Title: **Implementing the GEOSS Water Strategy: From Observations to Decisions**

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Abstract:  
  
In 2014, the Group on Earth Observations in collaboration with the Committee on Earth Observation Satellites published a report, *Implementing the GEOSS Water Strategy - From Observations to Decisions*, identifying priority areas in water-related issues where the application of Earth observations to decision-making would have significant societal benefits. This article provides a brief review of this report before summarizing the status of the implementation of its recommendations. An overview of the Strategy’s assessment of the needs and adequacy of water observations and their applications is introduced. The article identifies needs and plans for observational systems, related research support, and new approaches to information systems and user interactions based on recommendations in the Strategy and describes actions taken in response to the recommendations. It highlights the Strategy’s major themes, including Essential Water Variables, research and product development, interoperability, and capacity development. Finally, the article discusses significant achievements in the implementation of the Strategy, reviews actions taken by participating agencies and programs for each of the main themes, and summarizes the remaining challenges in achieving the full implementation of the Strategy.

**Key words:** Earth observations, Essential Water Variables, Research, Interoperability, Capacity Development

**Main Text:**

**Introduction**

The issues surrounding the availability and use of water on local, regional and global scales continue to challenge water resource managers. A great deal of public attention on water issues is directed at the needs of society for adequate clean water and the future of regional water availability under climate change. For more than four decades some experts have been warning about the vulnerability of our water resources and the world’s under-privileged populations who live in areas where water is at risk and are most vulnerable to environmental change (See Falkenmark and Lindh, 1976). These discussions have prompted the UN to approve water and sanitation as a human right for every person (UNGA resolution 64/292, 2010) and to direct nations to implement Integrated Water Resources Management approaches (see UN SDG Goal 6, Target 5). In addition, regional responses have been brought forward such as the European Parliament’s 2020 directive on the quality of water intended for human consumption (retrieved from <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=LEGISSUM%3Al28180>) and the need to ensure water resource managers can adapt to the impacts of future climate change on water resources (Kundzewicz et al., 2008). Although policy revisions can be useful in making general broad scale changes, water managers in a basin commission or a government ministry are often the ones who have to ensure changes happen in a safe and socially acceptable way. This article describes one way in which the Group on Earth Observations (GEO) is trying to empower decision-makers working within policy frameworks using management initiatives by providing access for decision makers to the best and most relevant information and helping them use the data to assess large-scale changes and guiding them to actions that minimize local and national risks.

GEO is a partnership of nations and organizations that seeks to realize a future where decisions and actions for the benefit of humankind are informed by “coordinated, comprehensive and sustained Earth observations” (GEO, 2005). Since its formation in 2005, this partnership has grown to include 113 member nations and 143 participating organizations (as of August 29, 2022) that work together to coordinate their observational assets and develop mechanisms for making their data and analysis tools available to users in many sectors.

GEO’s overall objective is to develop a Global Earth Observation System of Systems (GEOSS). It has adopted an inclusive view of Earth observations that encompasses observations from Earth-observing satellites, in-situ networks, and specialized observing platforms (e.g., submarines, drones, and citizens). GEO produces three-year work plans that outline each element’s goals and planned activities. The goals are achieved through voluntary contributions from GEO members. GEO has launched many services, including operational global services referred to as GEO flagships, and emerging services known as GEO initiatives because they have financial support and are moving toward a global service. AquaWatch (see <https://www.geoaquawatch.org/>) is an example of a water initiative. Smaller more developmental elements are recognized as community activities (soon to known as pilot initiatives) that are expected to progress toward full initiatives in time. In addition, GEO has four regional groups addressing Earth observations centered in the Americas, Africa, Asia Oceania and European regions. These groups provide a framework for cooperation among countries in each region in the use of Earth observations.

GEO advances awareness of the role of Earth observations in managing social and economic activities, especially for important public policy issues, such as climate change and sustainable development. As a result of a growing awareness of water issues, a large number of Earth observing satellites have been launched over the past two decades, many of which are dedicated to providing observations of an individual water cycle variable. The vision for the GEOSS Water Strategy was to make water observations more plentiful, accessible, meaningful, and usable for the water management through a set of coherent actions and plans to ensure that the water resources community locally and globally can access data and adequate display and analysis tools. Within GEO, the Strategy’s goal was to provide a framework for guiding decisions regarding priorities and strategies for the development, maintenance, and enhancement of water observations and data products, and plans for expanding the use of these data sets and products. It should be noted that the GEOSS Water Strategy addresses freshwater specifically and leaves ocean issues to the GEO Blue Planet initiative.

Both GEO and the Committee on Earth Observation Satellites (CEOS) recognized the benefit of such a strategy and supported its development. The preparation of the final report on the Strategy was overseen by GEO and led by the Integrated Global Water Cycle Observations (IGWCO) Community of Practice, with support from the Japan Aerospace Exploration Agency (JAXA) and the National Aeronautics and Space Administration (NASA). The Strategy assesses data availability and services in the context of the needs in priority application areas for decision-making in the water sector. Among other priorities, these topics include drought monitoring and prediction; early warning systems for floods; monitoring capabilities for the UN’s Sustainable Development Goals (SDGs), and for information to support climate change adaptation (GEO, 2014). The Strategy, summarized in the report *Implementing the GEOSS Water Strategy - From Observations to Decisions*, outlined opportunities and needs in a number of these areas and documented recommendations that, when implemented in totality, could significantly advance the implementation of a global water strategy. This article discusses the report’s major concepts and observations and highlights recommendations that require further attention.

GEO, with its comprehensive overview of the data needs for many socio-economic benefit areas, recognizes the pervasive use of water data for many applications within and beyond water management. Many different areas of society, from farmers irrigating their crops to urban planners designing expanded water systems for growing urban populations and health workers fighting waterborne diseases in Africa and elsewhere, benefit from better water data and information. These benefits would be enhanced by the improved harmonization of water observations in the atmospheric, terrestrial, ecological and socio-economic domains.

The GEOSS Water Strategy seeks to support the application of the principles that GEO has espoused, such as open access and open knowledge systems. For example, through its policy on the open exchange of data, analytical tools, and information, GEO facilitates access to observations and model outputs, thereby facilitating the development of integrated data products. GEO further advances the development of information architecture through software tools, portals, and program delivery support related to open data and open source software.

**2. The GEOSS Water Strategy**

**2.1. Purpose for the Development of the Strategy**

Given the challenges of water security, water managers must address the effects of more diverse releases of complex contaminants, growing public demand for more active adaptation to increasing climate change impacts, and growing expectations for water sustainability. These challenges come at a time when more data are available on water than at any other time in history. Systems are emerging that will access and analyze these data automatically to provide decision makers with much of the information they need. However, the transition to these new systems often occurs slowly and unevenly. The GEOSS Water Strategy seeks to address the wide range of data issues arising from these challenges, including acquiring, processing, disseminating, and using water observations and data products in more systematic ways. To this end, it reviews the data resources available and seeks to determine the steps that are needed to make water data more useful in decision-making processes.

To improve the effectiveness of Earth observation application, the Strategy focused on decision-making areas where the needs are greatest, namely: enhancing usable water supplies, adapting water resource systems to climate change, reducing water-related disease, improving clean water access for the poor, developing services to cope with water cycle extremes such as floods and droughts, planning and monitoring for the Water-Energy-Food Nexus (Lawford et al., 2013) and the UN SDGs (see <http://www.un.org/sustainabledevelopment/sustainable-development-goals/>; International Council for Science and International Social Science Council, 2015), and ensuring water services for ecosystems and biodiversity. Another recent development in the United States has been the U.S. decadal survey of Earth observations from space (National Academies of Sciences, Engineering, and Medicine, 2018), which sets priorities for the development priorities for new satellite missions in the U.S.A. for the next decade.

**2.2. Process for the Development of the Strategy**

The GEOSS Water Strategy reviewed the earlier Integrated Global Observing Strategy Partnership Water theme report (IGOS-P, 2004), the water tasks from the first decade of the GEO activities, and each activity’s ability to adapt to the new infrastructure and services developed by GEO. More than 70 international experts were engaged in developing the Strategy through participation in regional workshops held in San Francisco, (U.S.A.), Geneva, (Switzerland), and Ahmedabad, (India), ensuring that the report considered a diversity of approaches in water management. These experts included water managers and researchers in water cycle science and water resource applications as well as specialists in Earth observations. The Strategy included recommendations to address existing program gaps and remove obstacles slowing the adoption of new technologies.

