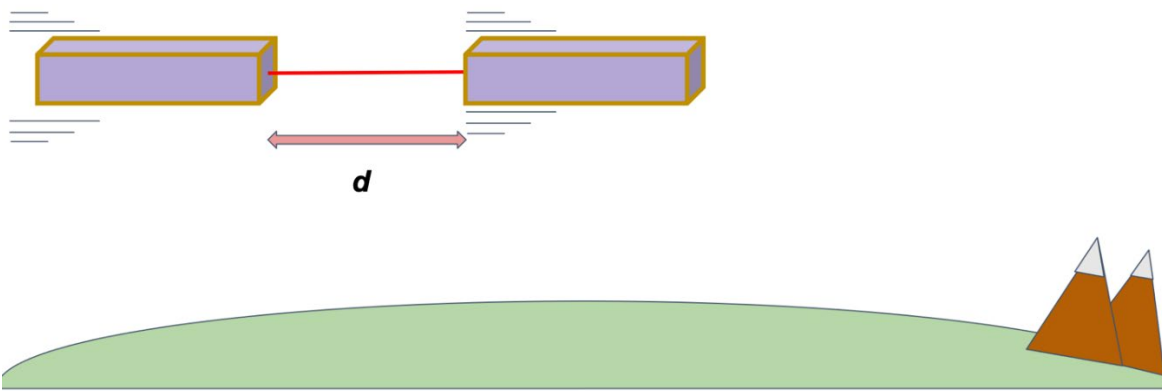


Figure 1.3 Satellites Approach a Large Land Mass in the Form of a Mountain Range

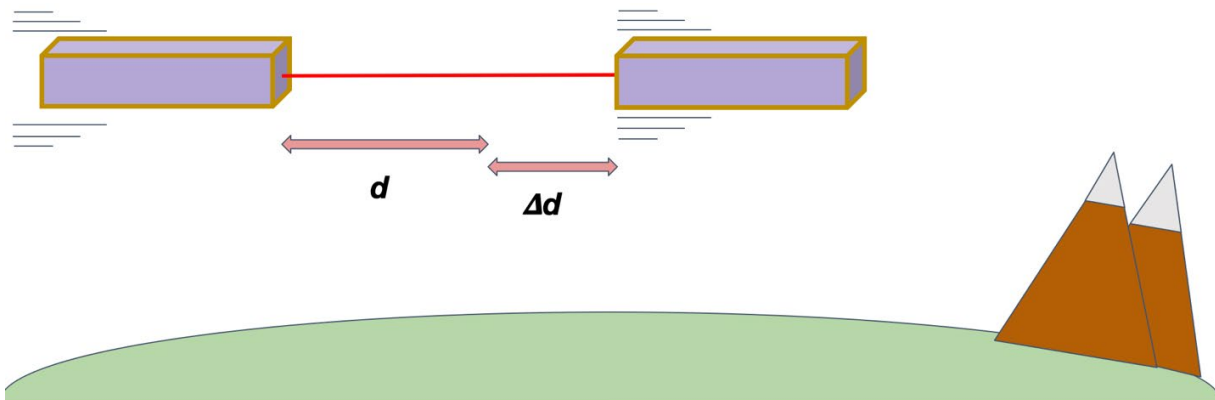


Figure 1.4 Distance Between the Two Satellites Changes as the Lead Satellite Feels the Gravitational Effect from the Mountain Range

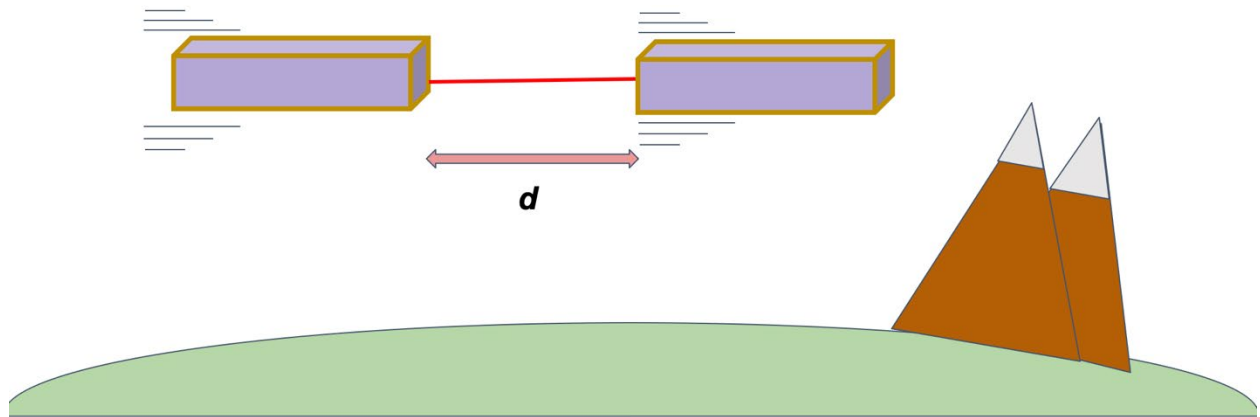


Figure 1.5 Trailing Satellite Then Feels Gravitational Effect from Mountain Range and the Distance Between the Two Returns to Normal

Each satellite is equipped with a k-band microwave ranging system, capable of measuring the change in distance between the two satellites within 10 microns (Dunbar, 2013). By measuring the change in distance between the satellites to such a high level of accuracy, it is possible to quantify the magnitude of the gravitational anomaly at the location where the satellites' positions were affected. Each spacecraft is also equipped with an extremely precise accelerometer to account for any changes in the distance between them that are not related to gravitational forces (Tapley, Bettadpur, Watkins, & Reigber, 2004).

The scenario depicted in Figure 1.3 through Figure 1.5 is obviously simplified for the purpose of clarifying the theory behind how these measurements are taken. In reality, after passing the mountain, the lead satellite continues to feel the effect from the mountain behind it and is slowed down slightly, thus changing the distance between the satellites once again. This simple depiction also doesn't take into account the effects from other masses in the area that could be altering the satellite's position. In reality the actual distance between the satellites is constantly changing.

This introduces the need to normalize the raw data. By normalizing this data to a mean, over time all of the spatially constant gravitational forces are eliminated from the dataset and only the masses that are actively changing in location and magnitude remain. The GRACE and GRACE-FO missions have been recording data on a more or less monthly basis since April of 2002. The mean for this data was calculated between the years 2004 and 2009. By normalizing the data to this mean, the datasets are transformed into an anomaly format where they display variations in gravity over time on a global scale. The discovery was made that the majority of these gravitational anomalies would be due to changes in water storage (Wahr et al., 1998) and ever since this data has been distributed by Jet Propulsion Laboratory as a total water storage anomaly dataset (SC Swenson, 2012).

Before the data is normalized however, the signal from the GRACE satellites still contains a lot of what GRACE data scientists refer to as “noise” (Schrama, Wouters, & Lavallée, 2007). This is due to a number of other factors that can impact the GRACE data such as atmospheric drag, subsurface tectonic activity, etc. There are also a number of errors in the raw data signal that have to be corrected via smoothing and other processing methods to make the data more accurate and therefore more valuable (Sean Swenson & Wahr, 2006).

The GRACE and GRACE-FO missions are managed by three critical institutions: Jet Propulsion Laboratory (JPL), University of Texas at Austin Center for Space Research (CSR), and the German Research Center for Geosciences (GFZ). Each of these organizations performs its own smoothing algorithms, filtering calculations, and other processes to remove the errors from the raw GRACE data signal. They each provide their own separate signal solution for the total water storage dataset which is then distributed by JPL. This is done with the goal to discover the benefits from different processing methodologies and to work towards a single

solution that provides the highest level of accuracy (F. Landerer, 2020d). Currently these three signal solutions are calculated using similar logic but can yield different results depending on the location in the world (Jing, Zhang, & Zhao, 2019; Sakumura, Bettadpur, & Bruinsma, 2014). There are also many other scientists experimenting with their own methods of processing the raw GRACE signal to produce more accurate signal solutions for the total water storage anomalies (Frappart, Ramillien, Maisongrande, & Bonnet, 2010; W. Sun et al., 2011; Sean Swenson & Wahr, 2006).

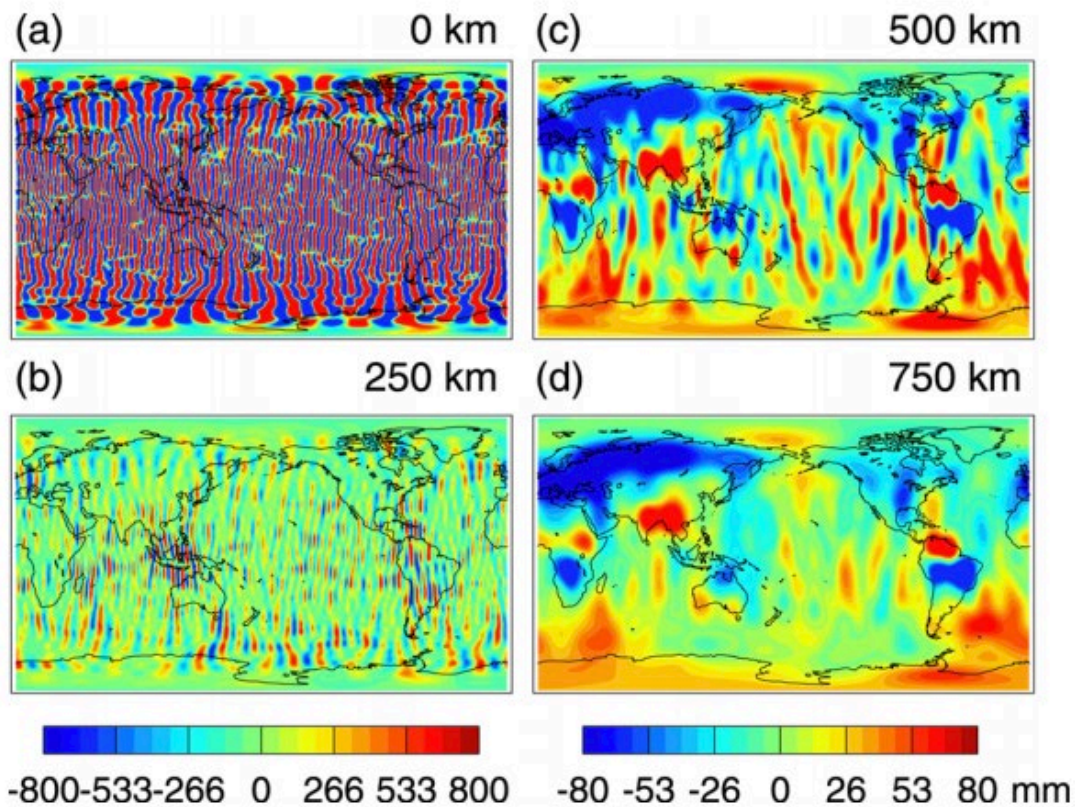


Figure 1.6 Shows Different Global Map Results from Study by (Sean Swenson & Wahr, 2006) (a) Shows the Unfiltered GRACE Data (b) - (d) Show Different Levels of Gaussian Filters Applied to Raw Dataset as Part of the Study

The GRACE satellites ended their mission in 2017, roughly 10 years after the end of their intended service life (Nelson, 2017). The GRACE Follow On mission was launched in May of 2018 to replace the first pair of satellites and continues to provide monthly mass data similar to the original GRACE mission (Callery, 2018). For many hydrologists and hydrogeologists, the GRACE mission's greatest contribution has been its ability to monitor changes in the world's water resources (NASA, 2003; Wahr et al., 1998). The GRACE total water storage anomaly dataset provides new perspective in the process of monitoring Earth's freshwater resources. In particular, it offers the means to measure groundwater resources without the use of *in situ* data.

1.3 Deriving Groundwater Data

In comparison to the calculations and measurements conducted by the satellites to generate the total water storage data, the theory behind isolating the groundwater component of the storage is relatively straightforward. With the addition of a land surface model, such as NASA's GLDAS-Noah model (Matthew Rodell et al., 2004), the surface water, snow water equivalent, plant canopy, and soil moisture components of water storage can be subtracted from the total water storage anomaly dataset to derive a groundwater anomaly dataset (Richey et al., 2015). This basic mass balance equation has been applied across multiple studies with varying land surface models and surface water measurements (Joodaki, Wahr, & Swenson, 2014; Khaki et al., 2018; Nanteza et al., 2012; Richey et al., 2015; R. Xiao, He, Zhang, Ferreira, & Chang, 2015).

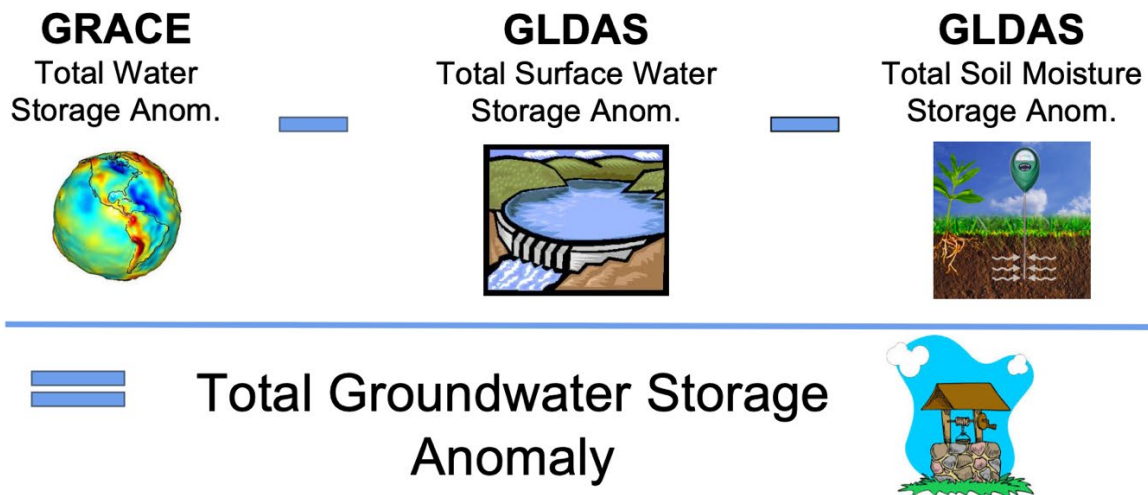


Figure 1.7 Simple Depiction of How Groundwater is Derived from the GRACE Total Water Storage Anomaly Dataset

Other scientists have assimilated the GRACE total water storage data into land surface models that estimate groundwater, essentially using the GRACE data to better calibrate the existing land surface models (Li et al., 2012; Tangdamrongsub et al., 2018). The data is being used for groundwater analysis in areas where data has rarely or never been collected before. For example, (Richey et al., 2015) used this data to demonstrate groundwater depletion in 37 of the world's major aquifers. The study found that the majority of the world's major aquifers are under stress and at risk of losing storage capacity. The GRACE data is global and can be applied used for groundwater analysis in almost any region in the world. This scientific breakthrough offers new hope for decision makers in areas where collecting groundwater data is particularly difficult.

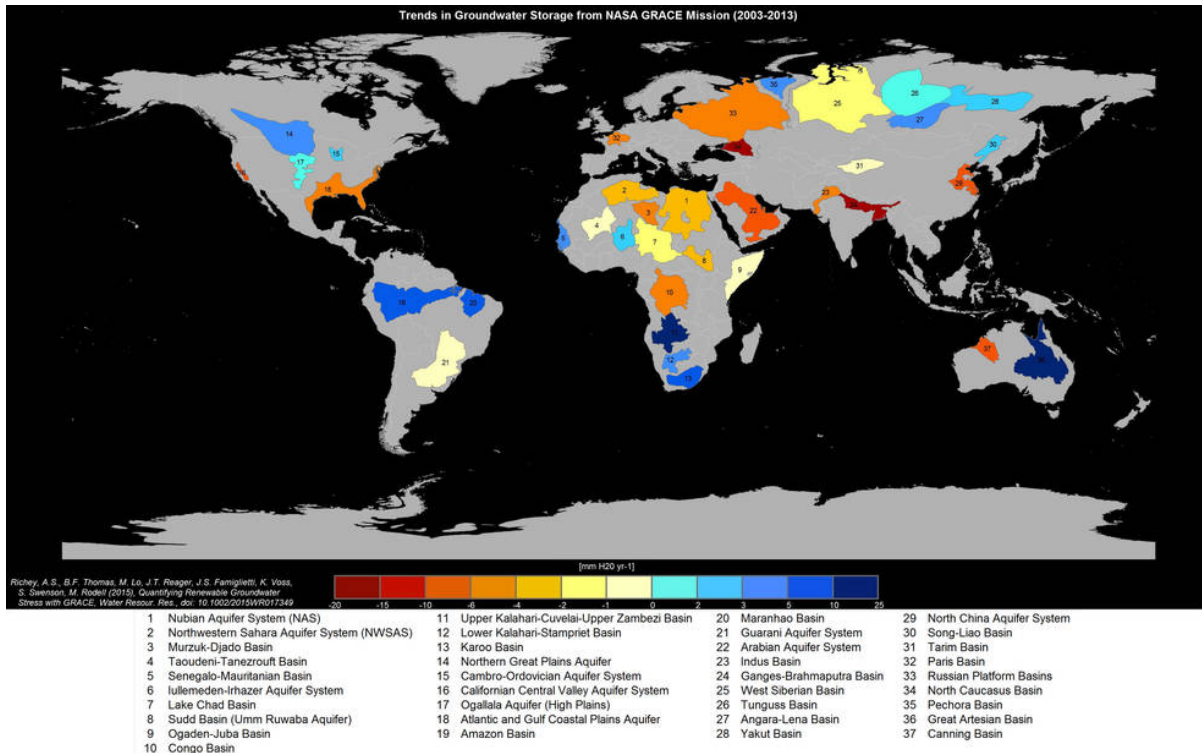


Figure 1.8 Map Showing the Status of the World’s Largest Aquifer Systems According to (Richey et al., 2015) Orange Shows Stressed Aquifers Blue Represents Healthy Aquifers

1.4 Existing Tools

A number of scientists have developed tools to help users view and interact with the GRACE data. The ANU GRACE Visualization Web Portal developed by (Darbeheshti, Zhou, Tregoning, McClusky, & Purcell, 2013) allowed users to view GRACE data pertaining to specific basins on the Australian continent. The tool permitted downloads of time series data from a total water storage anomaly dataset and at one point allowed users to generate an animation of the changes in water storage. Currently it appears the tool is no longer maintained. The data was also based on a French solution of the GRACE dataset (Bruinsma, Lemoine,

Gegout, Biancale, & Bourgogne, 2014) which is not among the most generally accepted data solutions. Other tools, like the GRACE Plotter tool developed by (Bruinsma et al., 2014), focus on comparing the results between the different GRACE dataset solutions and only offer simple time series data for specific locations. The University of Colorado has also developed a data viewer that allows users to view the most current total water storage datasets provided by JPL, CSR, and GFZ as well as a number of other datasets that are more relevant to GRACE data scientists than to local stakeholders. Like the ANU tool, clients can extract time series data from a specific longitude and latitude and it provides a dynamic map view in which users can adjust layer factors such as a smoothing radius ("University of Colorado GRACE Analysis Website," 2013). JPL has also recently released their own tool that allows users to interact with the JPL and CSR mascon GRACE datasets ("GRACE Data Analysis Tool," 2019). Users can extract

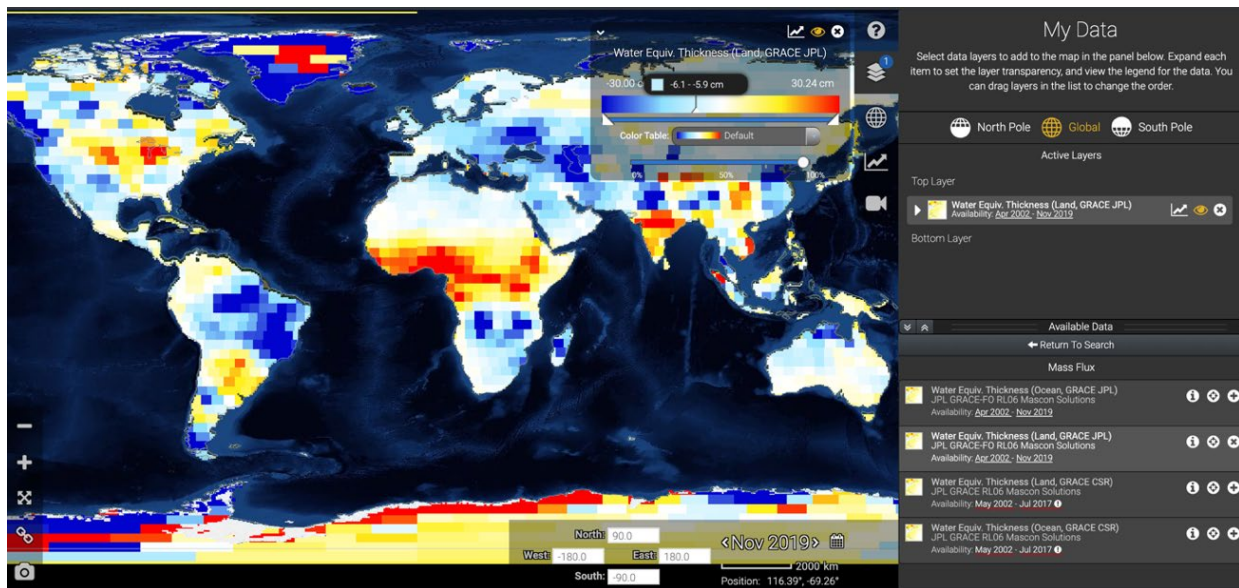


Figure 1.9 Image of JPL GRACE Data Visualization Tool ("GRACE Data Analysis Tool," 2019)

time series and generate video animation files of the layers changing over time. The JPL tool even allows users to extract a regional average time series from a square bounding box drawn by the user or for one of their predefined global basins. However, both the University of Colorado tool and the JPL tool do not provide any form of groundwater anomaly dataset nor do they provide a way for individuals to extract regional data for custom complex polygons.

