Chapter 14
Water Resources

> *With a growing population and a drying climate, Australia - like many rich nations - is running out of water. Solutions are not easy nor cheap ... and may require cities to tap their sewers*
>
> S. Phillips [1]

14.1 Why Monitor Variation in Fresh Water Resources?

Essential for life, fresh water is one of the basic necessities without which human beings cannot live! Some of its uses include:

- Domestic, agricultural (including livestock) and industrial usage.
- Means of transportation.
- Home to various biodiversity, e.g., fish, birds, reptiles, and mammals.
- Recreational areas.
- Basis for ecosystems such as wetlands.

Although much of the Earth is covered by water, most of it is unsuitable for human consumption, since 96% of it is found in the saline oceans. According to the U.N., only 2.5% of the roughly 1.4 billion cubic kilometers of water on Earth is freshwater, and approximately 68.9% of the freshwater is trapped in glacial ice or permanent snow in mountainous regions, the Arctic and Antarctica regions. Roughly 30.8% is groundwater, much of which is inaccessible to humans, and the remainder 0.3% comprise surface waters in lakes and rivers [2]. Of these 0.3% available for human and animal consumption, much is inaccessible due to unreachable underground locations and depths [3].

This scarcity is such that it is estimated that by 2050, about two billion people will be short of water, a potential cause of conflict [4]. So vital are water resources that it is difficult to discuss any monitoring of the environment without it. The importance of water as a resource, therefore, calls for sound environmental conservation measures

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that enhance its protection and management. It is in relation to this that the World Bank, as an emerging priority of its lending, decided to broaden the development focus in its 1993 "Water resource management policy paper" to include the *protection* and *management* of water resources in an environmentally sustainable, socially acceptable, and economically efficient manner [5]. The protection and management of water resources calls for an elaborate and well established monitoring program.

Essential components of a water level monitoring program are presented, e.g., by Taylor and Alley [6] as; *selection of observation wells*, determination of the frequency of water level measurements, implementation of quality assurance, and establishment of effective practices for data reporting. In selecting the observation wells, they state that the decisions made about the number and locations of observation wells are crucial to any water-level data collection program [6]. In regard to locations, GNSS satellites could contribute in generating a fast and accurate survey of well location-based data. These data could then be integrated with other information such as water level in a GIS system to enhance the accessibility of water level data, where the GIS plays the role of depicting the locations of the observed wells relative to pertinent geographic, geologic, or hydrologic features, e.g., [6].

Taylor and Alley [6] present areas where the monitored groundwater levels could be used. Some of these include: determination of the hydraulic properties of aquifers (aquifer tests); mapping of the altitude of the water table or potentiometric surface; monitoring of the changes in groundwater recharge and storage; monitoring of the effects of climatic variability; monitoring of the regional effects of groundwater development; statistical analysis of the water level trends; monitoring of the changes in groundwater flow directions; monitoring of the groundwater and surface water interaction; and numerical (computer) modelling of groundwater flow or contaminant transport.

Information on the spatial and temporal behaviour of terrestrial water storage, therefore, is crucial for the management of local, regional and global water resources [7]. This information will:

- Enhance sustainable utilization of water resources by, e.g., farmers, urban consumers, miners, etc.
- Guide water resource managers and policy makers in the formulation of policies governing its sustainable use, conservation and management. In particular, state water managers are more informed in regulating the utilization of water, e.g., for industrial and irrigation purposes.
- Benefit local environmental monitoring, management policies and practices that ensures a balance between sustainable utilization and environmental conservation and protection. Changes in water availability impacts upon the environment in several ways, e.g., any significant imbalance in its level affects the ecological system by influencing salinity, land subsidence and the vulnerability of wetlands ecosystem among others.
- Benefit various government agencies at various levels (national, provincial, and local) by providing data that enhances and compliments their work. Such agencies include departments of *water*, *agriculture*, *weather forecasting* and *climate* studies, and so forth.

The conservation and management of water is of paramount importance in areas with arid or semiarid climates, which include many parts of Australia, especially in times of severe drought, as experienced in Murray Darling Basin [7]. In 2006, Australia faced its worst drought in a century as seen from daily reports that were emerging in both the local and international media, see also [8]. A more grim picture of the future of the water situation for Australia was to follow from the IPCC [9] report, which stated that Australia's water crisis will worsen in the coming years due to drought! There clearly exists an urgent need to have efficient monitoring technique(s). One such technique that monitors changes in stored water, is the use of GRACE satellites (Sect. 9.3.3), which is demonstrated in the examples to follow.

Timely and precise information on the changes in stored water at smaller (localized) scales of economical values, e.g., urban consumption, agriculture, industries, and mining to within 10–14 days, so far achievable by GRACE satellite through, e.g., the Mass Concentration (Mascon) technique discussed in Awange et al., [10], will enhance sustainable conservation and management of this precious *dwindling* resource.

The availability of techniques that delivers information on the changes in stored water at a more local scale, is the first step towards realizing an efficient water society. Water resource managers are able to make decisions based on timely and accurate knowledge; thereby saving considerable resources that are often spent as a penalty of inefficient decisions based on a lack of information. In the south-western wheat belt of Australia, for example, accurate knowledge of changes in stored water will be beneficial to the sustainable utilization of water, while at the same time realizing the economic contribution of wheat farming to the overall Gross Domestic Product (GDP). A blind focus on the GDP's growth without paying attention to the state of salient contributors such as water stored in aquifers is detrimental, since a fall in the amount of the available water in such areas would definitely mean reduced yields.

Since the entire system of stored water is coupled within the hydrological cycle (Fig. 14.1), hydrologists will be in a position to better understand their local hydrological cycle, thanks to information at localized levels. Hydrologists will also be able to use such information to refine and calibrate local-scale models, e.g., rainfall runoff models [11], for further improvement in their hydrological cycles. This will also contribute to our understanding of the impacts of climate change on regional and global hydrological cycles. For the geodetic community, knowledge of the changes in local stored water is vital for assessing the impact of groundwater on the stability of continuously operating GNSS monuments (e.g., Fig. 5.12 on p. 81), which in turn affects the overall accuracy of geodetic networks (see Sect. 5.5).

Environmental studies also have a chance of greatly benefiting from information about changes in stored water. It is widely acknowledged that stored water (surface and groundwater) plays a key role in sustaining natural biodiversity and the functioning of the environment as a whole. Knowledge of the changes in water level is therefore essential for the very survival of the entire ecosystem, which could be adversely affected by extreme change in stored water. In wetlands, for example, some vegetation and ecosystems have been known to respond to water level fluctuations [12].

Accurate monitoring of changes in stored water at smaller wetland scales will thus help in the preservation and conservation of such wetland ecosystems. Changes in water level also brings with it environmental phenomena such as salinity, compacting of aquifers due to the removal of water causing land subsidence, and changes in the properties of the top 5 cm of soil. Information on changes in stored water thus contributes enormously to the environmental conservation and protection.

14.2 Gravity Field and Changes in Stored Water

In Sect. 5.6.1 we introduced the concept of the *geoid* (Fig. 5.18 on p. 88) as a fundamental physical surface to which all observations are referred to if they depend on *gravity*, and whose shape is influenced by inhomogeneous mass distribution within the interior of the Earth [13, p. 29]. In the discussion that follows, the concept of *gravity field variations* discussed in Sect. 9.3 is related to hydrological processes. Measurements of the time-varying gravity field by LEO satellites, e.g., GRACE discussed in Sect. 9.3.3 are the key to the contribution of GNSS to space monitoring of changes in water levels at basin scales. Such techniques now enable the monitoring of groundwater recharge, which is the most important element in groundwater resources management and could also be applicable to monitoring salinity management measures at the catchment level (see Sect. 16.4.2). For example, in 2009, GRACE satellites showed that north-west of India's aquifers had fallen at a rate of 0.3048 $\mathrm{m\,yr^{-1}}$ (a loss of about 109 $\mathrm{km^3}$ per year) between 2002 and 2008.[1]

14.2.1 Gravity Field Changes and the Hydrological Processes

The hydrological cycle (Fig. 14.1) refers to the pathway of water in nature, as it moves in its different phases through the atmosphere, down over and through land, to the ocean and back to the atmosphere [14]. The associated variations in gravity field are therefore caused, e.g., by

- the redistribution of water in the oceans, including e.g., El Niño and Southern Oscillation (ENSO) events,
- movement of water vapour and other components in the atmosphere,
- seasonal rainfall; snow and subsequent drying and melting,
- groundwater extraction, or
- drying and filling of lakes, rivers, and reservoirs.

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[1] The Economist, September 12th 2009, pp. 27–29: Briefing India's water crisis.

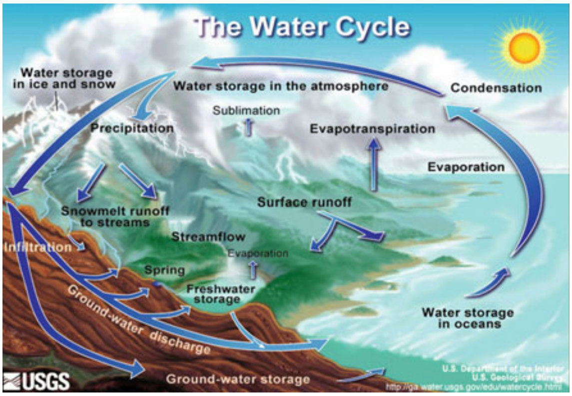

Fig. 14.1 Components of hydrological cycle that lead to temporal variations in the gravity field. *Source* US Geological Survey (USGS)

14.2.2 *Monitoring Variation in Stored Water Using Temporal Gravity Field*

The potential of using the relationship between temporal gravity changes and hydrology (Fig. 14.1) was first recognized by Montgomery [15] who estimated specific yield through a correlation between gravity and water-level changes [16]. In 1977, Lambert and Beaumont [17] used a gravity meter to correlate groundwater fluctuations and temporal changes in the Earth's gravity field. Goodkind [18] recorded observations from seven super conducting gravimetric stations to examine non-tidal variations in gravity and noted that at one of the stations (Geysers geothermal station), much of the variation could be correlated with rainfall and seismic activity. Such measurements had not been possible before the advent of super conducting gravimeters, thus providing evidence of the existence of temporal variation in gravity.

In 1995, while estimating the atmospheric effects on gravity observations around Kyoto, Mukai et al. [19] noted that changes in gravity around the station could have been caused by changes in underground water. In the same year, Pool and Eychaner [20] assessed the utility of temporal gravity-field surveys to directly measure *aquifer-storage* changes and reported gravity changes of around 100–134 μGal, equivalent to 2.4–3.2 m of water column, considering infinitely extended sheet approximation. Their results from the analysis of changes in stored water in the aquifer indicated an increase in the gravity field of 158 ± 6 μGal when the water table rose by about 17.7 m, providing further evidence of the possibility of using temporal gravity-field surveys to monitor changes in stored aquifer water. In fact, according to Bower and Courtier [21] who analyzed the effect of precipitation on gravity and well-levels at a Canadian absolute gravity site, 90% of the gravity variation was found to be due to the effects of precipitation, evapotranspiration and snow-melt.

