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Managing the Global Water System

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Abstract

An important new insight is that water in its various forms operates as a system on scales much larger than a single lake, river basin, aquifer, or municipality. Although the global cycling of water through the earth's physical system (ocean, atmosphere, terrestrial freshwater bodies) has long been recognized, researchers are only now uncovering a much wider net of connectivities that binds together the flow of water on a global scale. The connectivities are physical (e.g. upstream storages of water cause large scale changes in the residence time of surface water), economic (e.g. water is embedded in food and other products and traded internationally), and even institutional (e.g. decisions about trade of water technology have a global impact). This new awareness of connectivities has spawned the concept of the "global water system". Recent research has also made it clear that the global water system is undergoing large scale, unparalleled, and poorly understood changes that pose major risks to ecosystems and society. The policy community needs to respond immediately to these risks, and this response should take place at all levels, from local to global. At the global level there are three main tasks to take on. First, we need to expand our knowledge base about the global water system by extending the scope of earth observations, by conducting new large-scale field experiments, and by developing new tools for the simulation of the global water system. Second, we should expand global governance of the water system through various means (as a complement to governance at the local and other levels). Options include: an international convention on environmental flows, instituting water labeling of products at the international level, and enforcing water efficiency standards of internationally-traded products. Finally, we should challenge current assumptions about water use in the world by stimulating a public debate on the definition of "essential water needs" and by broadening the viewpoint of water professionals to include the global perspective.

Part I: The Worldwide Connectivity of Water

Although the earth is known as the "water planet", most water researchers and managers focus on scales much smaller than the planetary. Indeed, until a few decades ago it was typical for scientists to concentrate on individual lakes or streams and for water managers to concern themselves only with water supply in their community. But the introduction of "watershed thinking" in the 1960s enlarged the view of water researchers and engineers to encompass the river basin scale.

Now it is again time to enlarge our view of water science and management. The motivation comes from recent research showing that water is interconnected on a planetary level more tightly and in more ways than previously appreciated. Although the existence of a global hydrologic cycle has been recognized for decades, science is now uncovering a vastly wider web of biological, biogeochemical, and even socio-economic connectivities that bind water globally. Furthermore, we are only beginning to understand the nature of these interconnections and their implications for society and the rest of nature.

This new awareness of connectivities has spawned the concept of the “global water system”. Water is considered to be a global *system* in the conventional sense of being an entity made up of components linked together and working towards some common systemic functions. What are these functions? As a global system it transports energy and materials around the world through climatologic and geologic processes, makes moisture available where it is needed by organisms, and overall, contributes to the sustenance of life on earth. Humans are not only part of the system but exploit it by appropriating water and modifying watercourses. It is also clear that in pursuing their goals, humans have caused a drastic transformation of the system, as we describe below.

In this chapter we elaborate the idea of the global water system, especially its freshwater part, and point out its components and the connectivities that bind it together. We then discuss the widespread transformations going on in the system and the many uncertainties that remain about these changes. Finally we discuss threats to water security as a type of failure of fulfilling the functions of the system and discuss the kinds of interventions that may help us to cope with these threats.

Components and Connectivities

The global water system can be understood as a structure made up of three types of components – physical, biological/biogeochemical and human – that are linked internally and with each other through a network of connectivities or “teleconnections” (with spatial scales of hundreds to thousands of kilometers). (Figure 1). What are the major features of these components and their connectivities?

Physical components

Decades of research in climatology and hydrology have firmly established the physical connectivities of water in a worldwide system of stocks and flows. The cycling of water in a physical sense is the most obvious part of the global water system. By far the largest stocks are the world’s oceans, storing about 1.35 million km^3 of water and providing around 86% of the total continuous source of water for the atmosphere. Ice caps take a distant second place as a repository of moisture. Each year evaporation from the world’s oceans combined with evaporation/transpiration from the land provide a flow of nearly 500 000 km^3 of water to the atmosphere. This volume is returned to the earth’s surface as precipitation. The cycle is closed as about 40 000 km^3 of this precipitation find their way back to the ocean each year through rivers and subsurface watercourses.

Other physical connectivities arise from the interplay of land, atmosphere and hydrology which affects energy and moisture fluxes and can influence precipitation patterns over large areas. As an example, scientists hypothesize that moisture feedbacks between vegetation, soil and the atmosphere play a key role in the persistence of both dry and wet conditions over the Sahel in Africa.[1] Another well known example is the link between deforestation of the Loess Plateau of China and changes in sediment and flow characteristics of the Yellow River for hundreds of kilometers downstream of the Plateau. Uncovered soils wash off to the river and this substantially increases the river’s sediment load. Sediment settles out in the delta of the Yellow River, raises the riverbed, and thus contributes to more frequent downstream flooding.

