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Earth observations for global water security

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The combined effects of population growth, increasing demands for water to support agriculture, energy security, and industrial expansion, and the challenges of climate change give rise to an urgent need to carefully monitor and assess trends and variations in water resources. Doing so will ensure that sustainable access to adequate quantities of safe and useable water will serve as a foundation for water security. Both satellite and *in situ* observations combined with data assimilation and models are needed for effective, integrated monitoring of the water cycle's trends and variability in terms of both quantity and quality. On the basis of a review of existing observational systems, we argue that a new integrated monitoring capability for water security purposes is urgently needed. Furthermore, the components for this capability exist and could be integrated through the cooperation of national observational programmes. The Group on Earth Observations should play a central role in the design, implementation, management and analysis of this system and its products.

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Introduction

Concerns about the sustained availability of safe water are increasing based on the expansion of water problems around the world. Recent projections reported by the UN Department of Economic and Social Affairs (UNDESA) suggest that up to half of the world's population will be living in areas of high water stress by 2030 [1]. Furthermore, much of the world's population increase will occur in developing countries where water scarcity and water quality concerns are expected to cause tensions among sectors (e.g. agriculture versus urban users) and impediments to co-balancing human needs and ecological requirements. Every year more than one and a half million children and adults without access to safe drinking water and sanitation die or experience severe health problems [2]. In the face of these rising pressures on water resources, monitoring becomes critical on all spatial and temporal scales because it contributes a systematic and transparent approach for resolving water issues.

This article emphasizes the connections between water security, sustainable development, and Earth observations. By way of background, the UN adopted Millennium Development Goals (MDG) at its UN Millennium Summit in 2000 [3,4]. For more than a decade UN nations have regularly reported their progress in achieving these goals. As discussed at the Rio+20 UN Conference on Sustainable Development, new Sustainable Development Goals (SDGs) are being proposed to build upon the MDGs thereby contributing to the sustainability of the world's resources [5,6].

Linked to these goals is the concept of water security. Although some nations interpret water security in terms of water issues that could affect their own national security [7], this article has adopted the UN-Water working definition that describes water security as: 'the capacity of a population to safeguard sustainable access to adequate quantities of and acceptable quality water for sustaining livelihoods, human well-being, and socio-economic development, for ensuring protection against water-borne pollution and water-related disasters, and for preserving ecosystems in a climate of peace and political stability' [8]. For many of the 31 nations which are poor and currently under chronic water stress [9], it is very difficult to achieve water security without outside help. The first step in obtaining such help for all nations is to utilize better information in the management of the water that is needed by these populations and ecosystems. In addition, as natural variability and extremes are amplified by climate change, there is a need to augment water resource systems to cope with increased variability in the supply. In particular, engineered systems that are optimized based on the assumption of continuity in supply and demand patterns may become vulnerable to trends in light of non-stationarity in the water cycle [10•].

Across many regions, it is not possible for water experts to obtain the data necessary to carry out comprehensive assessments of threats to water security. Earth observations are an essential part of the required knowledge base. They encompass the wide range of information that can be obtained by sensors in the environment and those observing the Earth from satellites or aircraft. Some nations fail to collect adequate observations to document the current state or changes associated with their water resources. Other countries indeed collect the data, but do not distribute them to other nations or experts who could otherwise apply them in conjunction with sophisticated assessment tools. These attitudes towards data exchange and attempts to limit their beneficial use suggest that more proactive initiatives and policies on data exchange and alternative observational systems need to be developed to avert a strategic knowledge gap.

The Group on Earth Observations (GEO), a voluntary organization of 90 member nations and more than 65 international participating organizations, is developing a Global Earth Observation System of Systems (GEOSS) based on interoperability and data sharing [11]. Through its Water Task and its Integrated Global Water Cycle Observations (IGWCO) Community of Practice [12], GEO brings attention to the needs for: better *in situ* water observational networks and new space-based measurement systems, improved data sharing, stronger user engagement, and improved assimilation and modelling capabilities. In addition to regional projects, GEO currently is coordinating the development of global monitoring systems for forestry and agriculture.

We provide here a review of the data required to support water security decisions ('Information needed for addressing water security' section). The ability of observational systems to meet these requirements for each critical variable is then presented in 'Sources of data for improving water security' section, followed in the 'Information Integration and Decision Support' section by an assessment of the information integration needed to fill data gaps and to support applications for decision makers. The article concludes with a summary statement that underlines the need to develop a comprehensive Global Water Security Monitoring System (GWSMS).