**2.3. Principal Themes in the Strategy**

The GEOSS Water Strategy report recommendations can be divided into four principal themes. Since each recommendation follows from an analysis of the relevant needs, the reader is referred to the GEOSS Water Strategy report (GEO, 2014) for a complete discussion.

**2.3.1 Theme 1: Improved Data Acquisition for Essential Water Variables**

Essential Water Variables (EWVs) are those critical variables that are needed to meet the requirements of users for information to support their decision-making and to ensure that the information needed to close the water budget on multiple scales is always available. They are essential because without them the reliability of water resource management decisions would be diminished and water prediction services and global water cycle research would not have ready access to reliable initialization and validation data for models. Figure 1 is a schematic that outlines the global water cycle and the principal processes that drive it over most scales. These processes are important considerations in determining which water variables are essential.

The requirements for these variables were assessed through user needs surveys (Unninayar et al., 2010) among two primary client groups: water managers and hydrological researchers. Their needs helped inform the list of EWVs developed for the GEOSS Water Strategy (see Table 1). Many users benefit from the products that have resulted from research related to the water variables at different spatial scales. Some EWVs overlap with the Essential Climate Variables (ECVs) developed by the Global Climate Observing Systems (GCOS) in terms of the attribute measured, although requirements for spatial and time resolution, refresh rates, latency, and accuracy can be significantly different. For this reason, the Strategy promotes both the EWV and ECV perspectives. Combining geospatially consistent remote sensing data and high frequency in situ measurements makes more reliable data products possible at all time scales.

**(Insert Figure 1)**

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**Figure 1. The water and energy cycle in the Earth climate system (U.S. Global Change Research Program, 2003).**

The GEOSS Water Strategy includes a preliminary assessment of gaps between the needs for EWVs and current observational capabilities and makes a number of recommendations for ways to improve observational systems to support the acquisition of EWVs. In some cases, these recommendations relate to new sensors, in others continuity in the measurements, and in others, actions needed to expand usage of the data.

The Strategy focuses on the primary EWVs because there are other groups working on the supplemental EWVs and they are often addressed by other sectors and in general studies. Readers interested in more detail on space-based measurement systems are encouraged to refer to a recent CEOS Handbook on Earth Observations (CEOS, 2018a), or Liang and Wang (2019).

**(Insert Table 1)**

**Table 1. Primary and supplemental Essential Water Variables (EWVs) (adapted from GEO, 2014).**

|  |  |
| --- | --- |
| **Primary EWVs** | **Supplemental EWVs (apply to Water and related disciplines)** |
| **Precipitation** | **Surface meteorology** |
| **Evaporation and evapotranspiration** | **Surface and atmospheric radiation** |
| **Snow cover (including snow water equivalent, depth, freeze thaw margins)** | **Water vapor and clouds** |
| **Soil moisture/temperature** | **Permafrost** |
| **Groundwater** | **Land cover, vegetation, land use** |
| **Runoff/streamflow/river discharge** | **Elevation/topography and geological stratification** |
| **Lakes/reservoir levels and aquifer volumetric change** | **Surface altimetry** |
| **Mass balances of glaciers and ice sheets** | **Surface radiation** |
| **Water quality** | **Aerosols** |
| **Water use/demand (agriculture, hydrology, energy, urbanization, others)** | **Atmospheric radiation** |

The specific links between Water Management functions and the primary EWVs are described in more detail in Lawford et al. (2022). As might be expected, these variables are needed for most aspects of water resource management, although the emphasis will vary from one geographical area to another, especially in the case of snow and glaciers.

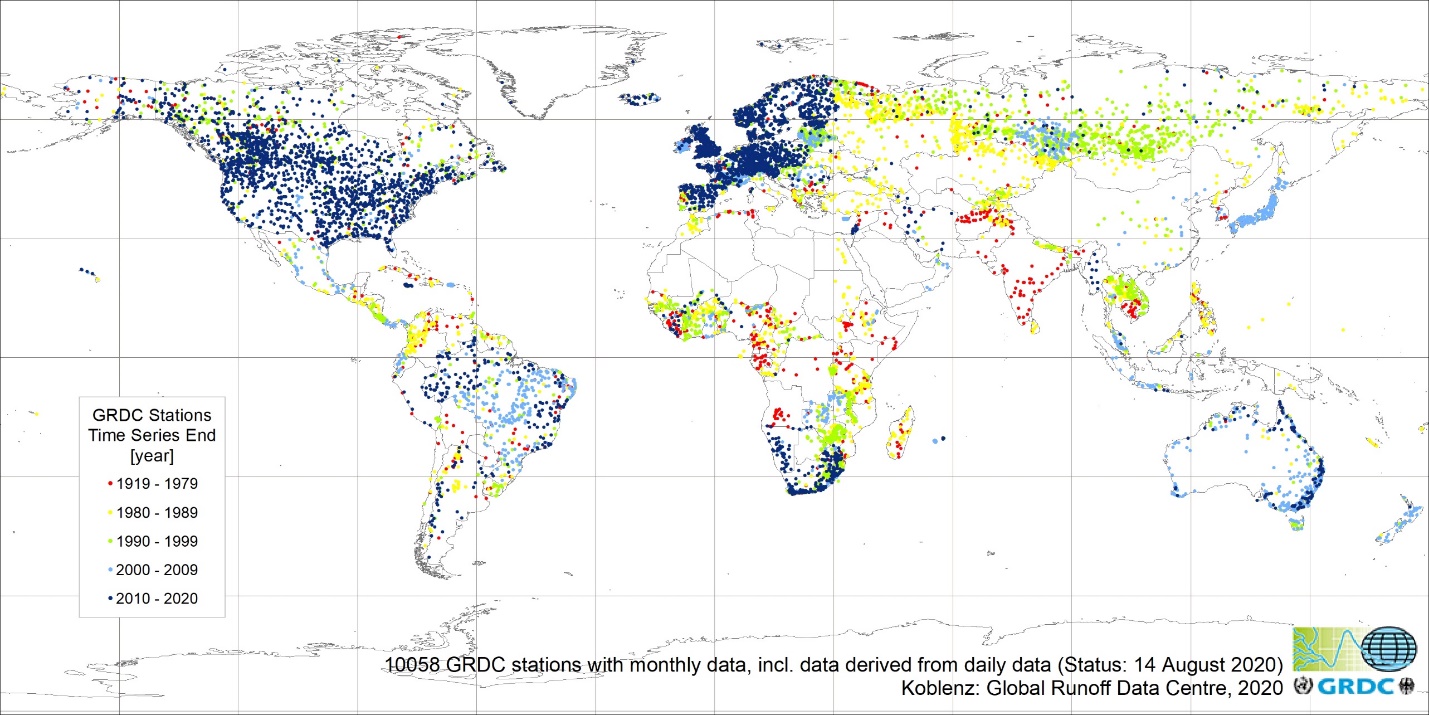
According to GEO surveys, precipitation was one of the most critical variables for analysis and planning (Friedl et al., 2012). The GEOSS Water Strategy noted that precipitation observational programs are better coordinated and the integration of precipitation data from different sources is more advanced than for other EWVs. Several precipitation products combine microwave and active satellite data and, in some cases, in-situ measurements. CEOS has successfully coordinated a precipitation constellation that harmonizes precipitation remote sensing capabilities around the world. Securing the sustainability of these observational systems remains a concern.

Evaporation and evapotranspiration flux values are also widely used and can be derived from a combination of satellite and in-situ measurements. The GEOSS Water Strategy calls for improved standards for processing and archiving evapotranspiration data, facilitating the development of integrated products, and operationalizing evapotranspiration data as both a EWV and an ECV.

Soil moisture can be obtained from satellite measurements for the shallow soil layer near the surface and from in-situ measurements for estimates in deeper soil layers. Standardized observational and analysis procedures are important requirements for soil moisture data archives. Validation for ESA’s Soil Moisture Ocean Salinity measurements comes from a “global” in-situ soil moisture database, while NASA’s Soil Moisture Active Passive mission relies on field campaigns where dense in-situ observations are taken in a specific area (Collinader, et al. 2017).

