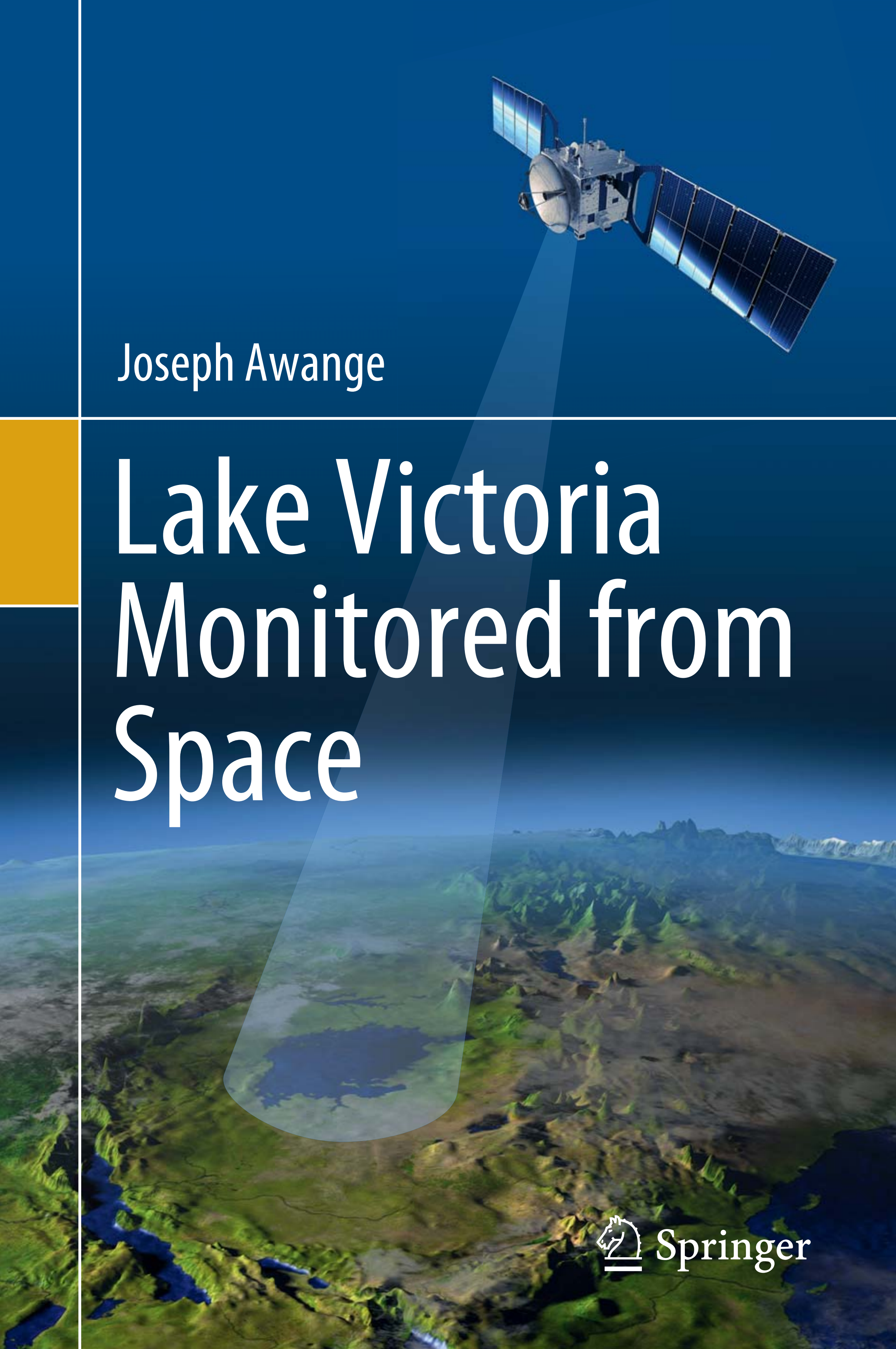

Joseph Awange

Lake Victoria Monitored from Space

Springer

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To the memories of my late parents (James Odhiambo Awange and Margaret Atieno Awange) and my late grandmothers (Amelea Gwada and Rosalina Omulo Odera). The love you showered on me is still fresh like the waters of Lake Victoria. You are greatly missed.