There is little doubt that the data provided by the GRACE mission, and the groundwater data that can be derived from it, are extremely valuable and have the potential to improve the management of water resources on a global scale, particularly in developing parts of the world. This leads to the question: why isn't this data being used by those who would likely benefit most from its implementation? The GRACE data is often difficult to understand and process for those without a background in programming or geospatial software. Although a number of GRACE web tools and toolboxes have been developed, many of them cater more towards the needs of GRACE scientists and those who have a strong foundational understanding of how the raw GRACE data is processed (Bruinsma et al., 2014; Feng, 2019; "University of Colorado GRACE Analysis Website," 2013). This makes it difficult for stakeholders and water users without technical backgrounds to make use of, and therefore benefit from, the GRACE satellite data. Many web tools also don't provide the JPL recommended ensemble average solution dataset (F. Landerer, 2020d). This recommendation comes based on findings by (Sakumura et al., 2014). The recommended dataset is simply the average of the JPL, CSR, and GFZ total water storage datasets however it is rarely a layer option in GRACE data viewers. In addition, GRACE web tools typically only provide the total water storage dataset. This makes it difficult for non-technical users and scientists alike to see how different types of water storage are changing within their area of stewardship.

Due to the fact that methods for deriving the groundwater anomaly dataset are still being debated in the GRACE community, most web tools do not provide any groundwater anomaly data to their users. There is also a lack of regional analysis features among published GRACE web tools. Some web tools provide a means for subsetting the global data for a particular region (Darbeheshti et al., 2013), however the subsetting process typically only involves masking the global dataset and often is not capable of subsetting complex polygonal regions on the fly ("GRACE Data Analysis Tool," 2019). This does make the data easier to see and understand in a map view, however the data is exactly the same as the data in the global dataset and therefore adds no additional perspective or insight for decision makers who are focused on a particular region.

1.5 Research Objectives

This research aims to develop an open-source web-application capable of bridging the technical gap between GRACE data scientists and decision makers in developed and developing countries throughout the world. This supports the global outreach objectives established by the SERVIR program, which provided the funding for this research. The purposes and goals of this web-application are as follows:

- 1) To make all of the GRACE satellite data, and in particular the groundwater data that can be derived from it, accessible to anyone with a web browser no matter the location.
- 2) To provide an interface that requires a low level of technical knowledge to operate and maintain.

- 3) To provide a regional analysis feature that delivers additional value and perspective, beyond the global data, to benefit stakeholders and decision makers in their efforts to manage their local groundwater assets.

This tool, appropriately named the GRACE Groundwater Subsetting Tool (GGST), enables all types of stakeholders to interact with the GRACE satellite data. The tool is built on a software called Tethys Platform, which is an open-source software platform designed to lower the barrier for web-app development (Swain et al., 2016). The application is accessible from any device with a web browser. It is open-source and can easily be deployed on a Linux server. It also provides a broad collection of GRACE datasets including the three, mission supplied JPL, CSR, and GFZ datasets along with the JPL recommended ensemble average of the three (Sakumura et al., 2014). Surface water and soil moisture storage datasets are also provided for reference and are derived from the GLDAS-Noah model (Matthew Rodell et al., 2004). The application delivers derived groundwater anomaly datasets for all four of these total water storage datasets that have been calculated following the most generally accepted methods published on JPL's website (F. Landerer, 2020a, 2020c). The tool offers access to all of its data via a map interface with animation capabilities, exportable time series graphs, and a REST API. The app has been designed to be easy to use and contains general instructions regarding recommendations to assist non-technical users in applying the data to their own personal regions of interest. The app also comprises a regional analysis feature which subsets the global dataset and generates a regional average time series and a derived storage depletion curve, offering additional perspective and making it easier for stakeholders to monitor the health of their local aquifer systems. This open-source web tool can also offer scientists an easily deployable framework for showcasing their research, has features that could be used to help validate their

results, and can be a means by which they can help their findings reach decision makers in various parts of the world. In this way, the GGST makes this vital data more accessible, comprehensible, and applicable for both engineers and non-technical stakeholders while at the same time encouraging GRACE scientists to share their findings with those end users who would benefit from them the most. This application will provide decision makers with additional perspective, a means for monitoring their groundwater resources, and will help in the efforts to create a cultural shift in how groundwater is managed in many parts of the world.

This thesis will discuss the data and methods used to develop the GRACE Groundwater Subsetting Tool including the front-end user interface and the features the app offers as well as the back-end computations related to the construction of the groundwater datasets and the regional subsetting process. It will also depict several regional case studies at the aquifer, national, and multi-international levels including Central Valley, California, Bangladesh, the La Plata River Basin, and the SERVIR Hindu Kush Himalaya region. Finally, it will postulate the potential impacts this web-application could have in both developed and developing parts of the world where *in situ* groundwater data is currently scarce or nonexistent.

2 DATA AND METHODS

2.1 Datasets Used

All of the datasets used in the web-application are downloaded, manipulated, and stored in NetCDF format (Rew & Davis, 1990). There are four different groups of datasets used in the GRACE Groundwater Subsetting Tool:

- 1) Total Water Storage Anomaly Datasets
- 2) GLDAS based Surface Water Storage Anomaly Datasets
- 3) GLDAS based Soil Moisture Storage Anomaly Datasets
- 4) Calculated Groundwater Anomaly Datasets

This section will outline the origins and basic methodology for calculating these datasets. The actual computational methods for generating the datasets themselves will be detailed in Section 2.4.1.

2.1.1 Total Water Storage Anomalies and Different Signal Solutions

As Mentioned previously, the GRACE and GRACE-FO missions are both joint ventures. They are supported by Jet Propulsion Laboratory (JPL), University of Texas at Austin Center for Space Research (CSR), and the German Research Center for Geosciences (GFZ). The GRACE Groundwater Subsetting Tool (GGST) hosts four total water storage anomaly datasets in total.

Three of these datasets are the JPL, CSR, and GFZ RL06 land mascon solution files distributed by JPL (F. W. Landerer & Swenson, 2012; SC Swenson, 2012; Sean Swenson & Wahr, 2006) and one is an ensemble average of the three previously mentioned signal solutions (Sakumura et al., 2014).

As a result of the findings of (Sakumura et al., 2014) and the recommendations on the JPL website (F. Landerer, 2020d), the GRACE Groundwater Subsetting Tool also provides the ensemble average of these three solutions. Sakumura found the ensemble average of the three solutions to generally provide a greater level of accuracy. This in turn provides a default solution for non-technical users to use if they lack the background to know which signal solution is best for their area of stewardship.

The datasets that can be downloaded from JPL are in the format of $0.5^\circ \times 0.5^\circ$ latitude longitude grids. However, the total water storage anomaly datasets hosted within the GGST application have been resampled to a resolution of 0.25° latitude \times 0.25° longitude to assist in the groundwater dataset calculations.

2.1.2 Surface Water and Soil Moisture from GLDAS Data

In order to extract the groundwater storage data contained within the GRACE total water storage datasets, the GRACE Groundwater Subsetting Tool also includes a Surface Water Storage Anomaly dataset and a Soil Moisture Storage Anomaly dataset. Each of these datasets were derived from various components represented in the 3-hour $0.25^\circ \times 0.25^\circ$ GLDAS-Noah model solution (Matthew Rodell et al., 2004). The components grouped into surface water and soil moisture are shown in Table 1. These components were chosen based off of several similar studies where groundwater was calculated using the GLDAS-Noah model (Nanteza et al., 2012;

Richey et al., 2015) and general information on the process outlined on the JPL GRACE Tellus website (F. Landerer, 2020c).

Table 1: A List of the GLDAS-Noah Model Components that Contribute to the Surface Water Storage and Soil Moisture Storage Datasets.

GLDAS Surface Water Storage Components	GLDAS Soil Moisture Storage Components
Storm Runoff	Root Zone Soil Moisture
Groundwater Runoff	Soil Moisture (0cm – 10cm)
Plant Canopy	Soil Moisture (10cm – 40cm)
Snow Melt	Soil Moisture (40cm-100cm)
Snow Water Equivalent	Soil Moisture (100cm – 200cm)

Each of these components are summed together to form two datasets, the total surface water storage and total soil moisture storage datasets. Then, to be able to accurately compare them to the GRACE total water storage anomaly datasets, the surface water and soil moisture datasets must be converted into an anomaly format as well. This is done by normalizing the data to a surface water mean and a soil moisture mean calculated using the model data from 2004 to 2009, to mirror the GRACE mean calculations (F. Landerer, 2020b). The time frame for the mean calculation allows us to directly compare it to the GRACE total water storage dataset and is necessary to calculate the groundwater dataset properly. The logic in Figure 2.1 is applied to both the surface water storage and soil moisture storage data compiled from the GLDAS-Noah model. These two datasets are the same regardless of the signal solution chosen by the user.

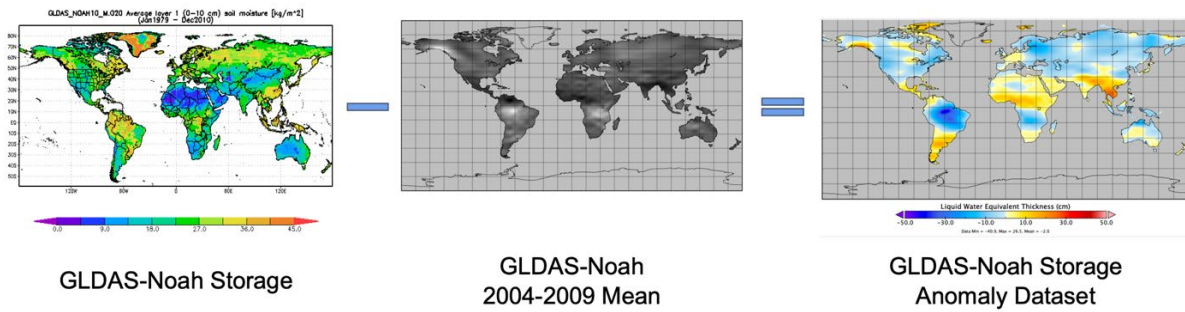


Figure 2.1 Converting GLDAS Data into Anomaly Datasets to Allow for Direct Comparison with GRACE Data

2.1.3 Derived GW Datasets

The groundwater dataset is calculated based on the logic that the GRACE total water storage datasets are made up of surface water, soil moisture, and groundwater storage components. A mass balance equation, Equation (2-1) shown below, is then applied to the datasets to extract the groundwater data.

$$(GWSa) = (TWSa) - (SMSa) - (SWSa) \quad (2-1)$$

In this equation, GWSa = Groundwater Storage Anomaly, TWSa = Total Water Storage Anomaly, SMSa = Soil Moisture Storage Anomaly, and SWSa = Surface Water Storage Anomaly. The methodology shown above was applied to each of the total water storage anomaly datasets mentioned in section 2.1.1 generating four groundwater anomaly datasets in total. This general process has been implemented in a number of studies and has proven successful in depicting changes in groundwater storage in various parts of the world (F. Landerer, 2020c; Nanteza et al., 2012; Richey et al., 2015).

2.2 Overall App Design and Features

To fulfill the objectives of this research, the Grace Groundwater Subsetting Tool contains a number of features focused on lowering the level of technical knowledge required to interact with GRACE mission data, specifically the groundwater data, and on providing the user with robust regional analysis capabilities. The application has several key pages: the home page, the global map view page, the regional map view page, the add region page, the manage regions page, and the update data page, each of which will be outlined in this section. The GGST is generalized in such a way that it can be used for almost any region in the world, and it accomplishes the goal of making global groundwater data more accessible to decision makers.

2.2.1 Home Page

Upon opening the GRACE Groundwater Subsetting Tool, users are brought to the following home page shown in Figure 2.2. The app is based on Tethys Platform's Django app infrastructure which provides for a very clean user interface (Nathan R. Swain et al., 2016).

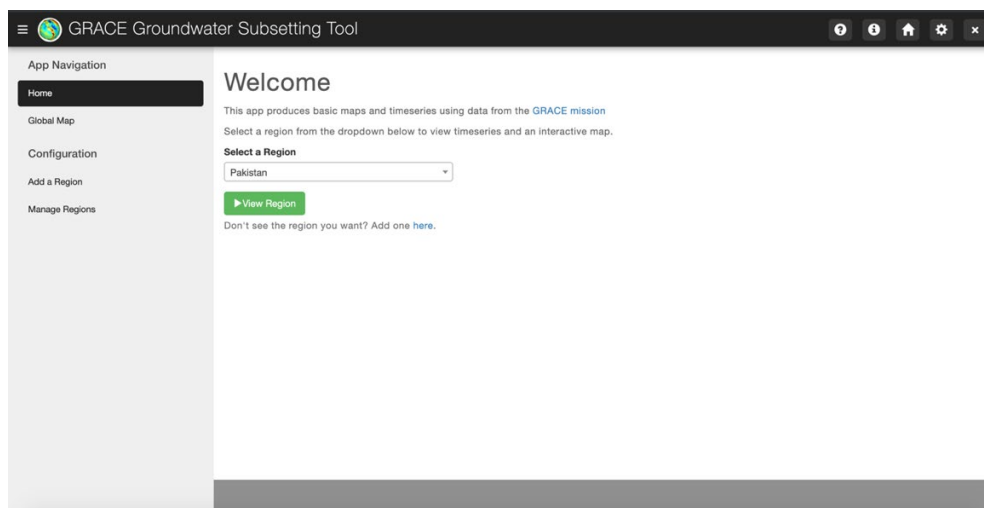


Figure 2.2 GRACE Groundwater Subsetting Tool Home Page

Every page of the GGST has an identical top menu bar which has a number of buttons to help facilitate the user's experience. The help icon, depicted with a question mark, is customized

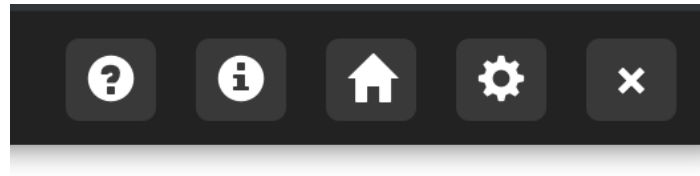


Figure 2.3 The GGST's Top Menu Bar

to provide guidance through the currently displayed page of the application. For example, on the home page the help icon brings up a dialog box outlining the different navigational links that users can choose to use to explore different parts of the application. The information button is a link to the REST API guidance document. This dialog provides instructions on how to access the data displayed in the GRACE application through the tool's REST API which will be outlined further in 2.2.7. In the center of the button group is the home screen icon which is a simple link that will bring the user back to the home screen from any other page within the application. The gear icon is to manage the application settings and the "X" is to close the application.

From this home page the user can navigate to any part of the application. In the main window, users can select a region of interest from a drop-down menu to view the region within the regional map view page. The user can also choose the option to add a new custom region if it is not present in the list of options provided in the drop-down menu. Located on the left-hand side of the page is a navigation menu which allows the user to navigate to the remaining pages

within the application. This navigational bar provides access to the global map view and the home page from any page within the application. It will also provide access to the add region and update data pages if the user has logged in with admin credentials.

2.2.2 Global Map View

The global map view page displays all of the application's global datasets, which were mentioned in sections 2.1.1 through 2.1.3. This includes the four-different total water storage anomaly datasets, the surface water and soil moisture storage anomaly datasets, and the four different groundwater anomaly datasets calculated from the different signal solutions. Figure 2.4 shows the global map view's user interface.

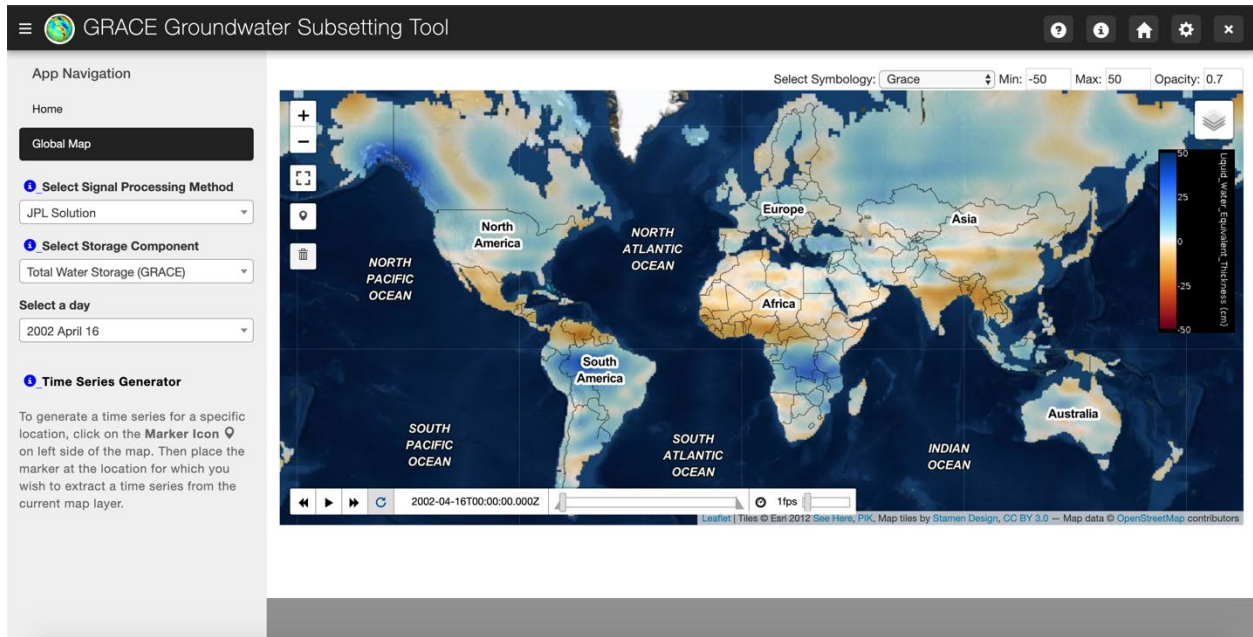


Figure 2.4 Global Map View User Interface

On this page, the navigation menu on the left side of the screen also includes several map controls under the global map tab. The first of these is the signal solution dropdown menu. The four options in this drop-down are the JPL, CSR, GFZ, and ensemble average signal solutions. This determines from which group of datasets the application selects the different water storage layers.

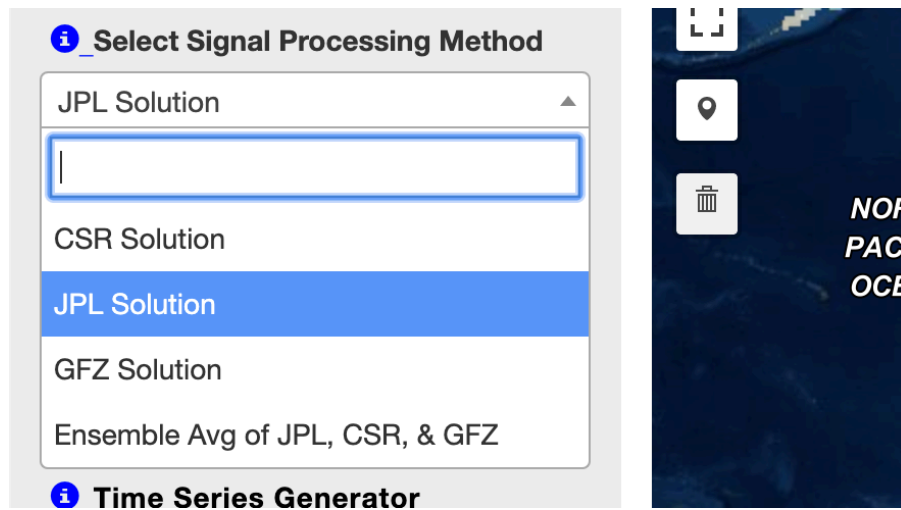


Figure 2.5 Signal Solution Drop-Down Menu Options

Below the signal solution drop-down menu is a second drop-down menu titled storage type. This dropdown menu allows the user to choose which storage anomaly layer is displayed in the map view (i.e. total water storage, surface water storage, soil moisture storage, or groundwater storage). The application displays the selected storage type from the group of datasets corresponding to the selected GRACE signal solution.

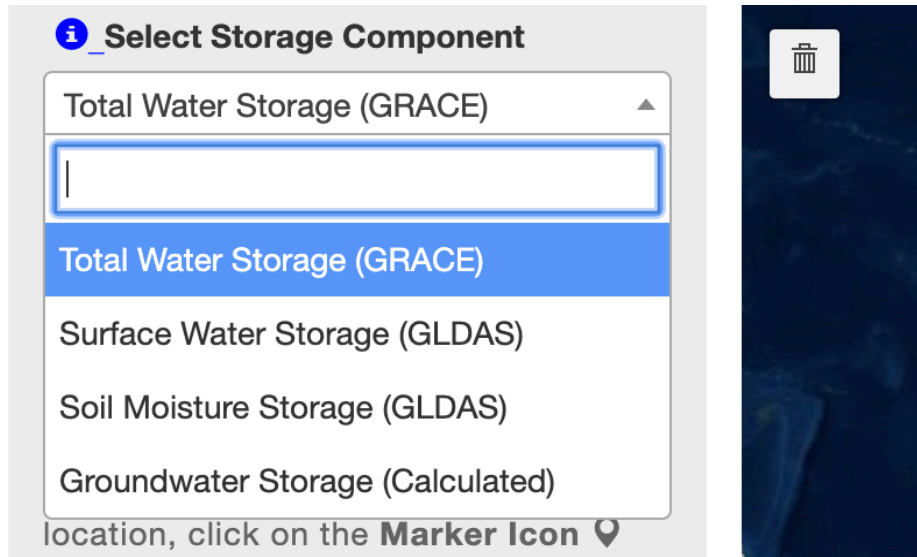


Figure 2.6 Storage Type Drop-Down Menu Options

The final dropdown menu contains all of the dates associated with the GRACE dataset time steps. This allows the user to jump to a specific point in time and view the status of different water storage layers. Any time any of these drop-down menus are changed, the application will update the map window on the fly and display the appropriate layers.

The map window itself contains a number of features that allow the user to customize the display of the different storage layers. Like most map windows it allows the user to pan and zoom and contains a legend along the right side to display the intervals at which the storage layer symbology is displayed. It contains several ESRI base layer options (ESRI, 2018; Map, 2015) and includes an optional overlay depicting all of the different international and state boundaries of many countries around the world (Haklay & Weber, 2008). This overlay layer is dynamic and increases in detail as the user zooms in on specific areas on the map.