Streamflow and runoff data are collected by National Hydrometeorological Services and disseminated through the Global Runoff Data Centre (GRDC). However, as the station distribution in Figure 2 implies, not all data collected locally find their way to the GRDC archive, resulting in difficulties in carrying out global assessments. Many countries have their own procedures for releasing and disseminating data which tends to limit data sharing across national boundaries and can lead to problems with transboundary flood warnings in some regions. Experts expect that the planned Surface Water Ocean Topography mission will provide surface height data for large rivers that will be useful in estimating water depth and flows on a global basis thereby reducing the emphasis on national in-situ data apart from calibration, short-term forecasting needs, and national and local assessments of water.

**Insert Figure 2**

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**Figure 2. Distribution of stations that reported their data to the GRDC based on an August 2020 assessment. (Courtesy of Ulrich Looser, GRDC; personal communication.)**

The provision of operational groundwater measurements and continental water storage measurements pose other challenges. The Gravity Recovery and Climate Experiment (GRACE) II mission provides data for groundwater monitoring on long time and large space scales, but many operational water managers want higher spatial resolution data to address problems in specific aquifers. The lack of global standards for quality control and the limited sharing of in-situ data increases the demand for satellite data and model data for global assessments. It would be advantageous if existing data centres could be strengthened, or a new data centre could be established to **facilitate and promote the international sharing of groundwater data, information, and knowledge required for sustainable groundwater resources development and management worldwide.**

Cryospheric variables (including snow cover, snow water equivalent, glaciers, frozen ground, and river and lake ice) are critical for monitoring climate trends and for predicting growing season water availability, particularly at mid- and high-latitudes. Data needs include improved satellite data coverage and more comprehensive in-situ snow measurements for estimating water availability, calibrating satellite snow water equivalent retrieval algorithms, and validating snowmelt models.

Water quality data are also needed for environmental monitoring and water resources management. Some water quality variables have attributes which allow optical and microwave satellites to provide data for estimating their values and monitoring their changes with time. Examples include chlorophyll concentrations, turbidity, and surface water temperatures. Within GEO, the AquaWatch initiative is taking the lead in developing an operational system for estimating water quality from satellite measurements. Sensors on satellite platforms that contribute water quality measurements include: the Operational Land Imager on Landsat 8, and the Multispectral Instrument and Ocean Color and Land Instrument on ESA’s Sentinel 2 and 3 satellite series. These observations, however, must be complemented by in-situ measurements to ensure local water is fit to use, particularly where the principal contaminants cannot be measured by satellite or their spatial scale is not adequate for assessing water quality in a small area of concern. Providing operational water quality services will require the integration of satellite and in-situ data along with simulation models.

To address the deficiencies in measuring EWVs, there is a particular need for a system that monitors quantities and changes of consumptive and non-consumptive water use. Although water use is an important EWV for water management, it is only partially calculable through measurements such as evapotranspiration because many uses (such as domestic water use) are not monitored routinely, or the data are held by private agencies. A fully functioning water use monitoring system is envisioned to include process models operating in conjunction with measurement systems. A concerted research effort is needed to address this EWV.

Secondary EWVs such as water vapor, humidity, and cloud observations are considered essential for global water cycle understanding and for improving precipitation forecasts needed for estimating the future availability of water resources. The characteristics of these secondary EWVs are described in detail in the GEOSS Water Strategy Report (GEO, 2014).

Developing appropriate policies and maintaining in-situ data networks that conform to international and global standards are major challenges. The GEOSS Water Strategy’s recommendations related to in-situ data acquisition need to be addressed within a broad framework that considers national needs for data to support sustainable development targets and indicators, climate change accords, disaster risk reduction goals, resource development, industrial and domestic needs, and ecosystem requirements. Data policies need to be coordinated so that they are more consistent across national boundaries and across all EWVs to facilitate effective global research and applications.

Many in-situ networks are supported by national governments to meet the information needs for public safety, aviation, industrial development, and other specific local needs. This is particularly true for precipitation, streamflow, water storage, groundwater, and water quality measurements. Some scientists (Fekete et al., 2012) have been warning that there has been a serious worldwide decline of in-situ observational networks over the past two decades. In situ observational networks must be recognized as national priorities so nations maintain the budgets needed to maintain and enhance these networks. Within many countries, networks for specific variables are planned and managed independently so that synergies among data systems are minimal. Collaboration between the water and climate communities could be helpful to ensure the development of EWV and ECV networks are harmonized. The need for better coordination of the surface networks themselves requires a body with broad coordination responsibilities.

The GEOSS Water Strategy encourages the scientific community to indicate their needs for the continuation and augmentation of in-situ data networks and associated data repositories, and to help draw attention to the need to address the declining in-situ observational networks used for mapping and assessing the EWVs listed in Table 1. The value and uses of expanded EWV networks (including soil moisture and groundwater networks) need to be documented along with design options and assessments of trade-offs for consideration by decision-makers.

Nations should share their data with global data centres if they wish to fully engage the scientific community in achieving the SDG targets and in effectively coping with climate change. With the advent of “big data” capabilities, citizen observations can provide additional coverage if they are incorporated into existing archives. A platform is needed to consolidate and quality control these observations and to merge them with observations collected by government agencies and scientific studies.

**2.3.2. Theme 2: Research and Product Development:**

Innovations for sensing the environment and for using these observations to support water management are needed. A number of the products considered in the GEOSS Water Strategy were data products for supporting research into tools and models to support water management. Specific needs include better satellite products for supporting land surface and hydrological modelling, individual and multi-sensor algorithms for improving the characterization of different land surfaces, and better soil texture maps and bathymetries for improving estimates of soil moisture and surface water storage. For example, Arrouays et al. (2015) advanced soil moisture assessments by developing a high-resolution global grid of soil properties. Other needs include improved radiative transfer models for mapping soil moisture in the presence of vegetation and improved techniques for validating satellite soil moisture and groundwater measurements.

Observations of river discharge, water extent, and surface water storage could utilize the same observational systems, including innovative altimeter missions for water levels (Biancamaria et al., 2016) and existing and future optical and radar constellations for water extent. Since the GEOSS Water Strategy was published water extent has been adopted as a new EWV.

The GEOSS Water Strategy anticipates that user demand will drive the product innovation process, but user engagement is needed to guide this process. The Strategy recommends that user needs should be assessed on a continuous, multilingual basis. The wide diversity of languages and formats for in-situ data available from different nations needs to be considered, and tools and applications that can access these data in different national information systems should be developed. The Strategy also recommends working with users to clarify the adequacy of existing products and services and to develop and establish new services. Close coordination among agencies and users in implementing existing and prototype future observational systems is essential to ensure smooth transitions from one system to the next. This is particularly important when satellites and models are transitioned from research to long-term operations.

**2.3.3. Theme 3: Interoperability and Coordination**

Currently, data exchanges can be delayed or do not take place because systems are not interoperable. System interoperability could assist in addressing user expectations for data access. In some parts of the world, data transfer systems are slow and inadequate because they rely on local internet services. A high priority should be given to modernizing communication networks in the developing world and to promoting system interoperability.

Interoperability among data and information systemsfacilitateswater data handling from acquisition and quality assurance to data exchange, dissemination, and applications. Consistent standards for quality control can promote the development of interoperable systems. The GEOSS Water Strategy proposes to pattern the quality assurance of water data after approaches used for climate data. A generic process that enables the traceability of changes and includes independent levels of data product validation such as the procedure outlined in (Zeng et al., 2015; Su et al., 2017) is needed, perhaps based on Blockchain approaches. Validation is also necessary for land surface and hydrologic models, data assimilation systems, and satellite measurements. The collection of specialized validation data during intense observation periods to support the development of the new observational systems is very useful for developing robust algorithms.

Since the GEOSS Water Strategy was published, GEO has announced several new initiatives that promote interoperability, including the GEO Knowledge Hub (GKH). Launched in 2019 by the GEO Secretariat, the GKH will provide comprehensive information and access to data for important applications of Earth observations so that anyone without major expertise could duplicate the process. The sharing of information through open access principles for data, procedures for data access, algorithms and analytical methods, and applications all promote more coordination among individual researchers. The discovery of data provided through the GKH will give data providers incentive to gain more exposure for their data through the development of systems that interact with each other thereby promoting interoperability. The GKH introduces procedures for sharing Earth observatons more widely, provides precise protocols for registering and sharing data across disciplines, and sets standards for transforming Earth observation data into knowledge-based services for evidence-based decision-making. It also provides links to the Earth observation data archives, related research papers and reports describing analysis techniques and methods, software algorithms and cloud computing resources to enable users to process data and satellite imagery to assist users in producing the desired results for their application. (see https://www.earthobservations.org/documents/pb/me\_202002/PB-16-07\_Draft%20Implementation%20Plan%20for%20the%20GEO%20Knowledge%20Hub.pdf). Opportunities are being sought to codify appropriate knowledge from responses to the GEOSS Water Strategy recommendations into some applications for the GKH.