Information needed for addressing water security

While one might consider that the data needed to support water security assessments are unique, in practice, they are the same variables used for water management decisions. Unninayar *et al.* [13] documented the data and information needs of water managers with different responsibilities for water data and services. When the information needs of water managers along with the needs of users from several sectors were reviewed, precipitation and soil moisture were the two most frequently requested variables. For water security issues, emphasis must also be placed on river discharge, surface water storage, snow water equivalent, groundwater, and water quality and sediments.

For water security applications, individual water management decisions must be contextualized since these decisions have cumulative impacts and consequences over time and space. For example, the simple approval of a water allocation request for irrigation water often proves to be more complex when assessed within a broader water security framework. Within such a framework, water supply projections, competing priority demands and water quality needs would also need to be evaluated in making assessments. Although the information used would rely on observations and hydrologic models, decision makers would need access to more accurate data with specific error estimates and access to the historical information necessary for contextualizing the decision into a broader regional or global water security framework.

Information for assessing water security needs must be provided to policy makers and politicians who are then able to publically articulate whether the water security situation is improving, remaining constant or deteriorating. This could be done most effectively if quantitative goals were set, supported by information from a monitoring system, such that policy makers could readily determine whether a nation or basin was progressing towards water security. The development of SDGs could be helpful for clarifying which variables and space scales need to be emphasized in a monitoring system. In addition, they could help to develop a more robust monitoring system by relying on fully objective and transparent sources of information based on Earth observations and serve as the recognized basis for decisions by the UN bodies or panels responsible for reviewing progress on the implementation of SDGs. This approach would enhance the more prevalent in-country evaluations and surveys that were commonly used to assess progress on the MDGs.

To address water security issues, decision makers require information on the current state of the system and on future states for assessing progress and problems and to facilitate planning and problem mitigation. These types of information are regularly reviewed by GEO at both the user need definition and the system development levels. With its focus on interoperability, data integration and analysis, and capacity development, GEO is in an excellent position to guide the development of a water strategy monitoring system as part of its post-2015 work programme.

Integration is important for the communication of information related to water security. Policy makers indicate that a few meaningful indicators are more relevant to their needs than large quantities of unprocessed data. They need indicators that answer questions such as: ‘How is the state of the system trending?’, ‘Are there particular areas that are trending differently (e.g. hot spots)?’ and ‘What steps do we need to take now?’ Indicators such as the human water security index [14•] have proved to be powerful tools for communicating global water conditions to a broad audience. A comprehensive water security index that incorporates the information needed to answer these questions could prove to be a very powerful tool for interacting with policy makers. For example, drought indices, which have gained a great deal of credibility over the last few years [15], are examples of some successful metrics upon which society increasingly relies.

Sources of data for improving water security

The commonly used phrase ‘You can’t manage what you can’t measure’ is simple yet profound. Water managers and stakeholders alike need access to appropriately cast information to pursue their stewardship of water resources. Both *in situ* and satellite observations of water cycle and water quality variables are needed. *In situ* measurements provide detailed histories of water system trends and variability at specific locations. Interpolation between these measurement sites using satellite data can provide estimates of the two-dimensional distribution of water cycle variables. Satellites provide data that are geospatially consistent and can often provide data fields at spatial resolutions not attainable from field-based measurements except for a few areas with high density *in situ* observational networks. The synoptic and repetitive global coverage of satellite data products provides water managers with the information needed to assess complex issues, including transboundary inconsistencies that arise from the mismatch between political and physical boundaries. Baseline data for strategic water goals can be developed from long-term, temporally consistent data products that have been developed to aid in water cycle research such as cloud cover, precipitation, radiation, snow, soil moisture, water levels, and vegetation type [16]. The current status of the most critical variables for water security, re-purposed to support water security objectives, is discussed below.

Precipitation

Precipitation is a key, if not arguably the primary determinant of water security. The absence of precipitation leads to droughts, crop failures, and shortages in water deliveries for industrial and domestic users. Excess precipitation leads to floods and infrastructure damage. Accurate precipitation measurements as well as forecasts are thus essential for planning purposes based on expected water availability over different time scales from hours to years. The complexities and uncertainties in precipitation predictions particularly at lead times of more than two weeks are leading some water managers to adopt risk management approaches to deal with these uncertainties [17,18]. For example, water managers in Chile are adapting to drought risk by incorporating forecasts of precipitation into a more probabilistic framework [19].

Arguably, the most accurate point measurements of precipitation still come from ground-based gauges, which together with adequate gauge densities provide precipitation fields over administrative units as well as drainage basins [20]. Gauge data also improve satellite data products. Hu et al. [21] showed that data products with gauge data are much more reliable than uncalibrated satellite data products.