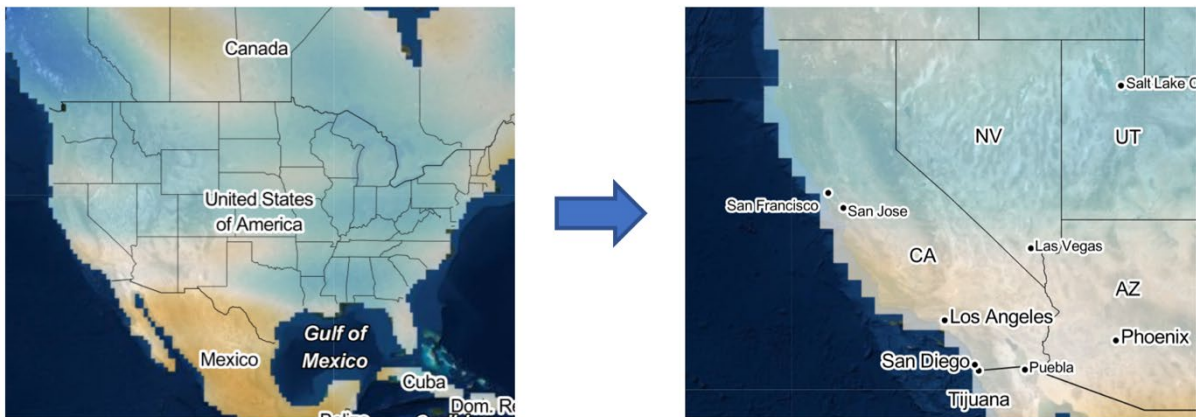


Figure 2.7 Example of Dynamic Stamen Toner Hybrid International and State Boundaries Overlay

The map display can be altered using a number of the controls located in the top-right corner of the window. Users can choose from a wide variety of color pallets, adjust the contour display ranges, and adjust the opacity of the storage layer being displayed. All changes made to these display options are made on the fly seamlessly updating the symbology of the layers appropriately.



Figure 2.8 Close Up of Different Symbology Controls

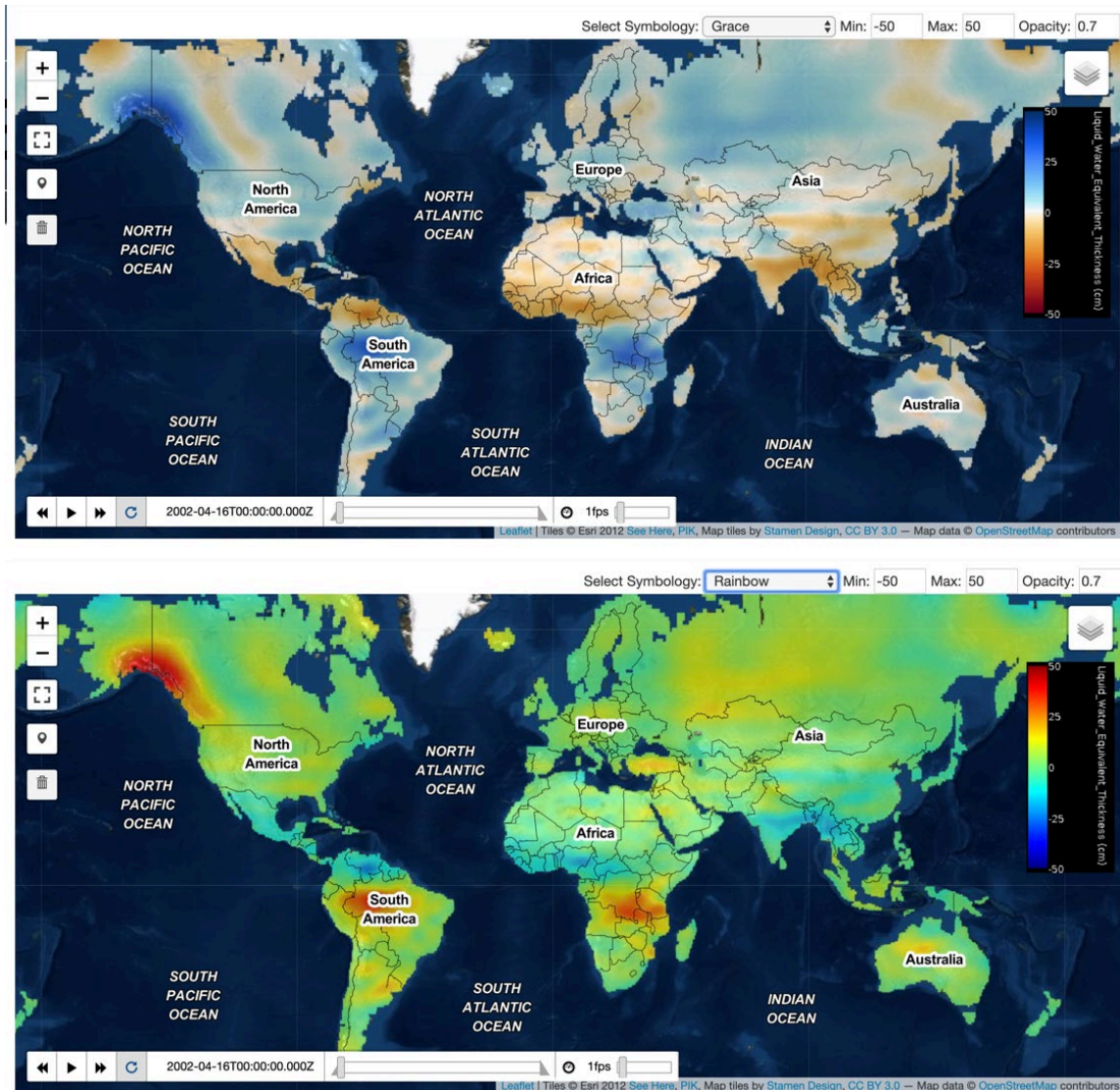


Figure 2.9 Example of Different Layer Symbology

The map also has animation capabilities. The user can animate through the time steps using the animation controls in the bottom left corner of the map window. The application allows the user to limit the start and end time steps of the animation, adjust the speed at which it animates through the layers, and toggle on and off the option to loop the animation when it is finished. This animation feature sets the GRACE Groundwater Subsetting Tool apart from other GRACE data visualization tools as the fly animation is not present in many other applications.



Figure 2.10 Map Animation Controls

In addition to the animation features the GGST also has the ability to extract time series data from a specific point on the map. The user can select a location on the map using the button under the zoom icon on the left side of the map. After placing a feature point on the map, the data from the global grid is extracted from the grid cell that contains the point and is displayed in the form of a time series graph.



Figure 2.11 Location of Place Point on Map Button

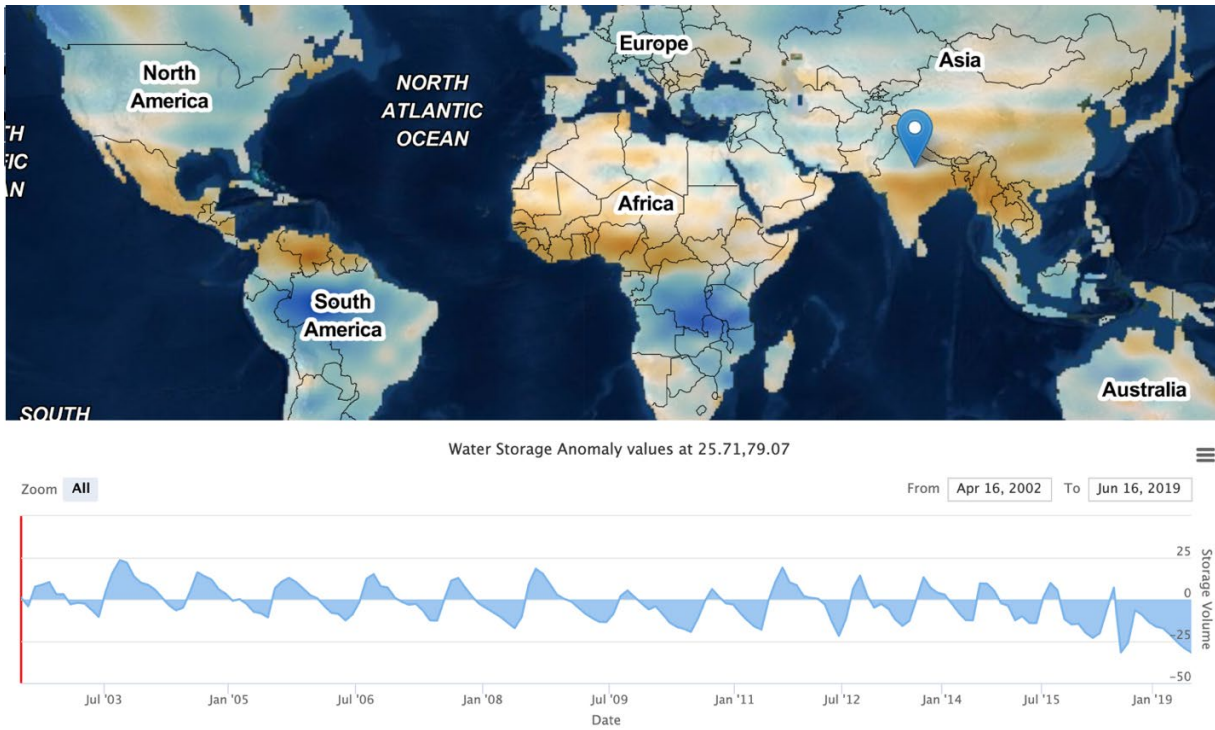


Figure 2.12 Example of Point Time Series Graph

The time series graph shows the changes in water storage relative to the 2004-2009 calculated mean for the grid cell where the point is located. The time series is dynamic in that it has a red tracker line that is programmed to correspond to the currently displayed time step in the map window. This means that as the map window animates through different time steps of a storage layer, the time series tracker updates to show where on the graph the current map layer is displayed. The time series has zoom features that can limit the field of view of the graph and can be exported to either a csv file or a number of image formats. In addition to the regular time series graph, the application also has the option to display the time series data as a storage depletion curve. The storage depletion curve graph shows the same time series data normalized to the starting storage variation value and converts the variations to units of acre-ft. This allows the user to see the changes in water storage relative to when the GRACE missions began

distributing data, April 2002. The storage depletion curve is a commonly-used tool in groundwater management and makes the GRACE data more comprehensible for decision makers and water users.

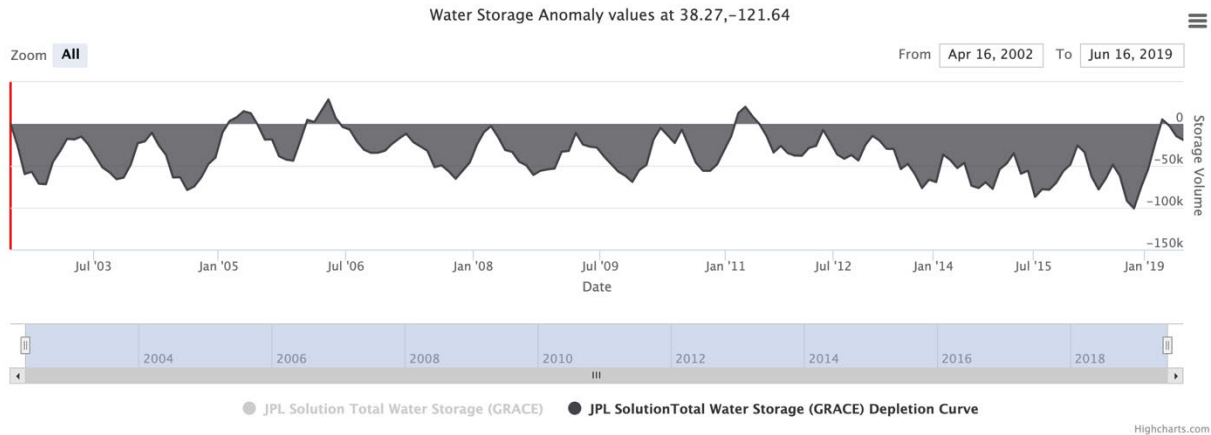


Figure 2.13 Example of a Point Time Series Storage Depletion Curve

2.2.3 Regional Map View

The regional map page has all of the same functional capabilities as the global map page, but there are also a number of additional features and types of data displayed to increase the value of the regional analysis for the user. The layers displayed in the regional map window are not based on the same mean as the global GRACE data. During the subsetting process, a regional mean is calculated to determine what value of storage variation is normal for the region as a whole. The grid cells in the region are then normalized to this value, thus the layers displayed in the map view reflect the grid cells' storage variations from the regional mean. This helps decision makers and groundwater managers monitor which resources in an area are considered healthy and which are below normal for the area. It also helps account for seasonal

variations in storage and it helps locate potential resources that contain more abundant sources of water than what is average for the region. A storage contours overlay is also included as an optional layer on the regional map page.

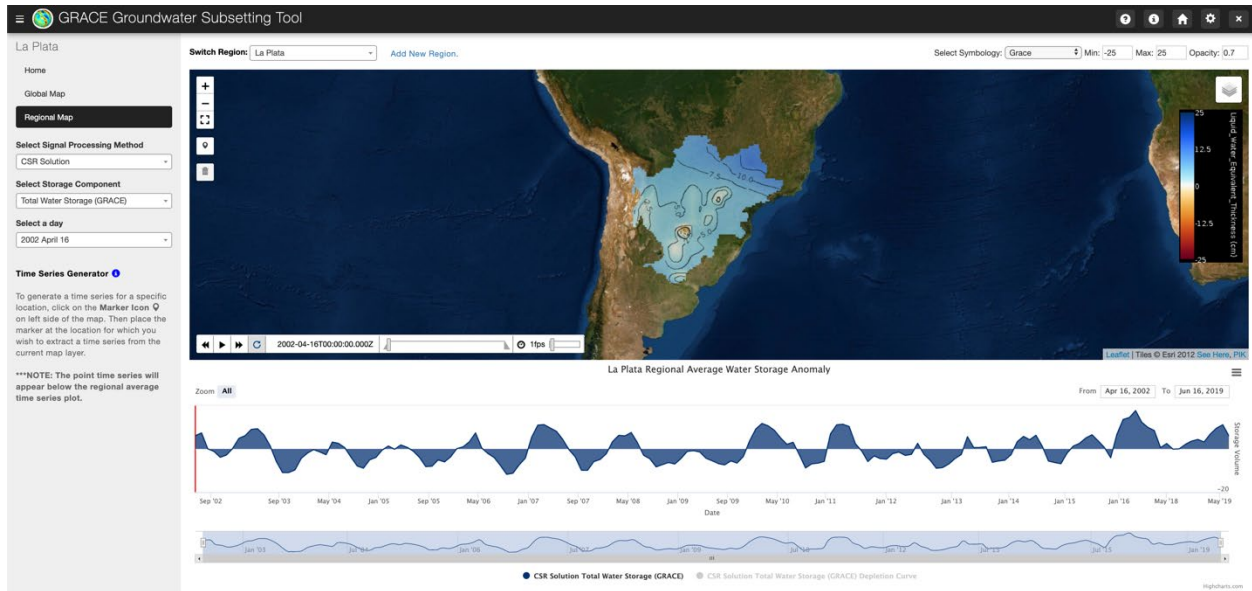


Figure 2.14 Regional Map View Page Layout

The most valuable metric generated from this regional average dataset however, is the regional average time series graph. Unlike the global map view which only displays the time series data after placing a specific point on the map, the regional average time series chart is displayed when the page is first loaded. This chart shows the variation in storage for the entire region over time. The regional average time series has all of the same dynamic features as the point time series chart mentioned in the global map page section. It also has the option to view the time series data in the format of a storage depletion curve. This is especially valuable for regional data because it creates an opportunity for groundwater managers to monitor the storage

in a specific aquifer, or monitor the total groundwater usage in a country as whole. Decision makers can upload regions that would essentially be impacted by potential public policies and monitor the influence of said legislation.

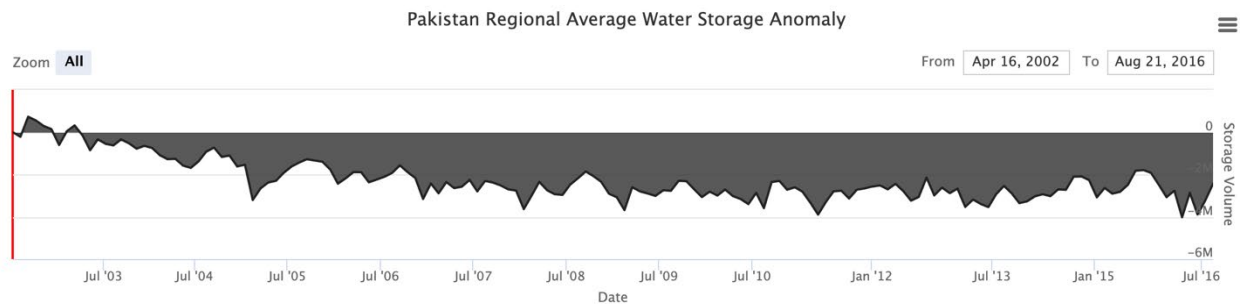


Figure 2.15 Groundwater Storage Depletion Curve of Pakistan from 2002-2016 in Acre-Ft.

The regional map also has the capability to extract time series data from a specific point on the map. This time series data however, is extracted from the global dataset and not the regional average layer. This allows the user to accurately compare the changes in a specific location to the changes within a larger regional area, thus giving the user the ability to monitor specific resources within a larger aquifer system. One final feature of the regional map page is the ability to switch to a different region using the drop-down menu in the top-left corner of the map. This is simply to facilitate switching between regions without having to return to the application's home page.

2.2.4 Add Region Page

The add region page contains a fairly simply interface where the user can add a new custom region to their instance of the application. The user provides a name for the region they

wish to upload along with the .SHX, PRJ, .DWG, and .SHP files for the shapefile of the region. The user can then click the add region button and a progress bar will appear and provide updates to the user regarding the status of the subsetting process. The subsetting process typically takes around 20 minutes to complete and displays a green “Success” message when the process is completed successfully.

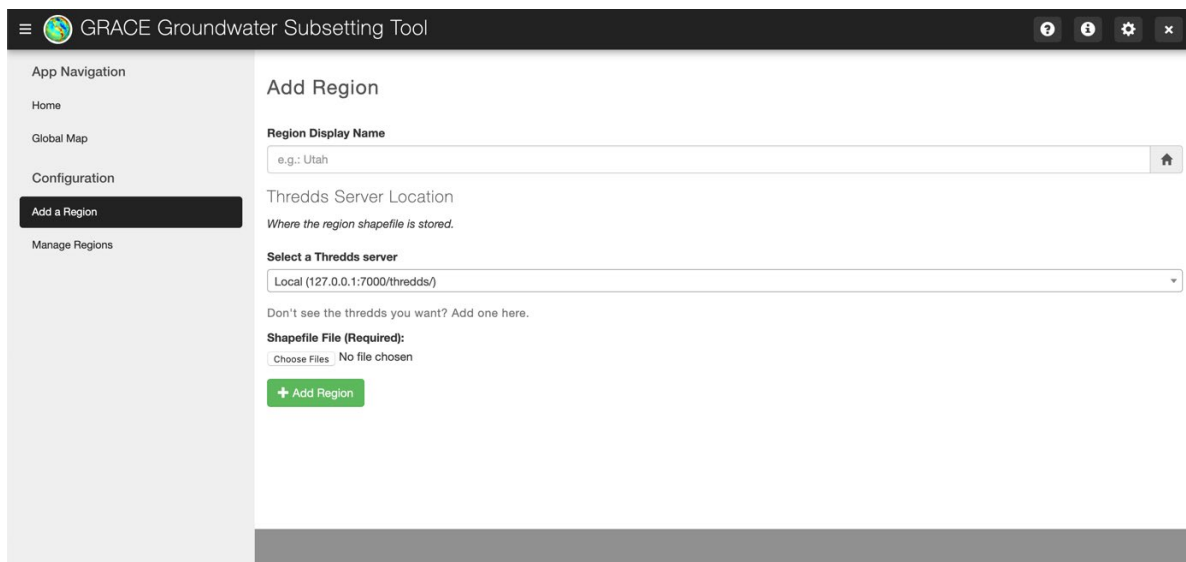


Figure 2.16 Add Region Page Layout

2.2.5 Manage Regions Page

The manage regions page displays a very simple table of every region that has been saved to the Postgres database within the user’s instance of the application. It displays various fields from the Postgres database including the region’s name, the area of the region, and the auto-generated region ID assigned to the region when it was added to the database. It also includes a

delete button which permits the user to remove unwanted areas from the database so that they no longer appear as viewable regions on the home page and regional map page.

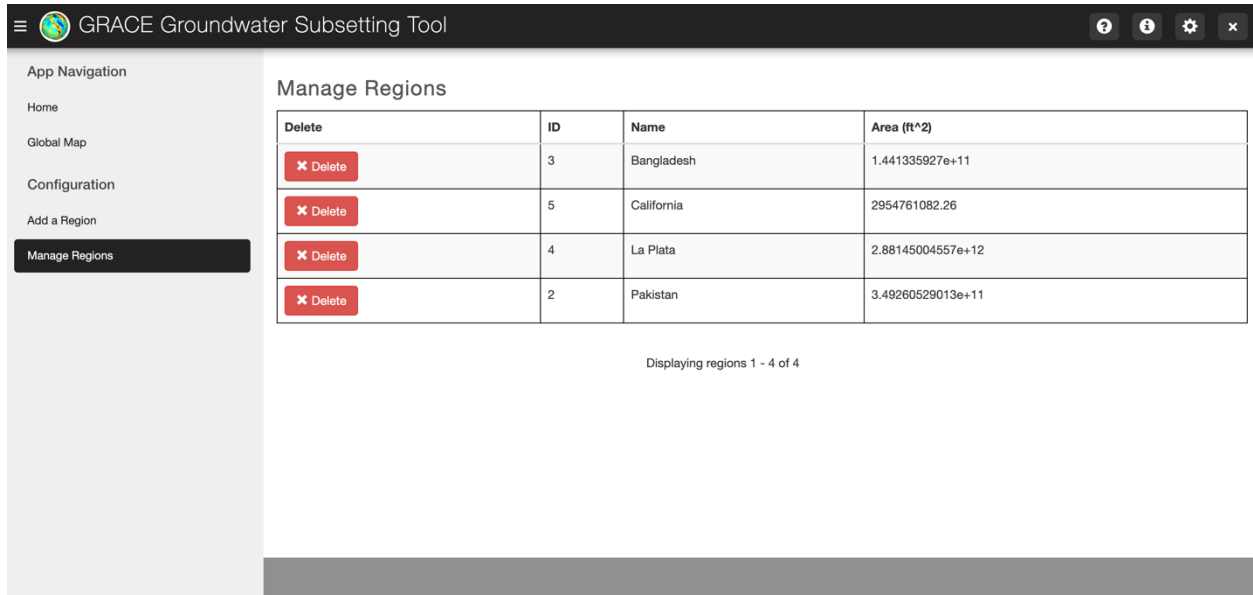


Figure 2.17 Manage Regions Page Layout

2.2.6 Automated Data Update

One of the key features in making this application low maintenance is the process that automatically updates the global anomaly datasets. Since the GRACE-FO mission is continuing to provide monthly data, it is important that the application have a way to automatically update this data to avoid non-technical users having to run scripts to reprocess the data themselves. Because of this, a simple function is executed when the application's home page is loaded that checks if new data is available from the GRACE-FO mission. If there is new data available, a

popup will appear informing the user that new data is available and asking if he or she would like to update their global dataset files.