The Global Drought Information System Initiative provides an example of how research, prediction capabilities, monitoring data, and modeling capabilities can be combined to identify droughts and classify their intensity. As outlined by Pozzi et al. (2013), effective drought monitoring requires an ability to measure (or, in some cases, estimate) multiple stores of water simultaneously. Although the current Global Drought Information System provides a global framework, full interoperability is difficult to achieve because many nations and regions continue to prepare their inputs independently by using a national analytical methods and national data sets.

Integration can also be supported by using land surface and hydrologic models as platforms for data assimilation efforts. The Global Energy and Water Exchanges project and NASA both support continued development of land surface data assimilation systems. These systems are very effective in estimating missing data and in some cases estimating variables that are not directly measured (e.g., root zone soil moisture).

Integration of data from different sources can lead to new data products that provide substantial benefits. Derived products for large areas are generally more accurate if they combine spatially consistent satellite data and high-frequency in-situ data to produce an integrated product. In some areas, such as Alaska and the Canadian Arctic, where in-situ data are very sparse, numerical models can be used to produce reasonable estimates for values at locations between stations in the sparse observational network.

**2.3.4. Theme 4: Capacity Development and Decision Support**

The GEOSS Water Strategy recognizes the need to train users on the use of Earth observation data so the full benefits of satellites can be realized. The Strategy provides recommendations for facilitating this training internationally. In general, it advocates continuing and expanding the water community’s capacity development efforts currently taking place in Latin America, Asia, and Africa, but it also recommends stronger linkages with regional GEO activities.

Users who provide feedback on their needs contribute to the design of future satellites. Table 2 (adapted from CEOS, 2017) shows how different sensors can meet a variety of needs for EWVs. For example, Table 2 shows soil moisture can be measured by radar and microwave imagers. It also shows that radar sensors could be applicable to a number of other EWVs. However, this is complicated by the fact that the time and space resolutions for some applications may be quite different than others. The value of the information may also be affected by the satellite and its orbital characteristics (e.g., polar orbiting, geostationary). Given the wide scope of requirements, the Strategy recommends that new products be developed in conjunction with users to ensure they are “fit for purpose.” In view of this list of challenges, we will now review what has been accomplished by the response to the recommendations in the GEOSS Water Strategy.

**(Insert Table 3)**

**Table 3: Synergies among satellite sensors in providing Essential Water Variables for water resource management (adapted from CEOS, 2017)**

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | **User needs benefitting from synergies among sensors** | | | | | | | |
| **Sensor’s and technologies’ synergies** |  | **Precipitation** | | **Soil moisture** | **Evaporation and evapo-**  **transpiration** | **River discharge** | **Surface water storage** | **Groundwater** |
| **Precipitation** |  | | **Irrigation water allocation and scheduling** | **Water balance Irrigation water allocation and scheduling** | **Water allocation and treatment** | **Water allocation Dam operation** | **Water recharge** |
| **Soil moisture** | **Radar Land surface temperature**  **Microwave imager** | |  | **Vegetation**  **Growth** | **Discharge prediction for allocation** | **Leakage from reservoirs** | **Aquifer water availability** |
| **Evaporation and evapo-transpiration** | | **High- resolution land surface temperature** | **High- resolution land surface temperature**  **Land cover maps** |  | **TBD** | **Storage water**  **loss** | **Aquifer water availability** |
| **River discharge** | **Radar** | | **Radar** | **TBD** |  | **Storage change and refill strategy** | **Ground water discharge in mountains** |
| **Surface water**  **storage** | **Radar** | | **Soil type and profile map** | **Surface temperature** | **Altimetry**  **water level**  **DEM** |  | **Aquifer**  **recharge** |
| **Ground water** | **TBD** | | **Data assimilation** | **Soil type and profile map** | **Soil type and profile maps** | **Data**  **assimilation** |  |
| **Observation**  **synergies** | **Radar,**  **High- resolution Land Surface Temperature, Microwave imager** | | **High resolution land surface temperature, Land cover maps, Radar, Soil maps, Data assimilation** | **Land surface temperature, Land cover maps,**  **Soil maps** | **Radar, Altimetry,**  **Soil type and profile maps** | **Radar, soil maps, Surface temp. Data assimilation**  **Altimetry** | **Data assimilation, Soil maps** |

**Legend**

**DEM: Digital Elevation Model**

**TBD: To Be Determined**

**3. Implementation of the GEOSS Water Strategy**

**3.1. Agencies and Programs Engaging in the Implementation of the GEOSS Water Strategy**

After the publication of the GEOSS Water Strategy, GEO members were invited to contribute to its implementation. Progress in implementing the GEOSS Water Strategy has come primarily through the voluntary efforts of agencies and programs, and through individual experts who have proposed actions that address the Strategy’s recommendations. Implementation activities are carried out through non-binding commitments. In most cases, the agencies and programs have been making progress on their commitments, although funding challenges have limited progress in other areas.

The GEO IGWCO Community of Practice has continued to monitor progress and to identify where new leadership may be required for a given activity. In some cases, it has taken steps to recruit leads or to adapt actions to more effectively address the recommendation. A summary of its most recent assessment of progress in implementing the GEOSS Water Strategy recommendations (March 2022) is shown by theme in Table 3.

**Insert Table 3 here**

**Table 3. Status of the implementation of the GEOSS Water Strategy recommendations by theme.**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **GEOSS Water Strategy Theme** | **Complete** | **In**  **progress** | **Beyond GEO** | **Total** |
| **Improved Data Acquisition for Essential Water Variables** | **7** | **9** | **5** | **21** |
| **Research and Product Development** | **1** | **13** | **7** | **21** |
| **Interoperability and Coordination** | **2** | **3** | **5** | **10** |
| **Capacity Development and Decision Support** | **2** | **5** | **0** | **7** |
| **Total** | **12** | **30** | **17** | **59** |

Overall, the GEO Water Strategy report contained more recommendations related to Themes 1 and 2 than for Themes 3 and 4. In the case of Theme 2 (Research and Product Development), few of the recommendations have been fully addressed and the theme has the highest number of recommendations to transfer to groups outside GEO. Although Theme 4 (Capacity Development) has the fewest recommendations, there are a relatively large number of on-going activities addressing these recommendations indicating that this theme is progressing well. It should be noted that in some cases the assignment of a recommendation to a single theme was somewhat subjective because some recommendations addressed more than one theme.

The three primary implementing organizations and programs carrying out these activities are described below. Other assisting organizations and agencies include the World Meteorological Organization (WMO), the Sustainable Water Futures Program, NASA, the National Oceanic and Atmospheric Administration (NOAA), JAXA, and the German Federal Hydrological Service.

**3.1.1. GEO and its Water Initiatives**

Both GEO and CEOS were engaged in the Strategy’s implementation. In addition to promoting its principles, GEO could benefit from the opportunities that the Strategy provides for discussions with UN Water and its member agencies, as well as international research programs such as Future Earth.

GEO supports the implementation of the Strategy through its GEO Global Water Sustainability (GEOGloWS), AquaWatch, Wetlands, and Drought initiatives and, more recently, through the GEO Earth Observations for the Water-Energy-Food Nexus Community Activity. Within GEO, GEOGloWS is the lead Initiative in GEO for addressing recommendations in the GEOSS Water Strategy. GEOGloWS mission of “connecting the demand for sound and timely environmental information to the supply of data and information about the Earth’s water system and to explore the science needed to achieve its goals” as outlined in Gutiérrez-Magness et al. (2017) aligns well with the vision of the GEOSS Water Strategy.

A number of national and international agencies in the USA, Europe and Asia are engaged in GEOGloWS. GEOGloWS receives support from NASA, NOAA and other US agencies. NASA has funded four major GEOGloWS projects, three of which supported the theme of capacity development and one which supported the interoperability theme, along with many smaller projects supported through the NASA DEVELOP program. NOAA supports the Initiative by providing the time and travel for the Initiative’s co-chair, and provides services and products in the fields of hydrology and hydrometeorology. More recently, funded projects have also come from the Centre National d'Études Spatiales (France) and the World Bank. GEOGloWS with its ties to AmeriGEO, has initiated a number of studies in Latin America that support the Strategy’s recommendations. Further details of GEOGloWS activities that support Themes 1,3 and 4 of the Strategy are given in the GEOGloWS 2020-2022 Work Plan (GEO, 2019a).