The last decade has also recorded increased use of temporal gravity field studies in monitoring changes in stored water, see e.g., [22]. It saw the beginning of satellite missions dedicated to monitoring temporal variations in the gravity field. Smith et al. [23] investigated the ability of ground-based gravity meters to monitor changes in soil moisture storage.

Moving from local tests to regional, a different application of gravity surveys was investigated by Damiata and Lee [24], who simulated the gravitational response to aquifer hydraulic testing. The synthetic system was composed of an unconfined shallow aquifer and the purpose of the investigation was to assess the potential of the gravity measurements for detecting groundwater extraction. Drawdown due to pumping causes a decrease in mass and consequently in gravity measured at the surface. The results showed that the gravitational response to aquifer testing could be used to monitor the spatial development of the drawdown cone. For the configuration considered in the investigation, the signal was of the order of tens of μGals and could be detected up to several hundred meters away from the pumping well.

Water storage changes, such as changes in soil moisture, snow and ice cover, surface and groundwater, including deep aquifers, can be monitored either by in-situ observations or indirectly through changes in gravity [25]. While in-situ observations provide valuable localized information, they suffer from limited spatial coverage for regional to continent-wide studies [26]. Any change in water storage also manifests itself in a change in the gravity field. This property can be used to infer water-storage changes from time-variable gravity observations as demonstrated by Rodell and Famiglietti [27] for 20 globally distributed drainage basins of sizes varying from 130,000 to 5,782,000 km^2 to assess the detectability of hydrological signals with respect to temporal and spatial variations. Space-borne techniques can provide time-variable gravity observations on a regional and global scale, thus allowing for large-scale water storage monitoring and the ability to close the 'gaps' between locally limited in-situ observations [11].

Since the launch of the GRACE satellite mission in 2002 (see Sect. 9.3.3), a new powerful tool for studying temporal gravity field changes has become available, and numerous articles assessing the potential of GRACE recovering hydrological signals have been published, see e.g., Awange et al. [28, and the references therein]. Tapley [25] provided early results of the application of the GRACE products for detecting hydrological signals in the Amazon-Orinoco basin. Following these results, numerous other authors have subsequently applied GRACE to detect hydrological signals in various situations and locations, see references in [28].

For instance, Ramillien et al. [29, 30] and Andersen et al. [31] investigated the potential of inferring inter-annual gravity field changes caused by continental water storage changes from GRACE observations between 2002 and 2003, and compared these changes to the output from four global hydrological models. It was possible to correlate large scale hydrologic events with the estimated change in the gravity field for certain areas of the world to an accuracy of 0.4 Gal, corresponding to 9 mm of water, see also [31–33].

Syed et al. [34] examined total basin discharge for the Amazon-Orinoco and Mississippi river basins from GRACE, while Rodell et al. [35] estimated groundwater storage changes in the Mississippi basin. Crowley et al. [36] estimated hydrological signals in the Congo basin, while Schmidt et al. [37] and Swenson et al. [38, 39] used GRACE to observe changes in continental water storage. Winsemius et al. [40]

compared hydrological model outputs for the Zambezi River Basin with estimates derived from GRACE. Monthly storage depths produced by the hydrological model displayed larger amplitudes and were partly out of phase compared to the estimates based on GRACE data. Likely reasons included leakage produced by the spatial filtering used in the GRACE data, and the difficulty to identify the time of satellite overpass as opposed to simply averaging over the whole period. Awange et al. [41, 42] used GRACE to study the fall of Lake Victoria's water level in Africa. This last example will be elaborated upon in more detail in Sect. 14.3.1.2.

As already discussed in Sect. 9.3.3, GRACE satellites detect changes in the Earth's gravity field by measuring changes in the distance between the two satellites at a 0.1 Hz sampling frequency. The variation in the distance between the two twin satellites caused by gravitational variations above, upon, and within the Earth all have an effect on the satellites. This variation in gravity could be due to *rapid* or *slow* changes caused, for example by the redistribution of water in the oceans, the movement of water vapor and other components in the atmosphere, the tidal effect of the Sun and Moon, and the displacement of the material by earthquakes and glacial isostatic adjustment. The data therefore must be processed to isolate these effects so as to retain only those which correspond to the process of interest, in this case, terrestrial water storage changes, see e.g., [43]. Equation (9.33) is used to compute changes in stored water. In the following examples, the application of GRACE satellites to monitor stored water resources are illustrated. It should be emphasized once more that GNSS do not directly measure changes in water storage but contributes as discussed in Sect. 9.3.3.

14.3 Examples of Space Monitoring of Changes in Stored Water

14.3.1 The Nile Basin

The Nile Basin (Fig. 14.2) is one of the Earth's most impressive examples of the influence of topography and climate on the flow conditions of a water system. The Nile has two major tributaries, the White Nile and the Blue Nile, the latter being the source of most of the river's water. The White Nile rises in the Great Lakes region of Eastern Africa, and flows northwards through Uganda and the South Sudan. The Blue Nile starts at Lake Tana in the Ethiopian highlands, flowing into Sudan from the southeast and meets the White Nile at Khartoum in Sudan. From there, the Nile passes through Egypt and ends its journey by flowing into the Mediterranean Sea. A basin as large as the Nile, which crosses such a wide latitude range (from ∼5° S to *ca.* 31° N) cannot be expected to experience homogeneous climatic and rainfall patterns over its extent. In addition, variations in the geology and soils of the basin strongly influence groundwater availability. Significant rainwater deficits and the variable duration of the rainy seasons over yearly to decadal time scales results in hydrological deficits that are not necessarily reflected in a direct response of the base flow, e.g., [44].

The East African lake region includes the countries of Burundi, Rwanda, Uganda, Kenya and Tanzania, and is the home to Lake Victoria, the world's second largest freshwater lake, and the source of White Nile [45]. From Lake Victoria, the waters are discharged to Lake Kyoga, which also receives water from its surrounding 75,000 km^2 catchment before flowing on to Lake Albert. In addition to the waters received from Lake Kyoga, Lake Albert is supplied by its upstream Semiliki basin and the Lake Edward sub-basin (Fig. 14.2). Together, Lakes Edward, Albert, and George form the western edge of the Nile Basin, comprising an area of 48,000 km^2, of which 7,800 km^2 is open water [46]. In the Sudd swamp region, the supply to the Nile benefits from two other basins, the Bahr-El-Ghazal (500,000 km^2) to the west and the Sobat (150,000 km^2) to the east, before exiting at Malakal.

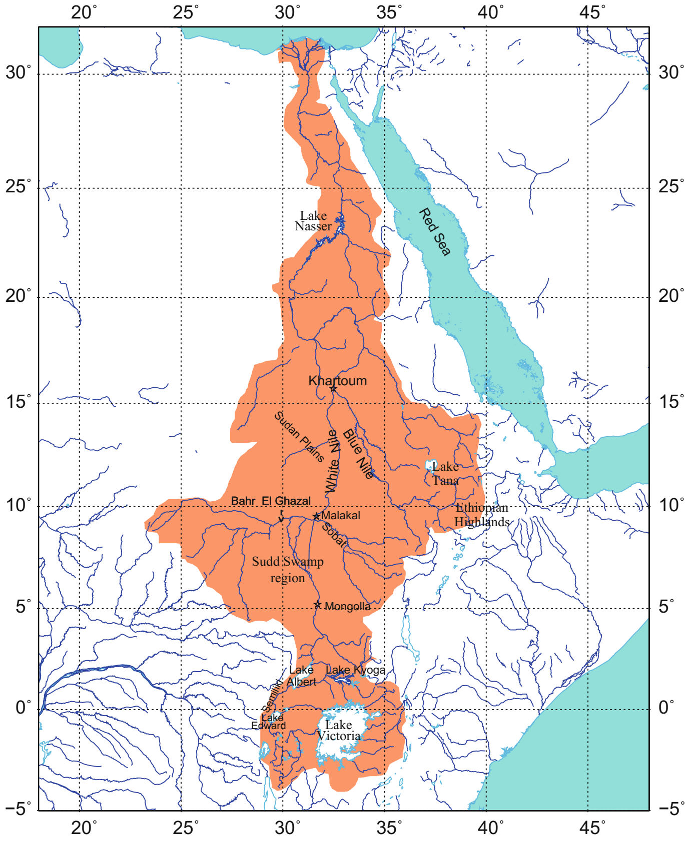

Fig. 14.2 The Nile Basin (*brown shaded* region) with the major features and place names as discussed in the text

The Ethiopian highlands are comprised of twelve significant sub-basins aggregated into four primary basins; Lake Tana (200,000 km^2, the main headwaters of Blue Nile, although it contributes less than 10% of the total Blue Nile flow), the upper Blue (150,000 km^2), the lower Blue (60,000 km^2), and the Dinda-Raghad (70,000 km^2). All together, they cover almost 480,000 km^2 and contribute approximately 65% of the river Nile's total water [46].

Lake Nasser region: The Egyptian desert starts from Khartoum, where the Nile flows northward towards Egypt through Lake Nasser (formed by the Aswan dam) and then to the Mediterranean Sea. Yates and Strzepek [46] reported a net loss of water between the joining of the Atbara river with the Nile north of Khartoum, and Lake Nasser due to evaporation and seepage.

14.3.1.1 Challenges Facing the Basin's Waters

The Nile river basin is one of the largest in the world, with an area of about 3,400,000 km^2 (almost one-tenth of Africa) and traversing some 6,500 km from south to north as it winds its way across the boundaries of eleven countries: Tanzania, Uganda, Kenya, Rwanda, Burundi, Democratic Republic of Congo (DRC), Eritera, Ethiopia, Sudan, South Sudan, and Egypt, e.g., [47]. As it flows through these countries, it supports a livelihoods of over 200 million people.

The Nile's water resources, however, have come under threat from both anthropogenic and natural factors, e.g., [48]. Anthropogenic influences have been fuelled by the increasing human population that has put pressure on domestic water needs, the supply of hydroelectric power, all coupled with the need to sustain economic growth. However, not only are the demands on water increasing, but the available water supplies appear to be decreasing, with environmental degradation of the upper Blue Nile catchment having increased throughout the 1980s [49]. Whittington and McClelland [49] found that about 86% of the annual Nile river flow into Egypt originates from Ethiopia, and warn of significant implications for Egypt and Sudan should Ethiopia undertake any potential extractions; this issue emphasizes the need for cooperation between the three Blue Nile riparian states.

Natural factors include the changing climate, which has been the subject of numerous studies, e.g., [46, and the references therein]. Therefore, a combination of human population growth, unsustainable water usage and development, and desertification are just some of the factors that threaten the Nile's ability to supply crucially needed water to the people of the basin.

The present-day state of the stored water variations and their relations to climate variability (e.g., El Niño and Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD)) in the Nile Basin are, however, also not well understood. Most studies dealing with the Nile Basin, however, have dealt mainly with modelling the impacts of climate change (e.g., [50, 51]), with very little being reported on how to monitor the spatial and temporal variations in the stored water (surface, groundwater and soil moisture) of the basin in a holistic manner, and linking them to climate variability. The reason for such few studies, e.g., [52–55] has been partly attributed to its large size, as well as the lack of appropriate monitoring techniques that could cover such a vast spatial extent. For instance, the hydrological water balance involves the flow of surface water, the movement of deeper groundwater, and the coupling of the land, ocean and atmosphere through evaporation and precipitation. Monitoring these components requires an accuracy and completeness of geographical data coverage that challenges conventional measurement capabilities.