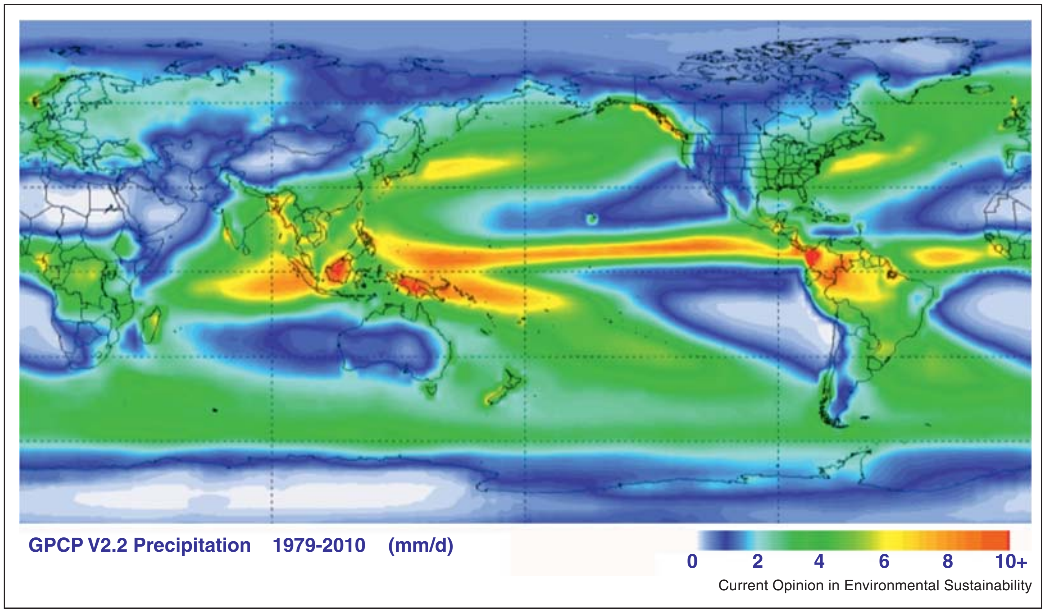
In recent decades, satellites have been able to provide increasingly reliable information on global precipitation. Initially, precipitation was derived from visible/infrared images from geostationary meteorological satellites (including GOES, GMS, and Meteosat) [22] and it is now supplemented by information from microwave sensors on polar-orbiting satellites such as the Tropical Rainfall Mapping Mission (TRMM, NASA/JAXA) which provides more direct estimates of rainfall. These data are used in the Global Precipitation Climatology Project (GPCP) (see Figure 1), which produces integrated satellite and gauge products of monthly mean precipitation from 1979 to the present [23]. These estimates will be provided by the Global Precipitation Measurement (GPM) Core Observatory that is expected to launch in 2014.

Soil moisture

Soil moisture connects climate dynamics with water and food security. Agricultural areas with inadequate soil moisture during the growing season frequently rely on irrigation to maintain soil moisture levels so that plants can grow vigorously in spite of dry conditions. On a global basis, irrigation accounts for 70% of the world’s water consumption with this number being much higher in some countries [24,25]. Soil moisture data could be used by knowledgable producers to ensure that only dry soil is irrigated thereby producing major water savings. In addition to ensuring plant growth, soil moisture also influences climate through the partitioning of energy between sensible, latent and ground heat. Soil moisture also has a feedback effect on regional precipitation [26] and determines runoff by affecting the partitioning of rainfall between runoff and infiltration. Estimates of soil moisture content are critical during floods because the amount of moisture in the soil affects the amount of runoff generated from a given amount of precipitation [27–29].

In situ soil measurements are routinely taken only in countries with recognized information needs and adequate budgetary resources to maintain an observational network. The lack of measurement standards for *in situ* measurements in different countries makes it difficult to produce consistent maps of soil moisture even on a regional basis. However, globally consistent surface soil

Figure 1



Long-term (1979–2010) integrated Satellite-Gauge (SG) GPCP annual average precipitation product. (Source: World Climate Research Project's (WCRP) Global Energy and Water Exchanges (GEWEX) Global Precipitation Climatology Project (GPCP) courtesy of Dr. George Huffman). The map shows the effect of the large scale atmospheric circulation patterns on the global distribution of precipitation with large amounts along the equator and smaller values in the subtropics, as well as continental effects that lead to higher amounts on the coasts of large continents and lower amounts in the interiors of Asia, Africa, Australia and North America.

moisture maps are now being provided by ESA's Soil Moisture and Ocean Salinity (SMOS) mission, which launched in November 2009 [30]. These new SMOS products are providing improvements over the soil moisture maps currently derived from AMSR-E, TRMM, and other satellites [31,32]. NASA's Soil Moisture Active/Passive microwave satellite (SMAP), which will provide higher resolution soil moisture products, is scheduled for launch in 2014. Although these missions provide information about the moisture contained in surface layers of the soil, they need to be used in conjunction with models to address the effects of vegetation and rugged topography on the signal and to provide estimates of the root zone moisture that are useful for agricultural applications.

