Title: A Data-oriented Strategy to support Water Resource Managers and Researchers

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

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Research Impact Statement

Data services enhanced by a global Water Strategy benefited water researchers and managers. The Strategy addressed data acquisition, interoperability, and capacity development issues.

Abstract:

Given the wide diversity of data services provided to national water management agencies, the Group on Earth Observations (GEO) in collaboration with the Committee on Earth Observation Satellites (CEOS) developed the approach described in the report, *Implementing the GEOSS Water Strategy - From Observations to Decisions* to develop more coherent and equitable data services for water management through the use of Earth observations. Among other water resource issues, it recognized the need to enhance data-enriched water management services to support decision making related to drought monitoring, flood warning, tracking and improving sustainable development and monitoring and ameliorating the impacts of climate change.

Needs associated with the Strategy's four themes: improved data acquisition for Essential Water Variables, research and product development, interoperability and coordination, and capacity development and decision support, are reviewed.

Responses to the recommendations have been undertaken by GEO, led by its Global Water Sustainability (GEOGloWS) initiative which includes NASA contributions, CEOS, and the Global Terrestrial Network for Hydrology (GTN-H). Progress on the themes is reviewed and benefits of these developments for international and US water management are identified. The commentary concludes with a summary of what has been achieved, what remains to be done, and the priority focus areas for implementation in the final year of the Strategy.

Key Words: Remote Sensing, Sustainability, Hydrologic Cycle, Data Management, Surface Water Hydrology

1. Introduction: Information Needs of Water Resource Managers and Researchers

The management of water resources continues to grow more challenging with new demands for water, new sources of pollution, growing concerns about the mounting impacts of climate change, new United Nations conventions such as the Sustainable Development Goals (SDGs) and human rights to water and sanitation, and the challenges water resource managers face in a number of regions to access and use data for timely decisions. Over the past three decades, the data available for the water community has expanded rapidly due to new satellite missions launched by government space agencies such as the National Aeronautics and Space Administration (NASA), the European Space Agency (ESA), and the Japan Aerospace Exploration Agency (JAXA), and most recently under planning by commercial enterprises. Within the USA, data and information services provided by the Consortium of Universities for the Advancement of Hydrological Sciences, Inc., the National Oceanic and Atmospheric Administration's (NOAA) National Water Center, and the United States Geological Service help meet the needs of many water managers and researchers in the public and private sectors. Internationally, services are provided through regional water management frameworks with data services being provided through the Group on Earth Observations (GEO), the World Meteorological Organization (WMO) and national hydrometeorological services. Under the leadership of GEO and the Committee on Earth Observing Satellites (CEOS), the GEO Integrated Global Water Cycle Observing Community of Practice (hereafter referred to as IGWCO) developed the Global Earth Observation System of Systems (GEOSS) Water Strategy (GEO, 2014) based on regional workshops held on three continents with water and remote sensing experts and supplemented by a review of past studies and the authors' personal experiences.

2. The Background and Scope of the GEOSS Water Strategy

The intent of the Strategy was to help GEO water-related activities become more effective in reaching the needs of water managers, practitioners, and researchers. Four strategic themes emerged from these consultations: data acquisition for essential water variables, research and product development, interoperability and coordination, and capacity development.

2.1 Improved Data Acquisition for Essential Water Variables

Although water issues differ by region and season, the measurement and use of certain variables have proven to be essential for good water management decisions. The concept of Essential Water Variables (EWVs) was codified in the GEOSS Water Strategy by building on the findings of an earlier GEO analysis (Unninayar et al., 2010). The Strategy reviewed the status of in-situ and satellite measurements of these EWVs and assessed how the data were processed, archived, and disseminated to users. In countries like the USA, the necessary data acquisition and processing functions are generally consistent on a national basis. However, wider disparities exist in some countries and regions where observational networks are not well supported, archiving services are not fully developed, and internet services are inadequate. Table 1 lists the primary EWVs and their relevance to water management issues, and summarizes the adequacy of observational systems and data services.