Joseph L. Awange
Perth Australia, September 2020

Foreword

Joseph L. Awange is truly an interdisciplinary scientist who was trained in geodesy, geomathematics, Geographic Information Science (GIS), and remote sensing, and he excels at addressing contemporary scientific questions and applications including climate change, hydrology, flooding, drought, and water resources management. Throughout his professional career, he has used novel mathematical formalism, geodetic and passive remote sensing observations, and four-dimensional assimilative hydrologic modeling regimes to quantify both surface and groundwater processes, toward solving timely scientific problems and applications to benefit people in need. Like his many excellent peer-reviewed publications and books, this book on *Lake Victoria Monitored from Space* is no exception. Using Lake Victoria or Victoria Nyanza, one of Africa's Great Lakes, as a poster child of water bodies under climate stress in northeastern Africa, he elaborated on the critical societal importance of global abundant and clear water resources, and focused on the need of accurate and timely observations to study, understand the anthropogenically impacted Lake Victoria's water and hazard managements, and the needed sound government policy for sustainability, and revision of obsolete laws to lessen or mitigate regional and international water conflicts. He is correct to postulate the need of spaceborne observations, for whom he is an expert on the exploitation of contemporary multiple passive optical and multi-spectral remote sensing, and innovative geodetic remote sensing. These geodetic sensors include the use of ground-based and potential spaceborne Global Navigation Satellite System (GNSS) Signal of Opportunity in L-Band bistatic radar reflectometry for measuring water level, soil moisture, and wind speed; satellite radar and laser altimeters for measuring water level and wave/wind speed; and the use of satellite gravimetry data collected by the Gravity Recovery And Climate Experiment (GRACE) and its successor, GRACE-Followon (GRACE-FO) twin-satellite missions to invert for temporal gravity fields at monthly sampling and a spatial scale longer than 333 km, half-wavelength. GRACE and GRACE-FO data would be the first satellite sensor to sense groundwater storage changes in aquifers, provided that the surface hydrology is known and remove from the retrieved gravity signal.

In a unique cross-disciplinary approach, the book articulated the various climatic impacts and explanations from natural and anthropogenic origins, which affected Lake Victoria and its vicinity, including the drastic increase and depletion of water level in the lake and dams, floods and droughts, water quality/security, crop health, food security, and economic implications. With no exception as in his many publications, Joseph L. Awange used data analysis methodologies including filtering, adjustment theory, and robust statistics, to quantify the hydrologic and other parameters, and their estimated uncertainties. This book is recommended for readers from a diverse disciplines, including physical and social sciences, policy, law, engineering, and disaster management.

October 2020

C. K. Shum
Ohio State University
Ohio, USA

Preface

This book employs a suite of remotely sensed products and advanced technologies to provide the first comprehensive space-based sensing of Lake Victoria, the world's second largest freshwater lake that supports the livelihood of more than 42 million people, modulates regional climate, but faces myriads of challenges. Proper understanding of the lake and changes in its physical dynamics (e.g., water level, shorelines and areal dynamics) resulting from the impacts of climate variation and climate change as well as anthropogenic (e.g., hydropower and irrigation) is important for its management as well as for strategic development before, during, and after climate extremes (e.g., floods and droughts) in order to inform policy formulations, planning and mitigation measures. Owing to its sheer size and lack of research resources commitment by regional governments that hamper its observation, however, it is a daunting task to undertake studies on Lake Victoria relying solely on in situ "boots on the ground" measurements, which are sparse, missing in most cases, inconsistent or restricted by governmental red tapes. Because of this, changes in its physical dynamics that have occurred due to climatic variation/change and anthropogenic impacts have not been thoroughly studied. For example, articles written on Lake Victoria referenced various figures for its dimensions (e.g., 66,400–69,485 km^2 for its area; 300–412 km for its maximum length; 240–355 km for its maximum width; and 3300–4828 km for its shorelines). These discrepancies are largely due to the difficulties of obtaining accurate data because of both the size of the lake and the lack of resources that have been committed for exploratory research by regional governments.

In this book, which provides a pioneering compilation of satellite applications to Lake Victoria, a suite of high spatio-temporal remotely sensed data, reanalysis products, as well as those of hydrological models are all employed to sense the lake's precious resource, water. With the advances in satellite technology, i.e., the maturity of the GRACE (Gravity Recovery and Climate Experiment) satellite mission among others, the lake's waters can now be accurately weighed from space. Remote sensing of this precious lake from space, therefore, shows its current state and that of its basin, challenges and potential. The book will be useful to those in water resources management and policy formulations, hydrologists, environmentalists, engineers and researchers.