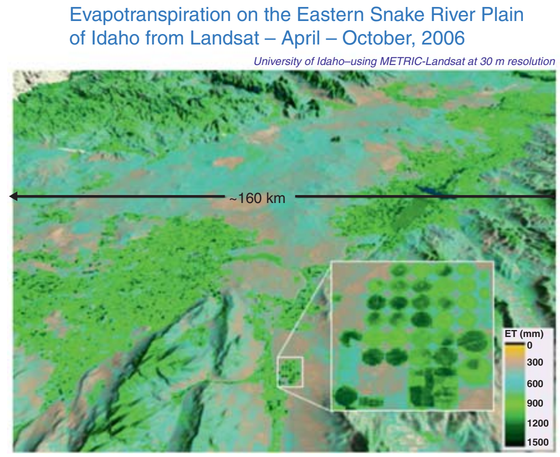
Evaporation and evapotranspiration

Evaporation accounts for significant losses of useable water from reservoirs, lakes and wetlands. Evapotranspiration (ET) is an essential part of plant growth and is closely coupled with the process of photosynthesis. In the Western USA, ET estimates derived from satellite data have mapped water losses associated with irrigation [33,34]. Applications of this information have resulted in large savings by reducing labour costs associated with monitoring irrigation water use. Figure 2 shows a high resolution ET product of the type that is used in these monitoring programmes [35,36]. Satellite and model estimates of ET are crucial for monitoring vegetation health and biomass production, and for accurate estimates of the components of the energy balance. ET is generally estimated from satellite data in combination with energy and water balance models. Model inputs are frequently obtained from the visual and thermal bands of GEO, MODIS, MERIS, AATSR, TRMM and Landsat satellite sensors. In particular, most satellite ET algorithms use the thermal bands to estimate land surface temperatures and ET [35]. Multiple thermal band remote sensing systems are needed to provide ET data at higher temporal resolution from geostationary platforms and moderate spatial resolution and daily imaging from polar orbiting systems such as MODIS (daily at 1 km) [35,37].

Runoff/river discharge

Runoff and river discharge are essential variables for water management since they represent water that is not bound to the soils or vegetation in the biosphere and hence is available for use in water resource allocation and delivery systems. Historical streamflow measurements are essential for many applications, including designing and operating engineering works (dams, reservoirs, river regulation, etc.). Real-time discharge measurements are needed for water-related services including navigation, flood protection, water supply for irrigation,

Figure 2



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Evapotranspiration mapping on the eastern Snake River plains of Idaho from Landsat data from April through October, 2006 using a 'METRIC' approach. Evapotranspiration water loss is shown in millimetres at the field scale to a 30 m resolution [36]. The circles are crop areas which have been irrigated by central pivot systems. The very light areas between the green circles have little vegetation and represent areas which received only the summer rainfall. These ET maps show where irrigation has occurred and how effective it has been for crop growth.

municipal and industrial water use, and the maintenance of environmental flows [38–40].

River discharge is generally determined using in-stream velocity measurements, knowledge of cross-sectional flow areas that then calibrate to hydrometric gauges which relate the water level to the river discharges using automated reporting systems [41]. Although these observations are critical for water security and climate model development, the number of hydrometric stations has been in decline for almost three decades due to budget reductions and privatization of data archives [42]. As Figure 3 shows these factors along with continued reluctance to share data internationally are making it difficult to maintain a comprehensive global in situ data archive. Currently, remote sensing techniques for discharge estimation are not suitable for replacing in situ streamflow observations but can provide highly valuable complementary information. Monitoring water levels using radar altimeters and other satellite based techniques [43–46] provides good vertical accuracy (5–10 cm) for large rivers in comparison to *in situ* observations during high water levels but are limited to wide rivers and larger lakes and reservoirs.