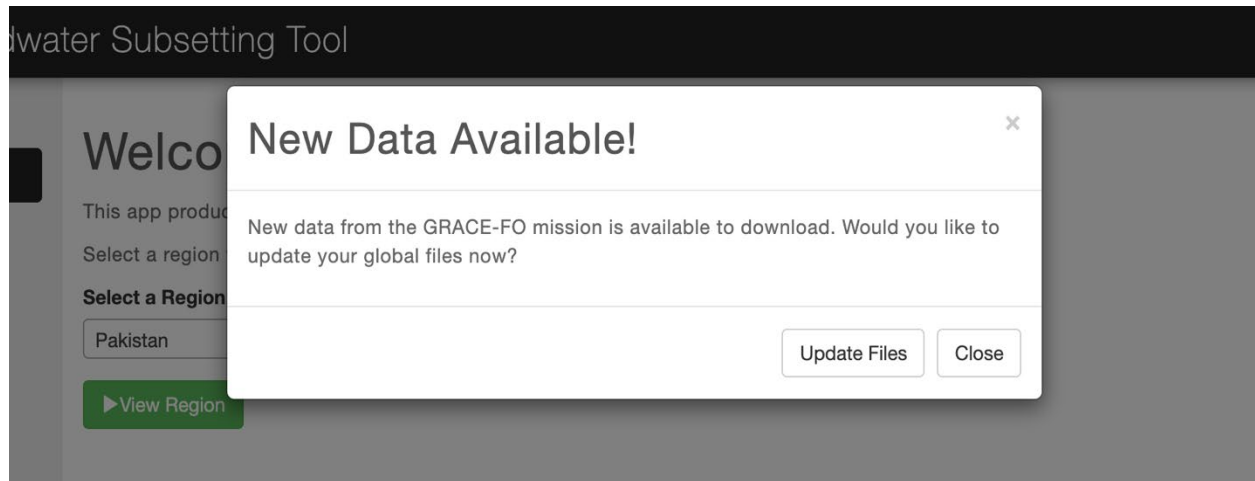


Figure 2.18 Update Files Popup Dialog on Home Page

If *Update Files* is selected, the app redirects the user to the update data page. This page has a very simple interface with one button that says “Update Files.” Upon clicking update files, the user is given one warning that the process will take several minutes and that no regional files will be updated by this process. In order to update the regional files the user will need to remove the current region from the database and re-upload it to the application using the add region page in order to include the new time steps in the regional average and subsetting calculations. If the user selects *yes*, the global files will be updated and will be available to view within the global map page once the update process is complete. Once the process is complete a message reading “Update Successful” The process of updating the global datasets will be outlined further in the Computational Methods section.

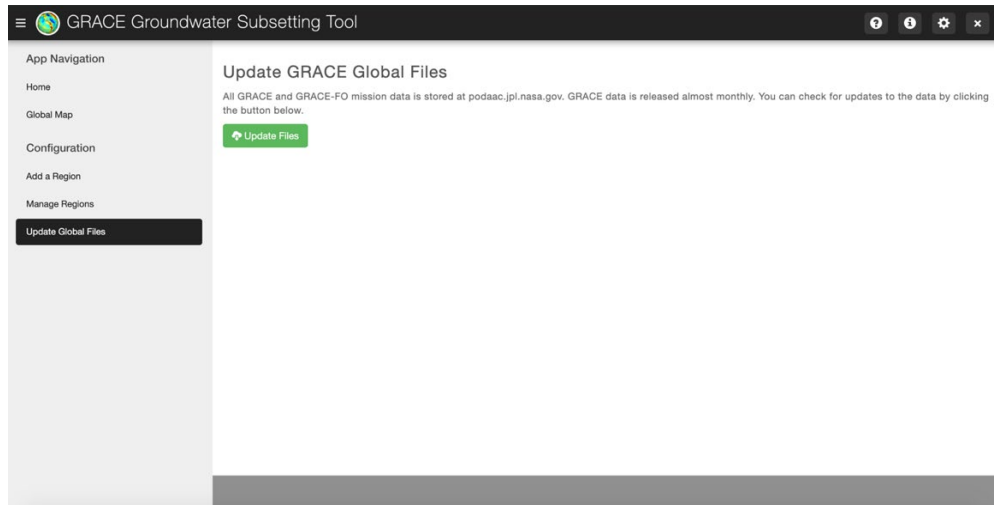


Figure 2.19 Update Files Page Layout

2.2.7 REST API

The REST API instructions are accessible from any page within the GRACE Groundwater Subsetting Tool's interface by clicking the information icon on the top menu bar. The REST API allows the user to access any of the datasets that can be displayed in the global map view and download the time series data from those datasets. This is done using a URL that includes a number of input parameters including specific latitude and longitude values. This in combination with the desired signal solution and storage type will allow the user to remotely extract time series data for a specific location in the world. Users can also specify a date range to only extract data for a specific time period however this parameter is optional. A comprehensive summary of the different input parameters required is displayed in Table 2. An example of a populated API link is given in the REST API dialog. A screen grab of this example link is shown in Figure 2.20.

Table 2: Input Parameters Required to Call the REST API

Parent App	newgrace			
Supported Methods	GET			
Returns	A JSON object with a time series for a given point.			
Parameters	Name	Description	Valid Values	Required
	latitude	Latitude in WGS 84 projection	Any value on land within the GRACE Explorer Domain (-60,90)	Yes
	longitude	Longitude in the WGS 84 projection	Any value within the GRACE Explorer Domain (-180,180)	Yes
	signal_solution	GRACE signal processing method	Use one of the following: (jpl, csr, gfz, avg)	Yes
	storage_type	Storage type you wish to access	Use one of the following: (tot, sw, soil, gw)	Yes
	start_date	Start Date for the forecast	Any date after 2002 April 4	No
	end_date	End Date of the Forecast	Any date after the start date	No

Example:

```
http://127.0.0.1:8000/apps/newgrace/api/GetPointValues/?latitude=20.7&longitude=80.2&signal_solution=csr&storage_type=gw
```

Figure 2.20 Example REST API Link

Once the URL parameters are in place the user simply has to paste the URL into the address bar of a web browser and the app will retrieve the petitioned data. The time series data is delivered to the user in the form of a comma separated JSON dump as shown in Figure 2.21.

```

{"values": [[101891520000, 8.284], [102098880000, 3.991], [102949920000, -23.871], [103213440000, -30.232], [103476960000, -10.285], [103740480000, 2.222], [104004000000, 8.894], [104271840000, 7.879], [104526720000, 10.857], [104781600000, 8.647], [105045120000, 5.673], [105265440000, 5.239], [105835680000, -11.471], [106103520000, -25.794], [106367040000, -19.987], [106630560000, -21.011], [106894080000, -11.773], [107157600000, -1.436], [107347680000, 2.722], [107697600000, 8.214], [107943840000, 4.298], [108207360000, 4.793], [108470880000, 1.489], [108734400000, -11.084], [108997920000, -11.03], [109265760000, -31.31], [109529280000, -25.111], [109792800000, -18.538], [110056320000, -4.077], [110319840000, 4.065], [110587680000, 5.819], [110842560000, 4.408], [111097440000, 1.948], [111360960000, 2.649], [111624480000, 3.533], [111888000000, 4.637], [112151520000, -15.958], [112419360000, -27.021], [112682880000, -30.475], [112946400000, -14.823], [113209920000, -1.457], [113473440000, 7.122], [113741280000, 11.09], [113996160000, 11.852], [114251040000, 1.917], [114514560000, 5.08], [114778080000, 3.15], [115041600000, 6.881], [115305120000, -0.364], [115572960000, -9.609], [115836480000, -17.507], [116100000000, -7.773], [116363520000, 3.046], [116627040000, 11.898], [116894880000, 17.315], [117149760000, 18.765], [117404640000, 21.729], [117668160000, 15.537], [117931680000, 13.893], [118195200000, 13.242], [118458720000, -15.431], [118726560000, -18.189], [118990800000, -16.886], [119253600000, -15.207], [119517120000, -0.389], [119780640000, 8.562], [120044880000, 15.722], [120307680000, 16.635], [120566880000, 15.022], [120830400000, 12.279], [121093920000, 8.419], [121357440000, 3.336], [121620960000, 2.757], [121888000000, -28.431], [122152320000, -24.106], [122415840000, -10.493], [122679360000, 1.453], [122942880000, 7.095], [123210720000, 12.295], [123465600000, 10.436], [123720480000, 13.04], [123984000000, 10.22], [124247520000, 9.402], [124511040000, 10.068], [124774560000, -25.778], [125042400000, -9.74], [125305920000, -19.288], [125569440000, -16.096], [125832960000, -1.621], [126096480000, 2.295], [126364320000, 9.259], [126632000000, 9.235], [126874080000, 6.724], [127137600000, 8.314], [127401120000, 4.773], [127664640000, 5.779], [127928160000, -1.311], [128196000000, -31.135], [128459520000, -23.822], [128723040000, -15.377], [128986560000, -10.111], [129250080000, -0.131], [129803040000, 11.854], [130027680000, 9.652], [130291200000, 5.695], [130554720000, 5.532], [131107680000, -15.662], [131349600000, -10.13], [131613120000, -21.238], [131876640000, -6.916], [132014880000, 1.039], [132546240000, 14.468], [132671520000, 15.432], [132930720000, 16.865], [133189920000, 15.317], [133405920000, 12.534], [133980480000, 9.498], [134244000000, -14.164], [134511840000, -16.009], [134749440000, -20.864], [135336960000, 5.953], [135565920000, 11.027], [135833760000, 14.812], [136080000000, 13.682], [136654560000, 15.304], [136870560000, 11.24], [137134080000, -11.797], [137397600000, -11.553], [138192480000, -15.16], [138456000000, -3.655], [138719520000, 5.572], [138926880000, 11.181], [139505760000, 11.687], [139760640000, 5.366], [140024160000, 9.403], [140261760000, 6.769], [140819040000, -6.725], [141082560000, -18.805], [141346080000, -15.236], [141618240000, -0.538], [142192800000, 6.738], [142395840000, 21.245], [142650720000, 12.922], [142914240000, 7.567], [143009280000, 10.052], [143696160000, -5.066], [143972640000, -6.281], [144223200000, -8.729], [145082880000, 9.126], [145294560000, 12.177], [145540800000, 9.652], [145812960000, 8.368], [146374560000, 10.385], [146603520000, 13.526], [146858400000, -26.824], [147178080000, -29.77], [152910720000, 0.864], [153118080000, -15.159], [154098720000, 1.577], [154232640000, 7.08], [154496160000, 14.091], [154764000000, 16.044], [155018880000, 16.039], [155273760000, 16.223], [155537280000, 14.758], [155800800000, 14.307], [156064320000, 13.724]], "point": [20.7, 80.2]}

```

Figure 2.21 Example of Results from REST API

This feature creates a door through which engineers, water users, and decision makers can easily access and extract the GRACE data themselves in a simple format that is easy to understand and manipulate. This increased accessibility allows engineers and scientists to both communicate the current health of the resources they manage to decision making officials, and it allows them to use the data in the way that best suits their circumstances. A REST API allows the application to be used in a wide variety of scientific applications that may range from presenting a simple time series graph displaying the declining storage of an aquifer to a group of decision makers, all the way to calibrating a regional groundwater model.

2.3 App Infrastructure

2.3.1 Overview

The GRACE Groundwater Subsetting Tool employs a number of software packages, mapping libraries, web mapping services, databases, and web programming frameworks in order

to provide all of the functionality outlined in section 2.2. The GGST uses Tethys Platform (Nathan R Swain, 2015) as a framework and couples the Leaflet JavaScript Library (Agafonkin, 2019a) with the THREDDS server software (John Caron & Davis, 2006) in order to display the GRACE datasets. It also occupies a simple Postgres Database for storing region data and relies on the NetCDF Operator toolbox (C. S. Zender, 2008) for processing the GRACE datasets. An architectural diagram of the GGST's infrastructure is shown in Figure 2.22. These software components are critical to the application's functionality. Each of their specific roles will be detailed further in subsequent sections.

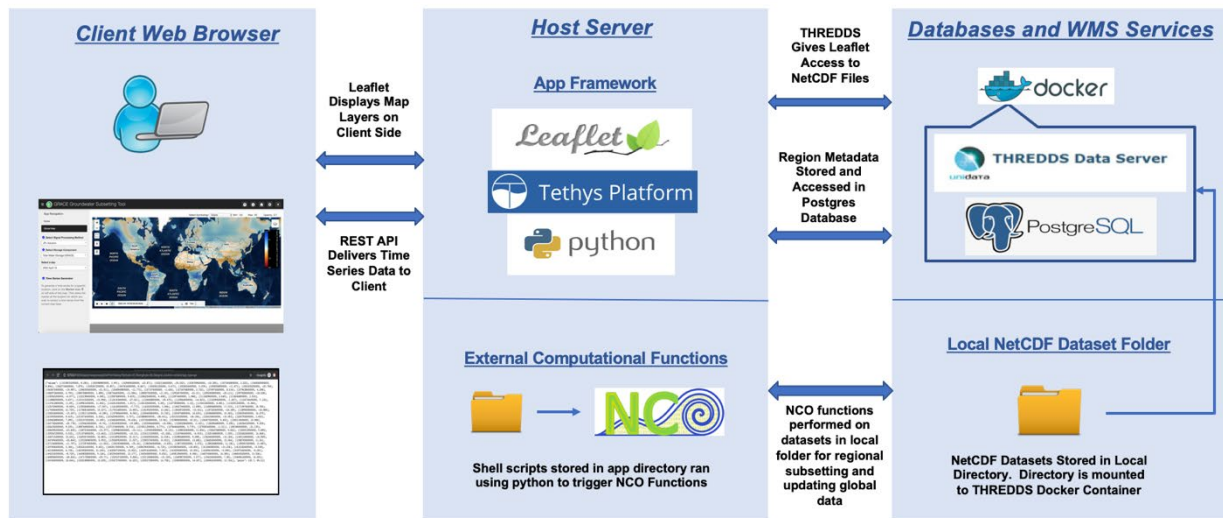


Figure 2.22 Architectural Diagram of the GRACE Groundwater Subsetting Tool's Software Infrastructure

The GGST and all of its included components are open-source. The application is licensed under the MIT license (Opensource.org, 2020) and is available on GitHub at <https://github.com/tmcstraw/GGST-Python2.7>.

2.3.2 Tethys Platform

The GGST is constructed using a framework called Tethys Platform (Nathan R Swain, 2015). Tethys Platform is a web-based app development framework for rapid deployment of end-user-focused tools that follow modern, consistent, scalable, cross-platform, reusable, web programming paradigms. Tethys is a relatively new software system built on commonly used web programming frameworks (e.g. Django, GeoServer, PostGIS, OpenLayers). It is stable and supported by a growing user and developer community.

Tethys Platform leverages recent advances in cloud computing to facilitate better use of large earth observation data sets and water resource models as decision-making tools (Snow et al., 2016). These modeling and visualization tools can be hosted on a server and used by multiple remote users via a web interface, which eliminates the need to procure and maintain high performance hardware typically required by models. Further, it deals with issues related to software installation and platform incompatibilities (Mac vs. PC vs. Linux, etc.), monitor and install software updates, or download large data sets; problems that are exacerbated in regions where financial and technical capacity can be limited. An internet connection and a web browser are all that is required to access the models and associated data.

The Tethys Platform software architecture is illustrated in Figure 2.23. Tethys is built on the Django framework and Python programming language—significantly lowering the barrier for app development (Nathan R. Swain et al., 2016). Tethys Platform apps are hosted in a Tethys Portal and are intended to ease the burden of science information access by enabling web based interaction with spatial resources stored in repositories such as the commercial ArcGIS Online or open-source approaches such as GeoServer and OpenLayers (Nathan R. Swain et al., 2016). The base of the system is the Tethys Software Development Kit (SDK) which integrates a broad suite

of open-source tools for rapid development of web-based water resource data and modeling applications. The Tethys software suite includes components for distributed computing, spatial publishing, geoprocessing, spatial data management, and visualization. It includes external connections for cloud computing and dataset storage and supports integration of both open-source components (GeoServer, OpenLayers, etc.) and proprietary systems (ArcGIS Online, ArcGIS Server, and ArcGIS JavaScript Mapping API) so that applications for stakeholders within collaborative organizations such as SERVIR can be custom-tailored to address a variety of needs and circumstances.

App views, or web pages, use the Django templating language, but the Tethys framework provides a base template that includes a standard layout for app pages with areas for a header, navigation links, action buttons, and primary content rather than requiring developers to start from scratch with each template using Django. This reduces the amount of repetitive coding required for developing web-apps and also leads to a familiar user interface experience.

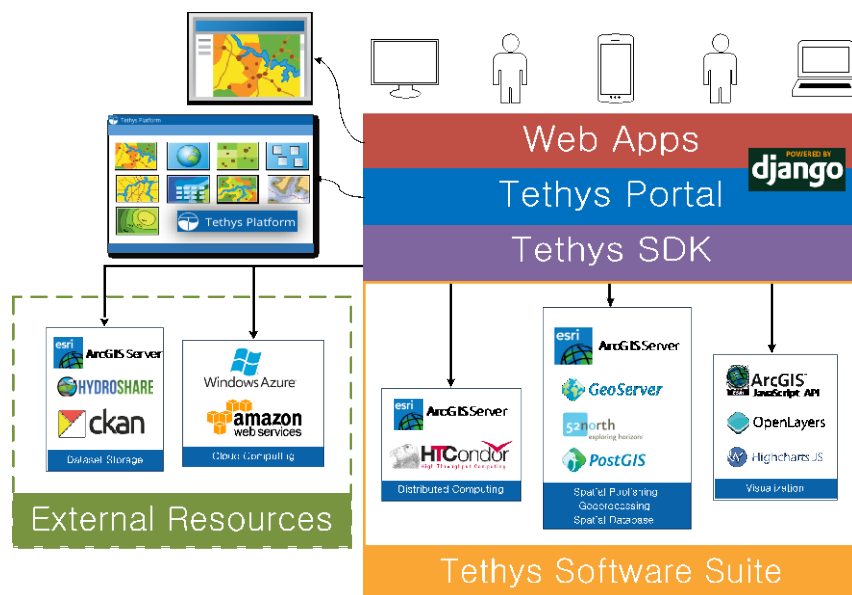


Figure 2.23 Tethys Platform Cloud-based App Architecture for Delivering SERVIR Decision Support Tools

Tethys Portal is the Tethys Platform component that provides the primary runtime environment for Tethys web-apps. It is implemented as a Django website project and it extends Django capabilities to provide the core website functionality that is often taken for granted in modern web-applications. It includes a user account system complete with user profiles and a password reset mechanism for forgotten passwords. It also provides a landing page that presents the associated Tethys Platform instance and an app library page that provides an access point for installed apps. It includes an administrator backend that can be used to manage user accounts, permissions, link to elements of the software suite, and customize the instance. A Tethys portal instance is illustrated in Figure 2.24. The GRACE Groundwater Subsetting Tool is built on Tethys Version 3.0 which relies on Python 3.0 for its scripting on the back-end.

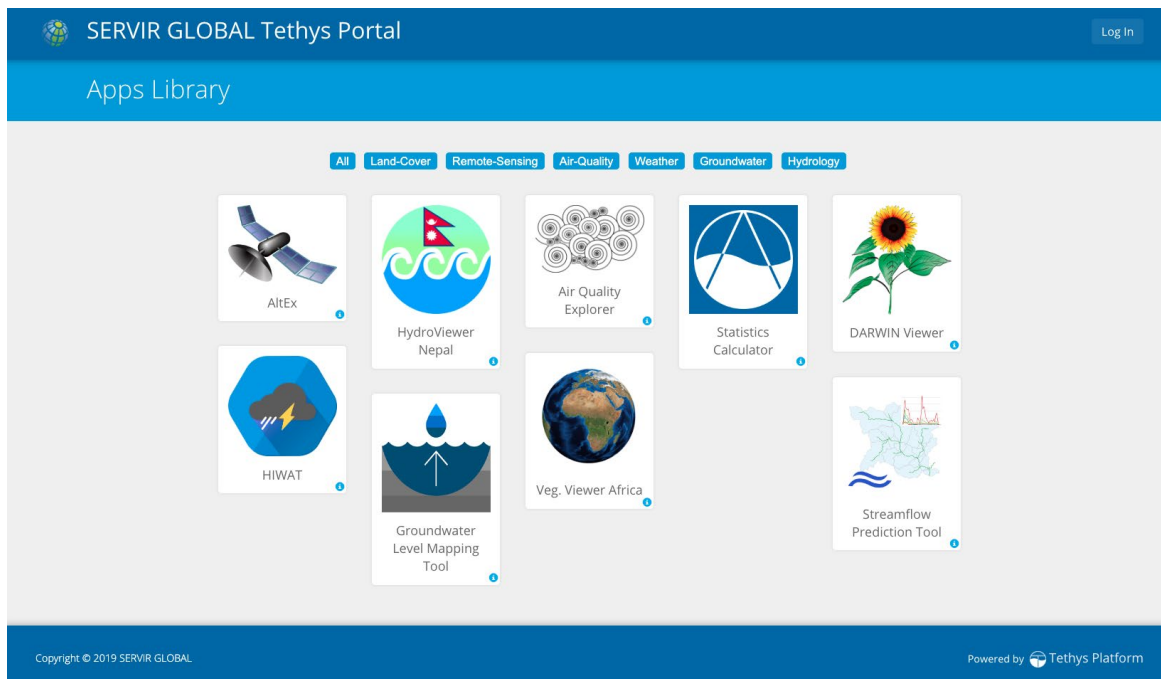


Figure 2.24 SERVIR Global Tethys Portal (SERVIR, 2019)

Two convenient features of Tethys Platform are that it facilitates the process of creating a Postgres database and it offers an easy course for developing a REST API. The Postgres database can be easily created when the application is first installed and runs within a Docker container. Once the app is installed and the database structure is generated the application can easily pass data back and forth between the user interface and the database. Tethys is able to perform a lot of the tedious legwork that is usually required to set up a custom database structure. Tethys also facilitates the creation of a REST API which allows a simply Python function to be called through a URL to facilitate the distribution of data from a particular application to its respective users. Both of these features were critical factors in the decision to develop the GRACE Groundwater Subsetting Tool using the Tethys Platform infrastructure.