Recife, Brazil; Karlsruhe, Joseph Awange
Germany; Kisumu, Kenya; Perth, Australia

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Part I Global and Lake Victoria's Water Resources

Part II Remote Sensing Techniques

Part III Sensing the Lake and Its Basin

Part I
Global and Lake Victoria's Water Resources

Chapter 1
Global Freshwater Resources

Several authors, politicians, leaders of international organizations and journalists have cautioned the world community that the increasing scarcity of freshwater resources might lead to national and international conflicts. When relating this to climate change forecasts – most of which indicate that climate change will have a significant impact on the availability of freshwater resources, on water quality, and on the demand for water – this is alarming news for humankind as it threatens human security.

– Molen and Hildering [1]

Accounting for water for environmental requirements shows that abstraction of water for domestic, food and industrial uses already have a major impact on ecosystems in many parts of the world, even those not considered "water scarce" [2]. In the absence of coordinated planning and international cooperation at an unprecedented scale, therefore, the next half century will be plagued by a host of severe water-related problems, threatening the well being of many terrestrial ecosystems and drastically impairing human health, particularly in the ***poorest regions*** *of the world [3].*

1.1 Diminishing Freshwater Resources

1.1.1 Status

Freshwater, influenced globally by climate variability/change [4–9], human use [10–12] and knowledge deficiency resulting from inadequate hydrometeorological observation stations [13–16], is one of the basic necessities without which human beings cannot survive since it is key to the sustainability of all kinds of life forms. Water

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has multiple uses namely; nutritional, domestic, recreational, navigational, waste disposal and ecological as it is a habitat for living and non-living organisms (biodiversity), etc. And, because it is indispensable to different sectors including manufacturing, agriculture, fisheries, wildlife survival, tourism and hydroelectric power generation, just to list but a few, it is a vital factor of economic production. For many countries, most freshwater endowments encompass surface waters, groundwater, wetlands and glaciers. Surface water bodies include lakes, rivers, swamps, springs, dams and water pans dispersed within different basins. In general, people living in the vast arid and semi-arid parts of the world rely heavily on groundwater resources. Gleeson et al. [17] puts the number of people living in regions where groundwater is threatened to be 1.7 billion. Furthermore, groundwater is also an important supplementary source of water for many urban households in most developing countries.

At a global scale, 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. Roughly 30.8% is groundwater, much of which is inaccessible to humans, and the remainder 0.3% comprise surface waters in lakes and rivers [18]. Of the 0.3% available for human and animal consumption, much is inaccessible due to unreachable underground locations and depths [19]. Jury and Vaux Jr. [3] caution that focusing on the global freshwater storage resource alone is misleading because much of the water is inaccessible. They suggest that humanity's freshwater resource consisting of rainfall used to grow crops, accessible groundwater, and surface water be considered.

1.1.2 Water Scarcity

Although no common definition of water scarcity exists, Rijsberman [2] defines a water insecure person as an individual who does not have access to safe and affordable water to satisfy his or her needs for drinking, washing, or livelihood. A water scarce area is then said to be an area where a large number of people are water insecure for a significant period of time, e.g., Rijsberman [2]. Rijsberman [2] points out that an area qualifies as a water-scarce area depending on, e.g., (i) the definition of people's needs and whether the definition takes into account the needs of the environment, the water for nature, (ii) the fraction of the resource that is made available (or could be made available) to satisfy these needs, and (iii), the temporal and spatial scales used to define scarcity.

Even though Rijsberman [2] argues that at a global scale, and from a supply and demand perspective, it is still debatable whether water scarcity is fact or fiction, it is incontestable that fresh water is increasingly becoming a scarce resource and shortages could drive conflict as well as negatively hit food and energy production [3, 20, 21] (see Fig. 1.1). That water shortage is emerging as one of the leading challenges of the 21st century has been documented, e.g., in [2, 22–24]. To underscore the