Groundwater

Groundwater is increasingly being used to meet water needs in places where precipitation, runoff and surface storage are inadequate to meet the demands. This overdependence on groundwater has led to long-term threats to water security where water is being withdrawn from aquifers much faster than natural processes are able to replenish it. This practice has led to land subsidence and deteriorating water quality [48,49].

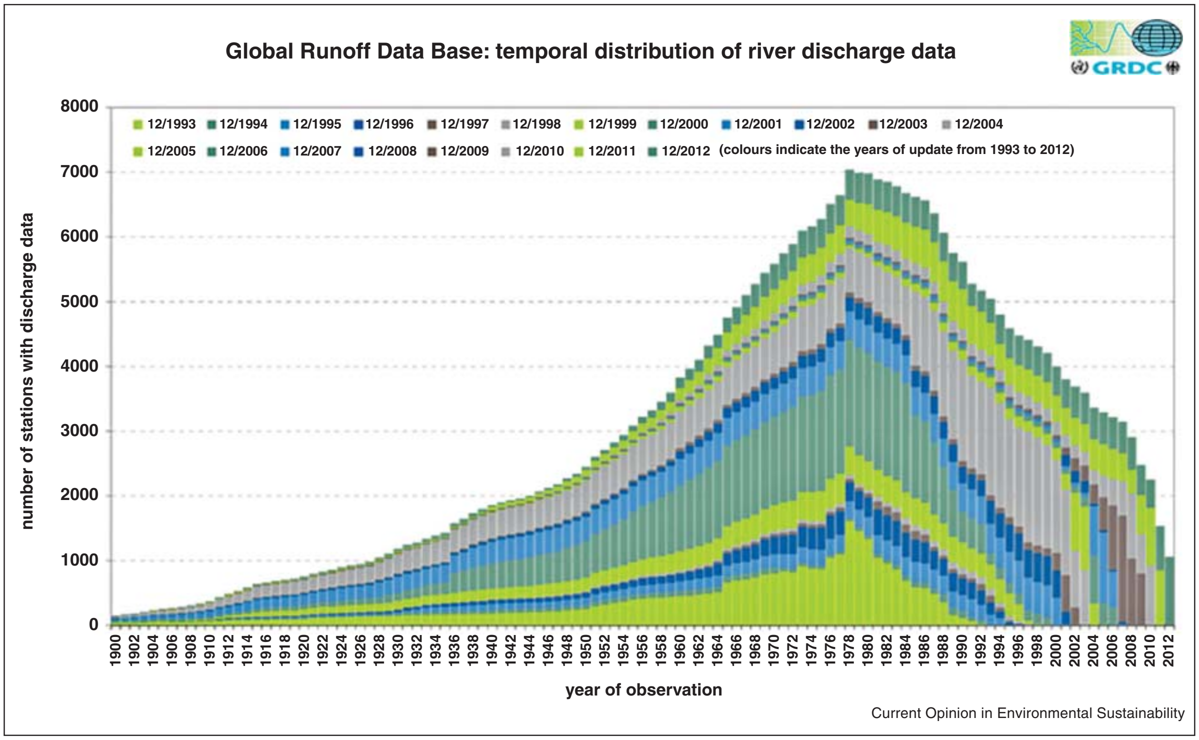
Most countries measure groundwater using well networks. Although these measurements are acquired most countries do not share them internationally. Furthermore, these data are not always systematically calibrated, making the development of a global groundwater data base very challenging [50•]. Large-scale assessments of groundwater changes are being developed from gravimetric measurements provided by the Gravity Recovery and Climate Experiment (GRACE) mission and postdata processing using a suitable data assimilation system. This technique is very useful in measuring changes in groundwater levels [51,52]. Although the measurements are of coarse scale, these products have highlighted some of the problems occurring in the Middle East and Northern India where groundwater pumping for irrigation purposes is dramatically reducing groundwater levels (see Figure 4) [53•].

Water quality and fluvial sediments

Water needs to be fit for its many roles in society. For domestic users this means that water must be safe to drink and use for other basic household purposes. In a growing number of areas industrial pollution and contaminants constrain the use of water. Without adequate water quality monitoring this water may be used even when it is hazardous to human and environmental health. *In situ* measurements are essential to accurately characterize water quality. The majority of water contaminants can only be measured by in-stream sampling and there is a continued requirement for field measurement programmes. However, as indicated by the absence of data from many countries in the United Nations Environment Programme (UNEP) Global Environmental Monitoring System (GEMS) Water Quality database [54], not all countries can afford this type of monitoring programme. In light of these limitations, there is evidence that certain types of pollutants such as algal blooms produced by nutrient rich runoff entering a lake could be operationally monitored from space [55]. Work is ongoing to determine the extent to which optical satellite data can be used to infer water quality by measuring sediment loading, chlorophyll concentrations, algal blooms, and general turbidity and to assess the extent to which these variables can be used as surrogates for other water quality variables [56].