Using GRACE, GLDAS (Global Land Data Assimilation System),[2] and TRMM (Tropical Rainfall Measuring Mission)[3] data for the period 2002–2011, Independent Component Analysis ICA-method, e.g., [56], is applied in the examples below to localize the Nile Basin's hydrological signals into their respective sources. In Fig. 14.3, it is seen that the dominant signal associated with the Lake Victoria Basin is localized for all the three data set. This clearly shows the contribution of the Lake Victoria basin to the Nile waters. An analysis of the correlation between these signals and climate variability indicate a strong correlation (0.85) between the GRACE's total water storage and ENSO for the period 2006–2011. This confirms the known fact that climate variability, particularly ENSO, influences the changes in stored water of Lake Victoria Basin, and should be taken into consideration in evaluating the basin's hydrology. Section 14.3.1.2 discusses Lake Victoria Basin in more detail.

Figure 14.4 shows the localization of the signals within the Ethiopian highlands, thus indicating the importance of the region to the Nile basin. The Blue Nile receives its waters mainly from the heavy rainfall in the region as seen from the TRMM results (Fig. 14.4; IC5). Any land use patterns that could alter the use of water within the region would be capable of significantly impacting upon the entire Nile Basin. GRACE signals show a correlation of 0.52 with ENSO while GLDAS show 0.44 with ENSO and 0.4 with the Indian Ocean Dipole (IOD) index. Compared to Lake Victoria basin, the correlation to climate variability is not so strong, nonetheless, the fact that the changes in the stored water in the Ethiopian highlands is influenced by climate variability is noticeable. Figure 14.5 shows the localization of the signals within the Bahr-El-Ghazal region, which also contributes water to the River Nile by joining the tributaries from Sobat around Malakal (see Fig. 14.2). Both GRACE and GLDAS signals show a correlation of 0.68 with ENSO respectively, thus indicating that the variability of the stored water is influenced by climate variability. Finally, Fig. 14.6 shows the dynamics around Lake Nasser along the Red Sea. After removing this signal, Awange et al., [52] found a decline in stored water in the Western Plateau within the Nubian Aquifer covering Lake Nasser (see Fig. 14.7) at a rate of 2.6 mm/year (cf. 3.5 mm/year in Sultan et al., [57]). The loss of water in this region is attributed by Sultan et al. [57] to the fact that most of the water is extracted from the Nubian Aquifer and used for agricultural purposes that largely occur throughout the winter season, and also due to the fact that the UweinatAswan uplift prevents recharge of ground water flowing from the South to the North. To strengthen this argument is the fact that expansions of some large irrigation schemes such as East Uweinat project has seen heavy utilization of groundwater. In the East Uweinat project, for

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[2] http://disc.sci.gsfc.nasa.gov/services/grads-gds/gldas.

[3] http://trmm.gsfc.nasa.gov/data_dir/data.html.

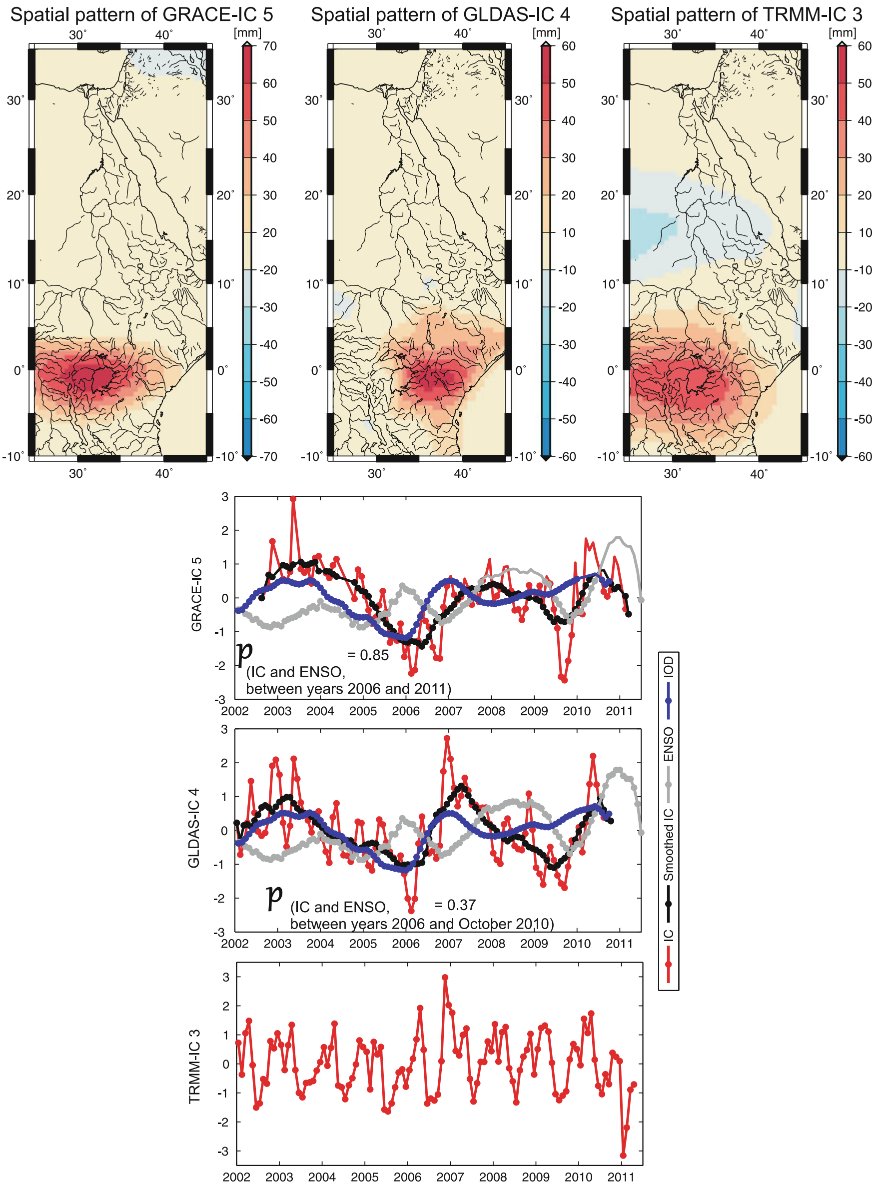


Fig. 14.3 ICA analysis of the GRACE, GLDAS, and TRMM data for the Nile basin. In this figure the signals are localized within Lake Victoria basin in all the data set

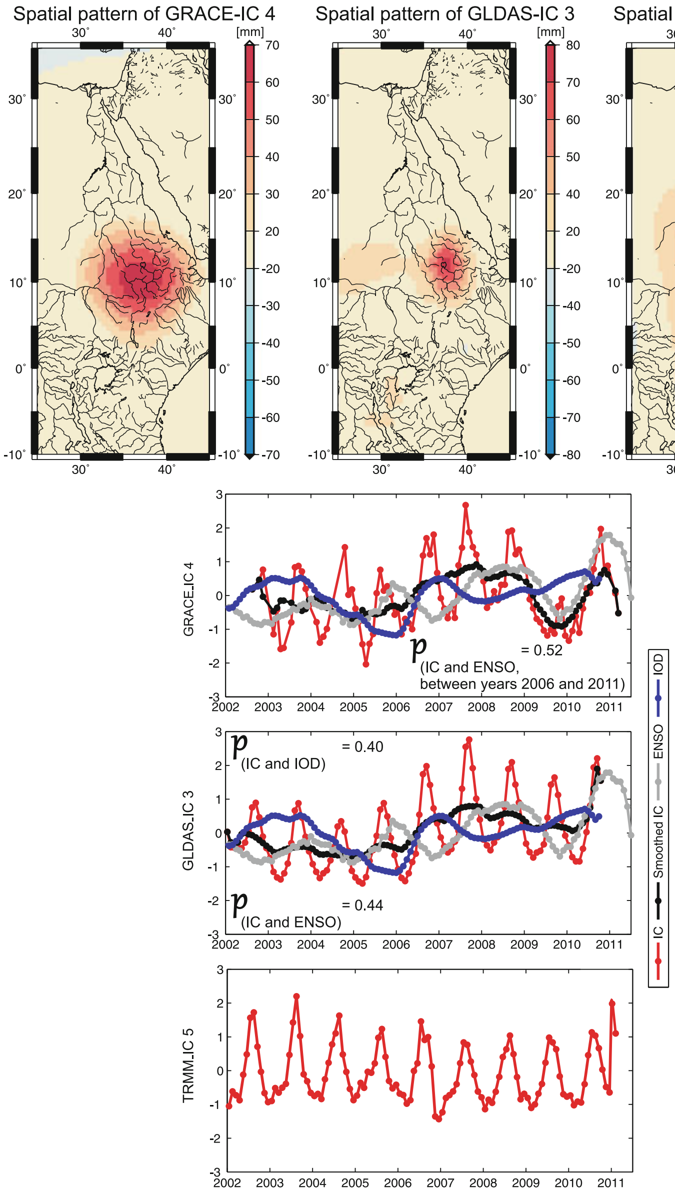


Fig. 14.4 ICA analysis of the GRACE, GLDAS, and TRMM data for the Nile basin. In this figure the signals are localized within the Ethiopian highlands in all the data set

