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Abstract: Fresh water is a basic requirement for terrestrial life, yet knowledge of changes in the volume of water stored and flowing in rivers, lakes, and wetlands is poor. Recent developments in satellite remote sensing promise more accurate monitoring of freshwater resources and better prediction of floods and droughts. Stream flow is traditionally estimated by measuring the water level and converting it to river discharge using an empirical relationship of level versus discharge. Without comprehensive measurements of surface water storage and discharge, the availability of freshwater resources cannot be predicted with confidence. Satellite measurements may enable hydrologists to move beyond the point-based observations provided by gauge networks to basin-wide measurements of discharge and storage. Remotely measuring surface water area is much easier than monitoring changes in the water volume over space and time. Altimeters measure the elevation of the water surface relative to a reference ellipsoid. A second approach provides simultaneous measurements of water surface area and elevation change to yield temporal variations in water storage. Instead of directly measuring spatial and height changes of a water surface, one may also measure the change in mass resulting from volumetric gains or losses in terrestrial water. By themselves, none of these technologies supply the water volume measurements needed to accurately model the water cycle and to guide water management. However, they provide a conceptual framework for a surface water satellite mission that could provide the required information.

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GEOPHYSICS

Tracking Fresh Water from Space

Fresh water is a basic requirement for terrestrial life, yet knowledge of changes in the volume of water stored and flowing in rivers, lakes, and wetlands is poor. Recent developments in satellite remote sensing promise more accurate monitoring of freshwater resources and better prediction of floods and droughts.

Stream flow is traditionally estimated by measuring the water level and converting it to river discharge using an empirical relationship of level versus discharge. Similarly, water level in lakes and reservoirs is converted to storage volume via level-volume relationships. Gauge measurements have helped to quantify flow in river channels. However, the gauging networks used for the level measurements are in deeline globally, and gauges are particularly sparse outside of industrialized regions (1).

Furthermore, estimates of the amount of surface water leaving a drainage basin assume that all the runoff generated upstream flows past a single downstream point. This is often not the case: Many river basins are marked by extensive wetlands and floodplains in which flow is diffuse and not flowing in a channel (see the first figure). Braided rivers are also problematic because their multiple, intertwined channels are constantly shifting, resulting in new channels with ungauged flows. Costs and logistics prohibit the installation of numerous gauges to characterize the flow dynamics in these environments.

Without comprehensive measurements of surface water storage and discharge, the availability of freshwater resources cannot be predicted with confidence. The performance of climate models with respect to land surface hydrology also cannot be evaluated. Comparison of model-derived flows with observations typically shows large modeling errors, sometimes greater than 100% (2). Such comparisons are only possible where there are stream gauges to verify discharge. Yet, in many areas — including much of Africa and the Arctic — surface water flow is not measured (7).

Knowledge of flow through nonchanneled environments such as wetlands and floodplains is particularly poor. Wetlands cover at least 4% of Earth's land surface (3) and up to 20% of humid basins such as the Amazon, but are represented poorly or not at all in most global climate models. In addition, these models generally ignore the effects of water management on the redistribution of water over much of the populated part of the globe.

The need for better knowledge of the global distribution of surface water resources is particularly acute, given population growth and the uneven distribution of water supplies (4). Furthermore, changing weather and climate may accelerate the hydrologie cycle, with unknown effects on freshwater resources (5).

Satellite measurements may enable hydrologists to move beyond the point-based observations provided by gauge networks to basin-wide measurements of discharge and storage. For example, areas inundated by floodwaters have been measured with Landsat imagery (6). However, clouds and vegetation can easily mask the underlying water, a problem that is common to all systems operating in the visible spectrum (see the first figure). Microwave radar [such as synthetic aperture radar (SAR)] overcomes this problem by penetrating clouds and canopy (7).

Remotely measuring surface water area is much easier than monitoring changes in the water volume over space and time. There are three different satellite-based approaches to calculating volume changes. The most straightforward method is to simultaneously measure water surface area and elevation; from a series of such maps, one can then calculate the volume gained or lost. A first step toward such measurements has come from radar altimeters, which were originally designed for use over the open ocean or ice sheets (see the second figure) (8).

Altimeters measure the elevation of the water surface relative to a reference ellipsoid.

Over the ocean surface, the elevation accuracy is on the order of a few centimeters, but two factors reduce the accuracy to tens of centimeters over terrestrial water bodies. First, terrestrial water bodies do not provide a sufficiently large surface area for averaging the multiple radar pulses used in ocean applications. Second, the shape of the returned radar pulse from the water surface deviates from the shape of a typical ocean-like echo. Today's altimeters provide only an elevation profile, yet ideal future instruments would also include area. Radar altimetry has been used to measure river surface slopes (8), which should be related to velocity and hence discharge.

A second approach provides simultaneous measurements of water surface area and elevation change to yield temporal variations in water storage. A first step toward such simultaneous imaging has recently come from interferometric SAR (9). This method is commonly used to generate maps of seismic deformation and glacial flow. Because water is highly reflective, microwave pulses from off-nadir imaging SARs reflect away from the SAR antennae, unless intercepted by vegetation. Thus, subtle height fluctuations across a floodplain's water surface can be mapped interferometrically with centimeter-scale accuracy. Such accuracy is required for understanding flow volumes across lowland floodplains. For example, an elevation change of only a few centimeters in the Amazon can be equivalent to flows greater than the average discharge of the Mississippi River.

Instead of directly measuring spatial and height changes of a water surface, one may also measure the change in mass resulting from volumetric gains or losses in terrestrial water. Starting in 2004, the Gravity Recovery and Climate Experiment (GRACE) satellites will provide monthly global measurements of Earth's gravity field (10). On this time scale, most gravitational variations over the land surface result from mass changes in the total water column (11, 12). The column total is the sum of atmospheric, surface, soil, and ground water volumes. However, because a mass's gravity field decreases rapidly with observing distance, GRACE is only sensitive to basins greater than about 200,000 km^2 (11, 12).

By themselves, none of these technologies supply the water volume measurements needed to accurately model the water cycle and to guide water management (13). However, they provide a conceptual framework for a surface water satellite mission that could provide the required information.

Such a mission — assuming that it passes careful modelbased evaluation — would need to have the following attributes: (i) sufficient spatial resolution (~100 m) to resolve channels, floodplains, and lakes contributing most of a basin's discharge; (ii) sufficient temporal resolution (a few days) to capture short flood events; and (iii) sufficient vertical resolution (a few centimeters) to measure subtle height changes responsible for significant discharge. Surface velocities might be helpful, but surface slope could be used as a surrogate, especially because surface velocity observations are often corrupted by wind effects. In effect, the mission would be a topographic imager that would yield a water map of volumetric gain or loss after each overpass (14).

Such a satellite mission would enable hydrologists to move beyond the pointbased gauging methods of the past century to measurements of the spatial variability inherent in surface water hydrology. Global coverage would ensure that, despite local economic and logistic problems, all countries could access measurements critical for forecasting floods and droughts, both of which have dramatic economic and human impacts.

GRAPH: Relative elevations of the Amazon River near Manaus (8). The TOPEX/POSEIDON radar altimetry measurements (triangles) agree closely with stream gauge observations (solid line). Spaceborne measurements are particularly valuable when gauge data are no longer available (for example, after 1997).

PHOTO (COLOR): The Amazon floodplain near Manaus, Brazil. Nearly 100% of the area is inundated, despite the lack of visible open water. Furthermore, much of the flow occurs outside the channel (photo center), making a single gauge nearly useless for measuring discharge. A series of water surface elevation maps would show how the volume of stored water changes with time.

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