The sediment budget of fluvial systems is characterized by the complex interaction of erosion, transport, deposition, storage and remobilization of sediment, which are also important processes for water security, because they affect water quality, infrastructure, economy and ecosystems [57,58,59•]. Some pressing problems concerning

Figure 3



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River discharge data holdings at the Global Runoff Data Centre (GRDC) [47]. The graph shows the effects of the time lag between the collection of data and its transmission to GRDC as well as the effects of national cutbacks in the number of hydrometric stations.

water security are the sedimentation of reservoirs [60], the impact of dams on downstream ecosystems and river sediment fluxes (e.g. [61] for the Yangtze River), as well as the contamination and eutrophication of inland and coastal waters through sediment-associated substances [62–64]. Holistic, interdisciplinary approaches involving the complete sediment system of a catchment [56,65] and improved data availability [66] are needed. Most sediment data are from *in situ* measurements collected by national and regional agencies, which operate monitoring stations or networks, research institutions and individual researchers, and operators of infrastructure like harbours and dams. Suspended sediment loads of water bodies can be derived from air-borne or satellite remote sensing data [56] and sediment yields can be modeled on a global scale (see e.g. [67]).

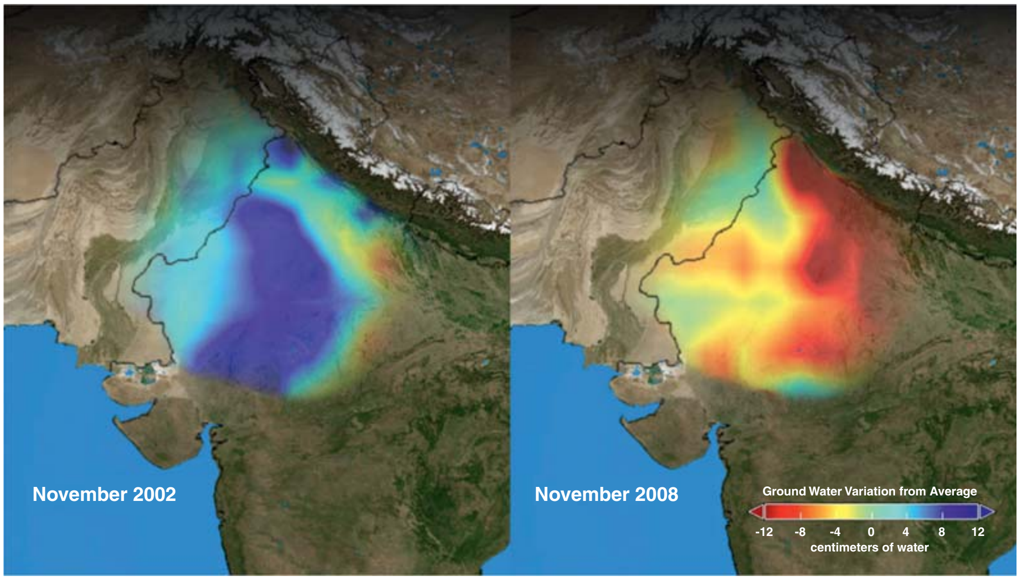
Information integration and decision support

On the basis of the discussion in 'Sources of data for improving water security' section, it is evident that there are many gaps in the data available for water management from the current set of *in situ* observational networks and satellite missions. Thus, to obtain the most accurate and comprehensive description of the spatial distribution of a given variable at a point in time it is often necessary to combine data from many different sources [68]. For example, precipitation data sets have been improved upon by integrating higher frequency *in situ* point measurements with less frequent but spatially consistent satellite data to give better rainfall accumulation estimates. *In situ* data and satellite data are also being combined through algorithms in the production of ET and soil moisture products [69,70].

In the case of river discharge where such estimates from space are only available today for the largest of the world's rivers, precipitation data can be used in combination with hydrological models to produce improved discharge estimates. Data-model integration is also being exploited in land data assimilation systems to provide higher spatial resolution or to derive quantities that cannot be measured directly (e.g. vadose zone soil moisture) and to ensure consistency in spatial data sets [71,72]. Figure 5 shows the principal elements of a Land Data Assimilation model.