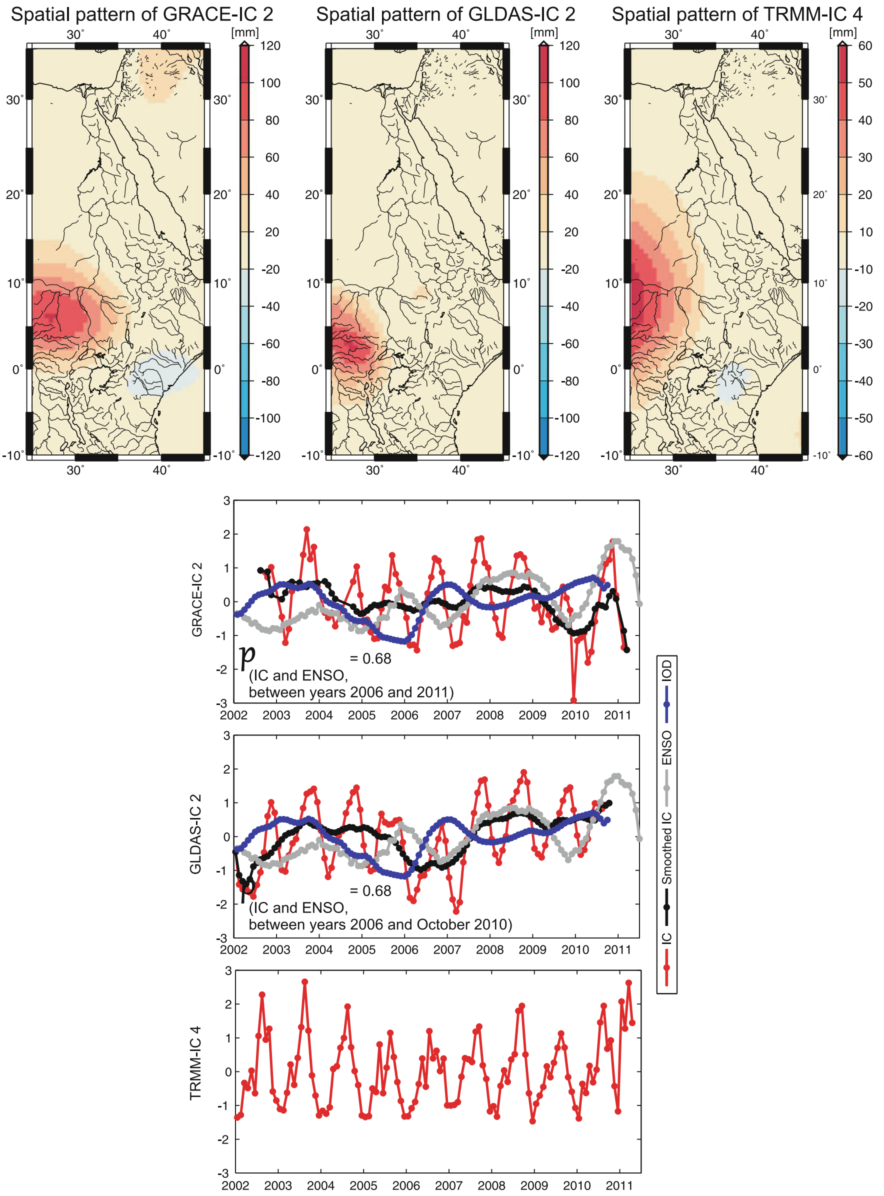


Fig. 14.5 ICA analysis of the GRACE, GLDAS, and TRMM data for the Nile basin. In this figure the signals are localized within the Bahr-el-Ghazal region in all the data set

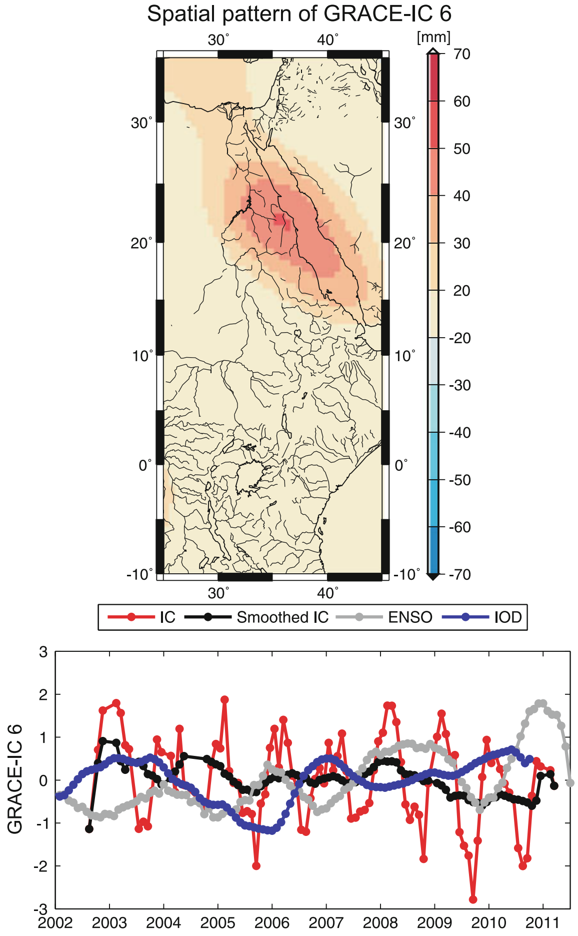


Fig. 14.6 ICA analysis of the GRACE, GLDAS, and TRMM data for the Nile basin. In this figure the signals are localized within the Lake Nasser region in GRACE data set

example, the lands reclaimed amounted to 1200 ha in 1992 and 4200 ha in 2003, with the target of reclaiming a total of 75,000 ha by 2022, all of which will be irrigated using groundwater, [58, 59].

Positive correlations between the changes in total water storages and IOD corresponding to cool waters in the Indian Ocean associated with large scale circulation changes that leads to above average rainfall in East Africa leading to flooding, while Indonesia and several parts of Australia experience drought have been documented e.g., [60, 61]. This is true for the Lake Victoria Basin, the Ethiopian highlands and the Bar-El-Ghazal regions which are also related to ENSO. For the Lake Nasser region, the effect of climate variability is negligible. For the definitions and measured indices of ENSO and IOD, see Sect. 17.6.4.

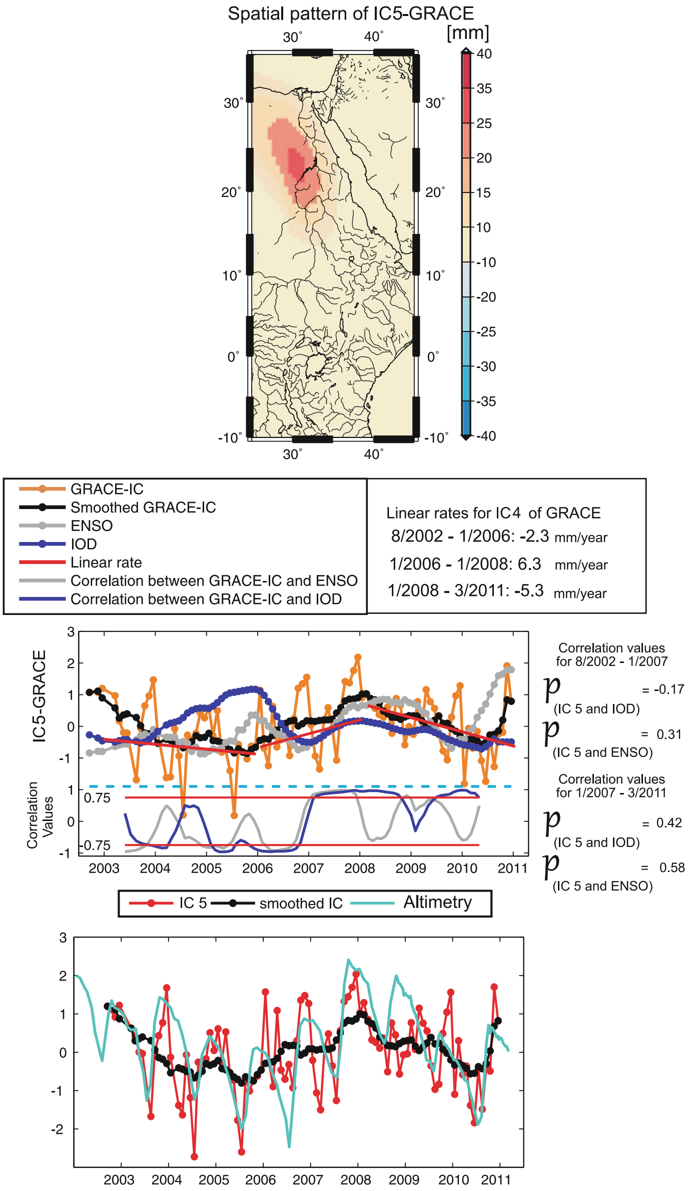


Fig. 14.7 Dominant independent pattern of GRACE-TWS changes for the Nasser region derived from GRACE-TWS changes after correction for the water storage changes of the Red Sea (see Awange et al., [52] for more detail)

Fig. 14.8 Lake Victoria basin. *Source* Kayombo and Jorgensen [65]

14.3.1.2 Lake Victoria Basin (LVB)

Lake Victoria (Fig. 14.8), the world's third largest lake and the largest in the developing world, is a source of water for irrigation, transport, domestic and livestock uses, and supports the livelihood of more than 30 million people who live around it [45]. Nicholson [62, 63] documents its significance as an indicator of environmental and climate change over long-term scales. Since the 1960s, the lake level had experienced significant fluctuation, see e.g., [62, 63]. From 2001 to 2006, however, Lake Victoria's water level showed a dramatic fall that alarmed water resource managers as to whether the lake was actually drying up. Kull [64] reported that the lake's levels fell by more than 1.1 m below the 10 year average.

With the receding of the lake waters, acres of land that were lost to the floods of the 1960s were fast being reclaimed, creating sources of conflicts between man and wildlife. In some beaches, e.g., Usoma in Kenya, wetlands that were once breeding places for fish were dying up, leaving areas of land as playing fields for children and farmland. Ships were now forced to dock deep inside the lake, while the landing bays needed to be extended. Those who directly depended on the lake waters for domestic use were forced to go deeper into the lake to draw water, thus exposing women and children to water-borne diseases and risks of snakes and crocodiles. Water intakes that supplied major towns and cities had to be extended deeper into the lake, thus causing more financial burden to the municipalities that were already strained financially [42].

With 80% of Lake Victoria water coming from direct rainfall, changes in the lake level are directly related to the variation in the water stored in its basin, which contributes around 20% in the form of river discharge. A decrease in stored basin water was therefore suspected to contribute to the drop in the lake level. An analysis of the stored water in the Lake Victoria basin in relation to rainfall and evaporation was therefore necessary as a first diagnosis. This would provide water resource managers and planners with information on the state and changing trend of the stored water within the basin. Such basin scale observations could only be achieved through the use of satellites such as GRACE. Conventional methods for studying variations in stored water such as the Artificial Neural Network, GIS (Geographical Information System) and remote sensing could not diagnose the problem, see e.g., [42].

Having been motivated by the potential of the GRACE satellites, Awange et al. [41, 42] undertook a satellite analysis of the entire lake basin in an attempt to establish the cause of the decline in Lake Victoria's water levels. The GRACE and CHAMP satellites (Fig. 9.9 on p. 161) together with data from the TRMM satellite were employed in the analysis. Using 45 months of data spanning a period of 4 years (2002–2006), the GRACE satellite data were used to analyze the gravity field variation caused by changes in the stored waters within the lake basin. Figure 14.9 presents the annual variation of the geoid in the lake's basin during the high rain season months of March, April and May (MAM) for the period 2002–2006. The GRACE results indicated that the basin's total water storage dramatically decreased at a rate of 6.20 mm/month. These changes are expressed in equivalent water thickness (also known as total water storage (TWS)) in Fig. 14.10. For the period 2002–2006, the results indicate a general decline in the lake basin's water level at a rate of 1.83 km^3/month [42]).