Scientists have documented many other examples worldwide of engineering works and land use changes that cause major changes in sedimentation and flow characteristics of rivers for very long distances downstream.

Biological and biogeochemical components

Water is essential for maintaining the integrity and biodiversity of both terrestrial and aquatic ecosystems. Hence, the living parts of the world's freshwater ecosystems, both aquatic and riparian organisms, are part of the global water system. Biogeochemical processes are also covered here, together with the many processes determining water quality in freshwater systems. Various biogeochemical connectivities occur in the global water system because water is an important medium for transporting carbon, nitrogen, phosphorus and other elements through the earth system, and serves as an important repository for these elements. Hence, the global biogeochemical cycles are intertwined with the global water system. Through its linkages with the carbon and other biogeochemical cycles, water helps regulate the release and sequestration of CO_2 and other radiatively-important trace gases. On the global scale, the hydrologic cycle is one of the principal vehicles controlling the mobilization and transport of chemicals and other constituents from the continents to the oceans.

Human components

The many manifestations of society's manipulation of water resources make up an essential part of the global water system. These include water engineering structures (reservoirs, canals), water-related organizations (financers of water infrastructure, water planning agencies, water companies), and water use sectors (municipal water utilities, thermal power plants). Society is not only a component of the global water system but also a major agent of change within the system.

We are only now beginning to realize the extensive connectivities that bind the socio-economic part of the global water system together. Some linkages are formed by economic relationships as in the case of the international flow of "virtual water" embodied in cross-boundary food trade. The basic idea of virtual water is that arid countries compensate for their water deficits by importing "virtual water" in the form of food products rather than using their own scarce water resources for growing food themselves. Since large volumes of water are needed to grow crops (e.g. cultivating a kg of grain requires roughly 1000 to 1500 l of water, depending on location and type) it follows that the enormous international trade in foodstuffs involves a similarly huge trade in virtual water. The annual global volume of virtual water imported in food is around 1250 km^3, a substantial number as compared to the 2400 km^3 of water annually withdrawn for irrigation.[2] On one hand, the virtual water concept can be thought of as a new variation on the old principle of economic competitive advantage. On the other hand, it provides new insight into how humanity mobilizes and controls a significant part of the hydrologic cycle.

Another form of socio-economic connectivity arises between centralized organizations and worldwide development of water infrastructure. Only now are researchers beginning to uncover the sweeping influence of centralized development agencies, banks, private water companies and other organizations on the worldwide water system. Decisions taken in a few world capitals about the structure of water pricing or the sale of water engineering are having wide-scale impacts on water use and supply. As the world economic system becomes ever more integrated it should be expected that more water-related connectivities will emerge.

The System Transformed

Far from being a static, the global water system is undergoing changes that are wide-spread, world-wide, and concurrent. In the following paragraphs we review some important changes.

The *physical characteristics of freshwater systems* are undergoing a major transformation which include persistent changes in precipitation and hydrologic patterns, changes in runoff and the retention time of freshwater on the continents, modification of the sedimentation characteristics of rivers, as well as alteration of the moisture fluxes between the atmosphere and terrestrial environment. One sign of widespread changes is that the flow and storage characteristics of 172 out of 292 of the largest river systems in the world have been significantly altered by impoundments.[3]

Climate change will have a growing and more noticeable impact over the coming decades on freshwater systems throughout the world. Some semi-arid and arid regions (e.g. northeastern Brazil, western United States, southern Africa) are likely to have significantly declining average river discharge and groundwater recharge. As recently reported by the Intergovernmental Panel on Climate Change, more than one-sixth of humanity lives in river basins fed by snow and glacier-melt, and these basins are particularly vulnerable to climate change. At first, winter discharge will drastically increase because of warmer temperatures. After some decades it will decrease in a similarly drastic fashion because of the depletion of glacial ice.

Although the local mechanisms of physical changes are fairly well understood, many questions remain about the global manifestation of these changes as well as their intensity. For example, what will be the combined impact of climate change and flow diversions on the hydrologic regimes of rivers and freshwater inflows to the world's estuaries?