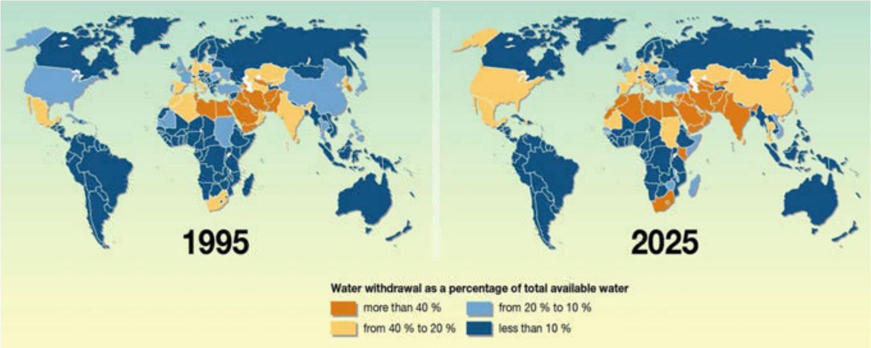

Fig. 1.1 Increased global water stress. *Source* [37]

seriousness of water shortage, the World Bank in its 1992 World Development Report pointed out that 22 countries faced severe water shortage while further 18 were in danger of facing shortages if fluctuation in rainfall persisted [25]. Recent studies, e.g., [26–29, 80, 81] point to fluctuation in rainfall in parts of Greater Horn of Africa where most low income earners depend on rain fed agriculture for food production, thus suggesting that the water shortage problem is not fading away any time soon. A more gloomy picture is the estimate that by 2050, about two billion people will be short of water, a potential cause of conflict [30]. That a large population of the world will face water scarcity is supported by several studies, e.g., [5, 31–34], with the most likely to be affected dwelling in Africa, Asia and the Middle East, see, e.g., [24, 35, 36, 82]. Already, model projections, see e.g., [7] suggest a 40% of the population languishing under water scarcity, with 57% likely to be water stressed by 2015 and 69% by 2075 [23, 31].

By reviewing several publications on water in relation to poverty and environmental degradation nexus, Duraiappah [25] presents activities that lead to water shortages. ***First***, there is the issue of the commercial interest of the rich and wealthy driven primarily by power, greed and wealth that benefits from market and institutional failures (e.g., absence or misuse of water property rights). ***Second***, Duraiappah [25] attribute over usage of water supply by the small holders (the poor) to water subsidies that provide incentives. Of the two groups, the poor are more likely to be affected by water shortages as compared to the rich, a situation that could contribution to environmental degradation on the one hand, which would lead to poverty on the other hand, i.e., endogenous poverty causing environmental degradation, see, e.g., Duraiappah [25].

This picture leads Jury and Vaux Jr. [3] to warn that "without immediate action and global cooperation, water supply and water pollution crisis of unimaginable dimensions will confront humanity, limiting food production, drinking water access, and the survival of innumerable species on the planet". They list the following four factors to support their hypothesis that the world is headed towards a future where billions of people will be forced to live in places where their food and water requirements will not be met [3]:

1. Unlike estimates of the global supply of scarce minerals or underground fuels, which are surrounded by uncertainty, planetary supplies of water are relatively well characterized. No large deposits of groundwater await human detection in readily accessible locations, so that any new resources discovered will be very expensive to develop.
2. Many vital human activities have become dependent on utilizing groundwater supplies that are being exhausted or contaminated.
3. Much of the population growth projected for the next century will occur in areas of greatest water shortages, e.g., Africa and Asia, and there is no plan for accommodating the increases.
4. Global economic forces are luring water and land from food production into more lucrative activities such as biofuel, see, e.g., [38, 39, 79], while at the same time encouraging pollution that impairs drinking water quality for a large and ever-growing segment of the population.

Evidently, the management of water resources' conflicts, focusing on negotiation, mediation and decision-making processes, in order to prevent, manage and resolve water conflicts is emerging as a contemporary and topical research issue.

Physical water scarcity is evident in densely populated arid areas in many parts of Central and West Asia, and North Africa with projected availabilities of less than 1000 m^3/capita/year [2]. This has a wide range of negative impacts and ramifications. For instance, it results in higher incidences of waterborne, water-related or sanitation-related diseases such as malaria, diarrhoea and skin infections. In addition, as has been pointed out before, increasing cases of water conflicts, especially between pastoralist and farming communities along lower and upper river basins, as witnessed in water stressed countries like Kenya [41] (with a renewable freshwater per capita endowment estimated at about 548 m^3/capita/year [40]), are also likely to heighten food insecurity. Alcamo [31] point to the fact that 12% of the global basins are already vulnerable to water withdrawals. On the gender scale, since women are the primary collectors, users and managers of water for domestic use in most developing countries, water scarcity disproportionately affects them because it is they who have to trek long distances, often all day, in search of water. Against the above background, is the growing realization today that availability of sufficient, accessible and quality potable water is not only a matter of great socio-economic and political importance, but also one of fundamental human rights, see e.g., [42–45].