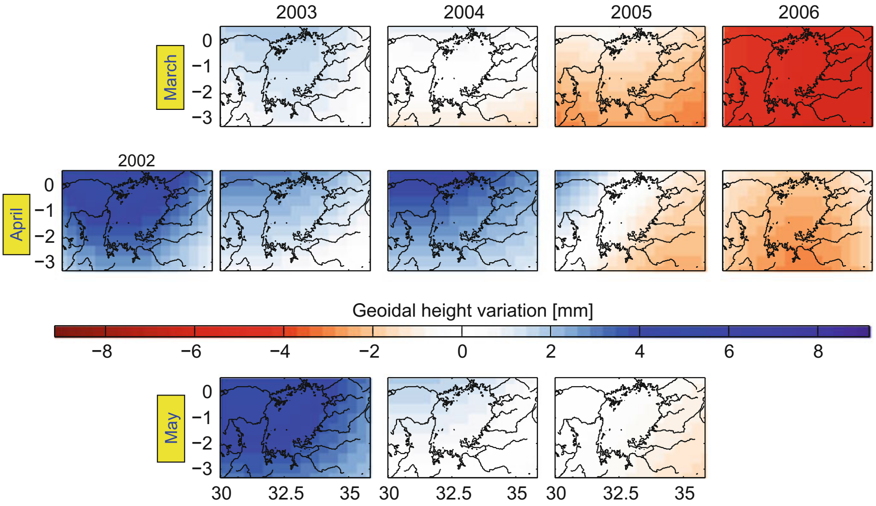


Fig. 14.9 Inter-annual comparison in the geoid during the high rainy season of MAM from 2002–2006. The figure indicates a decline in total water storage in the Lake Victoria basin during this period. *Source* Awange et al. [42]

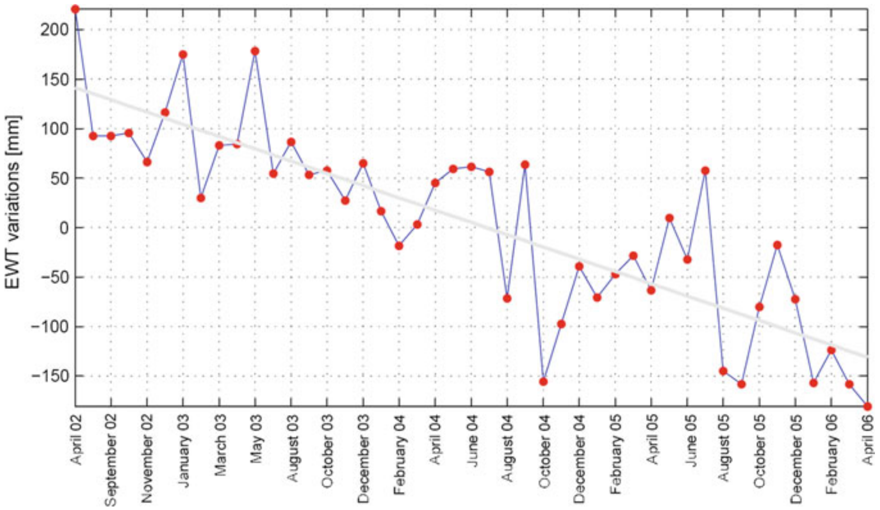


Fig. 14.10 Lake Victoria basin total water storage (equivalent water *thickness*) changes between 2002–2006, as seen by the GRACE satellite. The figure indicates that the GRACE satellites observed a general decline in the lake's basin waters over this period (cf. Fig. 17.2 on p. 359 obtained from satellite altimetry). *Source* Awange et al. [42]

To validate the GRACE results, TRMM Level 3 monthly data for the same period of time were used to compute mean rainfall at a spatial resolution of 0.25° × 0.25° (25 × 25 km), as shown in Fig. 14.11, from which the rainfall trends were analyzed (Fig. 14.12). TRMM rainfall data over Africa has been validated, e.g., in Awange [66]. To assess the effect of evaporation, GNSS remote sensing data (59 CHAMP satellite occultations) for the period 2001–2006 were analyzed to define if tropopause warming took place (see the approach in Chap. 9). The results indicated that the tropopause temperature fell in 2002 by about 3.9 K and increased by 2.2 K in 2003 and remained above the 189.5 K value of 2002. The tropopause heights showed a steady increase from a height of 16.72 m in 2001 and remained above that value reaching a maximum of 17.59 km in 2005, an increase in height by 0.87 m. Temperatures did not, therefore, increase drastically to cause massive evaporation. TRMM results indicated the rainfall over the basin (and directly over the lake) to have been stable during this period (see Figs. 14.11 and 14.12). Since rainfall over the period remained stable, and temperatures did not increase drastically to cause increased evaporation, the remaining major contributor during the period 2002–2006 was suspected to be discharge from the expanded Owen Falls dam. Awange et al. [42] concluded, thanks to the GRACE and GNSS satellites, that the fall in Lake Victoria's water level between 2001 and 2006, also noted in Sect. 14.3.1, was due to human impact on the basin's environment (i.e., expanded dam) as opposed to natural factors.

In a related work, Swenson and Wahr [67] used satellite gravimetric and altimetric data to study trends in water storage and lake levels of multiple lakes in the Great Rift Valley region of East Africa for the years 2003–2008. GRACE total water storage

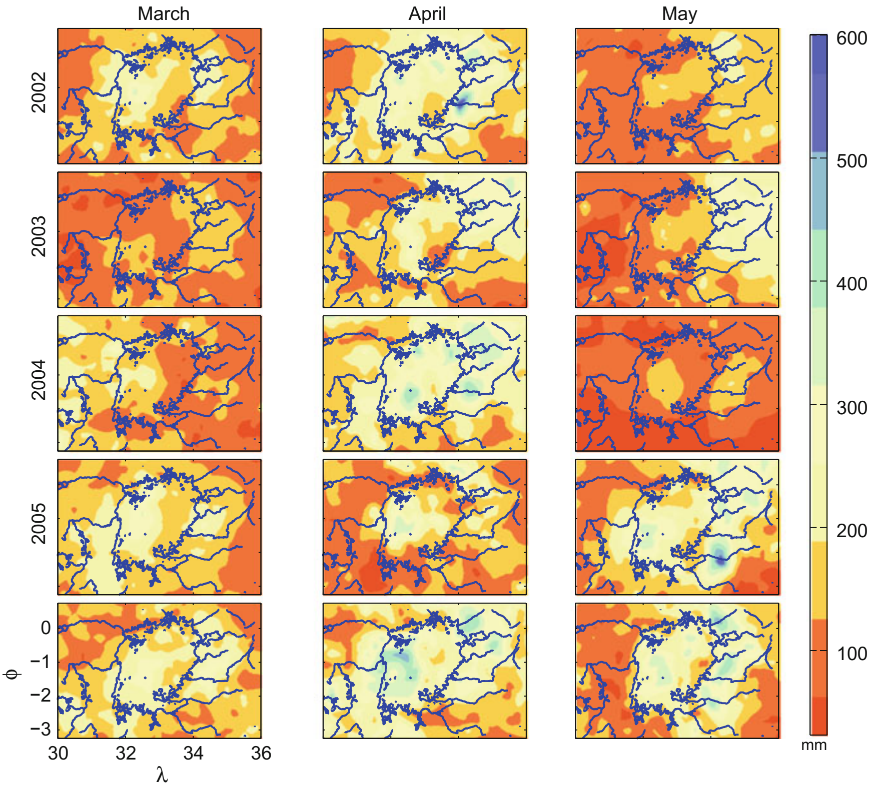
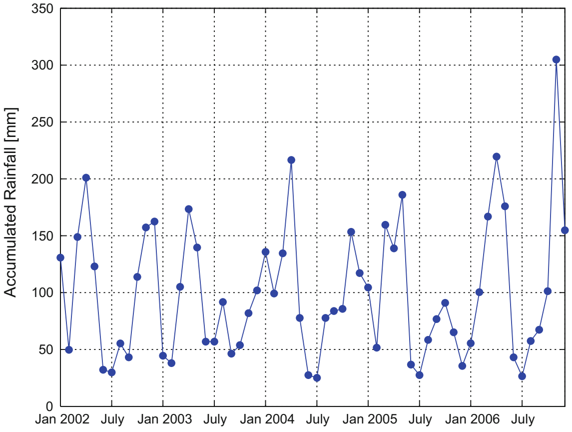


Fig. 14.11 Inter-annual comparison of rainfall over the Lake Victoria basin during the high rainy season of MAM from 2002–2006 using TRMM results. *Source* Awange et al. [42]

Fig. 14.12 Time series of rainfall 2002–2006 for the lake Victoria basin as observed by the TRMM satellite. *Source* Awange et al. [42]



estimated by Swenson and Wahr [67] corroborated the findings of Awange et al. [42] that the lake's water level had declined by as much as 60 mm/year, while their altimetric data indicated that levels in some large lakes in the East African region dropped by as much as 1–2 m. Swenson and Wahr [67] concluded that the largest decline occurred in Lake Victoria and, like Awange et al. [42], attributed this to the role of human activities.

Both the findings of Awange et al. [42] and Swenson and Wahr [67] provide evidence that the GRACE satellites (supported by GNSS) could be used to provide independent means of assessing the relative impacts of climate and human activities on the balance of stored water that does not depend on in-situ observations, such as dam discharge values, which may not be available to the public domain.

14.3.1.3 Application of GNSS to LVB Water Conflict Resolution

Let us revisit Fig. 2.1 on p. 19 where we have three boats with fishermen from each of the three East African countries that boarder Lake Victoria. If the three boats were in the middle of the Lake, with no visible land mark on the horizon, the fishermen would be at a loss to know which country owns that portion of the lake. In this case, they will not know whether they are in Kenyan, Ugandan or Tanzanian territory. Fishermen have frequently found themselves in this situation and the end result has often been conflict, leading to arrests and the confiscation of boats and fishing equipment. In such cases, hand-held GNSS receivers and a map could easily resolve such a dilemma. A real-case scenario is illustrated by Migingo Island in Fig. 14.13,[4] which is an island currently disputed between Kenya and Uganda due to it being home to the dwindling Nile Perch (*Lates niloticus*) fish. Owing to uncertainty about the boundary, GNSS receivers were used by a team of surveyors from both countries to mark the boundary and establish that the disputed island belongs to Kenya.

14.3.2 Understanding the Decline of Lake Naivasha

14.3.2.1 The Lake Naivasha Basin

Lake Naivasha (00° 40’ S - 00° 53’ S, 36° 15’ E - 36° 30’ E) is the second largest fresh water lake in Kenya with a maximum depth of 8 m. It is situated in the Central African Rift Valley at an altitude of 1890 m above sea level and is approximately 80 km northwest of the Kenyan capital, Nairobi. Its basin (Fig. 14.14) lies within the semi-arid belt of Kenya with mean annual rainfall varying from about 600 mm at the Naivasha township to some 1,700 mm along the slopes of the Nyandarua mountains, with open water evaporation estimated to be approximately 1,720 mm/year [68]. Mount Kenya and the Nyandarua Range capture moisture from the monsoon winds,

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[4] Source: http://www.nation.co.ke.