Other GEO water-related initiatives such as AquaWatch (GEO, 2019b) also contribute to the implementation of the Strategy. AquaWatch has led the implementation of recommendations relate to water quality issues. In its efforts to develop an operational system for delivering near-real time water quality data (primarily satellite data) to users it has addressed Theme 3 recommendations. Although not featured in direct responses to the Strategy’s recommendations, the Wetlands and Drought Initiatives have provided input to the formulation of the Strategy and contributed insights on options for advancing the Strategy’s concepts, assessments and recommendations.

**3.1.2. Committee on Earth Observing Satellites (CEOS)**

CEOS is a federation of national space agencies from around the world that coordinates civilian satellite Earth observation missions and develops new programs to promote Earth-observing satellites. It coordinates seven satellite constellations, including one for precipitation, and maintains working groups to support the implementation of capacity development and data democracy, climate observations, calibration and validation, disasters, and information systems and services.

In response to the GEOSS Water Strategy recommendations, CEOS undertook two reviews, both of which provided important insights on planning satellite systems for water applications. These two reviews (described in more detail in Section 3.2.1) followed a preliminary assessment by CEOS of all of the Strategy’s recommendations that were relevant to satellite observations. CEOS members chose two topics for review based on their potential contributions to implementing the GEOSS Water Strategy and, the level of interest of the CEOS member agencies in the issue.

**3.1.3. Global Terrestrial Network – Hydrology (GTN-H)**

GTN-H is a joint program of WMO and GCOS which is led by the International Centre for Water Resources and Global Change (see <https://www.waterandchange.org/en/>). It coordinates a federation of global hydrometeorological data centers, many of which operate under the auspices of UN agencies. The data centers and networks archive many EWV data sets: some for climate purposes (e.g., precipitation and runoff), some for water quality monitoring (e.g., Global Environmental Monitoring System (GEMS) Water Data Centre), and most recently water planning (e.g., water use data through AQUASTAT, a UN Food and Agriculture Organization data center). Table 4 lists the GTN-H data centers and their contact information.

**Insert Table 4**

**Table 4. Global data centers federated under GTN-H and the data types they archive.**

|  |  |  |  |
| --- | --- | --- | --- |
| **Name** | **Acronym** | **Data** | **Web** |
| **FAO's Global Information System on Water and Agriculture** | **AQUASTAT** | **Anthropogenic Water Use** | **http://www.fao.org/nr/water/aquastat/main/index.stm** |
| **Global Groundwater Monitoring Network** | **GGMN** | **Groundwater** | **https://www.un-igrac.org/special-project/ggmn-global-groundwater-monitoring-network** |
| **Global Network of Isotopes in Precipitation/Rivers** | **GNIP/GNIR** | **Isotopes in Precipitation and Rivers** | [**https://nucleus.iaea.org/wiser**](https://nucleus.iaea.org/wiser) |
| **Global Precipitation Climatology Centre** | **GPCC** | **Precipitation** | [**https://www.dwd.de/EN/ourservices/gpcc/gpcc.html**](https://www.dwd.de/EN/ourservices/gpcc/gpcc.html) |
| **Global Runoff Data Centre** | **GRDC** | **River Discharge** | **http://grdc.bafg.de/** |
| **GEMS/Water Data Centre** | **GWDC** | **Water Quality** | **https://gemstat.org/** |
| **International Data Centre on Hydrology of Lakes and Reservoirs** | **HYDROLARE** | **Lakes and Reservoirs** | **http://hydrolare.net/** |
| **International Soil Moisture Network** | **ISMN** | **Soil Moisture** | **https://ismn.geo.tuwien.ac.at/en/** |
| **Laboratoire d’Études en Géophysique et Océanographie Spatiales CLS** | **LEGOS** | **Lakes/Reservoirs and River Discharge (Remote Sensing)** | **http://www.legos.obs-mip.fr/** |
| **National Snow and Ice Data Center** | **NSIDC** | **Snow and Ice** | **https://nsidc.org/** |
| **World Glacier Monitoring Service** | **WGMS** | **Glaciers** | **https://wgms.ch/** |

GTN-H continues to develop plans for addressing specific recommendations to support the implementation of the GEOSS Water Strategy by providing and improving its data services, reviewing user requirements, increasing user engagement, advocating for open data and improved in-situ observation networks, documenting quality assurance procedures, inventorying data services, and facilitating open access to hydrological information.

**3.2. Progress on the Implementation of the Themes:**

This section summarizes the actions that have been undertaken on a voluntary basis in response to the recommendations in the GEOSS Water Strategy, primarily by the three lead organizations and programs referenced above. Each sub-section reviews the present status of implementation of each of the Strategy’s four themes.

**3.2.1. Implementation of Theme 1: Improved Data Acquisition for Essential Water Variables**

Under JAXA’s leadership, CEOS formed the Water Strategy Implementation Study Team, which carried out in-depth feasibility studies for two GEOSS Water Strategy recommendations including an assessment of the feasibility of a “Water-Train,” or a Water constellation for EWVs, and a second study exploring the potential for using satellites to monitor water quality variables. After completing these studies, CEOS also organized a “Freshwater from Space” Workshop at the Delft Institute for Water in the Netherlands in November 2018 to consider how CEOS should address EWVs.

Although the requirements for important variables are partially met at present, the temporal and spatial resolutions need to be improved and data latency needs to be reduced. Although it began as an assessment of a “Water-Train” concept analogous to the A-Train (Stephens et al., 2002), the CEOS study team concluded a Water Constellation would be more feasible. The “Water Constellation Feasibility Study” (CEOS, 2017) assessed benefits and synergies of using different sensor combinations to meet the water community’s observational requirements for six priority EWVs. Table 5 (adapted from CEOS, 2017) shows how data from one sensor type can be used to assess different EWVs. Although a microwave imager can provide critical input for precipitation, soil moisture, and evapotranspiration monitoring, long term continuity for this sensor is in doubt. The study concluded it was premature to launch a water cycle constellation until further more detailed assessments are carried out.

**Insert Table 5**

**Table 5. Satellite sensors that could contribute to a Water Constellation (adapted from CEOS, 2017)**

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | **Precipitation Radar** | **Microwave**  **Imager**  **(MWI)** | **Microwave**  **Sounder**  **(MWS)** | **Thermal IR**  **Radiometer**  **(TIR)** | **Optical Sensor** | **Radar**  **L/C/X**  **band** | **Altimeter** | **Gravity-field measurement** | **Remarks** |
| **Precipitation** | **X** | **X** | **X** | **X** |  |  |  |  | **Microwave Imager is strongly preferred to a microwave sounder and thermal Infrared radiometer.** |
| **Soil moisture** |  | **X**  **37GHz**  **is critical** |  | **X** |  | **X**  **L-band is preferred** |  |  | **Microwave imager plus thermal infrared radiometer can improve accuracy and resolution** |
| **Evaporation and evapo-transpiration** |  | **X** |  | **X** | **X** |  |  |  | **Pairs of cloud-free thermal images are needed.** |
| **River discharge** |  | **X** |  |  | **X** | **X** | **X** |  | **Improvement of altimeter revisit time is needed.** |
| **Surface water storage** |  |  |  | **X** | **X** | **X** | **X** |  | **Digital Elevation Model data is required to estimate water volume** |
| **Ground water** |  |  |  |  |  |  |  | **X** | **Soil moisture and evapotranspiration are closely related with ground water in data assimilation.** |

**Legend:**

**GHz – Gigahertz**

The dimensions of water quality are even more complex than those of water quality and optical sensors still need to play a central role in water quality monitoring systems even with the expected new applications of hyperspectral systems. The second in-depth CEOS Study report, entitled “Feasibility Study for an Aquatic Earth Observing System” (CEOS, 2018b) addressed these complexities. AquaWatch is developing a satellite-based information service similar to the type envisioned in this report. This approach could be strengthened by new missions, including a hyperspectral mission, to provide a more diverse set of observations for water managers concerned with water quality.

AquaWatch continues to work toward the delivery of an information system for users. Together with GEMS Water, AquaWatch has addressed the GEOSS Water Strategy’s recommendation for workshops on water quality issues and on in-situ measurement techniques for water quality assessments. AquaWatch and GEMS Water also have produced a handbook of best practices for water quality measurements.