2.2 Research and Product Development

Identifying innovations for more effectively measuring water in the environment and for increasing the use of these observations for supporting water management are ongoing challenges. Specific needs include better satellite products to support hydrological and land surface modelling, individual and multi-sensor algorithms to improve the characterization of different land surfaces, and better soil texture maps and bathymetries to improve estimates of soil moisture and surface water storage. The GEOSS Water Strategy anticipates that user demand will drive the product innovation process, but more user engagement is needed to initiate and strengthen this process. The Strategy recommends that user needs should be assessed on a continuous international basis, and that data providers work with users to clarify the adequacy of existing products and services and to develop and establish new services. The GEOSS Water Strategy also identified a need for greater investments in research and product development.

2.3 Interoperability and Coordination

Interoperability among data and information systems facilitates water data handling from acquisition and quality assurance to data exchange, dissemination, and application. Currently, data exchanges can be delayed or do not take place at all because many data systems are not configured to share data in a seamless, automatic way. One key step in developing interoperable systems involves the adoption of standard data formats and the implementation of consistent standards for quality control. Modernizing communication networks is also foundational for system interoperability. Although challenges exist, system interoperability must be achieved to assist in addressing user expectations for improved data access.

Integration of information from different sources is needed for new data products. Derived analyses for large areas are generally more accurate if they combine spatially consistent satellite data and high-frequency in-situ data to produce integrated products. In some areas, where in-situ data are very sparse, such as Alaska and the Canadian Arctic, numerical models with data assimilation capabilities can be used to produce reliable estimates at locations between stations.

2.4 Capacity Development

The GEOSS Water Strategy recognized the need to train water managers on the use of Earth observations so that the full benefits of satellite data can be realized. In general, the Strategy advocates continuing and expanding the water community's capacity development efforts currently taking place in Latin America, Asia, and Africa. It also seeks stronger linkages with regional GEO activities. The Strategy encourages the expanded use of water information in interdisciplinary science initiatives such as Future Earth programs (see https://futureearth.org/).

3. The Implementation of the GEOSS Water Strategy

Over the past eight years, efforts have been directed to implementing the Strategy and its recommendations. These efforts have come primarily through the voluntary efforts of programs and agencies as well as individual experts. GEO, CEOS, and the Global Terrestrial Network in Hydrology (GTN-H) program have led the way with these efforts.

Through its GEO Global Water Sustainability (GEOGloWS) Initiative primarily, and also its AquaWatch, Wetlands, and Drought initiatives, GEO has made substantial contributions to addressing these recommendations. As outlined by Gutiérrez-Magness et al. (2017), GEOGloWS is supported by a number of national and international agencies in the USA and Europe, including NASA, which funded four major GEOGloWS projects along with smaller GEOGloWS projects through its DEVELOP activity, the Applied Remote Sensing Training Program, and through support for a GEOGloWS Secretariat.

CEOS, a federation of the world's national space agencies, coordinates civilian satellite Earth observation missions and develops new programs to promote Earth-observing satellites. It reviewed all of the Strategy's satellite-related recommendations and followed up with more in-depth studies for two of the recommendations. GTN-H, a joint program of WMO and the Global Climate Observing Systems (GCOS) program, led by the International Centre for Water Resources and Global Change (https://www.waterandchange.org/en/), coordinates the federation of global hydrometeorological data centers, many of which operate under the auspices of United Nations agencies. GTN-H contributed by strengthening the archival of in-situ river runoff, precipitation, and soil moisture data, and national agricultural water use data through liaison with the Food and Agriculture Organization's AQUASTAT Data Centre. Other organizations and agencies assisting in this implementation include the French Centre National d'Études Spatiales (CNES), ESA, JAXA, NASA, NOAA, the Sustainable Water Futures Program, WMO, and others. The IGWCO continues to monitor progress and to provide biannual updates.