Other types of data integration are also relevant to monitoring for water security. Developing information for decision makers often requires that the analysis of

Figure 4



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Groundwater variations estimated from GRACE reveals massive groundwater depletion in northwest India. The figure shows trends in groundwater storage during 2002–2008, with increases in blue and decreases in red [53•].

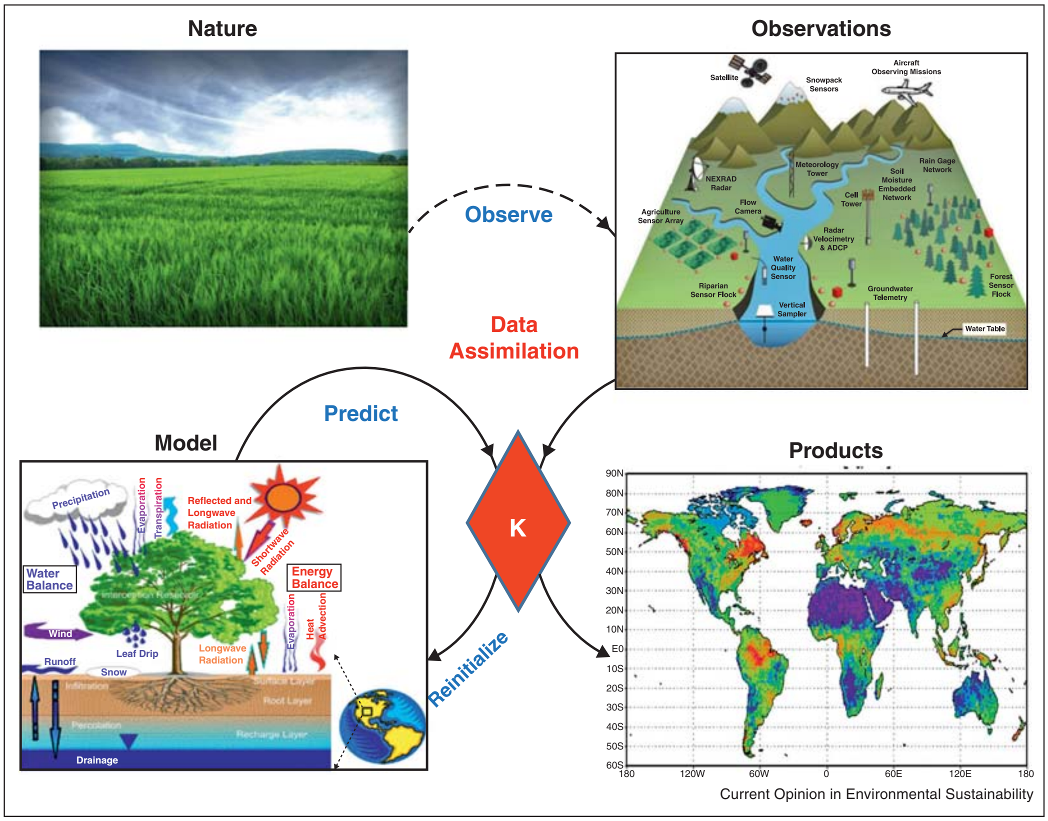
hydrologic data or model output be integrated with other types of information to assess how water security is trending in the context of some other change agent. In particular, these analyses must often be used in conjunction with a prediction model because decision makers need both analysis and prediction information to assess future states and potential impacts on water security. For example, it is often not enough to know that soil moisture values are decreasing but what, more specifically, are the effects of this decrease on crop production (see [73] for a soil moisture example). New areas where data-model integration is required includes assessments of the status of the Water-Energy-Food Security Nexus [74] and the incorporation of water security processes in Earth system models (see Ringler *et al.* in this special issue.)

Within GEO a major activity known as the water cycle integrator is being developed [12]. Plans for this initiative consider integration between observational systems, data sets, analysis techniques, models, research and policy, and education. A functional version of this Integrator is under development at the University of Tokyo [75,76].

Water security and emergency response has benefited from another, though less structured, approach to integration that involves development of platforms such as the SERVIR hubs from which information can be made available in many formats to a wide range of users [77]. NASA and USAID have established regional SERVIR hubs in East Africa, the Hindu Kush–Himalayan region, and Central America. Satellite based water information is made freely available from these hubs to users in the regions.