Within the GEOSS Water Strategy the collection, archival, and dissemination of data for individual EWV variables was also assessed. Although most satellite data and data products are archived, gaps exist in the availability of some in-situ data. For example, although national in-situ soil moisture networks have not been fully integrated into a global network, an archive of data from national and regional networks has been developed (referenced in Table 4). This archive, recently relocated to the German Hydrological Institute from the Technical University in Vienna, has been accepted as a GTN-H data centre.

Another gap related to evapotranspiration arose from the similarity among variables. While evapotranspiration is recognized as a EWV, it had not been included as an ECV. GCOS has relied on flux tower measurements and model results for inputs to an evaporation from land variable as its ECV (Miralles et al., 2020). As a result of the GEOSS Water Strategy recommendations, discussions between IGWCO and GCOS experts led to a reconsideration of the decision to exclude satellite based evapotranspiration measurements from ECVs even though their values are generally similar to the evaporation from land measurements. It is timely because more high-frequency land surface temperature measurements for evapotranspiration computations are available from the new Landsat 9 satellite and the operation of ECOSTRESS[[1]](#footnote-1) on the International Space Station.

Obtaining adequate funding to maintain in-situ networks for global water assessments and to ensure all collected data are made available through global data centres is a long-standing challenge. While river discharge is measured in nearly all countries, ensuring the timely transfer of data from national archives to the GRDC remains a challenge (see Figure 2). The time lags for data as they move from the observation site to becoming quality-controlled data in a national archive and then to the GRDC global data archive needs to be shortened to encourage a wider range of global applications for streamflow data. Some discussions by GRDC management with experts from WMO and national hydrometeorological services have been directed at improving this situation. In addition, the development of sophisticated hydrological models and improved satellite data for river stage height information has improved regional and global water assessments.

Considerable progress has been made in the area of groundwater and surface water storage measurements, although challenges still remain. The GRACE-II mission provides data on groundwater variations that have many applications (such as drought impact monitoring and assessments of regional groundwater used for irrigation), demonstrating the value of these observations even though they have relatively low spatial resolution and long repeat intervals. New sensors on ESA Copernicus mission should help to address this need. A comprehensive archive of global in-situ groundwater levels from national archives should be established to better support the validation of groundwater measurements derived from remotely sensed data. The UN’s International Groundwater Resources Assessment Centre, which undertakes regional and global assessments, would be a candidate for this role because it already collects such information for major aquifers and some nations.

The Centre National d'Études Spatiales and NASA continue to make final preparations for the Surface Water and Ocean Topography mission scheduled for launch in December, 2022. It will provide calibrated global data needed for the analysis of water extent and river and lake stage on a global basis, thereby helping to fill a gap in data on EWVs. AQUASTAT, a UN Food and Agriculture Organization Data Centre, which has recently joined the GTN-H Network provides national water use data to the water community.

GEOGloWS has taken the lead in developing the full implementation of the EWVs and presented a plan to GEO to undertake the development of a consultative process to refine the EWV definitions and develop a plan for a service to acquire and distribute EWV data. These and related plans have been delayed by COVID-19. Through their interactions with users, the GEOGloWS EWV exercise and the GEO Earth Observations for the Water-Energy-Food Nexus Community Activity both plan to contribute to understanding how different data types are used in decision-making.

Individual research initiatives are now looking to citizen science to address the gaps that exist in a number of in-situ data networks. While there are encouraging developments in these new approaches, issues of data consistency, standardization of approaches, and overall frameworks for managing these types of data systems still need to be developed.

* + 1. **Implementation of Theme 2: Research and Product Development:**

A number of the GEOSS Water Strategy recommendations in the area of research and product development went beyond the capabilities and interests of the GEO Water community. New product development is a priority for each of the implementing organizations but primarily in areas that support each organization’s mission. Data products that demonstrate the added value of openly shared in-situ observations are potentially important drivers for improving data acquisition at the global data centers and could encourage more investment in developing and maintaining observational networks. Similar arguments could be made for increasing support for satellite data acquisition by national space agencies. GEO has a central focus on new product development and much of its software infrastructure has been put in place to facilitate this activity. Given that a number of the needs for research and new products identified in the GEOSS Water Strategy fall outside the remit of the implementing groups, a concerted effort is planned to engage targeted organizations with the expertise and resources to address those recommendations that still need attention.

User requirements are not static and tend to be influenced by instrument capabilities. GEOGloWS has undertaken surveys with user communities in the Americas to obtain feedback on their satisfaction with current services, and interest in new products, which will help to update the information about user needs in the GEOSS Water Strategy. Once user requirements are further clarified, the holdings of global data centers should be evaluated and new products identified and developed.

GEOGloWS has overseen a number of capacity development efforts with support from the NASA DEVELOP program, which have led to a global streamflow prediction system and service within the GEOGloWS flood protection framework. This development, which is being led by Brigham Young University (Nelson, 2017), has used a hydrologic model, global satellite data, and regional in-situ data to establish forecast services. Initially, this model was used to establish services in six pilot areas, including Brazil, Nepal, the Dominican Republic, Thailand, and Argentina (Nelson, private communication). Recently, with the help of ESRI and its Living Atlas, the GEOSS Architecture Implementation Pilot Initiative, and collaboration with the European Centre for Medium to Long Range Forecasting, the Brigham Young University system has developed into an open access system that can be applied at any location around the globe.

The GEOSS Water Strategy highlights the need to integrate in-situ and space-based measurements. GTN-H is active in supplementing terrestrial observations with space-based satellite observations, especially with regard to water storage in lakes and reservoirs, and streamflow using altimeter observations provided by the Laboratoire d’Études en Géophysique et Océanographie Spatiales’s Hydroweb (see <http://ctoh.legos.obs-mip.fr/data/hydroweb>). The GTN-H International Data Centre on the Hydrology of Lakes and Reservoirs is assembling in-situ and altimeter data for a number of lakes for monitoring purposes.

Data assimilation is also important for integrating data from different sources. NASA continues to develop advanced data assimilation systems that bring satellite and in-situ data along with more static data on land cover and topography into a model framework to produce complete suites of high-resolution soil moisture and land surface products (Reichel et al., 2018).

**3.2.3. Implementation of Theme 3: Interoperability and Coordination**

The GEOSS Water Strategy made observations regarding data management and data sharing policies and indicated a number of steps that could be taken at the national level and by international data centers to implement better procedures for reporting and disseminating data (GEO, 2014). Obtaining sufficient calibration and validation data for water research remains a challenge because the data must meet accepted accuracy standards and be freely available. Small instrumented basins and supersites are often the best sources of representative hydrologic data. These ongoing data sets are even more valuable when supplemented by periodic intensive field campaigns.

In response to concerns expressed in the GEOSS Water Strategy about the restrictions on data transfer practices by the Global Precipitation Climatology Centre and the GRDC, GTN-H has initiated a review of current practices as a first step in developing plans for greater harmonization of services provided by all its data centers.

GEO has a number of common services that could support the implementation of the GEOSS Water Strategy’s recommendations. Assistance from the GEOSS Architecture Pilot Initiative, which coordinates the development and testing of new data platforms, develops standards for metadata and data access mechanisms, and supports the development of near real-time data and data product delivery, could be very helpful for developing new integrated data systems. Other GEO resources that support the implementation of the GEOSS Water Strategy include the GEOSS Portal (<http://www.geoportal.org/>) and the GEO Knowledge Hub. The University of Tokyo’s Data Integrated Analysis System, NASA (Giovanni), and ESA (Copernicus) are examples of data services that provide users with access to a wide range of water data. An emphasis on the interoperability of systems is important to ensure regional systems will be capable of combining different data sources to produce integrated data products.

Interoperability is needed across observation systems to provide more comprehensive inputs to EWV products, and across sectors to support integrated information systems for addressing complex issues such as the Water-Energy-Food Nexus. Integrated information systems (Lawford, 2019) could be designed to bring together data, data products, model outputs, and even socio-economic data to inform multi-sector decision makers about a range of issues. A GEOGloWS project has focused on data access among interoperable systems. This project provided software for accessing and using data products relevant to water security problems anywhere in the world. The system uses Tethys apps to help users navigate to the required data and to produce products and services for any location in the world (Kattar et al., 2020). The GEOGloWS global flood prediction system described in Section 3.2.2 uses a version of this data system combined with a hydrologic model to provide a basic service platform that accesses satellite data, other global datasets, and local data sources as input to flood predictions.