3.1 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 a review of the Strategy's satellite-related recommendations and followed that with two in-depth feasibility studies for two specific recommendations. The first study involved an assessment of the feasibility of a "Water-Train," or a Water constellation for EWVs. Its final report, "The Water Constellation Feasibility Study**"** (CEOS, 2017), assessed the benefits and synergies of using different sensor combinations to meet the water community's observational requirements for six priority EWVs. The second report, led by Australia, was titled "Feasibility Study for an Aquatic Earth Observing System" (CEOS, 2018). It explored the potential for using satellites to monitor water quality variables and outlined strategies for a global monitoring system for water quality. The report provided guidance for the GEO AquaWatch initiative, which is building a water quality information service. 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.

Other gaps addressed in implementing this theme included support for the efforts to acquire the calibrated global data needed for the analysis of water extent and river and lake stage on a global basis, and a review by GCOS to assess the feasibility of including satellite-based evapotranspiration as an Essential Climate Variable.

Issues related to declining in-situ hydrometeorological networks outlined in the GEOSS Water Strategy may be partly addressed through a new WMO program, the Systematic Observations Financing Facility, which is intended to provide technical and financial assistance to less developed countries to generate and exchange basic observational data.

Given that user requirements are not static and that expectations increase as instrument capabilities increase, there is a growing need to update the user requirements listed in the GEOSS Water Strategy. GEOGloWS has undertaken surveys with user communities in the Americas to obtain feedback on their satisfaction with current services and to gauge interest in new products, which will be useful for updating the information about user needs in the GEOSS Water Strategy.

3.2 Implementation of Theme 2: Research and Product Development

Although new product development is a priority for each of the implementing organizations, a number of the GEOSS Water Strategy recommendations in this area went beyond the capabilities of the GEO Water community. NASA, through its Water Applications program, supported three GEOGloWS projects that have developed tools to improve decision-making for water resources in South Asia. One study explored the use of Earth observations to improve the management of irrigation water reservoirs in the upper Indus River Basin using methods reported in Hill et. al. (2020), while a second study used improved snowmelt estimates to provide more accurate predictions of flows into irrigation water reservoirs. In the Lower Mekong River Basin, a system for monitoring surface water storage using integrated multi-satellite products is providing new tools for water management agencies in Viet Nam and Cambodia (Kim et al., 2020).

Studies at the GTN-H's International Data Centre on the Hydrology of Lakes and Reservoirs led by the Russian State Hydrological Institute are using altimeter observations provided by the Laboratoire d'Études en Géophysique et Océanographie Spatiales's Hydroweb (http://ctoh.legos.obs-mip.fr/data/hydroweb) to improve archives of water extent and volume for the world's lakes and reservoirs.

The need for more funds to support research and development has been partially addressed through the World Meteorological Organization and its Hydrological Research Strategy and its recent call for proposals (See. https://public.wmo.int/en/resources/meteoworld/call-collaboration-and-partnerships-wmo-vision-and-strategy-hydrology).

Through NASA's continued development of advanced land data assimilation systems, fields of EWVs and other land surface properties based on the integration of satellite and in-situ data together with more static surface variables are regularly available for use by planners for design and monitoring (Reichel et al., 2018).

3.3 Implementation of Theme 3: Interoperability and Coordination

Responses to the Strategy's recommendations have improved data access among interoperable systems. A NASA-supported GEOGloWS project uses Tethys apps to help users navigate to the required data and to produce products and services for any location in the world (Khattar et al., 2020). The GEOGloWS global flood prediction system (see Gutiérrez-Magness et al. (2017)) uses a version of this data system combined with a hydrologic model to provide a basic service platform that enables the use of satellite data, other global datasets and forecasts, and local data sources as input to a global system for flood predictions.

GEO has helped to address the need for interoperability primarily through 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. Other GEO infrastructure that supports the implementation of the GEOSS Water Strategy and capacity building more generally include the GEOSS Portal (http://www.geoportal.org/) and the GEO Knowledge Hub. Interoperability is needed across observation systems to facilitate the implementation of an EWV information system, and across sectors to support integrated information systems. Copernicus (ESA), the Data Integrated Analysis System (University of Tokyo), and Giovanni (NASA) are also examples of data services that integrate across disciplines and provide access to a wide range of water data.