2.3.3 Leaflet JS Library and THREDDS Server

In addition to the stack of Tethys tools shown in Figure 2.23, the app also makes use of the Leaflet JavaScript Library (Agafonkin, 2019a) and the THREDDS server software (John Caron & Davis, 2006) for animation of the netCDF files. The Leaflet JavaScript library contains several built-in methods, options, and events that cater well to datasets that span large temporal distributions. It also possesses easy-to-implement animation controls as well as quick methods for switching between layers and time steps (Agafonkin, 2019b). Leaflet has a number of extensions such as the *Leaflet.Draw* extension, which is used for the time series data extraction mentioned previously in section 2.2.2. The user is able to place a point anywhere on the map and generate a time series plot for the layer data in that particular location (Toye, 2020). The *Leaflet.TimeDimension* extension is also used and aids in the application's animation functionality ("Leaflet.TimeDimension," 2019).

As a companion to the Leaflet JavaScript Library, the THREDDS server technology, developed by Unidata (John Caron & Davis, 2006), was chosen as the web mapping service for the netCDF files. THREDDS servers are designed with enhanced capabilities of hosting netCDF datasets on a server and providing access to them through a WMS service (John Caron & Davis, 2006). The original version of the GRACE Groundwater Subsetting Tool used GeoServer to host separate GeoTIFFs for each time GRACE time step. It then reloaded the displayed raster layer and stepped through each GeoTIFF chronologically in order to animate the GRACE data in the map view. After a sufficient period of testing, the performance of the THREDDS server was found to be significantly better than that of GeoServer in terms of displaying and animating raster datasets, and allowed the GRACE data to be stored in netCDF format, eliminating the need to manage the large, and ever growing, number of GeoTIFF images. Having the files in netCDF format is also a benefit since all of the groundwater processing, explained later in section 2.4.1, is performed using netCDF files. The THREDDS server allows the image layers for the different time steps of the netCDF files to be cached on the client, allowing for even faster animation speeds and updating of layers (John Caron & Davis, 2006). THREDDS also allows the user to supply custom palettes, contour lines, and legends to the displayed layers. This makes it easy to provide an esthetically pleasing and informative map interface that even non-technical users could interact with and understand. The THREDDS server is setup using a Docker container and is mounted to a local folder on the host server. This way, processing can be performed on the files locally using Python and NetCDF Operator (NCO) bash commands (C. S. Zender, 2008). THREDDS automatically scans for changes in the files and shows the updated results without requiring a sever restart. THREDDS works seamlessly with the Leaflet JavaScript library.

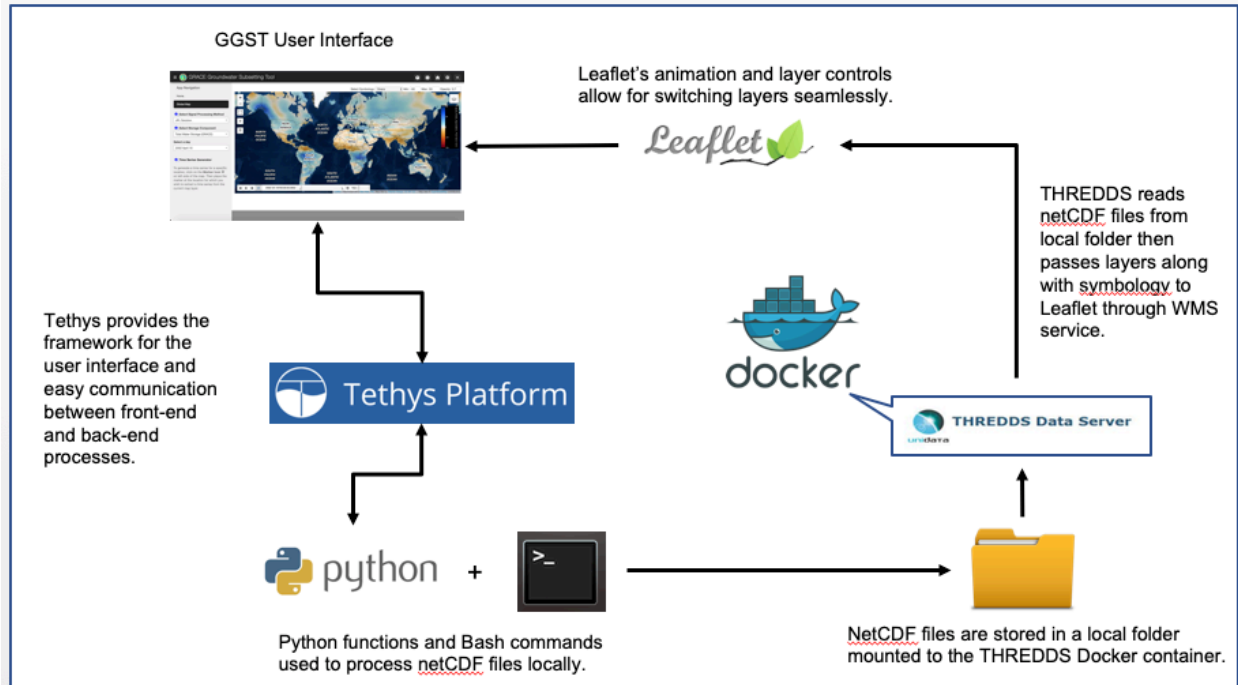


Figure 2.25 Map of the GGST's Infrastructure

2.3.4 HydroShare as Global File Repository

The GRACE global files are stored as a public resource and can be accessed by anyone at *hydroshare.org*. HydroShare is an open-source collaborative system within which hydrologic data and models can be shared online (Tarboton et al., 2012; Tarboton et al., 2014). Unlike some data repositories that are limited to hosting only a few classes of resources, HydroShare is capable of storing a large variety of file types (Horsburgh et al., 2016) and serves as an ideal place to host the global GRACE datasets. The global files contain all of the data from the first GRACE mission. If a user desires to set up a new instance of this application, he or she will need to download the global files from the HydroShare repository located here:

<http://www.hydroshare.org/resource/d6900bc0dd5d47caafa6d1e8a91b676b>. After downloading

the files, the user will simply need to move them to the locally mounted THREDDS folder. Then, once the GRACE Groundwater Subsetting Tool has been properly installed, the automatic update dialog will prompt the user to download all of the appropriate files from the GRACE-FO mission and the application will concatenate the new time steps to the existing global datasets.

2.4 Computational Methods

2.4.1 Calculating Groundwater

To derive the groundwater storage component from the total water storage anomaly that is computed from the raw GRACE data, we use a fairly standard approach where we subtract estimates of surface water and soil moisture simulated by the GLDAS-Noah Land Surface Model (F. Landerer, 2020b; Richey et al., 2015). The GLDAS-Noah model contains a large catalogue of variables. For this workflow, we extracted ten different volumetric variables from the model and divided them into two categories. Storm Runoff, Groundwater Runoff, Snow Melt, Snow Water Equivalent, and Plant Canopy were all considered to be contributors to surface water storage while the Root Zone Soil Moisture and the four Soil Moisture variables, ranging from 0cm – 200cm in depth, were considered to be contributors to the volume of soil moisture storage (Matthew Rodell et al., 2004).

Each time step for the GLDAS-Noah model is provided as its own separate netCDF file and is downloaded using the *wget* library (Nikšić, 1996) and a Python script that only downloads the files that correspond to the time steps of the most recent GRACE total water storage anomaly file. The majority of the processing performed on the netCDF datasets is done using a library of Bash commands developed by (C. S. Zender, 2008) called NetCDF Operator (NCO). Using

various tools in NCO, all of the time steps are concatenated together and the data is consolidated into ten netCDF files: one containing each of the corresponding GRACE time steps for each GLDAS variable mentioned previously. The netCDF files for each of the variables are then summed together resulting in two netCDF datasets: one containing the total volume of surface water at each time step and the other containing the total volume of soil moisture at each time step. A unit conversion is then performed to convert the data from $\text{kg}\cdot\text{m}^2$ to liquid water equivalent thickness in centimeters. The specific commands used for performing these processes can be found in the NCO User Guide (C. Zender, 2016).

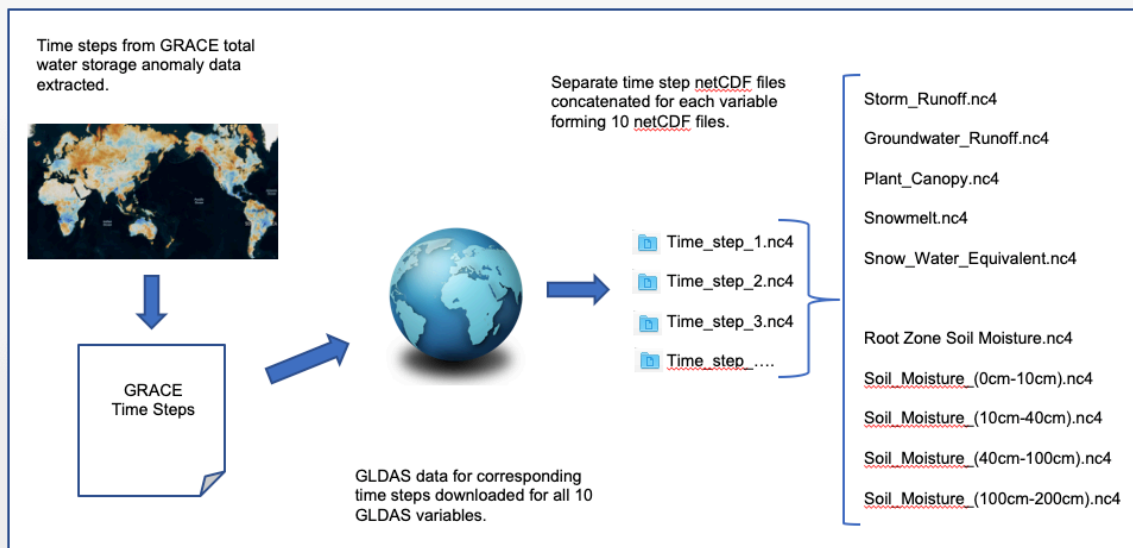


Figure 2.26 Process of Downloading and Concatenating GLDAS Variables

In order to produce the groundwater anomaly dataset, the GLDAS dataset must also be converted to an anomaly format. In the interest of remaining consistent with the GRACE files and to follow the general recommendations by JPL (F. Landerer, 2020b), the mean used to

convert the files to an anomaly format is calculated using the same time frame as the GRACE mean (2004-2009). The netCDF weighted average tool in NCO is used to produce two new single time step netCDF files each containing a grid with the 2004-2009 means for the total surface water and total soil moisture data respectively. NCO's netCDF binary operator tool is then used to subtract the mean grids from each time step of the total surface water and total soil moisture netCDF files. This yields one total surface water storage anomaly netCDF file and one total soil moisture storage anomaly netCDF file.

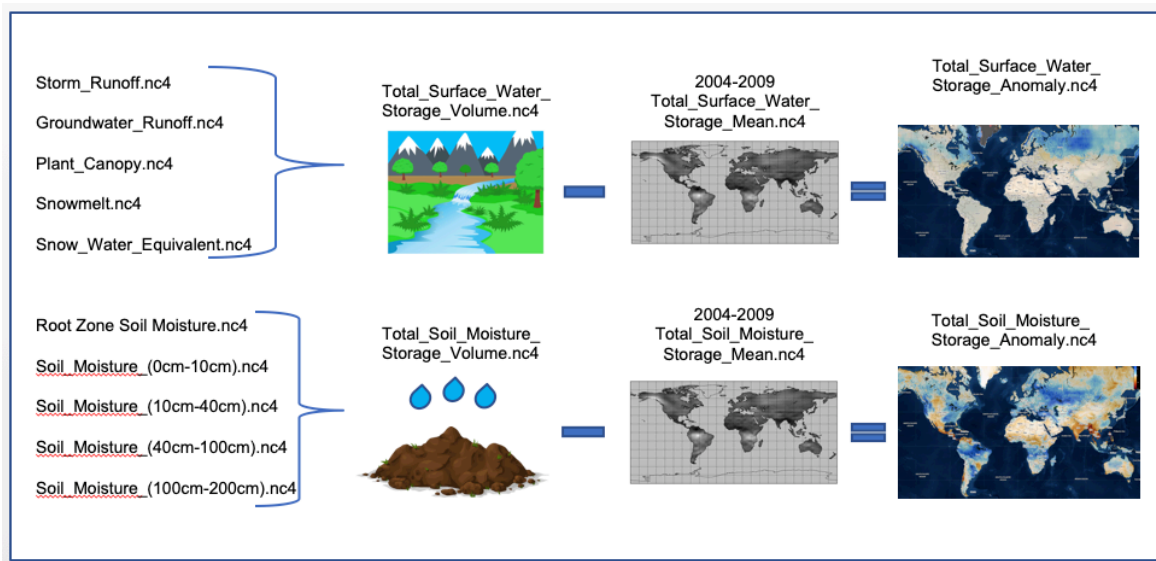


Figure 2.27 Process of Aggregating GLDAS Variable and Converting Files to Anomaly Format

Based on general practices suggested by JPL (F. Landerer, 2020a), the scale factors file provided by JPL must be applied to each of the total water anomaly datasets before subtracting the GLDAS data. The scale factors restore a part of the GRACE signal that was lost during the filtering and smoothing processes and allow the GRACE values to be compared to the GLDAS

data. Using the NetCDF Binary Operator tool in NCO (C. Zender, 2016), the scale factors file is multiplied across every time step of the GRACE total water storage anomaly netCDF file and the necessary signal amplitudes are restored to the file. NCO's ability to broadcast operations across temporal and spatial dimensions makes this process relatively quick and optimal in comparison to other scripting methods (C. S. Zender & Mangalam, 2007). The netCDF file is then re-gridded from its $0.5^\circ \times 0.5^\circ$ resolution to a $0.25^\circ \times 0.25^\circ$ resolution using the *ncremap* tool in NCO so that it matches that of the GLDAS files.

Once the GRACE total water storage anomaly and the GLDAS surface water and soil moisture anomaly files are in the same resolution and are both in anomaly format, the surface water and soil moisture anomaly values are subtracted from the total water storage anomaly dataset. The result is a derived global groundwater anomaly dataset spanning the same temporal distribution as the original GRACE total water storage anomaly files.

2.4.2 Updating Global Datasets with New GRACE-FO Data

One of the challenges with the global GRACE data is the complexity of the process required to extract the groundwater anomaly from the provided total water storage anomaly files. The procedure to calculate the groundwater anomaly requires a number of intricate steps and computation time varies depending on computer hardware. This a process that transpires once a month as new GRACE-FO data is released. In order to decrease the level of technical knowledge required to maintain this web-application, a process to automatically update the global GRACE files is performed. In an effort to simplify the updating process, a basic JavaScript function checks the JPL *podaac* archive for new GRACE-FO files with time steps that are not present in the current GRACE global datasets located on the user's machine or server.

The *wget* library (Nikšić, 1996) is then used to download the files in the archive that need to be added to the local global datasets. A simplified version of the groundwater processing shell script is then run on the newly downloaded GRACE-FO netCDF files to convert them to the proper grid size and generate the surface water, soil moisture, and groundwater storage files for each of the missing time steps. These files are then appended to their respective global netCDF files using the NetCDF Record Concatenator tool, *ncrcat*, within NCO (C. Zender, 2016). The THREDDS server reads these updated files immediately and does not require a restart to display the newly edited global files. This update function does not currently update the regional data. To update regional data, the user would merely have to remove the current region from the database using the manage regions page, and then add the region once again so that the most recent time steps would be included in the subsetting process.

2.4.3 Regional Analysis Subsetting Methods

The regional analysis feature of the GGST offers a unique and valuable perspective on how resources are changing within a particular region. Instead of simply masking the area outside the region from the global dataset, the web-application calculates a regional mean for each time step and displays variations from these regional mean values for each time step. The process includes summing all of the values of the cells that lie within the specified region's bounds, which values are variations from the 2004-2009 mean, and averaging them in order to calculate a new regional mean for each time step. In this way, the mean is transformed from a geographically, grid cell-based mean (one mean value per grid cell applied across all time steps) to a temporal mean (a different mean for each individual time step applied to all of the grid cells within the region). This new set of regional mean values are saved to a one-dimensional netCDF file. This file becomes the regional average time series graph that is displayed when a region is

loaded on the region map page. The new regional mean values are then subtracted from each grid cell for their given time step, generating a dataset that displays the variations from the regional mean dataset. This type of analysis provides additional perspective in discovering how resources are changing in the region and helps account for seasonal variations that occur in water storage. Further applications for the regional average datasets will be addressed in the Case Studies and Results section of this paper.

The original regional analysis processing script was developed in Python by Cedric David, a GRACE scientist at Jet Propulsion Laboratory, and was given the name SHBAAM (David, 2019). David's SHBAAM script subsets the global dataset to include only a regional area and generates a regional average time series. His script was used in the original version of the GRACE Groundwater Subsetting Tool, which only displayed the JPL version of the total water storage anomaly dataset. The first version of the GGST did not include any of the GLDAS or groundwater data layers nor any of the other signal solutions for the total water storage dataset. As more storage types and signal solutions were added to the GRACE Groundwater Subsetting Tool, performance issues related to computation time and server timeout began to surface and it no longer became practical to use the original version of the SHBAAM Python script in the application. David has since upgraded the SHBAAM script to a more robust toolbox capable of calculating the groundwater anomaly dataset and subsetting specified regions (Purdy et al., 2019). However, this toolbox is not used in the current version of the GGST. The current release of the GRACE Groundwater Subsetting Tool uses the NetCDF Operator library (NCO) to execute similar logic that existed in the SHBAAM Python script. Using chained-up Ajax controllers and the *os* Python library, the web-application executes a series of shell scripts containing NCO Bash commands in order to subset each of the global datasets. NCO is able to

efficiently average the cells within the region bounds and subtract the calculated regional mean from the global dataset values (C. S. Zender & Mangalam, 2007). Each shell script is part of its own Ajax call in order to avoid server timeout issues and to provide feedback to the user on the status of the subsetting process. The regional files are then stored in the locally mounted THREDDS folder, and the bounds, area, name, and ID of the region are stored in the application's Dockerized Postgres database.

2.4.4 Time Series Extraction Processes

The process of extracting time series data is done through a Python function using the netCDF4 Python library (Whitaker, 2019). The Python function takes the latitude and longitude as an argument and uses the netCDF4 Python library to open the netCDF file and extract the data for the grid cell at the specified location using a for loop. Within the loop structure, it populates the data extracted from each time step into a JSON object.

In the case of the point time series data, this function is triggered by an Ajax controller once the point is placed on the map. The coordinates are extracted from the point's location automatically and passed into the Python function. The JSON object is then passed back to the user interface and used to populate the time series graph generated by the Highcharts JavaScript library (Hønsi, 2020).

The REST API uses the same Python function but is triggered by the URL containing the arguments for signal solution and storage type as well as the latitude and longitude coordinates of the desired data. The JSON object is then returned as a JSON dump in the user's web browser as shown previously in Figure 2.21.