Interoperability facilitates prediction and data assimilation systems enabling them to more efficiently provide comprehensive results. Hydrologic prediction models can also benefit from near real-time data from multiple satellites to improve the accuracy of their initialization fields and their final predictions. To realize the benefits of better interoperability, the GEOSS Water Strategy recommended that service gaps related to data-sharing and standards be addressed especially for in-situ data by the adoption of modern standards for open data stewardship and accessibility at national and GTN-H global data centers.

Models are used to provide outputs in near real-time when they are integrated into an operational system. Examples of these systems include NOAA’s Weather Research and Forecasting prediction services and Princeton University’s drought monitoring system, which produce real-time regional outputs for detailed analysis and predictions of water cycle variables and drought over North America, Africa, and in the case of NOAA models, the globe. Global systems such as the NASA Land Information System are also run routinely and need timely access to global data from interoperable systems. Recent reductions in the lag between the time when the observations were taken and the time when high resolution land data assimilation products become available to users have increased the value of these products for decision makers.

The GEOSS Water Cycle Integrator project at the University of Tokyo provides a comprehensive framework across sectors and includes a harmonized approach to collecting, analyzing, and interpreting water data. Details regarding a prototype Water Cycle Integrator system can be found at [www.wci.t.u-tokyo.ac.jp/en/](http://www.wci.t.u-tokyo.ac.jp/en/).

* + 1. **Implementation of Theme 4: Capacity Development and Decision Support**

The GEOSS Water Strategy contributes to improving water security worldwide by developing capacity for using data and information to facilitate more effective water management. This includes facilitating data accessibility globally and enabling their interpretation by decision-makers to help make water management more equitable world-wide. Contributions to this goal are achieved in part by offering training programs and developing applications in developing countries. The goal also is advanced by supporting the convergence and harmonization of observations, the transfer of new analysis techniques and the knowledge of how to use them, and interoperable systems for use by experts to enable them to more effectively support water management in developing countries.

The GEOSS Water Strategy envisioned that new capacity development activities would build on past collaborations and partnerships, create new ones, make better use of agency infrastructure and programs, increase user engagement in the design and production of new products, and harmonize capacity development across water activities around the globe. An important aspect of achieving this goal involves enhanced collaboration among water-related capacity development efforts in different regions.

Water-related capacity development should account for regional differences with regard to climate, physiography, differences in the capacity to provide data services and water management accounting for differences in languages and cultures. GEO recognized some of these differences when it adopted regional groups for the Americas, Africa, Europe, and the Asia-Oceania region.

In addition to the user consultations in Theme 4, similar consultations have occurred in each of the themes. In Theme 1, users provided their perspectives on which variables they felt were essential. In Themes 2 and 3, users have been consulted through surveys on their satisfaction with existing products and their priorities for new products. Through GEOGloWS, users have also been consulted regarding the ways streamflow forecast products could be customized to better meet their needs.

Information infrastructure put in place globally by agencies from the developed world is another valuable asset for international capacity development. The NASA/United States Agency for International Development (USAID) SERVIR program disseminates NASA products through its five active regional hubs. Two of these hubs are in Asia (Nepal and Thailand), two are in Africa (Kenya and Nigeria), and one is in South America (Colombia). The hubs provide satellite-based Earth observations, imaging and mapping data, geospatial information, predictive models, training, and science applications to help improve regional and local environmental decision-making. GEO water-related capacity development activities have benefited from the support provided by these hubs.

GEO water activities use the internet extensively for training purposes. GEOGloWS fosters training and development webinars and in-person training in Spanish and English. AquaWatch has been hosting a series of webinars on key developments that support its plan for an operational water quality service based on satellite data for the world’s inland lakes and coastal waters. Although this wide array of webinars and on-line training is available, a GEO web-based clearinghouse for water-related training and webinar opportunities has not yet been developed.

The GEOSS Water Strategy advocated for more harmonization of GEO water-related Capacity Building activities. Some progress has been made in harmonizing these activities. In particular, GEOGloWS and the Asian Water Cycle Initiative (AWCI) have agreed to partner and follow GEO’s open source principles for capacity development. The initial focus for GEOGloWS/AWCI activities will involve issues related to water for agriculture.

**Americas**

GEOGloWS, in collaboration with AmeriGEO, has developed capabilities that have contributed to water management across the Americas. Based on support from NASA, NOAA, USAID, and the World Bank, GEOGloWS has developed a strong capacity development component that benefits countries throughout Latin America. Some of these activities have been supported by the NASA DEVELOP[[2]](#footnote-2) program which has funded a number of short-term GEOGloWS projects in the Americas. DEVELOP projects are useful in providing new understanding, assessing the feasibility of larger studies, exploring broader applications through demonstration projects, and developing Web portals. Water managers in Latin America can now readily use different types of satellite data in their water management activities as a result of training programs in English and Spanish offered through GEOGloWS and supported by NASA’s Applied Remote Sensing Training Program (ARSET).

**Asia:**

The Asian Water Cycle Initiative (AWCI) coordinated by International Centre for Water Hazard and Risk Management and the University of Tokyo continues to address many water-related capacity development needs in Asia. In its initial stages, under the leadership of the University of Tokyo and JAXA, AWCI worked with the Japan International Cooperation Agency and Asian Pacific Network to develop in-country and on-line training programs and workshops at the University of Tokyo.

While individual projects and workshops remain important, in more recent years AWCI has focused on national government services with support from the Asian Pacific Network. Recently, under AWCI’s leadership, national plans have been implemented for water data integration for Myanmar, Indonesia, the Philippines, and Sri Lanka. These plans include adapting and implementing national platforms on resilience and disaster tailored to each nation’s development status and technical capabilities. The developments utilize information systems such as the University of Tokyo’s Data Integrated Analysis System and others. This approach was featured in the UN High Level Panel on Water in its 2018 report "Making Every Drop Count - An Agenda for Water Action" (UN High Level Panel on Water, 2018).

AWCI continues to address research needs related to floods, droughts, climate change adaptation, and, where appropriate, water quality. It remains committed to studies that share data, models, experiences, and knowledge among the platform participant organizations. During the COVID-19 Pandemic AWCI frequently implemented e-Learning based capacity building.

NASA has supported GEOGloWS projects aimed at developing tools to improve decision-making for water resources in South Asia. Reporting on a study that explored the use of Earth observations to improve the management of irrigation water reservoirs in the upper Indus River Basin, Hill et. al. (2020) demonstrated that improved snowmelt estimates could provide more accurate predictions of flows into the reservoirs storing water for irrigation in the following summer. According to Kim et al. (2020) integrated multi-satellite products combined with tools for water management by agencies in Viet Nam and Cambodia can be used by agencies in the Lower Mekong River Basin to monitor surface water storages.

Other related capacity development activities in Asia include ESA’s Dragon project in China, NASA/USAID SERVIR hubs in Nepal and Thailand, and national programs such as Japan’s national capacity development activities.

**Africa:**

Many capacity development projects in Africa build upon TIGER-NET, a project initiated by ESA that has supported applications of satellite data to water management and resource management problems in Africa over the past two decades. GEOGloWS has worked with the Space Climate Observatory to provide climate adaptation schemes over the major African Basins. In collaboration with the Centre National d’Études Spatiales hydrological programme, data are being applied to manage the Congo-Oubangui-Sangha Basin in Africa. The International Centre for Water Hazard and Risk Management, in collaboration with the African Water Cycle Coordination Initiative, is undertaking an assessment of the Niger River Basin. Two NASA/USAID SERVIR hubs also support capacity building in Africa by facilitating the distribution of data and data analysis tools in Africa.

Readers who are interested in the GEOSS Water Strategy and affiliated training programs mentioned here are encouraged to explore the following Web sites:

1. NASA’s Applied Remote Sensing Training (ARSET):

https://appliedsciences.nasa.gov/what-we-do/capacity-building/arset/arset-water-resources-trainings

1. GEOGloWS: <https://training.geoglows.org/en/latest/index.html>
2. ESA’s Research and User Support: <https://rus-copernicus.eu/portal/>
3. NASA/USAID SERVIR Workshops and Training (Global):

<https://servirglobal.net/Global/Our-Work/Capacity-Building/Training-Workshops>

* 1. **Next Steps in Implementation:**

In order to track the status of actions related to the recommendations in the report, the IGWCO CoP maintains a rolling review of developments and issues a report semi-annually. In some cases the developments are in direct response to the GEOSS Water Strategy or they were undertaken for other reasons but still provide a positive response for an issue raised in the Strategy. In cases where the groups addressing a recommendation have achieved their objectives and addressed all (or most) of the concerns that gave rise to the recommendation, further actions are no longer being tracked. In other cases, the progress is slower than expected and more effort is needed. There also are a number of recommendations where the issues would be best addressed by groups outside the GEO water community and efforts are being made to engage these other groups.