1.1.3 Impacts of Climate Variability/Change on Freshwater

Intergovernmental panel of climate change [83] projects a temperature increase of 1.5 °C by 2030, an increase which will definitely have an enormous impact on the world's freshwater. That temperature has been on the rise due to human's carbon footprint had been noted in the previous IPCC (2007 and 2013) reports [84]. Infact, [85] points to the fact that the global and ocean temperatures rose by 0.85 °C [0.65–1.06 °C] over the period 1880–2012, 0.89 °C [0.69–1.08 °C] from 1901–2012, and 0.72 °C [0.49–0.89 °C] between 1951 and 2012. Change in climate resulting in the temperature rise above as well as climate variability exemplified through indicators such as global teleconnections such as ENSO [86, 87] impact on the availability of freshwater. For instance, climate variability influence extreme whether/climate conditions resulting, e.g., in increased frequency and severity of droughts [81, 88, 89]. Droughts majorly affect the surface water although a long spell could also impact on groundwater [90, 91]. Moreover, the influence of climate variability/change on the hydrological cycle impacts on precipitation, which is the main recharge of freshwater.

1.1.4 Water-Poverty-Environment Nexus

Water plays a significant role both in poverty alleviation and environmental related issues. With regard to poverty, food policy contributes toward the overall goal of eradicating extreme poverty and hunger, and is dependent on water as one of the drivers for realizing such a goal, see e.g., Hanjra and Qureshi [46]. It provides a key component of agricultural requirement for food production as well as for domestic use. If people are able to provide food, then absolute poverty measure of a society could arguably be low. Indeed, that water and food security issues are closely linked has been pointed out, e.g., by [10, 46]. Rijsberman [2] is even more direct by stating that water will be the major constraint for agriculture in the coming decades, more so in the continents that experience high percentage of poverty such as Asia and Africa.

The problem, however, is that more focus is placed on the water crisis, which is likely to be fuelled by increased population leading to about 1.2 billion lacking water. To the contrary, less documentation exist for the large part of the population that live in rural areas below the poverty line. Duraiappah [25], through literature review, identified

- water shortage, and
- water pollution

as the two major issues within the water sector that plays an important role in the poverty-environmental degradation nexus. Understanding the link between poverty and environment in relation to water, therefore, calls for a more closer look at the whole issue of water scarcity in relation to the poor rather than a holistic approach where such scarcity is viewed in terms of the total population. This in essence calls for poverty eradication measures to incorporate issues that will address water scarcity and insecurity. This is partly because if the poor are unable to access clean and safe water, food productivity will be hampered leading to hunger and malnutrition hence less productivity. Also, lack of access to safe drinking water by the poor will only aggravate the risk of water borne diseases such as cholera. When the low income group are faced by such water-borne diseases, their productivity deteriorates and they risk losing their jobs, and hence sources of income. The expected outcome of loss in income is that the low income earners will experience economic and social hardship, which over time results in poverty, thus exemplifying how environmental degradation causes poverty, e.g., [22, 25].

1.2 Water Resource Monitoring

1.2.1 Need for Monitoring

The importance of water as a resource, therefore, calls for sound environmental conservation measures that enhance its protection and management. It is in relation to this that the World Bank, as an emerging priority of its lending framework, 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 [40]. The protection and management of water resources calls for an elaborate and well established management and monitoring program, e.g., [47, 48].

Information about water resources and the environment is inherently geographic. Maps, whether on paper or in digital Geographical Information System (GIS, see e.g., [47, 48]) formats, continue to be the medium for the expression of engineering plans and designs. This is because we are basically concerned about the spatial distribution and character of the land and its waters. Johnson [49] argues that weather patterns, rainfall and other precipitation, and resultant water runoff are primary driving forces for land development, water supplies, and environmental impacts and pollution. Our water resources systems comprise dams and reservoirs, irrigated lands and canals, water supply collection and distribution systems, sewers and storm water systems, and flood plains. These systems are designed in response to a complex mix of topography and drainage patterns, population and land use, sources of water, and related environmental factors [49, 92].