3 CASE STUDIES AND RESULTS

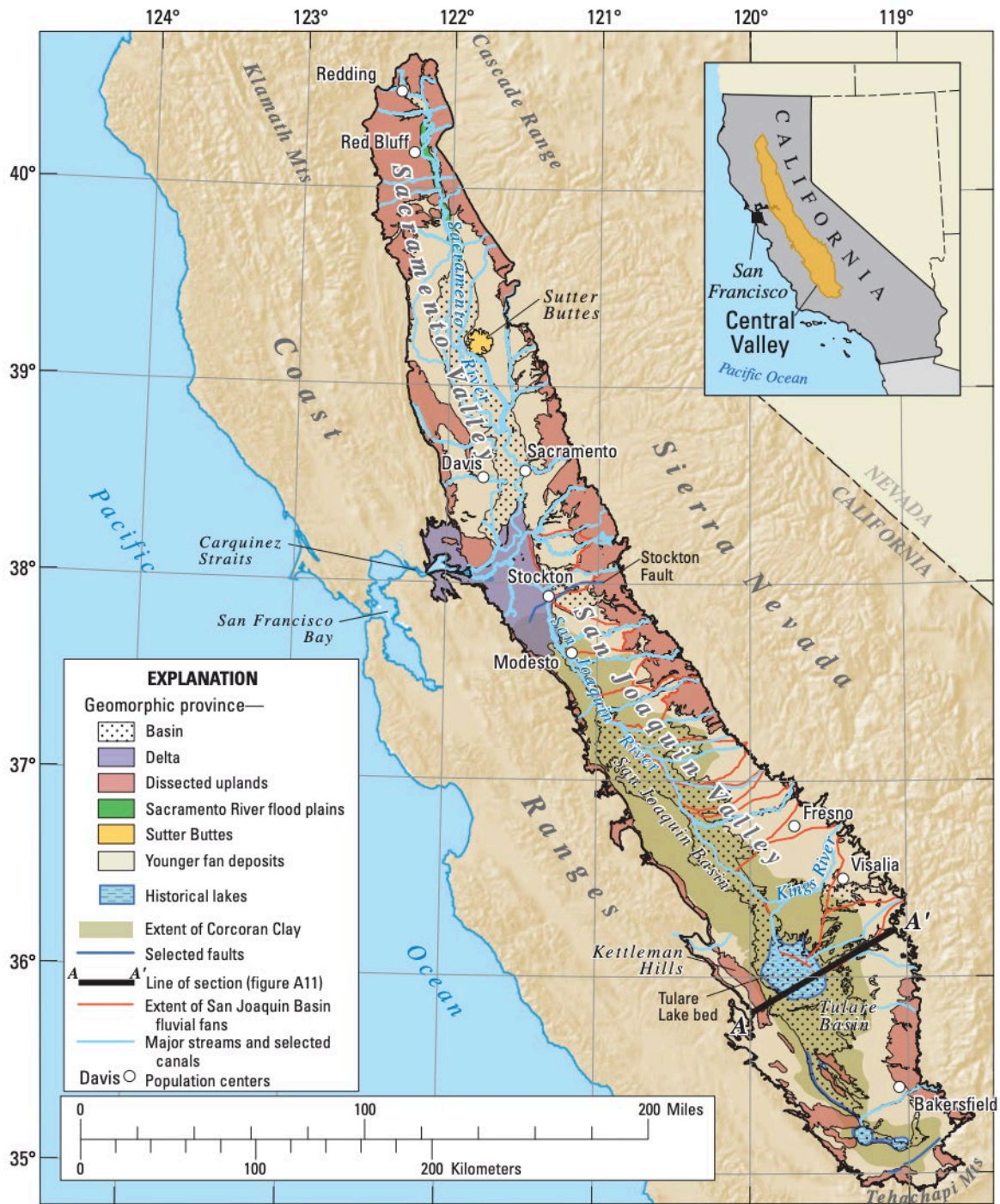
These case studies demonstrate examples of analyses that can be performed using the GRACE Groundwater Subsetting Tool and discuss some of the benefits of applying the features of this web-application. In circumstances where the groundwater data from the GGST is validated against other studies, the corresponding signal solution used by those involved in the comparative study is used in the validation process. In all other instances, the ensemble average signal solution datasets are used to extract all of the time series and map data included in these sections.

3.1 Central Valley California: Analysis on the Aquifer Level

At the end of 2011, California, USA entered some of the driest years ever recorded in the state's history (Richard Seager, 2014). The state's Central Valley area comprising an area of nearly 52,000 square kilometers accounts for 1/6th of the country's irrigated land and grows over 250 different types of crops (Faunt, 2009). The region also accounts for 1/5th of the nation's groundwater demand and is located directly over the second-most pumped aquifer system in the country, the High Plains Aquifer being the most pumped (J. Famiglietti et al., 2011). With the significant lack of precipitation from 2011-2016 and the inability for the state to have large water storage facilities due to earthquake risks, groundwater became the primary freshwater resource for irrigation and consumer use. After the first few years of the drought, it became apparent that

the groundwater resources were being depleted and overdraft was occurring, causing a decrease in the quality and quantity of groundwater storage in central California (Levy & Christian-Smith, 2011).

In years since, the agriculturally rich Central Valley area of California has become a poster child for groundwater depletion as well as a site for study regarding how conservation efforts can improve the management and maintenance of groundwater resources (Hanson, Lockwood, & Schmid, 2014). The drought resulted in a number of new policies including the Sustainable Groundwater Management Act which was passed in September of 2014 (Blomquist, 2016). As one of the first significant pieces of legislation passed in California related to groundwater management, the groundwater management act serves as a starting point for improving the management of groundwater resources in the Central Valley region. However, the effectiveness of this legislation is under scrutiny due to the fact that groundwater extraction rates have yet to decline and storage depletion is still occurring within the Central Valley (Massoud, Purdy, Miro, & Famiglietti, 2018). The legislation relies on local, community level water managers to develop their own sustainable groundwater management plans by 2020 or 2022, delaying the much needed implementation of management policies (Kiparsky, 2016). It is due to the region's history of drought and the variety of stakeholders that were affected by the policy changes, that Central Valley, California made for an ideal case study for the GRACE Groundwater Subsetting Tool.



Shaded relief derived from U.S. Geological Survey National Elevation Dataset, 2006.
Albers Equal Area Conic Projection

Figure 3.1 Map Depicting California's Central Valley Region (Faunt, 2009)

To begin, the California Central Valley region was added to the app interface by uploading a polygon shapefile of the area using the add region page. The region’s bounding area was then subset from the global datasets using the methods described previously in Section 2.4.3. As a result of the subsetting process, the regional average time series depicted below was generated for the Central Valley region.

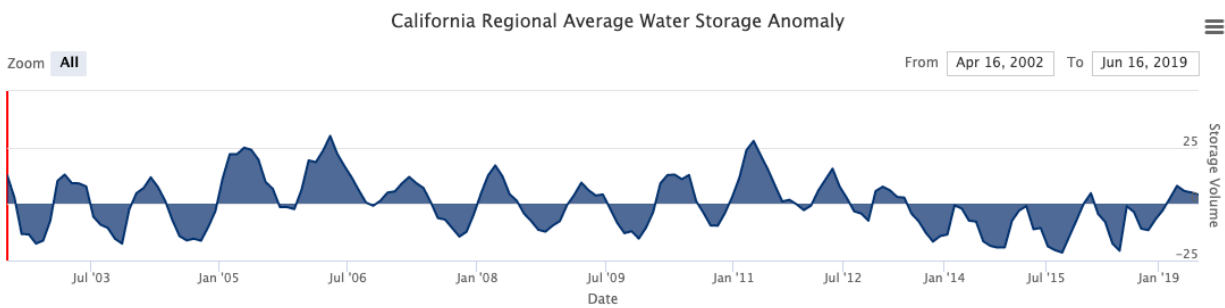


Figure 3.2 Central Valley, California Total Water Storage Anomaly Regional Average Time Series

This particular regional average time series is based on the ensemble average signal solution and displays the total water storage anomaly dataset for the region. The time series depicts a general decline in water storage beginning in the year 2012 and a continuing deficit in water storage through the next several years, with some seasonal fluctuations.

The GGST’s ability to isolate and display the different types of water storage allows for an even more detailed analysis of the water resources in the region. The time series charts generated can be exported in PNG, JPG, CSV, and a number of other formats allowing comparisons to be made between the different storage types. As we look at a particular location near Fresno, California which sits above the San Joaquin basin, the largest basin of the central

valley aquifer system, we can take the drought analysis even further. By breaking down the total water storage into components of surface water, soil moisture, and groundwater, it becomes clear that the decline in groundwater storage from 2012 until now is the most significant of the three components.

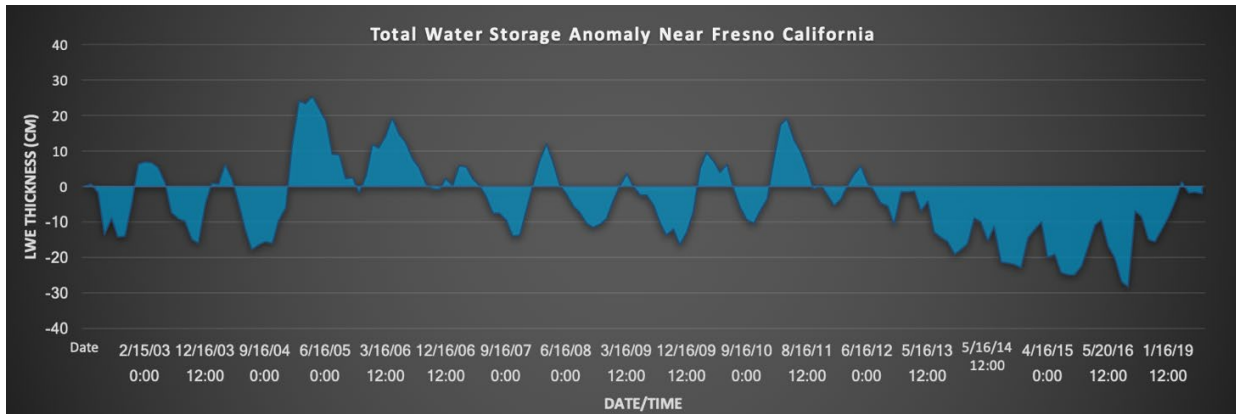


Figure 3.3 Total Water Storage Anomaly Time Series Near Fresno, CA

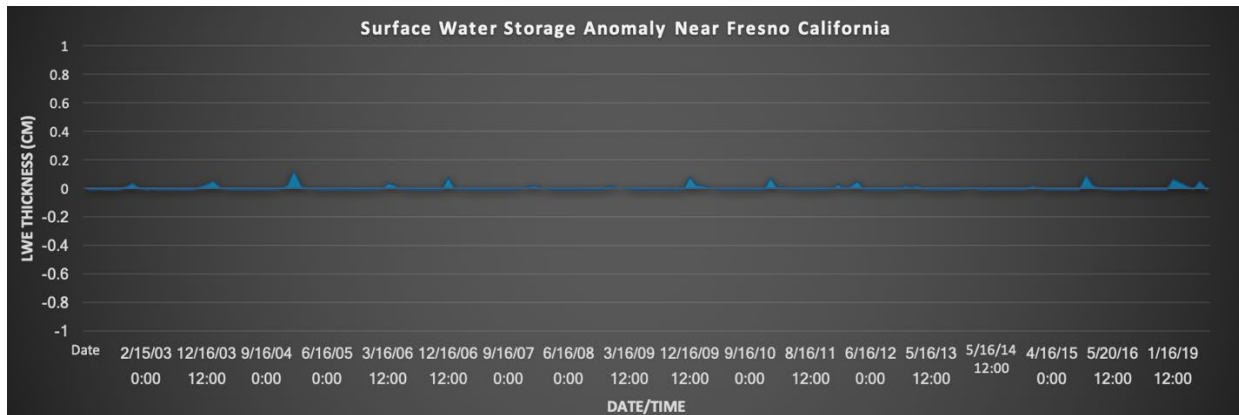


Figure 3.4 Surface Water Storage Anomaly Time Series Near Fresno, CA (Smaller Scale Shown Compared to Other Figures for Fresno).

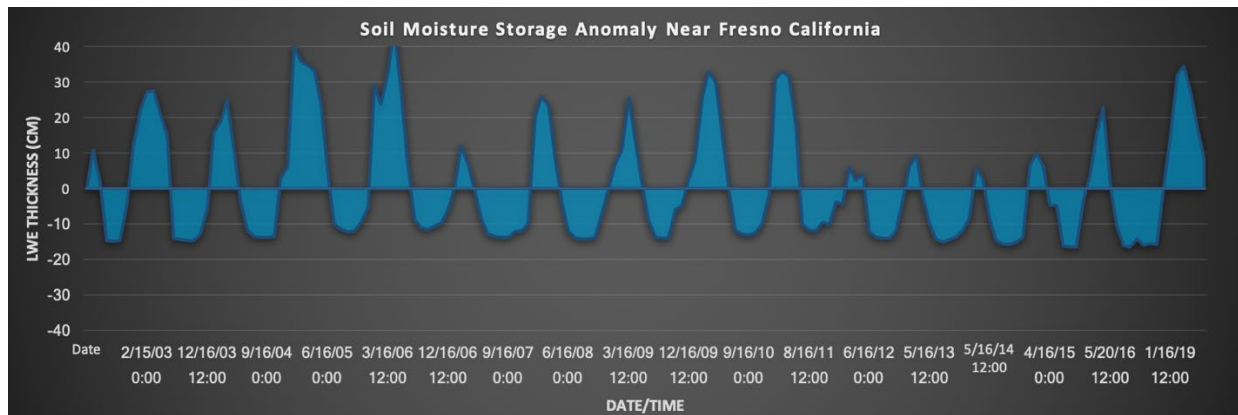


Figure 3.5 Soil Moisture Storage Anomaly Time Series Near Fresno, CA

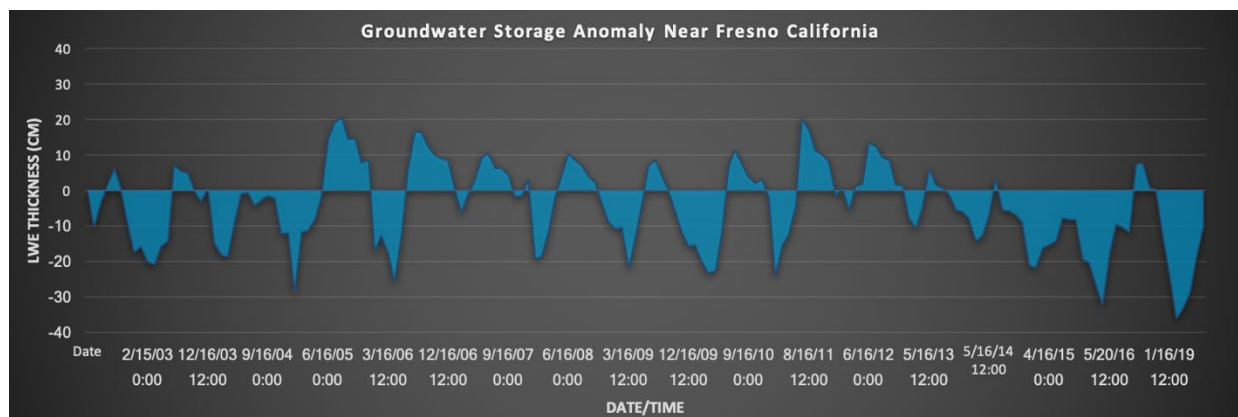


Figure 3.6 Groundwater Storage Anomaly Time Series Near Fresno, CA

In this way, the GGST shows potential to be the means of visually communicating water storage fluctuations to stakeholders who lack a technical background. By providing the ability to export this data in a chart format, decision makers, engineers, and local water users can actually see how their personal choices and current local policy are affecting the water supply.

In a separate study of California's Central Valley involving GRACE derived groundwater data (J. Famiglietti et al., 2011), it was estimated that the Central Valley was losing on average $-2.04 \text{ cm} \pm 0.39 \text{ cm}$ of groundwater per year. The GGST datasets showed a loss per year average between -1 cm yr^{-1} and -3 cm yr^{-1} depending on the signal solution used. A similar study estimated that during the 2012-2016 drought, Central Valley experienced a loss of around -11.2 km^3 per year (M. Xiao et al., 2017). The GGST groundwater dataset estimated a loss of -12.4 km^3 per year. In both of these cases, the groundwater anomaly dataset calculated by the GGST is within 1 cm of the other methods. The total water storage anomaly GRACE datasets have a minimum uncertainty of $\pm 1.5 \text{ cm}$ (Jiang et al., 2014). This groundwater dataset has even higher levels uncertainty due to propagating errors from the GRACE total water storage and GLDAS model components (J. Famiglietti et al., 2011). With the GGST's groundwater anomaly dataset being within this range of uncertainty, these studies serve as a good "gut check" validation for the use of this dataset.

Each of the above-mentioned studies used a far more complex method for extracting the groundwater data that involved custom filtering and smoothing as well as comparison with multiple land surface models and measured rainfall and reservoir data. This shows that because of the levels of uncertainty that exist, even a more simplified approach to calculating the groundwater anomaly dataset still yields results that are accurate enough to monitor long term drought trends.

One possible application of this data is to help verify the effectiveness of groundwater management policies. When trying to determine the effectiveness of any policy change or water management initiative, all possible factors that could contribute to changes in water storage should be considered. However, if a proper and thorough analysis is conducted, the time series

feature of the GRACE Groundwater Subsetting Tool could potentially be used to monitor the impact that policy changes have over extended periods of time particularly for areas that lack sufficient *in situ* data.

It is reasonable to recognize that in more developed parts of the world monitoring wells remain one of the most effective methods for observing changes in groundwater storage. However, even in such situations the GRACE data can be useful as a second form of validation. It can also be used to help calibrate regional groundwater models in order to improve the projected storage volumes of aquifer systems (A. Y. Sun, Green, Swenson, & Rodell, 2012). The app's REST API allows the user to painlessly extract data for particular calibration points and bypasses the need for engineers to download and manipulate the netCDF datasets. This makes the app of particular value at the aquifer analysis level in cases where sufficient well data is available to construct a groundwater model.

For situations like the drought in California, the GRACE Groundwater Subsetting Tool can easily be deployed on a city or state maintained server and the California region can be added to the app along with a few of the larger aquifers in the state if desired. Since the app checks for data updates and automatically downloads new data from the GRACE-FO mission, it eliminates the need for the user to have a knowledge of how to update the global datasets.

3.2 Bangladesh: Analysis on the National Level

Bangladesh is home to just over 160 million people. Like many developing countries Bangladesh is centered around an ever-growing agrarian economy. It is estimated that approximately half of its population relies on agriculture to support its livelihood (Purdy et al., 2019). Bangladesh also experiences some of the most extreme rain events in the world due to

the monsoon season which occurs between June and September each year (Dash, Rafiuddin, Khanam, & Islam, 2012). The country is located at the confluence of the Brahmaputra, Ganges, and Meghna Rivers which form the world's largest delta and introduce large amounts of surface water into the region (Gain, Immerzeel, Sperna Weiland, & Bierkens, 2011; M Shamsudduha & Uddin, 2007). However, due to the intensity of the flows during the monsoon season and the lack thereof during the dry season, Bangladesh relies heavily on groundwater resources for sustaining its agricultural production. This is especially true for an area known as the Rajshahi district located in the northwest region of the country which is home to a more arid climate and is highly susceptible to drought (Aziz et al., 2015; Habiba, Hassan, & Shaw, 2013). In addition to these issues, over pumping of groundwater in parts of the country has led to serious levels of arsenic contamination in the water as well as unsustainable depletion of the groundwater storage (Islam, Chou, Kabir, & Liaw, 2010; Mustafa, Abdollahi, Verbeiren, & Huysmans, 2017). Studies are indicating that the occurrence of groundwater abstraction is depleting the amount of available storage within the aquifer system causing it to experience progressively reduced recharge during the monsoon season each year (Mohammad Shamsudduha, Taylor, Ahmed, & Zahid, 2011).

Bangladesh is home to a network of both shallow and deep aquifer systems that have varying impacts on the environment. Since the northwest region of the country contains unique climatic challenges as well as increased groundwater demands compared to the less arid parts of the country, managing groundwater resources on a national level may not be the most effective as each region of the country may face different challenges in preventing over pumping (Alyssa A. Moir, 2018; Kiparsky, 2016). This can be seen with the GRACE Groundwater Subsetting Tool's various time series features. For example, the groundwater storage regional average time

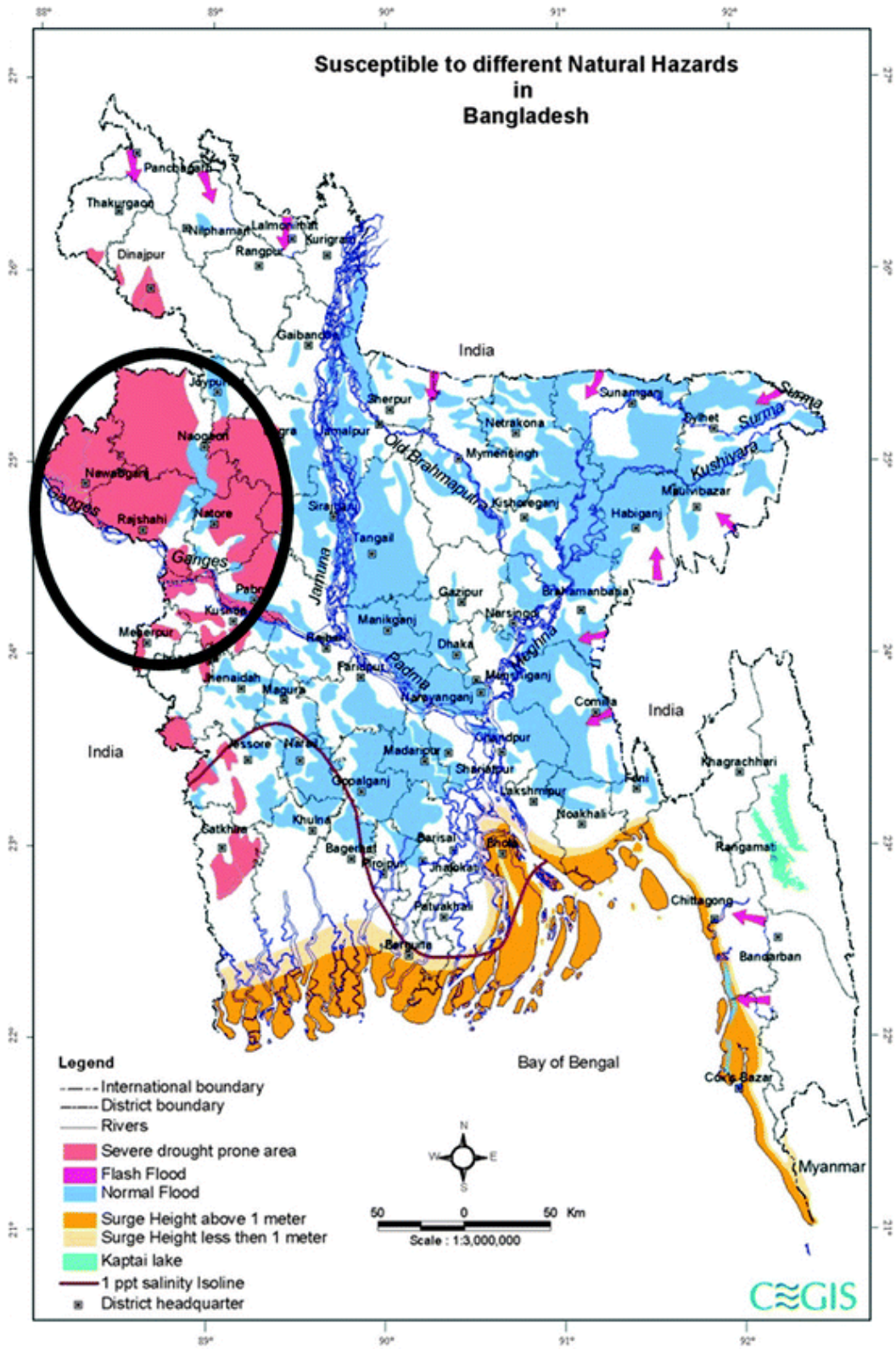


Figure 3.7 Map of Bangladesh and Rajshahi District, Circled in Black (Habiba et al., 2013)

series for Bangladesh as a whole is shown in Figure 3.8 below. Based on this particular time series, the groundwater depletion in the area seems less severe than some other regions observed in this section.