During the next three years, GTN-H will work with its data centers to address the data services issues for in-situ data. It will focus on carrying out a review of the services and data exchange practices of its data centers. GTN-H plans to develop a discovery service for available station data and data products for its partner networks to facilitate access to data and encourage users to further develop products of value through new applications.

GEOGloWS will continue to develop initiatives to support capacity development, to advance the implementation of the EWVs, and to develop new applications of Earth observation data that support public policies and the program’s overall goals. GEOGloWS plans to continue to expand its extensive capacity development efforts beyond the Americas to Africa and Asia.

Although CEOS has indicated that it considers its commitments to the GEOSS Water Strategy are complete, it has indicated a willingness to work on other water-related projects that fulfil other needs and at the same time may address some of the Strategy’s recommendations.

At this stage of the Strategy’s implementation, the IGWCO Community of Practice has identified four priorities for more attention in the next three years namely 1) development of the EWV concept and the design of a supporting data system to make these data readily available; 2) development of a comprehensive system for monitoring water use; 3) modernization of data handling procedures of the GTN-H global data centers responsible for in-situ data collection and data services, and 4) expansion of the water applications for the GEO Knowledge Hub.

During the next three years, the IGWCO Community of Practice will work with the GEO Secretariat to engage other groups such as UN-Water, WMO (including the World Climate Research Programme and GCOS), United Nations Environment Programme, and UNESCO, which could have interest in some of the unassigned recommendations.

The reliance of this initiative on voluntary help at every stage of its development explains why some projects have funding and they proceed quickly while others without sustained funding are slow to advance. GEOGloWS has been successful in garnering and mobilizing resources and has the potential to contribute more broadly to the GEOSS Water Strategy assuming suitable projects are identified.. In addition, AquaWatch and, to a lesser extent, the GEO Wetlands, and Drought initiatives, supplement GEO’s overall contribution to the implementation of the Strategy’s goals. Some future support is also anticipated for the GTN-H to strengthen its contributions to climate data services and a joint approach to ECVs and EWVs at the global data centres.

In light of changing scientific and societal requirements for observation-based water information, there is a need to produce an updated version of the GEOSS Water Strategy for the 2025 – 2035 decade and beyond. This revise document should identify emerging challenges and technologies that will present major opportunities and challenges n the future.

**4. Summary:**

The GEOSS Water Strategy is unique from other water strategies such as those Water Strategies developed Global Water Partnership and the US government because it focuses on Earth observations and their integration into water management through the GEOSS framework. It was formulated from the most appropriate concerns arising from the discussions at regional workshops held on three continents and from the personal experiences of its lead authors. In this article, the progress in implementing the Strategy has been reviewed against its four themes: Improved Data Acquisition for Essential Water Variables, Research and Product Development, Interoperability and Coordination, and User Engagement and Capacity Development. The advances that have occurred in these major themes through the efforts of principal implementation groups have been summarized. The Strategy follows the GEO policies for open data and analysis tools promoting greater use of observations through full and open access to data and open software tools. Interested organizations and programs responded to the recommendations with planned sets of activities for addressing the recommendation. In particular, three principal organizations, GEO, CEOS and GTN-H provided substantial volunteer efforts to address the recommendations. However, gaps still exist. For example, more attention should be given to the Strategy’s recommendations related to the need for more user engagement and the application of modern tools for in situ data acquisition, processing and dissemination.

The GEOSS Water Strategy sets out a path for advancing water-related observational and information services. It envisions a process of systematic transformation within the programs led by GEO members and within participating organizations and through open data practices including advances in data integration and through new collaborations such as the SDGs (especially Goal 6 on water), disaster risk reduction, climate change, the Water-Energy-Food Nexus, and ecosystems. The concept of integration is advanced through the production of EWV data products, developing information platforms and multi-sectoral data services, and utilizing data assimilation frameworks.

Within the bounds of a voluntary program the GEOSS Water Strategy was successfully implemented in a number of areas. GEOGloWS has made substantive contributions through the innovative use of government programs and infrastructure. Other GEO initiatives have had good intent but on occasion have been limited by insufficient resources to support substantive activities related to the Strategy’s recommendations.

CEOS, the space arm for GEO, has addressed a number of recommendations in the GEOSS Water Strategy. CEOS has been very helpful, especially in the first three years of implementation, in providing assessments and perspectives on the status of existing and planned satellite developments.

GTN-H provides an important link with GCOS and WMO and will have a central role in developing data exchange policies and protocols in cooperation with GEO. The funding situation is complex for GTN-H because it is a coordination mechanism and must balance its resource commitments and responses towards the GEOSS Water Strategy with a number of other demands, including climate change monitoring. However, future GTN-H contributions will depend to some degree on their success in encouraging contributions from UN Organizations.

At this stage of its implementation, it is clear that the GEOSS Water Strategy has been successful in a number of areas, including:

1. In Theme 1, the CEOS assessment of the synergies between sensors for measuring EWVs identified ways in which planned sensors could be coordinated to provide more near simultaneous EWV measurements. Also, for Theme 1, AQUASTSAT joined the GTN-H federation of data centres, strengthening opportunities to engage the Centre in supplying water use data in support of water security projects.
2. For Theme 2, the development of a GEOGloWS flood prediction system which has been scaled up from regional pilots to function as global system. This approach provides a model for how other applications could be scaled up and integrated with global forecast systems.
3. For Theme 3 an interoperable system for the exchange of data and analyses has been developed and implemented through a NASA-funded GEOGloWS project.
4. For Theme 4, GEOGloWS and the AWCI agreed to work collaboratively to seek ways to harmonize their capacity development activities and share their experiences. Also in Theme 4, Web-based training programs have advanced significantly, allowing for greater access to training in data and services that support water management decisions. The strong collaboration between GEOGloWS and AmeriGEO with NOAA and NASA support has led to innovations that have strengthened water management in Latin America.

The following challenges slowed the implementation of the GEOSS Water Strategy:

1. The concept of the co-generation of products requires further encouragement because the co-generation approach is not part of the training of most creative academic scientists and engineers.
2. Many organizations are fully engaged with their own agendas and do not have the capacity to take the lead in research and product development activities that may not be deemed to be within their program priorities. It may be difficult to engage agencies in taking on responsibility for these projects without being able to provide them with some tangible incentives.
3. Lack of funding for proposed studies by GEO initiatives that supported the GEOSS Water Strategy and for GTN-H efforts to carry out assessments and upgrades of data services in support of water services more generally.

In conclusion, the authors believe that the GEOSS Water Strategy has either directly or indirectly influenced many developments over the past decade related to data support for water management by providing motivation and guidance through voluntary and best-effort projects and encouraging activities by a number of organizations. Given the evidence, the authors consider that the Strategy, a form of “grass-roots” effort for addressing issues related to many aspects of data services for the water sector, is a useful way for individual experts and small groups at different levels to communicate their needs to large international programs, national services, and space agencies. In addition to obtaining useful ideas and feedback on data needs and services, the broad inputs from different levels of responsibilities within organizations, and from different nations to this Strategy have helped to increase awareness of the value of open water data, analysis tools, and information systems, and the great potential to using water-related data and information to support better decision-making in water management.

**Data Availability Statement:**

Information about this study is freely available from the lead author or from the Integrated Global Water Cycle Observations Community of Practice and will be made available on request. The actual data from specific studies reported here are retained by the responsible agencies of the investigators and in most, if not all, cases the data are treated as open access data.

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1. ECOSTRESS refers to NASA’s ECOsystem Spaceborne Thermal Radiometer Experiment which is being carried on the International Space Station. It acquires thermal data around the world to measure the temperatures of plants and assess their demands for water. [↑](#footnote-ref-1)
2. DEVELOP is a NASA-sponsored program that integrates NASA's Earth observations to help address the challenges of environmental change and improve life on Earth (see develop.larc.nasa.gov for more details). [↑](#footnote-ref-2)