Fig. 14.13 The disputed Migingo Island in Lake Victoria (right). GNSS receivers were used to establish that the island belongs to Kenya, thus resolving a territorial dispute between Kenya and Uganda. *Source* Daily Nation, Kenya

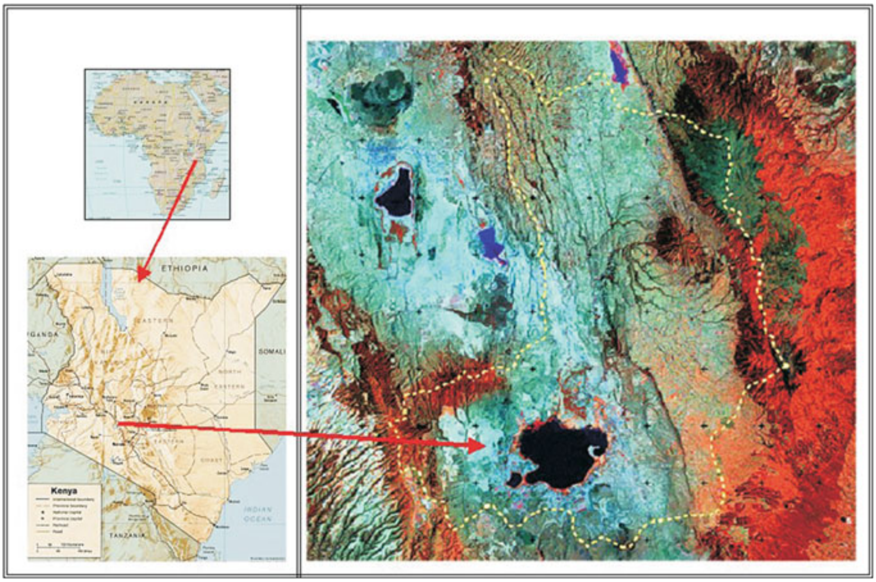


Fig. 14.14 Location map of the Lake Naivasha Basin. *Source* Becht et al. [68]

thereby casting a significant rain shadow over the Lake Naivasha basin [68]. Unlike Lake Victoria, which has its highest rainfall during the March–April–May (MAM) wet season, e.g., [42, 69], Lake Naivasha basin experiences its highest rainfall period during April–May–June (AMJ). There is also a short rainy season from October to November. The lake's levels therefore follow this seasonal pattern of rainfall cycle, with changes of several meters possible over a few months. Imposed upon this seasonal behaviour are longer-term trends, for example, there has been a change in the lake's water level of 12 m over the past 100 years [68].

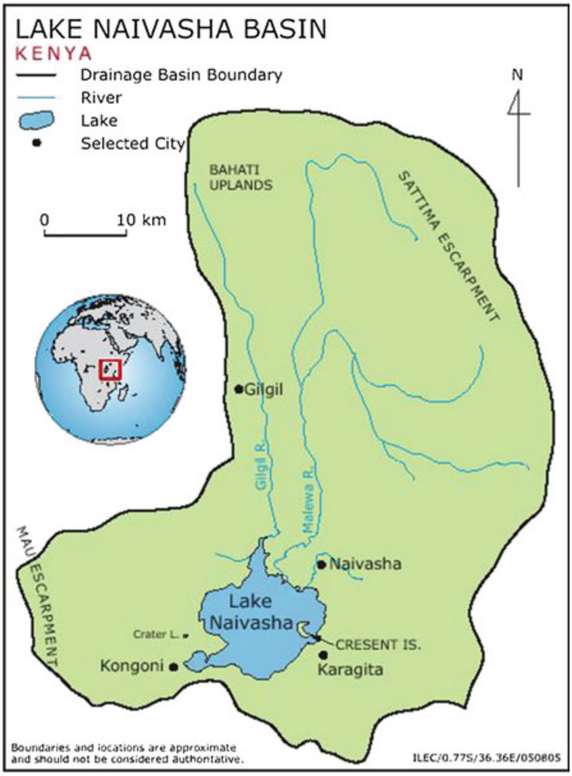


Fig. 14.15 The Lake Naivasha drainage system. Three rivers flow into the Lake; Gilgil, Malewa, and Karati. The Lake's outlet is through an underground system to the south. *Source* Becht et al. [68]

The lake is fed by three main river systems: the Gilgil, the Malewa and the Karati, the last of which only flows during the wet season (see Fig. 14.15). There is also a groundwater inlet into the lake from the north, and an outlet to the south, which when combined with the river systems and the biochemical and geochemical sedimentation processes that remove ions such as sulphates and carbonates from the water, results in the freshness of the lake [70, 71]. Becht et al. [68] state that whereas a small portion of the groundwater evaporates and escapes in the form of fumaroles in the geothermal areas, the remaining water flows into Lakes Magadi and Elmentaita, taking thousands of years to reach them. The basin's water balance has been calculated from a model based upon long-term meteorological observations of rainfall, evaporation and river inflows [72]. This model reproduced the observed level from 1932 to 1982 with an accuracy of 95% of the observed monthly level, differing by 0.52 m or less [73]. This pattern was, however, noticed to deviate after 1982 and by 1997, the difference had reached 3–4 m [68]. In fact, the onset of this reduced ability to model the lake's level coincides with the increase in horticultural and floricultural activities.

In general, three contemporary global water issues can be identified as occurring in this region, namely *water scarcity/availability*, *water quality*, and *water security*. Several previous works have focused on the problem of water quality and competition for water resources within the area. Water quality studies have endeavoured to analyze the physical, chemical and biological characteristics of the water, which represents a measure of the condition of water relative to the requirements of one or more biotic species and/or to any human need or purpose. Most studies have concluded that the main causative factors for the deterioration of the water quality of Lake Naivasha are the large quantities of sediment inflow from the catchments of the Malewa and Gilgil Rivers, polluting inflows from Naivasha town and the intensive floriculture enterprizes adjacent to the lake, see e.g., [74]. These pollutants include high levels of phosphates, nitrates, pesticide residues and other agro-chemicals.

The use of GNSS in monitoring water pollution discussed in Sect. 18.2 could also be applied to Lake Naivasha to map the sources of point pollutants. Although water security issues are a reality in the Lake Naivasha basin, few studies have been done to better understand the underlying issues. Carolina [75] asserts that the area of Lake Naivasha basin is of high economic and political importance to Kenya, which presents a wide variety of economic activities around the water resources with many different stakeholders often competing for the water resources.

The flower industry in Kenya has experienced a phenomenal growth, maintaining an average growth rate of 20% per year over the last decade. It is an industry that is the second largest export earner for Kenya, employing between 50,000 – 60,000 people directly and 500,000 others indirectly through affiliated services [76]. Although flowers are now grown in many areas with temperate climate and an altitude above 1,500 m in Kenya, the region around Lake Naivasha still remains the nation's main floriculture farming center. The foremost categories of cut flowers exported from Kenya include: roses, carnations, statice, alstromeria, lilies and hyperricum. Indeed, Kenya is arguably the largest exporter for flowers in the world, supplying over 35% of cut flowers to the world's largest market - the European Union [76].

14.3.2.2 Impacts of Flower Farming

Lake Naivasha (Kenya) is the only freshwater lake in the Great Rift Valley of East Africa in an otherwise soda/saline lake series [77]. In fact, it is the freshness of the water of Lake Naivasha that is the basis for its diverse ecology [71]. However, recent years have seen a rapid decline in its extent to the point where questions are being raised in the local media as to whether the lake is actually dying.

So unique is Lake Naivasha in the chain of East African Rift Valley lakes that in 1995 it was declared a Ramsar site due to its importance as a wetland. Lake Naivasha and its basin supports a rich ecosystem, with hundreds of bird species, papyrus fringes filled with hippos, riparian grass lands where waterbuck, giraffe, zebra and antelopes graze, dense patches of riparian acacia forest with buffaloes, bushbuck and other species, swampy areas where waterfowl breed and feed and, at the same time, magnificent views of the nearby volcanoes [68]. The lake also supports local fishery and tourism, and is used for recreation, water sports, subsistence farming and hunting. The surrounding lands are dominated by the cultivation of flowers, vegetables, fruit and cereals, as well as power generation [72].

In fact, the *floriculture* industry in this area provides large quantities of flowers that are exported to Europe and other countries of the world. The growth in the flower industry has been favored by the permeable and fertile soils, low rainfall, reliable supply of good quality water, favourable climatic conditions, availability of cheap labour, and easy access to Nairobi airport [68]. Since much of the water used in the flower farms comes from irrigation, the only source, therefore, is the lake and its basin. The lake and basin also supply drinking water to Nakuru (of which Naivasha is part of, with a population of about 1.6 million as per the 2009 census) located 160 km north west of Nairobi.

The study of fluctuations in Lake Naivasha's water levels has been carried out, e.g., by [62, 78]. Richardson and Richardson [78], for instance, state that the lake was nearly twice as extensive in the 1920s as it was in 1960–61. Nicholson [62] noted trends of lower levels during the first half of the 19th century, very high levels during the last decades of the 19th century, with a rapid decrease occurring during the 20th century. He further points out that the lake returned to a relatively large extent during the 1960s, but this ended in the 1970s, a fact also stated by Richardson and Richardson [78] who point out that the wetter years beginning in 1961 saw a sharp rise in the levels of Lake Naivasha, as well as of Lakes Elmenteita and Nakuru. The decrease in the lake's water level between the 1920 to 1960s is attributed by Richardson and Richardson [78] to a slight trend of decreasing rainfall during this period, averaging 5 mm/year over the basin, between 1920 and 1949 (see also [79]), as well as an increase in human consumption from river influent and boreholes.

In the 1980s, the fall of the lake's level continued, with the local Olkaria geothermal power station and subsurface drainage thought to be the main culprits [80]. But then, there was little notice taken of the influence of the flower farms, since the first farms had just started in the early 1980s, see e.g., [68]. However, during the 1990s, over 100 km^2 of land around lake Naivasha was converted to floriculture for the European-cut flower trade, e.g., [73]. With this growth came an influx of workers leading to a greater extraction of water from the lake, local aquifers, and the inflowing rivers for the agriculture, floriculture and domestic use by the rapidly increasing population [73].

At this point, the impact of such development on the lake's resources begun to be felt, with its size shrinking due to this direct extraction from the lake and also indirectly from closely connected aquifers. In the work of Abiya [81], the exploitation of the resources of Lake Naivasha is said to pose serious threats to the fragile lake ecosystem and its biodiversity. Abiya [81] considered the dynamics of the changing lake ecosystem, the imminent threats to this system, and the community-based approach towards the sustainable utilization of the lake. Their study showed that the sustainable use of the lake was not going to be fully realized without a sound management plan, and recommended the enaction of consolidated environmental legislation in Kenya, which will enable the strengthening of environmental conservation and the protection of natural resources [81]. This in turn has led to other proposals for the sustainable use of the lake and basin, e.g., [70, 71].

In the last decade, the lake's level has continued to drop with floriculture being blamed for excessive water extraction from the lake and aquifers, and the small holder farms in the upper catchment being blamed for nutrient loadings, see e.g., [73, 82], leading to outcry in both the local and international media that this Ramsar site could be dying as a result of the very resource that it supports, see e.g., [82]. For example, Mekonnen and Hoekstra [82] observed that the total virtual water exported in relation to the cut flower industry from the Lake Naivasha basin was 16 Mm^3/yr during the period 1996–2005. Other factors that have also been proposed as influencing Lake Naivasha's water changes include irregular rainfall patterns [71], and trade winds [83]. All of these discussions therefore point to the need for the *reliable mapping* of the lake and its basin in order to properly understand the dynamics of this area. This need for accurately monitoring the lake was captured by Becht and Harper [72], who state that there is an urgent need to accurately measure all abstractions and provide consistent, reliable, hydrological and meteorological data from the catchment, so that a 'safe' yield may be agreed upon by all stakeholders and the sustainable use of the lake waters achieved.