In general, the planning and engineering design processes used in the development and management of water resources involve different levels of data abstraction. Data are collected and used to characterize the environment at some level of detail, or scale. In seeking to make decisions about plans and designs, data must be collected to describe the resource, and procedures or models must be developed to predict the resultant changes. These data and models help us understand the real world, and this understanding guides our decision making [49].

According to Taylor and Alley [50], essential components of a water level monitoring program include; *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, the authors state that the decisions made about the number and locations of observation wells are crucial to any water-level data collection program [50], see also [91]. In regard to locations, Global Navigation Satellite Systems (GNSS) satellites [51, 52] 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., [50].

Taylor and Alley [50] present areas where the monitored ground water 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, e.g., [91]; 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) modeling 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. This information will [53]:

- 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 enhance and compliment their works. 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 semi-arid climates, which include many parts of Australia, especially in times of severe drought, as experienced in Murray Darling Basin [53]. In 2006, Australia faced its worst drought in a century as was seen from daily reports that were emerging in both the local and international media. A more grim picture of the future of the water situation for Australia was to follow from the IPCC [54] 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) that will enhance the analysis of water scarcity at river basin or more localized scales. Indeed, this argument is supported by Rijsberman [2] who states that the global analysis of water scarcity is of very limited use in assessing whether individual or communities are water secure. To this effect, Rijsberman [2] states:

> The river basin is more and more adopted as the appropriate scale to understand the key processes with increasing water scarcity as human use goes up to the point where basins "close".

One such technique that has emerged supreme in monitoring changes in stored water at river basin scales, is the Gravity Recovery and Climate Experiment (GRACE) satellites [55] discussed in details in Sect. 5.3.3; see details in [47, 48, 51, 52, 90].

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) 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 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. 5.3), 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 [56], 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.

Environmental studies 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 [57].

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. Remote sensing and GIS [47, 48] can be used to monitor the water quality. This is possible by employing multispectral, multi-temporal image data and analyzing parameters such as the distribution of suspended sediment, turbidity and chlorophyll. These indicators can be determined through regression analysis.

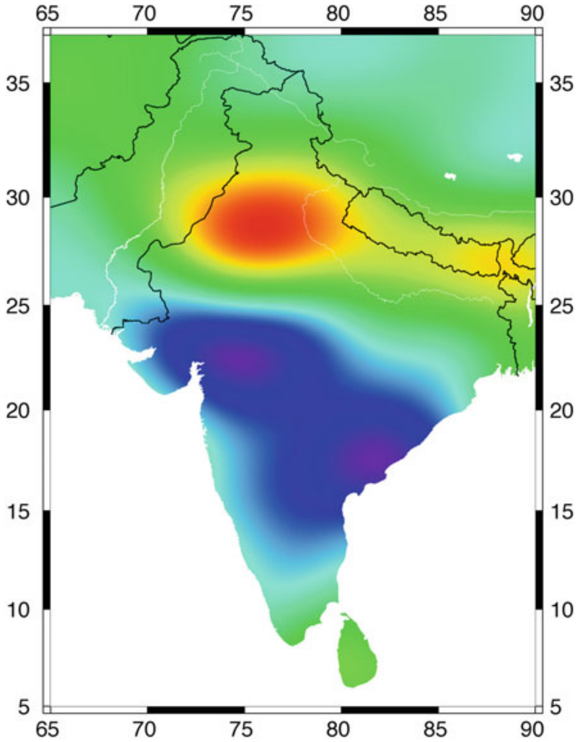

Fig. 1.2 Groundwater changes in India (2002–2008). Groundwater recharge is indicated by blue while depletion is indicated in red. *Source* NASA (I. Velicogna/UC Irvine)

1.2.2 Monitoring of Stored Water at Basin Scales

In Awange and Kiema [47, 48, 51, 52], the *geoid* is introduced 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 [58, p. 29]. In Chap. 5, the concept of *gravity field variations* is related to hydrological processes. Measurements of the time-varying gravity field by LEO (low earth orbiting) satellites, e.g., GRACE discussed in Sect. 5.3.3 are the key to the contribution of space monitoring of changes in water levels at basin scales, see e.g., [59]. Such techniques now enable the monitoring of groundwater recharge, see e.g., [60, 61, 90], which is the most important element in groundwater resources management and could also be applicable to monitoring salinity management measures at the catchment level. For example, in 2009, GRACE satellites showed that north-west of India's aquifers had fallen at a rate of 0.3048 m yr^{-1} (a loss of about 109 km^3 per year) between 2002 and 2008, see Fig. 1.2.[1]