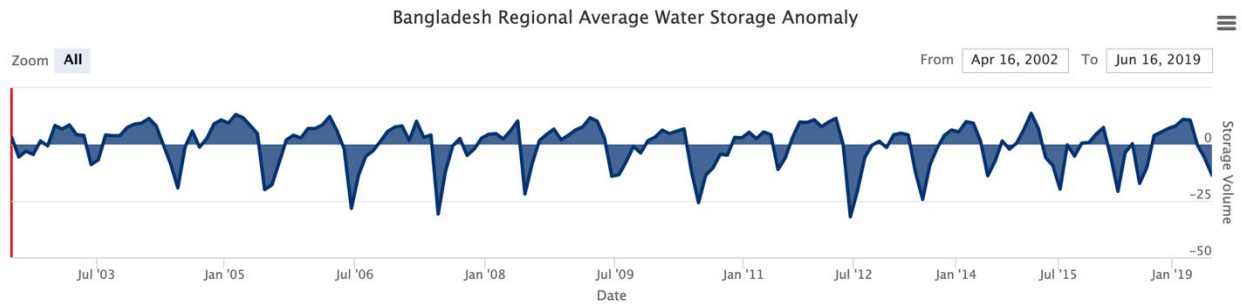


Figure 3.8 Groundwater Storage Anomaly Regional Average Time Series for Bangladesh

The magnitudes of the seasonal fluctuations are quite high but this is to be expected due to the high rainfalls during the monsoon. However, if the point time series is used to extract groundwater anomaly data a location in the Rajshahi district specifically, it yields the results shown in Figure 3.9.

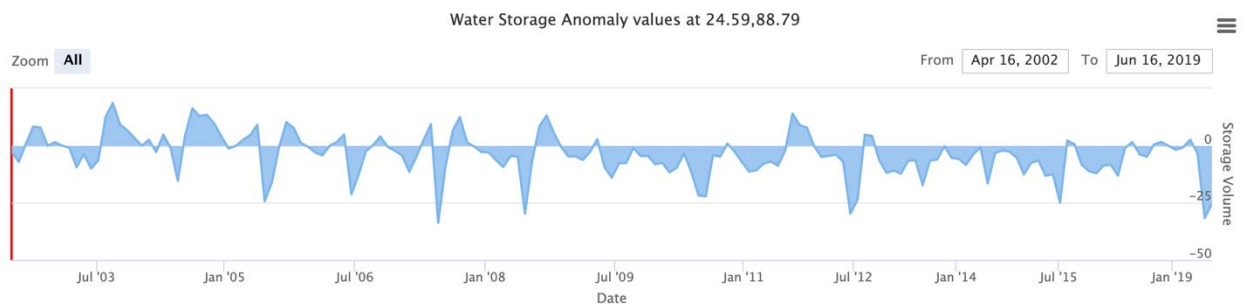


Figure 3.9 Rajshahi District Groundwater Storage Anomaly Time Series Data

Based on well levels in the area (Rahman & Mahbub, 2012), this time series better indicates what in reality is occurring in the more arid, northwestern part of the country. Another GRACE based study in Bangladesh found that the country as a whole had an average groundwater deficit of -0.75 cm per year and the northwest part of the country experienced average losses of -0.88 cm per year (Purdy et al., 2019). The GGST results support these findings with a country wide deficit of -0.91 cm per year and a deficit in the Rajshahi district of -1.0 cm per year. This transmits to -1.34 km^3 and -1.48 km^3 respectively. The country-wide value of -1.34 km^3 is within the reasonable range of *in situ* measurements for storage deficits, between -0.85 and -1.61 km^3 per year (M Shamsudduha, Taylor, & Longuevergne, 2012)

Both the regional average time series and the point time series data can add value to a national analysis. By looking at Bangladesh's resources as a whole and then comparing them to a struggling region, like the Rajshahi district, decision makers can start to examine whether resolutions to the overuse of groundwater should be concentrated around implementing more restrictive public policy, or reallocating existing resources located in other parts of the country. This allows decision makers to analyze the "big picture" status of small aquifers within the country's borders while still monitoring the country's ability to manage its groundwater resources as a whole.

3.3 La Plata River Basin: Analysis on the Multi-International Level

The La Plata River Basin is one of the largest river basins in the world. Its drainage area covers over 3.1 million square kilometers and stretches across five different South American countries. It sits directly south of the Amazon River Basin and is a critical drainage area for

agricultural production and hydroelectric power in south-central South America (J. Chen et al., 2010; Moreira et al., 2019).

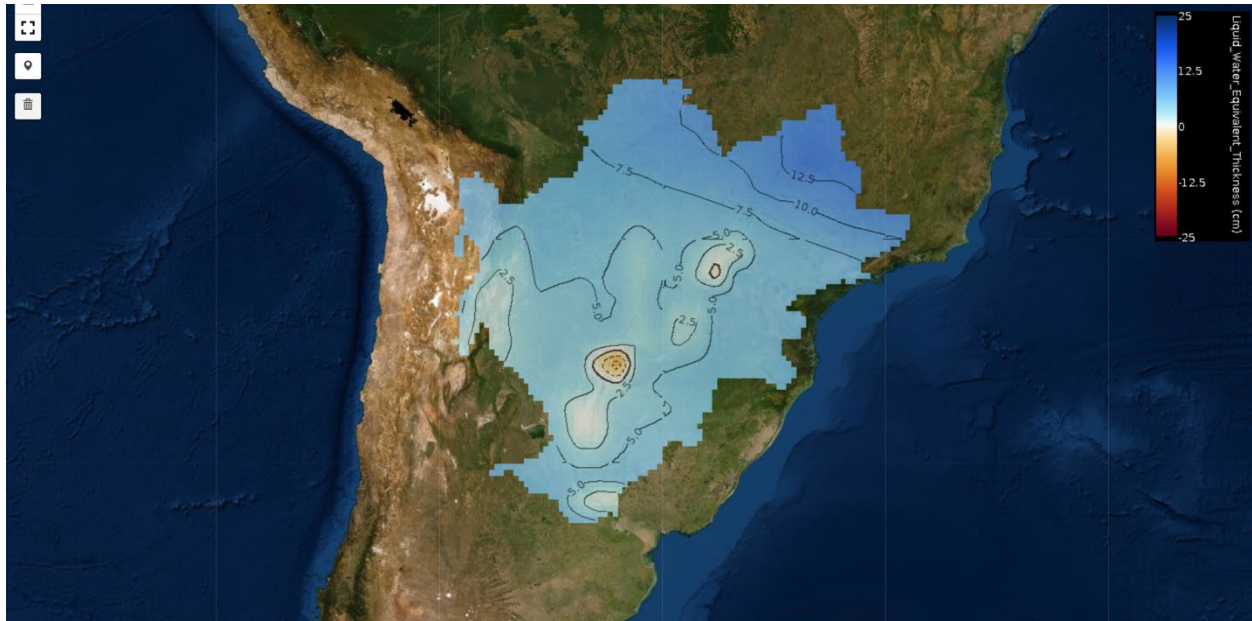


Figure 3.10 Map of GRACE Data for the La Plata River Basin

However, the region has a chronic history of extreme hydrological events and drought, as well as a history of over allocating its water resources in recent years. During 2008 and 2009, the region experienced a significant drought which peaked in the austral fall, roughly March, of 2009 (J. Chen et al., 2010). The impact of this drought on the total water storage of the region can be seen on the regional average time series of the total water storage anomaly generated by the GGST in Figure 3.11. The regional average time series shows the peak of the 2009 drought when typical seasonal runoff fell short of typical trends for the region.

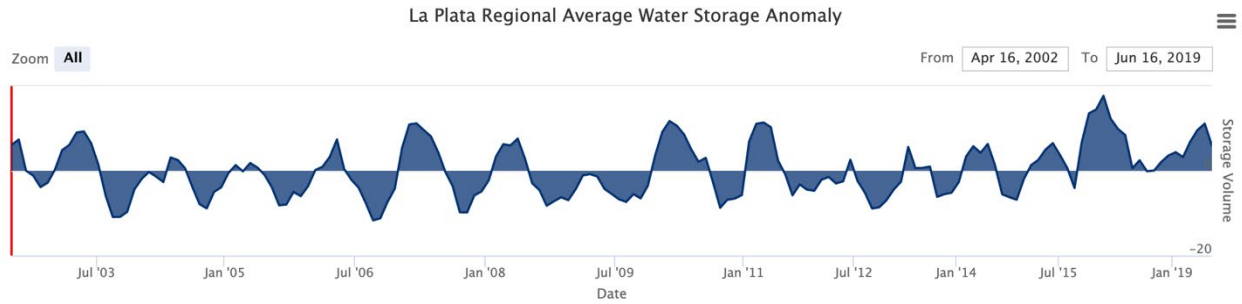


Figure 3.11 Regional Average Time Series for Total Water Storage in La Plata River Basin

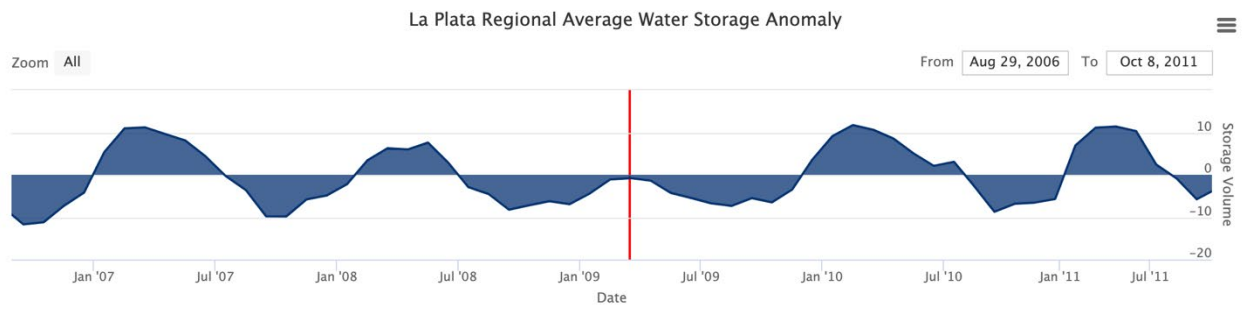


Figure 3.12 Subset of from Regional Average Time Series for Total Water Storage in La Plata Basin (2009 Drought Marked by Red Line).

It is common for groundwater use to increase during times of drought. Looking at the groundwater storage anomaly data for the region offers additional perspective regarding correlations between available groundwater storage and drought trends. Groundwater is often the last type of water source to react to drought conditions (Mendicino & Versace, 2007) which explains why the groundwater trends lag slightly behind the total water storage trends.

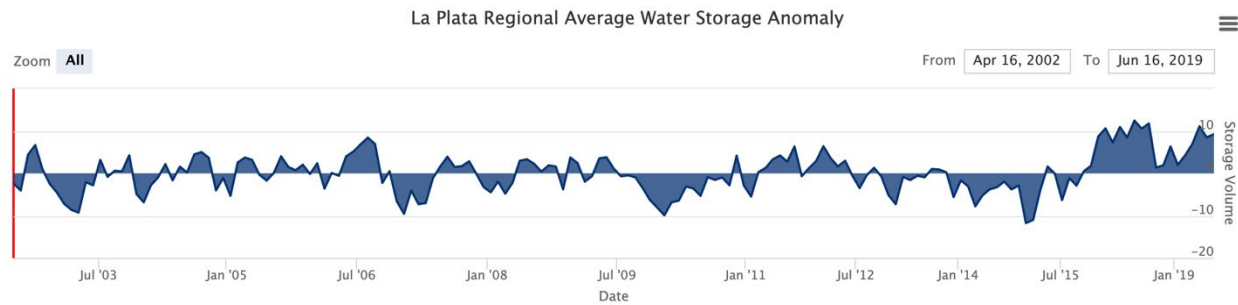


Figure 3.13 La Plata Regional Average Time Series for Groundwater Storage Anomaly Data

The graph in Figure 3.13 shows a steady decline in groundwater storage beginning in June of 2009 with the largest deficit of ~ -10 centimeters being recorded in January of 2010. This is within reasonable range of the values calculated by (J. Chen et al., 2010) who found the average total water storage deficit to be ~ -12 centimeters during the drought's peak for just the southern part of the La Plata basin where the drought was most severe. The peak of the groundwater deficit shown in Figure 3.13 corresponds with the total water storage graph in Figure 3.11 which shows the return of typical seasonal rainfall trends starting in late 2009 and early 2010. This once again demonstrates how the GRACE Groundwater Subsetting Tool can be a means for monitoring groundwater usage during times of drought. It can also help justify the needs for changes in public and international policy. Since no reduction in groundwater depletion was seen until after the seasonal rains had returned, it raises the question, what would have happened if this drought had lasted longer than a year? What long term policies are currently in place to help better manage groundwater resources during events like this? As decision makers have the opportunity to interact with this data, these types of questions will surface and will help developing countries on the path to better groundwater management practices

The La Plata Basin is unique in that it stretches across five different countries. Each of these countries has its own water management practices, its own agricultural demand for water, and its own culture among water users. Since the drainage basin covers such a large geographical area, those dependent on the water storage provided by this basin are often directly impacted by the practices and policies of other water users from different countries who also live within the drainage area. They are also affected by drought conditions that may only be present in upstream regions of the basin but not in their immediate area. This was the case between the years 2011 and 2015 as north-eastern and south-eastern Brazil experienced a prolonged drought that significantly impacted the water supply for the basin (Marengo, Torres, & Alves, 2017; Nobre, Marengo, Seluchi, Cuartas, & Alves, 2016). This dip in the total water storage can be seen more clearly in the anomaly data in Figure 3.14.

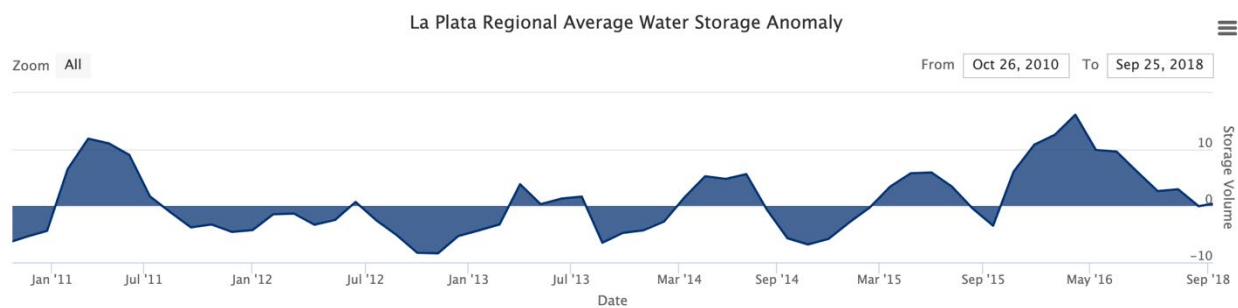


Figure 3.14 Excerpt from Total Water Storage Anomaly Time Series Shown in Figure 3.11

Similar to the drought in 2009, this also resulted in a consistent deficit in groundwater storage, shown in Figure 3.15. This introduces the growing need for international collaboration when it comes to water resource management in general, and especially when it involves groundwater.

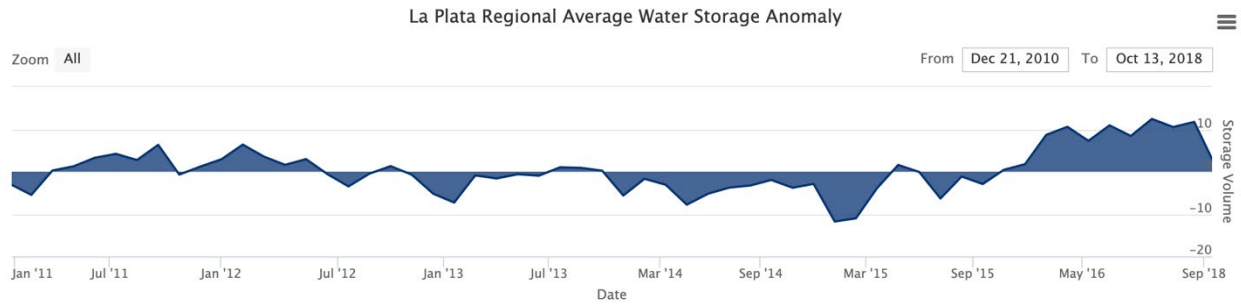


Figure 3.15 Excerpt from Groundwater Anomaly Storage Time Series Shown in Figure 3.13

Many of the world’s larger aquifer systems span across multiple countries (Richey et al., 2015). These aquifer systems are consistently being accessed by water users with different cultural backgrounds and on whom different water management policies, or a lack thereof, are being enforced (J. S. Famiglietti, 2014). Another major road block that water managers face is the lack of desire for neighboring countries to share groundwater data between one another (Purdy et al., 2019). Transparency, particularly in developing parts of the world, is often not the desired policy. Because the GRACE data is publically available, it could change this data hoarding mindset and has the potential to unite water managers and decision makers when it comes to international aquifer systems. Many global organizations are currently trying to improve the management of transboundary aquifers. For example the Association of Hydrogeologists and UNESCO's International Hydrological Programme have developed the Internationally Shared Aquifer Resource Management Programme to help improve the joint international management of shared water resources (Puri & Aureli, 2005). UNESCO’s International Groundwater Resources Assessment Centre focuses almost entirely on transboundary groundwater resources and works to improve the sharing of data, policies, and practices among countries that share common aquifer systems (IGRAC, 2015). The GRACE

Groundwater Subsetting Tool could create new opportunities for global organizations and water managers from different backgrounds to work together on policies aimed at improving the management of geographically large sources of water.

3.4 SERVIR Hindu Kush Himalaya Hub: Analysis on the Global Organization Level

For large, globally focused organizations like SERVIR, the GRACE Groundwater Subsetting Tool has two particular benefits in addition to those outlined in the previous three case studies. One of these benefits is related to the structure around which SERVIR manages its operations. SERVIR has five regional hubs each containing a number of countries with varying degrees of natural resources. From a managerial standpoint, the GGST can be used to compare and contrast the challenges and successes in different regions throughout the world.

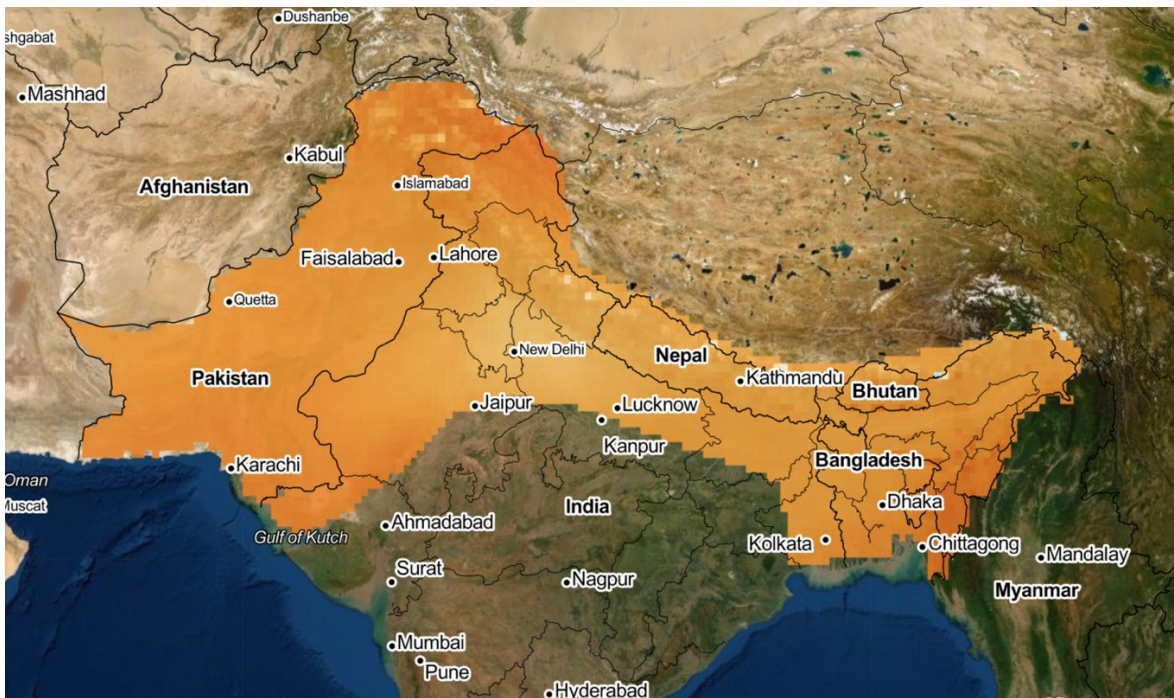


Figure 3.16 Map of Regional Average Groundwater Anomaly for SERVIR's Hindu Kush Himalaya Region

SERVIR's Hindu Kush Himalaya region is composed of the countries of Nepal, Pakistan, and Bangladesh. For the purposes of this case study, portions of northern India were also included in the region bounds due to the location of the transboundary aquifer systems in this region. In this region of the world, groundwater is primarily used for irrigation. This presents an opportunity for the GGST to be used to correlate groundwater usage with growing seasons for the crops produced in different locations and by different countries within the SERVIR Hindu Kush Himalaya region.