However, lack of reliable basin mapping techniques hampered the proper mapping of changes in the lake basin, while also not allowing accurate predictions of the likely future situation, despite modelling methods being used to calculate its water balance, e.g., [72]. The situation is compounded by the fact that Lake Naivasha has no surface outlet that could assist in hydrological monitoring, and the fact that changes in its water level occur rapidly, over the order of several meters over just a few months, shifting the shoreline by several meters [68].

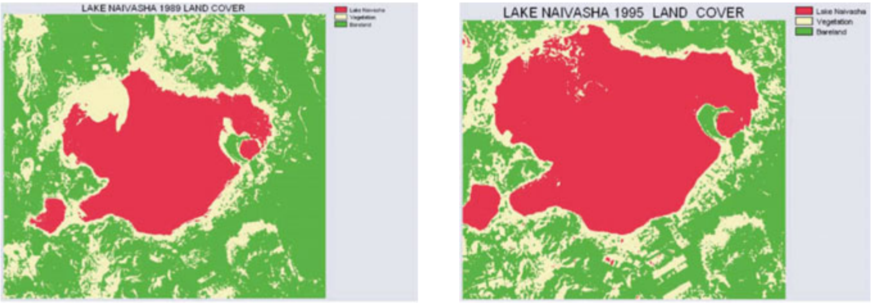
The emergence of satellite based methods offers the possibility of providing a broader and more integrated analysis of the lake and its basin. Using products from the GRACE gravity mission, changes in the stored water in the region extending from the Lake Naivasha basin to Lake Victoria may be assessed to determine whether the changes are climatic or human induced. Changes in precipitation can be examined by the analysis of products from the TRMM, allowing the determination of how much of the fluctuations in Lake Naivasha are related to changes in precipitation behaviour.

The fluctuations in the water level of Lake Naivasha can be determined using both ground-based tide gauge observations and satellite altimetry data (TOPEX/Poseidon and Jason-1; see Sect. 9.4 on the contribution of GNSS). These results may in turn be related to the use of satellite imagery (e.g., Landsat) and change detection techniques to map the shoreline changes of Lake Naivasha, analyzing the trend of changes over the period of interest, and correlating shoreline changes with proposed causes. In general, the combination of different data sets, both space-borne and ground based, provide a valuable contribution to understanding the hydrological behaviour of the East African Great Lakes region, e.g., [60].

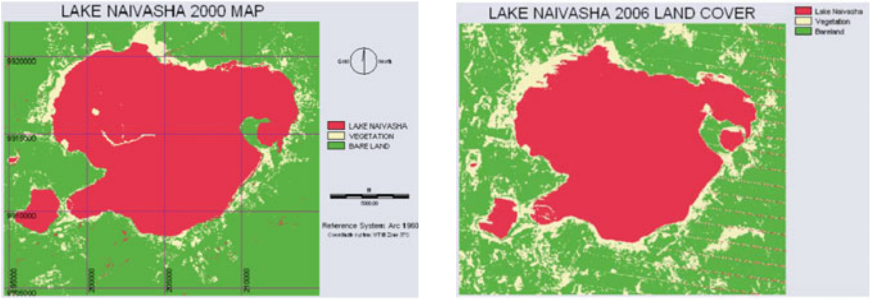
Example 14.1 (Satellite-based monitoring [84]).

Several different types of space-borne observations were used in Awange et al. [84]:

(1) GRACE gravity-field products (2) precipitation records based on TRMM products (3) satellite remote sensing (Landsat) images (4) satellite altimetry data



(a) Results for 1989 Image (b) Results for 1995 Image



(c) Results for 2000 Image (d) Results for 2006 Image

Fig. 14.16 Surface-type classification results for the considered Landsat images. **a** 1989, **b** 1995, **c** 2000 and **d** 2006. GNSS satellites were used to georeference the satellite images. *Source* Awange et al. [84]

and (5) flower production data. In addition, data from an in-situ tide-gauge station were used. The results of Awange et al. [84] confirm that Lake Naivasha has been steadily declining with the situation being exacerbated from around the year 2000, e.g., Fig. 14.18, with water levels declining at a rate of –10.2 cm/yr and a shrinkage in area of –1.04 km^2/year (see e.g., Fig. 14.16 where GNSS was used to *georeference* the satellite imagery). This rapid decline can be traced largely to anthropogenic activities, a proposal supported by a coefficient of correlation R^2 value of 0.976 between the quantity of flower production and the lake's level for the period 2002–2010 (Fig. 14.17), a period during which such production doubled, see e.g., Fig. 14.19. These results, supported by the use of GNSS show that there is therefore a need for those different communities and interest groups that depend upon Lake Naivasha to better formulate their management plans, a need which can exploit results such as those presented in [84].

♣ End of Example 14.1.

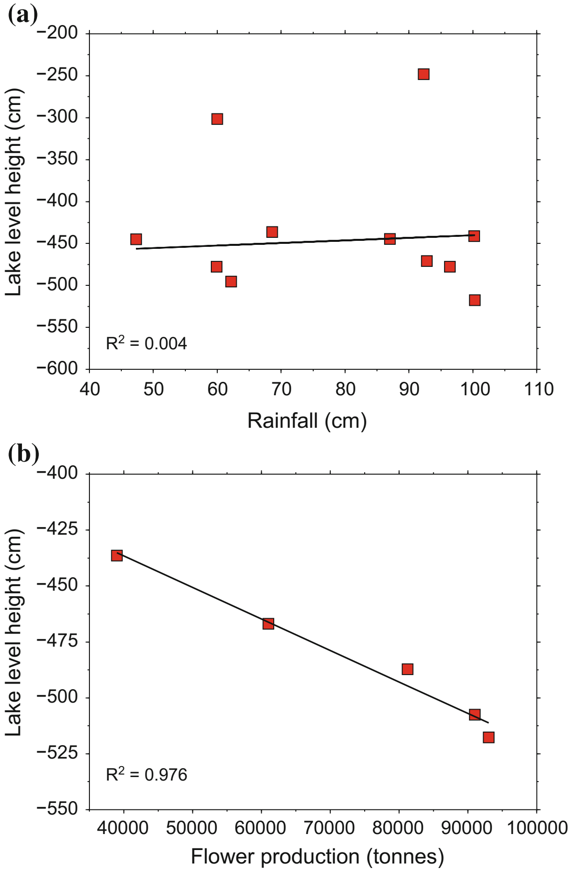


Fig. 14.17 Comparing annual average lake levels with **a** TRMM rainfall and **b** flower exports. The solid lines are fitted linear trends, along with their correlation coefficient. A strong correlation coefficient (0.976) is noticed between the Lake's level and flower export between 2002–2010, the period when the flower export picked (see Fig. 14.19). *Source* Awange et al. [84]

14.3.3 Water, a Critical Dwindling Australian Resource

Warning of Australia's acute water problem (see e.g., Fig. 14.20) had already been sounded by the National Land and Water Resource Audit (NLWRA [85]), which reported that Australian water resources were scarce and in high demand by agricultural, industrial and urban users. The alarming finding of the report was the fact that 26% of the river basins and 34% of the groundwater management units in Australia were approaching or beyond sustainable extraction limits.

The NLWRA highlighted the need for information that could assist in improving water resource management and conservation. Steffen et al. [86] issued a further alert that Australia would be faced with the impacts of climate change on its water quantity due to decrease in precipitation over parts of Australia.

Even though the need for up-to-date information on stored water resource to support policy formulation and management issues had already been realized, e.g., NLWRA [85], and specifically with the prevailing drought conditions in Australia,

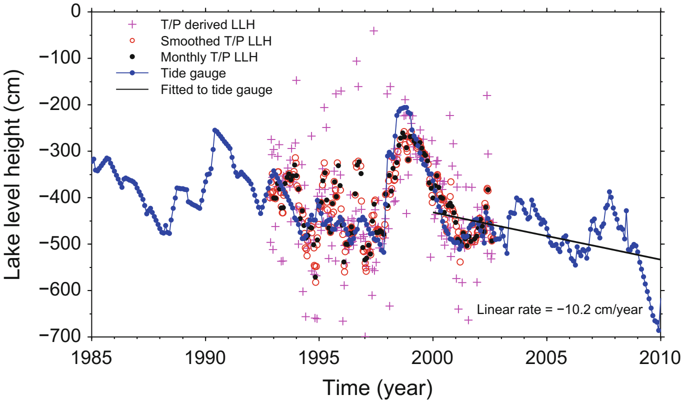


Fig. 14.18 Time Series of lake level height (LLH) changes for Lake Naivasha as provided by satellite altimetry (T/P), and a tide gauge. GNSS satellites support the satellite altimetry as discussed in Sect. 9.4. *Source* Awange et al. [84]

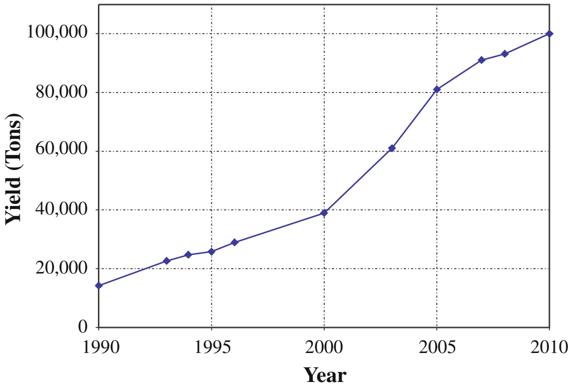


Fig. 14.19 Annual flower exports from Kenya. *Source* Awange et al. [84]

the lack of appropriate techniques that offered high spatial and temporal resolution monitoring of changes in stored water remained a stumbling block [11]. The problem was further compounded by the fact that groundwater suitable for human consumption and utility is normally trapped inside aquifers (see Sect. 14.1) that are beyond reach of modern remote sensing methods. With the introduction of GRACE satellites (Sect. 9.3.3), however, the situation changed. In Awange et al., [28], its possibility to monitor changes in Australia's stored water was reported.

Example 14.2 (Monitoring changes in Australia's stored water [10]).