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

1.3 Why Monitor Lake Victoria?

Lake Victoria (Fig. 1.3), the world's second largest freshwater lake, and the largest in the developing world, is a resource shared by the three East African countries: Kenya, Uganda and Tanzania. It is a source of water for irrigation, transport, domestic and livestock uses, and supports the livelihood of more than 42 million people who live around it [62, 93]. Its fish products, (i.e., Tilapia and Nile Perch) are exported the world over [62]. Its role as an indicator of environmental and climate change on long-term scales together with its global significance are documented, e.g., in Nicholson and Yin [65] and Awange and Ong'ang'a [62]. Since the 60s, the lake level has exhibited fluctuations as pointed out by Nicholson [63, 64] . The sharpest rise in the lake water level occurred during the El'Nino rains of early 60s and 1997/1998. Some reports, e.g., [66] suggest that the lake level rose by 2.5 m following the 1960s floods. Kite [67] attributed this rise to over-lake precipitation.

Although the lake has continued to attract worldwide attention due to its significance and other environmental phenomenon such as water hyacinth, in the last decade, and perhaps most threatening, Lake Victoria water level receded at an alarming rate causing concerns as to whether the lake was actually drying up as it happened in the pre-historic time, see e.g., [10]. According to Kull [68], the lake levels

Fig. 1.3 Lake Victoria basin (*Source* Kayombo and Jorgensen [70]) and weather stations (black triangles) in the Kenyan part of the region

dropped to more than 1.1 m below the 10-year average. Water levels have remained above average for more than 40-years, but current water levels are below normal and the lowest level since September 1961. The socio-economic impacts of this drastic fall in Lake Victoria water level have been reported in Awange et al. [10, 69]. At the time of writing this book (2020), the lake level has risen to a point where people are wondering whether it is retracing its shorelines of the 60s. Continuous monitoring of the lake, therefore, is paramount to its sustainable utilization, policy formulation and management.

1.4 Objectives and Aims of the Book

As part of the solution to water scarcity problem, quick fix approach has revolved around supply management approach where infrastructures, e.g., dams have been constructed or expanded to increase the available water supply. Rijsberman [2] argue, however, that although the quick fix approach has largely succeeded in producing cheap food, water supply, and sanitation to a large number of people, many people still do not have access to safe and affordable drinking water despite huge investments. Rijsberman [2] states:

> …close to half the world population lacks access to sanitation, many rural poor do not have access to water for productive purposes, groundwater levels in key aquifers are falling rapidly, many rivers are no longer reaching the sea, etc.

As a shift from this school of thought, Rijsberman [2] points to the emergence of integrated water resource movement that has brought about organizations such as the World Water Council and the Global Water Partnership that is pushing for a demand management approach seeking;

1. to involve users more in the management of water, often through the establishment of forms of water user associations;
2. to price water and/or make it a trade-able commodity; and
3. to establish river basin authorities that integrate the usually fragmented government responsibilities for water into a single authority responsible for a hydrographically defined area, the river basin.

It is in support to item (3) above that satellites have been recognized as having the potential to provide space-based estimate of changes in terrestrial water storage. In essence, they are tools that 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 space techniques offer such opportunity [10, 71–74]. This is because one of the environmentally important signals detected by satellites such as GRACE is the temporal, e.g., gravity field variation induced by changes in the distribution of water on and below the Earth's surface, i.e., hydrology, e.g., [74]. Satellite altimetry provides the possibility of monitoring sea or lake surface heights as was demonstrated for Lake Naivasha [75]. Other studies undertaken with respect to use of GRACE to monitor hydrology include, e.g., [53, 60, 76–78, 90].

The aim of this book, therefore, is to provide a space (satellite) view of Lake Victoria. Owing to its large basin [94, 258,000 km^2], "boots on the ground" monitoring of Lake Victoria in terms of the fluctuation of its level, impacts of climate change and anthropogenic factors, the behaviour of vegetation within its basin, and the extremes, e.g., droughts, is practically impossible. The most viable approach is to turn to space techniques to remote sense the lake [95], what is demonstrated in the present book.

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