In 2018, GEO announced the launch of its Knowledge Hub, which promotes interoperability by making comprehensive open-source information available for data, algorithms, systems, and applications. The GEO Knowledge Hub, which serves as an important element of GEO's strategy for interoperability, provides precise protocols for registering and sharing information and data across disciplines and sets standards for transforming Earth observations into knowledge-based services for evidence-based decision-making. Approaches are being explored to assess how the water community could create a suitable water contribution for the GEO Knowledge Hub based upon ideas from the GEOSS Water Strategy.

3.4 Implementation of Theme 4: Capacity Development

Capacity building is supported by offering training programs and implementing new applications in developing countries. The goal is also advanced by supporting the convergence and harmonization of observations, transferring new analysis techniques and demonstrating their use, and designing interoperable systems to enable experts 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 infrastructures and programs, increase user engagement in the design and production of new products, and harmonize capacity development across water activities around the globe. The achievement of these goals could be enhanced by more collaboration among water-related capacity development efforts in different regions.

By providing feedback on their needs, users continue to contribute to the design of future satellite missions. 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." Together with the UN Global Environmental Monitoring System, GEO AquaWatch has addressed the GEOSS Water Strategy's recommendations for workshops on water quality issues and data needs for water quality assessments. They also developed a handbook of best practices for water quality measurements.

New data and decision-support services to water managers must consider many factors. GEO has addressed the differences arising from climate, physiography, capacity to provide data services and water management, languages, and cultures by adopting regional groups for the Americas, Africa, Europe, and the Asia-Oceania regions. Information infrastructure such as the NASA/United States Agency for International Development SERVIR program with its regional hubs in Asia (Nepal and Thailand), in Africa (Kenya and Nigeria), and in South America (Colombia), provide an asset for capacity development in the water sector.

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 application and training programs that benefit countries throughout Latin America. Short-term GEOGloWS projects supported by the NASA DEVELOP program have provided understanding of water management problems, explored broader applications through demonstration projects, and developed web portals. The in-person and distance training programs in English and Spanish that are offered through GEOGloWS and NASA's ARSET have benefited many water managers in Latin America.

Asia

The Asian Water Cycle Initiative coordinated by the International Centre for Water Hazard and the University of Tokyo continues to address many water-related capacity development needs in Asia. The activities have progressed from individual projects and workshops to supplying systems for national government services. National plans for water data integration for Indonesia, Myanmar, the Philippines, and Sri Lanka have been implemented. These plans include adapting and implementing national platforms on water resilience and disasters tailored to each nation's development status and technical capabilities. These developments utilize information systems such as the University of Tokyo's Data Integration Analysis System and build on a commitment to share data, models, experiences, and knowledge among the platform participant organizations. The Asian Water Cycle Initiative frequently implemented e-Learning based capacity building programs during the COVID-19 pandemic.

Capacity building in Asia is also enhanced by ESA's Dragon project in China, the 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 continues to support applications of satellite data to water management and resource management problems in Africa. The GEOGloWS Work Plan for 2023-2025 (GEO, 2022) calls for more studies and applications in Africa, many of which will likely be carried out in collaboration with the Space Climate Observatory which provides climate adaptation schemes over the major African basins. Related studies are being carried out by the CNES hydrological programme to better manage the Congo-Oubangui-Sangha Basin and by the Japanese International Centre for Water Hazard and Risk Management to assess water issues in the Niger River Basin. Two SERVIR hubs facilitate the distribution of NASA data, products, and analysis tools in Africa.

4. Remaining Priority Actions

GEO continues to support the implementation of the GEOSS Water Strategy as GEOGloWS plans to continue to expand its capacity development efforts beyond the Americas to Africa and Asia. While CEOS has completed its negotiated commitments to the GEOSS Water Strategy, GTN-H has some targeted plans and actions that remain to be implemented.

A number of actions noted here are primarily responses to the GEOSS Water Strategy recommendations, while others were undertaken for multiple reasons but do contribute to the Strategy's goals. Some recommendations would be best addressed by groups outside the GEO Water community, and efforts are being made to engage these other groups.