In order to use the GRACE satellite for monitoring the variation in Australia's stored water, Awange et al. [10] investigated the regional 4° × 4° mascon (mass concentration) GRACE solutions provided by GSFC (Goddard Space Flight Center, NASA) for their suitability for monitoring Australian hydrology, with a particular focus on

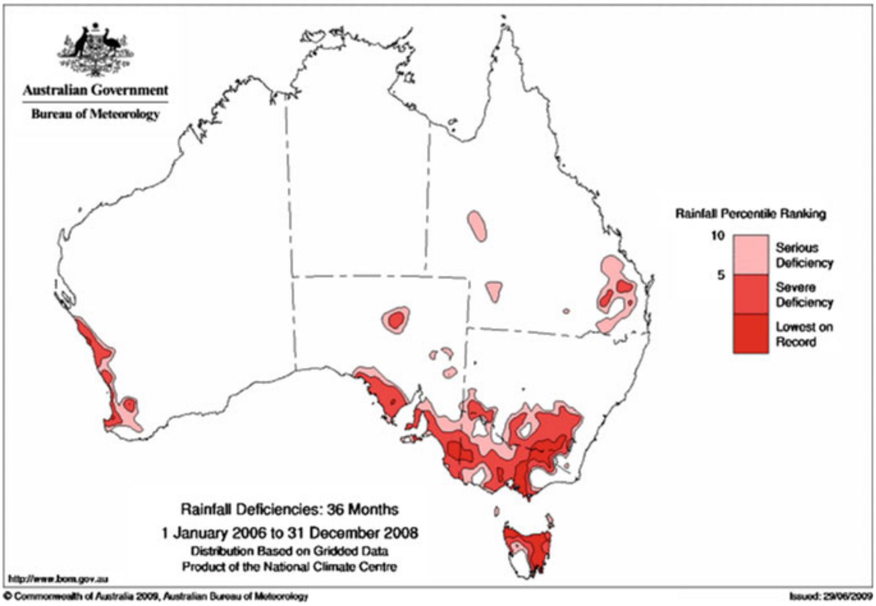


Fig. 14.20 Rainfall deficiencies for the period 1st January 2006 to 31st December 2008 (3 years, Source: BOM)

the Murray-Darling Basin (MDB). Using principal component analysis (PCA) and multi-linear regression analysis (MLRA), the main components of the spatial and temporal variability in the mascon solutions over both the Australian continent as a whole and the MDB in particular were analysed and the results compared to those from global solutions provided by CSR (the Center for Space Research, University of Texas at Austin) and CNES/GRGS (Centre National d'Études Spatiales/Groupe de Recherche de Geodesie Spatiale, France) and validated using TRMM, water storage changes predicted by the WaterGap Global Hydrological Model (WGHM) and ground-truth (river-gauge) observations. The results of Awange et al. [10] indicated that for the challenging Australian case with weaker hydrological signals, all the solutions gave similar results.

For the PCA results in Fig. 14.21, the Australia-wide case was considered mainly to compare the different GRACE releases among themselves and with TRMM and WGHM time-series. The results of the PCA analysis for the first two modes are shown in Fig. 14.21. It was noticed that most of the variability were contained in the first mode (>50%), while considering the first 2 modes accommodates between 63% (for CNES/GRGS) and 81% (for mascon) of the total variability of each signal. The 1st mode (upper panel, Fig. 14.21) shows similar behaviour among all data sets, with all data displaying a general north-south varying empirical orthogonal function (EOF) pattern and strong annual signal in the principle components (PC), indicative of seasonal variations. The annual signal is also apparent in the 2nd PC mode (lower panel, Fig. 14.21), especially for the GRACE time-series, although less so for the filtered TRMM and WGHM results.

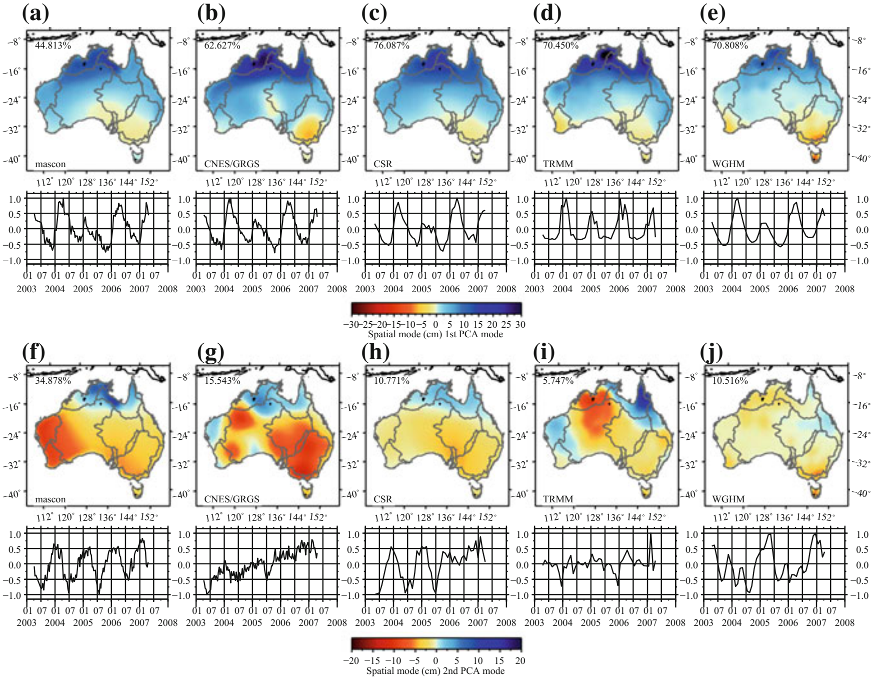


Fig. 14.21 Results of the PCA applied to the whole of Australia for the 1st and 2nd modes. *Top rows* **a**–**e** the 1st mode results, *bottom rows* **f**–**j** the 2nd mode results. **a**, **f** mascon, **b**, **g** CNES/GRGS, **c**, **h** CSR, **d**, **i** TRMM and **e**, **j** WGHM. Australias drainage divisions (from the Australian Bureau of Meteorology, see the Acknowledgements) are marked by the *grey* boundaries (Lambert conformal conic projection). *Source* Awange et al. [10]

The dominant signal in northern Australia is a result of the annual monsoonal rains, and is much stronger than that in the southern part of the continent. Therefore, the 1st mode is dominated by changes in the north, which may lead to smaller hydrological changes in the south being excluded from this mode. The northern signal is very obvious in the 1st mode EOF patterns for all data sets examined, and also in the 2nd mode EOF for the mascon, CNES/GRGS, CSR and TRMM time-series. The PC of the 2nd modes also appears to show strong linear trends in the time-series, especially for the CNES/GRGS and CSR results. For both the 1st and 2nd modes, Central Australia shows a relatively low signal, a consequence of the aridity of this area having small hydrological changes. The shift in the seasons that receive the high rainfall (summer in the north, winter in the south) can be seen by the opposite signs in the signals given by the EOF (time-series in the upper panels, Fig. 14.21).

The Australia-wide results therefore show that all the GRACE solutions provided similar results and were able to identify the major climatological features of Australia, in particular the dominance of the monsoonal rainfall over northern Australia, and the offset (∼6 months) between the northern and southern wet seasons, as well

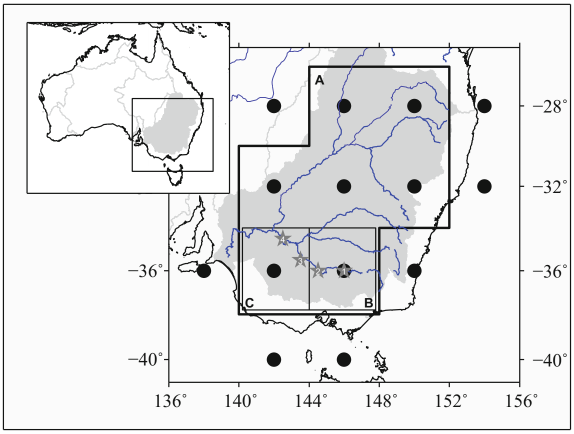


Fig. 14.22 Location map of the Murray-Darling Basin (MDB). The *grey shading* marks the basins extent, with Australias other river basins also outlined in *grey*. Black filled circles are the centres of the mascon grid cells provided by GSFC (4° × 4° grid). The *thick black*-bounded area (A) covers most of the MDB, while the finer *black*-bounded areas (B and C) are examined with respect to ground-truth data in the form of river-gauge data (numbered stars). The river-gauges are at Yarrawonga (1), Swan Hill (2), Euston (3) and Torrumbarry (4). *Source* Awange et al. [10]

as the areas of mass gain (northern Australia) and loss (the MDB in the southeast and southwest Western Australia).

♣ End of Example 14.2.

Example 14.3 (Localised Murray-Darling Basin. Source: Awange et al. [10]).

Awange et al. [10] further examined the MDB to determine how the GRACE solutions performed for more localized areas, since the MDB is one of Australia's most important regions for agricultural production and is an area that has been severely affected by the recent drought conditions [87, 88]. First, they examined the area outlined in Fig. 14.22 denoted as A, which is defined by the mascon grid elements that cover much of the MDB. Figure 14.23 compared the inferred stored water variation from each data set.

Examining the three GRACE solutions in Fig. 14.23 over the time period covered by the mascon solutions (grey shaded area), Awange et al. [10] noted that the time-series generally follow each other reasonably well, as also shown by the resulting cross correlation values, i.e., CSR and CNE/GRGS, being global solutions, appear to be in closer agreement with each other ($R = 0.83$), than when compared to the mascon (mascon to CNES/GRGS, $R = 0.70$, and mascon to CSR, $R = 0.74$). The correlation between GRACE solutions is relatively high (>0.7), although much poorer when the GRACE solutions are compared to the TRMM and WGHM time-series (<0.5).

♣ End of Example 14.3.

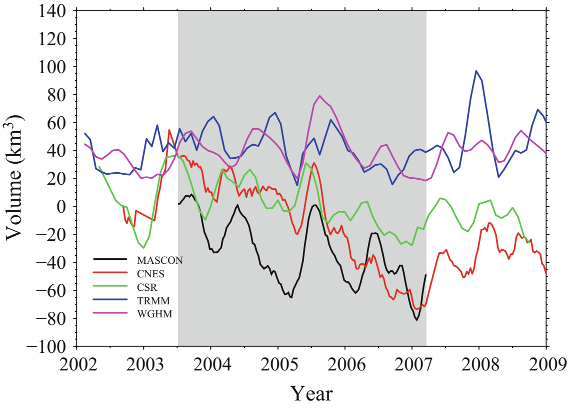


Fig. 14.23 The change in water storage over the MDB, as outlined by sector A in Fig. 14.22 for the data sets used in this work. A three-month moving average has been applied to each time-series. The *gray shading* marks the time span over which the mascon solutions are available. Cross-correlations between pairs of data sets are listed in Awange et al. [10]

14.4 Concluding Remarks

The GRACE satellites had been recognized as having the potential to provide the first space-based estimate of changes in terrestrial water storage. In essence, it is a tool that will assist water managers in conserving and controlling the utilization of dwindling water resources in a sustainable way. Water is arguably one of the most precious resource in the world, therefore, it is logical to try to monitor its distribution as efficiently as possible, and GRACE offers one such opportunity, see e.g., [89]. This is because one of the environmentally important signals detected by GRACE is the temporal gravity field variation induced by changes in the distribution of water on and below the Earth's surface, i.e., hydrology, e.g., [28]. Satellite altimetry provides the possibility of monitoring sea or lake surface heights as was demonstrated for Lake Naivasha. GNSS plays a pivot role in supporting these satellites as discussed in Chap. 9. GNSS also plays a major role in providing location-based information for monitoring groundwater wells, and source of water pollutants as discussed in Chap. 18. Its application to coastal water resource are presented in the next chapter. Other studies undertaken with respect to use of GRACE to monitor hydrology include, e.g., [90–93].

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