These centres along with other application studies are providing evidence that water information can have major social benefits when it is made readily available in a timely manner. The SERVIR systems in Asia and Africa are providing flood warning services that are saving lives. The node in Nepal is using an eight-day transboundary forecast system based on JASON-2 satellite altimetry and a flood forecast model to produce flood warnings. These models and global data sets are providing information across national boundaries in areas where up to one-third of casualties from transboundary flooding have occurred [78]. In East Africa, SERVIR capabilities are strengthening national hydrometeorological services. The Kenyan Department of Water Resources Management and Rwanda services are adopting SERVIR tools to provide their officials with flood warnings with sufficient lead times so people can evacuate before the flood arrives. Currently the East Africa SERVIR node is incorporating its flood alerts into its mobile text-alert system. At the larger scale, a Global Flood Monitoring System (GFMS) (see http://flood.umd.edu/) is being developed which will use TRMM Multi-Satellite Precipitation Analysis

Figure 5



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Major elements of a land data assimilation model (modified from [72]). Observations from different sources are consolidated and used to initialize a model, which then makes a prediction for the next time step that is evaluated against the next set of observations. The K in the figure refers to the Kalman filter which is the mathematical core for the data assimilation system.

(TMPA) information and a global hydrological model to provide near real-time flood warnings quasi-globally to 50°N–50°S.

Such integrated systems have been used successfully in the water and food security agenda. The Famine Early Warning System Network (FEWSNET), for example, monitors water and drought conditions in Africa by combining information on vegetation and soil moisture conditions with precipitation forecasts to estimate the likelihood of drought or a famine. The system is particularly useful for sub-Saharan Africa and other arid regions where satellite data can help to monitor the progress of drought conditions [79]. At present, the system is providing information derived from Earth observations to more than 30 of the world's most vulnerable, water stressed countries to provide food supply stability to these water-insecure areas. As the effects of climate change become more evident in countries like Sudan, where there has been a recent 20% decline in rainfall with severe impacts to crop production and pastoral communities, the value of such systems becomes evident. Global systems for assessing food production based on assessments of water variability have also been developed and are being applied to improve decisions on global food reserves [80].

Satellite observation and modelling tools are being applied in the Nile Basin to identify water losses and to inform irrigation decisions [81]. Satellite-derived information on land cover and soil properties, including MODIS-derived irrigation maps are used in a high-resolution Nile LDAS to produce estimates of hydrologic storages and fluxes at 5-km grid cells across the Nile Basin. These products are used in regional decision support systems to monitor irrigation needs and use. This system provides but one example of how various functions within a water information system could be harmonized to produce a water security monitoring capability.

Water security and ecosystem state are also being addressed. Through the European Space Agency's (ESA) TIGER project [82], the degradation of the Saloum and Casamance estuaries in Senegal have been assessed using SPOT and Landsat data. Using these data for the 1984–2010 period, investigators found that saline soils expanded while the mangrove system has been degraded. Land desertification, salinization and vegetation degradation that reflect increasing water and soil salinity were also observed. Satellite data were the only source of data to objectively confirm the experiences of local people who reported this degradation.

Conclusions and recommendations

Given the growing importance of water for humankind and the environment, and the potential for future water shortages, it is evident that water security must be addressed as an urgent development imperative. The authors believe that water security issues should be embedded in the UN Development agenda and the SDGs. Furthermore, the formulation of the goals should ensure there is a clear role for Earth observations to contribute to monitoring progress towards these goals.

Given the criticality of water security, goals and targets beyond the SDGs should be discussed and should serve as the basis for a GWSMS. An ideal monitoring and information system should combine existing and potential national and regional capabilities as well as new systems and insights. It should be flexible and address global, regional and local needs. The first phase of the system should integrate *in situ*, satellite and model data to produce a suite of water security products. The second phase should incorporate the prediction capabilities of Numerical Weather Prediction and climate centres and the scenario development efforts of the research community.

This monitoring system also should address critical water security issues on multiple scales, from the global to the local scale. It should build on GEO principles and infrastructure to ensure the information necessary for decision making is made freely available and accessible to all. This principle will encourage transparency in the assessment process and will help to empower each individual to contribute to improved water security stewardship.

To this end, we recommend that organizations and nations step forward to engage in the design, funding and implementation of a GWSMS. A critical part of the GWSMS will be the synergies, interoperability and integration within a holistic water security system framework. GEO is already organizing and providing a blueprint for consolidating national and regional Earth observation capabilities into the GEOSS. Within this framework, GEO would be well positioned to lead the planning of a GWSMS. To be successful, it would also need to engage GEO member nations and organizations such as UN-Water, especially WMO and UNEP, and CEOS. Commitments should be sought from nations that they will maintain and strengthen, as needed, the long-term capacity of *in situ* and satellite Earth observations. Additional support could be garnered through major international research initiatives, like Future Earth, as well as through funding by the Official Development Agencies.

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