During its final phase, the implementation of the Water Strategy will focus on 1) developing the EWV concept and designing a supporting data system to make these data more widely available; 2) developing a framework for a comprehensive system for monitoring water use; and 3) modernizing data handling procedures at GTN-H global data centers.

5. Conclusions

The GEOSS Water Strategy is unique in its focus on Earth observations and their integration into water management through the GEOSS framework. The Strategy promotes greater use of observations through full and open access to data and software tools. Through volunteer efforts, three principal organizations (GEO, CEOS, and GTN-H) and individual experts have contributed substantial effort to addressing the Strategy's recommendations.

The concept of integration is advanced in a number of areas, including the production of EWV data products, developing data services such as information platforms, and data assimilation frameworks. As a result of emerging priorities, such as monitoring for global water security and emerging technologies, the implementation of the Strategy has undergone some dynamic changes. Given the changes to priorities, enabling technologies, and relevant program structures, consideration is being given to revising the Strategy in the next two or three years. This will provide opportunities for professional water associations, such as the American Water Resources Association, to provide more input into future problem and needs assessments and statements in the future.

The GEOSS Water Strategy is being successfully implemented in a number of areas through the commitment of a number of agencies and volunteers despite limited funding. However, with more substantial support the responses could have been more robust. Future endeavors to address these priorities should seek opportunities for funding early in the planning process. These plans will need to develop the Strategy's potential to encourage stronger links with public policy priorities such as the UN Sustainable Development Goals (especially Goal 6 for water), disaster risk reduction, climate change, emerging programs related to the Water--Energy-Food-Nexus, and ecosystems.

In conclusion, the authors believe that the GEOSS Water Strategy has either directly or indirectly influenced many developments related to data support for water management. Given the evidence, the authors consider that the Strategy, a form of "grass-roots" effort for encouraging activities to address data services for the water sector, is a useful way for diverse groups and individuals to communicate needs to large international programs, national services, and space agencies; to raise awareness of the value of open water data, analysis tools, and information systems, and to make users aware of the great potential that exists in using water-related data and information in decision-making.

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Data Availability Statement:

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

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Table 1: Summary of primary Essential Water Variables (EWVs) with identifiable measurement options and demonstrated end-user applications/sectors. In the first two columns, Y indicates that current observational systems can provide what is needed, and P indicates that the system only partially provides what is needed. For the other columns, an asterisk (*) indicates that the variable is needed for managing the water issues noted at the head of the column.

EWVs [Primary EWVs adapted from GEO, 2014]. Some variables and parameters have been combined for simplicity	Remote Sensing (Satellite and airborne)	In-situ Observation Networks	Water Resources Planning	Water Allocations	Adaptation to Climate Change	Water for Agriculture/ Forestry	Hydropower Production	Water Quality Monitoring	Environment Flows/Ecosystems	Health and Disease Control	Floods and other Natural Disasters	Drought Relief and Management	Urban Water Management	Waste Disposal
Precipitation	Y	Y	*	*	*	*	*	*	*	*	*	*	*	*
Evaporation and Evapotranspiration	Y	Y	*	*	*	*	*		*	*	*	*	*	*
Snow Cover (and Depth, Freeze Thaw Margins)	Y	Y	*	*	*	*	*	*	*	*	*	*	*	*
Soil Moisture/Temperature	Y	Y	*	*	*	*			*	*	*	*		
Groundwater	Y	Y	*		*	*		*			*	*	*	*
Runoff/ Streamflow/ River Discharge	Y	Y	*	*	*	*	*	*	*		*	*	*	*
Lakes/ Reservoir Levels	Y	Y	*	*	*	*	*	*	*		*	*	*	
Glacier/Ice Sheet Balance	P	P	*	*	*	*	*		*		*		*	
Water Quality	P	Y	*	*	*	*		*	*	*	*	*	*	*
Water Use/Demand	P	P	*	*	*	*	*	*	*		*	*	*	*