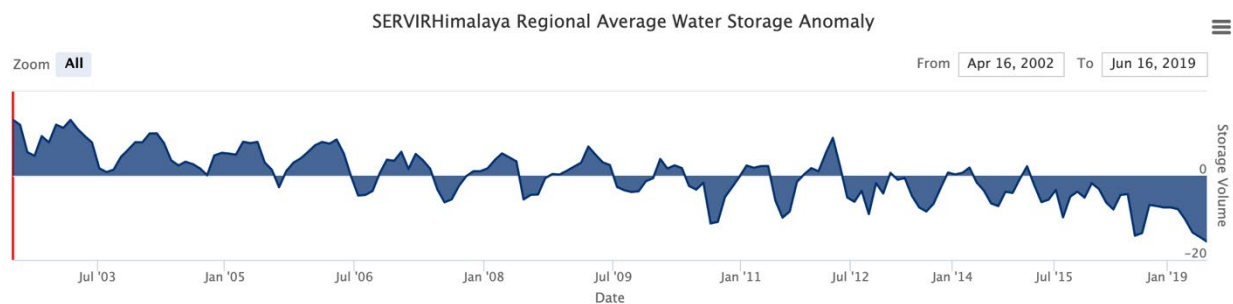


Figure 3.17 Groundwater Anomaly Regional Average Time Series for Hindu Kush Himalaya Region

The transboundary aquifers along India's northern border, shown in Figure 3.18, are accessed by all of the countries in this region. However growing seasons and therefore intensities of water demand for different locations within the region vary depending on the type of crop planted. For example, Bangladesh's peak season for water demand occurs between March and May each year (Mohsenipour, Shahid, Chung, & Wang, 2018).

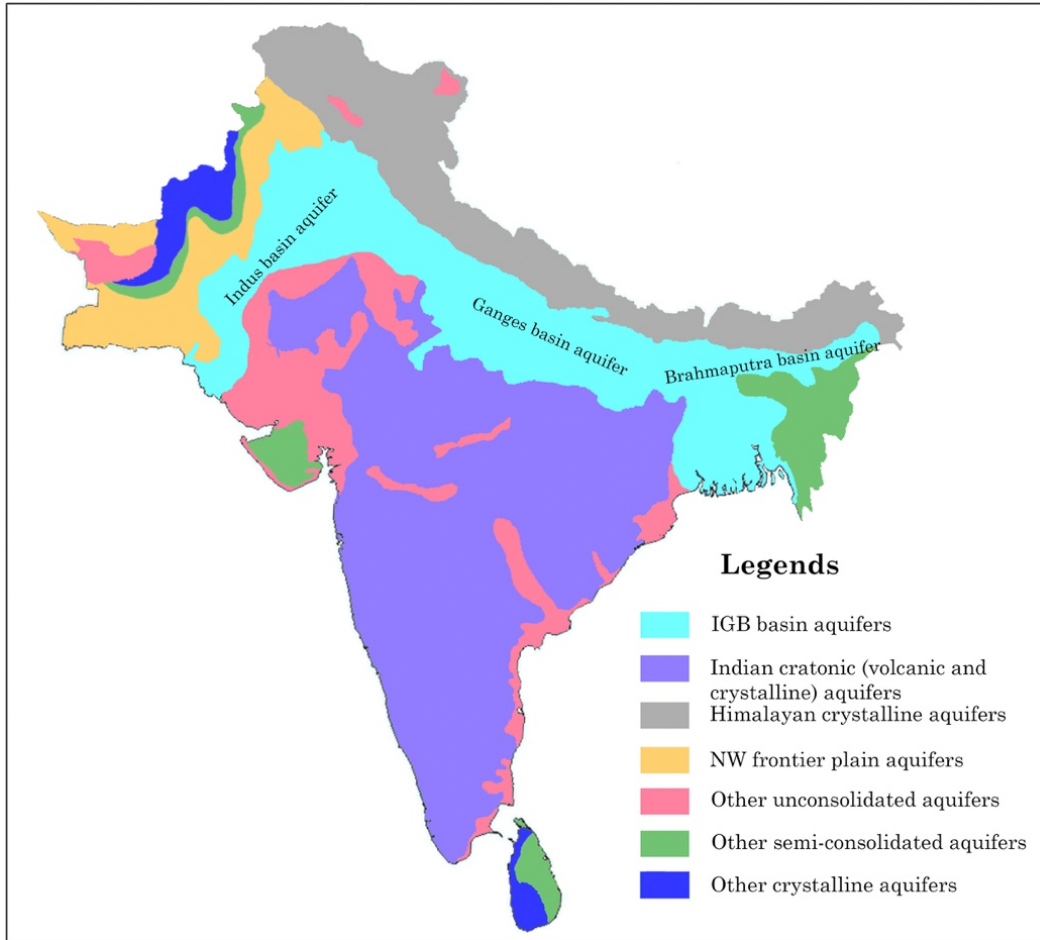


Figure 3.18 Map of Major Transboundary Aquifers Along India's Northern Border

During seasons of peak water demand, groundwater is extracted in larger quantities in order to irrigate farmland. The deficit in groundwater storage in northwestern Bangladesh can be seen on the GRACE Groundwater Subsetting Tool’s global groundwater anomaly map. As further evidence of the correlation, the time period of the peak water demand corresponds with the peak seasonal groundwater deficits in the point time series of the agriculturally focused Rajshahi district in northwestern Bangladesh. The peak deficits in groundwater storage consistently occur between May and June every year, corresponding to the agricultural trends of critical water demand.

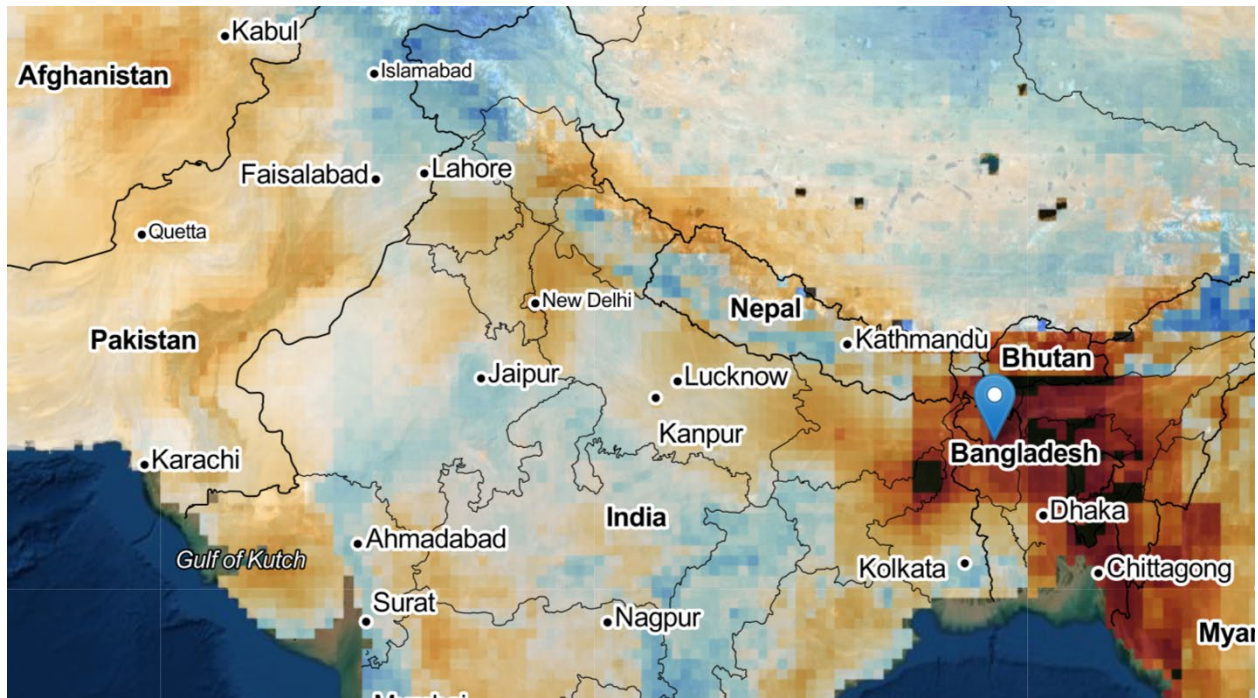


Figure 3.19 Global Groundwater Anomaly Map Shows Deficit in Bangladesh During Season of Peak Water Demand (June 2012)

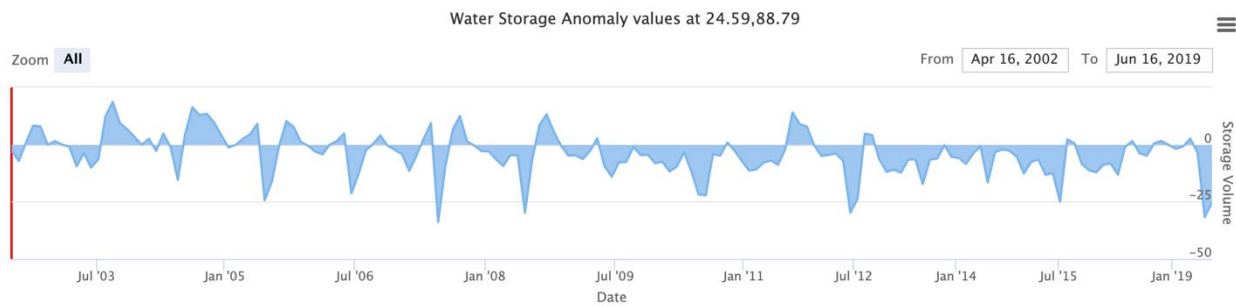


Figure 3.20 Rajshahi District Groundwater Storage Anomaly Time Series Data

However, Figure 3.19 shows that for other areas of the Hindu Kush Himalaya region and even for other parts of northern India, there are far less or no groundwater losses occurring at the time that they are occurring in Bangladesh. This is due to a difference in growing seasons. Rice,

sugarcane and wheat are among the most water intensive crops grown in the region as they are grown solely under irrigation (Shiferaw, Reddy, & Wani, 2008). In the past farming these water-demanding crops came with the risk that drought conditions may cause an insufficient supply of water during the monsoon and the crop yield could be significantly diminished and as a result less profitable. However due to government subsidized electricity costs to encourage agricultural production, groundwater pumping has become much more affordable (Shah et al., 2008). This has made it a reliable resource during times of drought and has encouraged farmers to plant more water intensive crops, increasing the demand for water in the region. For the northern and northwestern areas of India growing these crops, the peak seasonal water demand occurs between June and September (Shiferaw et al., 2008).

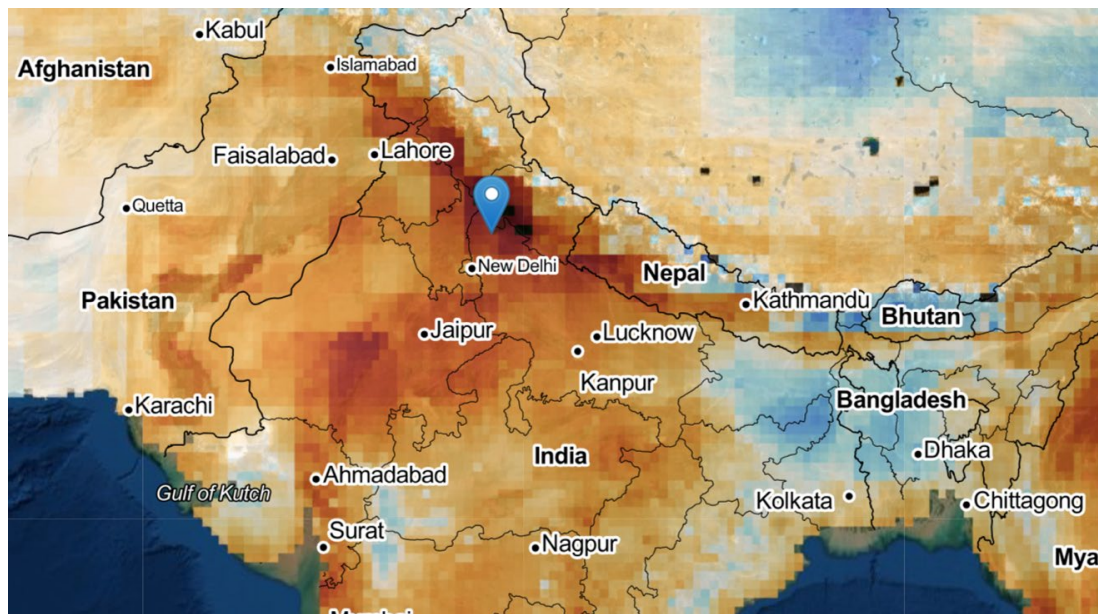


Figure 3.21 Global Groundwater Anomaly Map Shows Deficit in Northern and Western India During Season of Peak Water Demand (September 2012)

In comparison to Figure 3.19 showing Bangladesh experiencing its seasonal peak groundwater deficit due to irrigation demand in June of 2012, Figure 3.21 shows the global groundwater anomaly map just three months later. It is clear that groundwater extraction increases considerably during the irrigation season of water intensive crops. This is confirmed by the point time series graph in Figure 3.22 which has been extracted from an agricultural area just north of New Delhi (Ambast, Tyagi, & Raul, 2006). The time series shows all of the seasonal peak deficit values occur between July and September each year which correspond to the previously mentioned growing seasons.

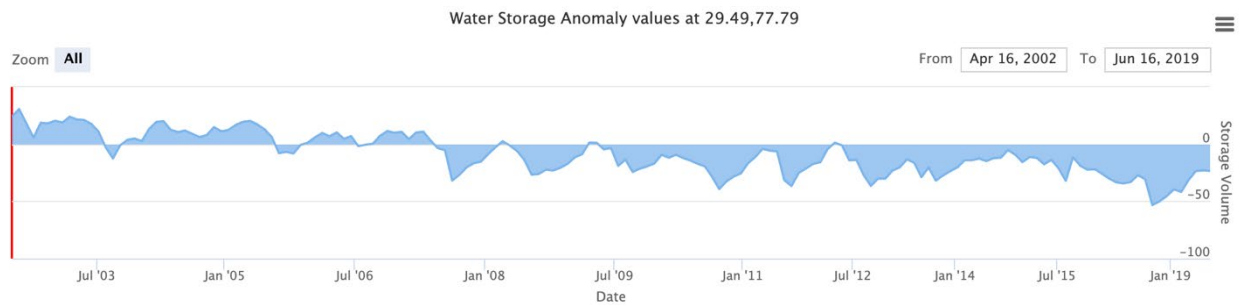


Figure 3.22 Groundwater Anomaly Time Series for Agricultural Area North of New Delhi Along the Ganges Basin Aquifer

This evidence of correlation between different types of crops grown in various countries and their effect on the aquifer system as a whole is of great value to global organizations like SERVIR. The GRACE Groundwater Subsetting Tool provides an easy method for accessing this data so that it can be used to monitor groundwater use in multiple areas during their respective irrigation seasons. Using this tool, water managers in global organizations can perform further analyses to determine where irrigation restrictions need to be put in place based on when the

Hindu Kush Himalaya region's groundwater deficits are at their highest and which growing season those deficits correspond to. Location time series graphs or smaller regional analyses graphs can then be used to monitor impacts that policy changes have on specific areas of the aquifer region.

The drought and groundwater monitoring capabilities of the GGST assist in determining the success or failure implemented policies have on different locations. With data from the GGST as a reference, global organizations can begin to analyze what cultural influences exist in different regions of the world that are impeding sustainable groundwater management and if those obstacles have been overcome in other territories.

The GRACE Groundwater Subsetting Tool can also give decision makers at global organizations like SERVIR an idea of the magnitude of drawdown occurring in different parts of the world. Although magnitude of drawdown should not be the only factor considered when prioritizing improvement efforts, for example magnitude doesn't indicate the amount of storage remaining in an aquifer, this feature can help quantify the drawdown statistic. Decision makers can then take this data into account when they are in the process of selecting regions where the organization's resources should be focused.

A secondary benefit of using the GRACE Groundwater Subsetting Tool at the global organization level, is that its results can help target areas where partnerships and international relationships can be formed and improved. By analyzing multiple complex national systems as contributing pieces to larger multinational regions, areas that would benefit from international collaboration become more apparent as the application helps visualize how depleting resources in one area are affecting the larger region as a whole. With a lot of work being done in establishing policy related to transboundary aquifer management (Puri & Aureli, 2005), this

becomes even more significant as it can help measure the potential impact, or lack of impact, specific international management practices are having on the aquifer.

SERVIR currently hosts its own Tethys Portal at <https://tethys.servirglobal.net/apps/>

The organization maintains the server and many of the applications are designed to be low maintenance. Other global organizations could follow this same pattern and provide access to decision makers in developing countries who don't have the technical knowledge, funds, or infrastructure to host the application on a server themselves. Installing the GGST on a portal like this is one method of deployment that could place the GRACE Groundwater Subsetting Tool and its data in the hands of local decision makers and water users.

4 DISCUSSION AND FUTURE APPLICATIONS

The above case studies highlight the features of the GRACE Groundwater Subsetting Tool and offer ideas for their application among water users, decision makers, engineers, modelers, and leaders of global organizations. One of the primary purposes of this research is to provide a means whereby a diverse demographic of users with different cultural backgrounds, unique skill sets, and varying levels of technical expertise can personally interact with and benefit from the GRACE satellite data. Each of the above-mentioned categories of users play an important role in improving groundwater management practices in all parts of the world. By providing a common tool that can be used by any one of these groups that helps them better understand their role and impact in sustainable groundwater management, this application opens the door to future collaborative efforts between them. As time goes on, the processing of the raw GRACE signal and the total water storage datasets are going to improve in accuracy (W. Sun et al., 2011; Sean Swenson & Wahr, 2006) and the methods for calculating groundwater are sure to become more exact and efficient (Castle et al., 2014; H. Chen, Zhang, Nie, & Guo, 2019; J. Famiglietti et al., 2011; Purdy et al., 2019). The GRACE-FO satellites recently tested a laser ranging system as a potential replacement for the microwave emitter measuring devices in the next generation of GRACE satellites. The prototype laser system yielded results that were at least 10 times more accurate than the microwave emitter measurements (Callery, 2020; Wuchenich et al., 2014). This makes the future of GRACE satellite data extremely promising and creates all kinds of

opportunities for more detailed analysis of aquifer systems.

For this reason, it is necessary to establish a stable infrastructure that can house future datasets and introduce that infrastructure to users who can benefit from the GRACE data and subsequently the derived groundwater data. Recent trends in groundwater management practices are advocating for a greater focus on local governance and accountability (Alyssa A. Moir, 2018). In many developing countries, this often requires a cultural change and education at both the decision maker and the water user levels. In a study on participatory modeling, (Von Korff, Daniell, Moellenkamp, Bots, & Bijlsma, 2012) concludes that including stakeholders and policy makers in the water management process can lead to better quality decisions, better acceptance of decisions, and to the development of social capital, or to say a group's ability to network, work together, and resolve conflict. These benefits have the potential to change the culture surrounding poor groundwater management in developing countries. Each region facing issues of groundwater depletion has its own unique challenges making it difficult to provide a blanket solution to the problem (Shah et al., 2008). It will require stakeholders on both the policy making and water user levels to cooperate to improve the management of the world's groundwater resources. The GRACE Groundwater Subsetting Tool has the potential to be the means by which these changes can transpire.

5 CONCLUSIONS

As a review, the objectives of this research were:

- 1) To make all of the GRACE satellite data, and in particular the groundwater data that can be derived from it, accessible to anyone with a web browser no matter the location.
- 2) To provide an interface that requires a low level of technical knowledge to operate and maintain.
- 3) To provide a regional analysis feature that delivers additional value and perspective, beyond the global data, to benefit stakeholders and decision makers in their efforts to manage their local groundwater assets.

The GRACE Groundwater Subsetting Tool provides all three of the total water storage signal solutions distributed by JPL, CSR, and GFZ. It also provides the recommended ensemble average solution as a default for users without a background in GRACE data processing. In addition to the total water storage anomaly data, the GGST also hosts the surface water and soil moisture anomaly datasets derived from the GLDAS-Noah model. Most importantly, it makes a GRACE derived global groundwater anomaly dataset publically available to anyone in the world with a web browser. This groundwater dataset has gone through high-level validation through comparison to previous GRACE based aquifer studies (J. Chen et al., 2010; J. Famiglietti et al., 2011; Purdy et al., 2019) and through correlations with drought trends in various locations.

Publishing these additional datasets outside of the total water storage anomalies is groundbreaking, and not typically seen in other GRACE data visualization tools (Darbeheshti et al., 2013; "GRACE Data Analysis Tool," 2019; "University of Colorado GRACE Analysis Website," 2013). In addition to the datasets themselves, the GGST's methods for delivering the data to users are wide-ranging. Users have the ability to view the data in raster format, in an animation, through time series graphs, and through a custom REST API. These methods allow for applications spanning from presentation graphics to extracting data for calibrating regional groundwater models.

The GRACE Groundwater Subsetting Tool is 100% open-source and can easily be installed on a Linux server. It automatically updates the global data files without users ever having to perform any kind of commands or gain any type of in-depth understanding of programming or GRACE data processing. The user interface is clean, simple, and provides detailed instructions on every page of the application. The tool also performs a complex regional analysis and subsetting process with the only input being a shapefile of the desired region of study. The application is designed to be low maintenance and requires a low level of technical knowledge to use, making it easy for any user to interact with the GRACE satellite data.

Finally, the GGST provides a robust regional analysis feature that allows users to generate regional average time series and storage depletion curves on the aquifer, national, and international levels. It is one of few tools that offers the ability to upload custom, non-rectangular regions to the interface and process the regional average datasets on the fly. With the addition of the surface water, soil moisture, and groundwater datasets, it allows users to view regional mass balances and breakdown the storage components of the region. This regional data, coupled with the point time series tool, makes the application capable of performing comparison

analyses of different locations within a region in order to analyze how one area of the region is impacting the territory as a whole. The case studies of this section outline just a few of the many applications of the regional data generated from the GRACE Groundwater Subsetting Tool.

This tool has the potential to help all types of users interact with this crucial data and feel more responsible for their personal role in the management of groundwater. It contains all of the features necessary to monitor long term groundwater storage trends and their relationship to drought, agriculture, and much more. It's public, open-source nature offers transparency in transboundary aquifer management and encourages the establishment of new international management policies and partnerships. With a considerable amount of effort focused on implementing the application in developing countries, the GRACE Groundwater Subsetting Tool could be the means of improving stakeholder education and involvement and of developing a culture of better groundwater management practices in economically stressed regions throughout the world.

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