The *biological and chemical characteristics of freshwater systems* are undergoing wide-spread modifications, including major alterations in dissolved oxygen levels and other important water quality parameters as well as long term changes in the flux of sediments and nutrients delivered by freshwater systems to oceans. Chemical and physical modifications of freshwater systems have constricted the habitat of aquatic organisms and severely impacted aquatic ecosystems. An example is the River Rhine which has experienced more than a century of channelization and riparian development leaving it isolated from 90% of its original floodplain. Some rivers, such as the Colorado and the Yellow rivers, often do not reach the ocean. More than 20% of freshwater fish species have become threatened, endangered or extinct within the past few decades.[4]

The continent of Africa could endure particularly wide-ranging transformations of its water chemistry and biology. Recent scenarios point to a four- to eight-fold increase in wastewater loadings over most of Africa within the next four decades, [5] suggesting a likely worsening of freshwater quality. What will be the implications of these increased loadings on water chemistry and biology? What will be the spinoff effects on aquatic ecosystems and the freshwater fishery which is an important protein source for inland African countries?

Widespread changes are also occurring in the *anthropogenic use of water,* with declining trends in water withdrawals in some industrialized countries and rapid increases over most river basins in the developing world. The structure of the water economy is also rapidly changing in the developing world as water use in the domestic and manufacturing sectors claim a larger and larger fraction of total water withdrawals. Furthermore, only now have scientists begun to study the underlying causes of global changes in water use, and an open question is which factor – demographic change, economic growth, technological change, consumption patterns, or other– will be most important and where? As water abstraction rapidly expands we should expect sharper competition between households, irrigated farmers, electrical utilities and other water users. What impact will this competition have on achieving the Millennium Development goal of halving the world's population without access to sustainable water supply by 2015?

Although changes are taking place throughout the global water system, not all parts of the world will be affected to the same degree. A key question is, where will the most important changes occur, and how much of the world will be affected? According to one estimate, future "hot spot" areas with increasing abstraction and/or decreasing availability related to climate change will cover 7 to 13 percent of the world's river basin areas.[6] (Figure 2).

Part II Intervening in the Global Water System

Why Intervene at the Global Level?

We have seen that the global water system is undergoing important changes in its physical composition, its chemical and biological characteristics, and in its human dimensions. What implications do these have on water security? From the viewpoint of the global water system, water security can be seen as a long-term but temporary balance between water users and water availability or services. On one hand, water availability and quality are determined by the spatial and temporal patterns of precipitation and other meteorological phenomena, the structure of watercourses, the characteristics of the earth's surface, and wastewater loadings. On the other hand, human water users (households, municipalities, industries, water sports enthusiasts) or non-human water users (aquatic and riparian organisms and their ecosystems) adjust over time to the spatial and temporal pattern of water availability or services. The system is shaken out of this temporary balance by rapid or abrupt changes in the global water system, some of which are described above. It is also made unstable by continuing pressure from water users aspiring to higher water use to support a higher standard of living.

From the systems viewpoint, a breakdown in water security represents a *systems failure* in that the global water system cannot fulfill the goals of water users. The failure is most often manifested as too little water, or more precisely, a gap in many parts of the world between the water available to water users and their current requirements or aspirations. Depending on local and regional circumstances, this gap can disrupt aquatic ecosystems, cause temporary or persistent water shortages, displace current water users with those having a competitive advantage, cause a decline in living standards or hinder its improvement.

How can we as human agents in the global water system cope with global threats to water security? How should we intervene to address failures of the system? In reality society acts every day through conventional water management to ensure or enhance water security at the local and river basin level. The wide palette of response options is shown in Box 1.

But when is it appropriate to intervene at the global level as compared to the local or watershed level? Here are a few different circumstances: First, when the driving forces of change are global in scale, as in the case of climate change impacts on water resources. Second, when changes are driven by worldwide institutions such as multinational water companies or international funding agencies. Third, when connectivities are global or large-scale in nature as in the case of the strong feedbacks between land, atmosphere and hydrology in the Sahel region, or the large volume of virtual water that links nations together through international food trade. Fourth, when a threat arises to a globally important part of the system, such an impending extinction of an aquatic or riparian species or the deterioration of vital ecosystem services. Fifth, when an important change occurs concurrently throughout much of the world, as in the case of rapidly increasing water withdrawals and wastewater discharges in developing countries. Given these justifications for intervening globally, what form should these interventions take? A few of the many options are laid out in the following paragraphs .

Intervention Number One: Extending our Knowledge Base of the System

A prerequisite for selecting the right way to intervene is to know enough to act wisely. But as shown by the many questions raised above, the knowledge base about the global water system is quite weak, and special effort is needed to improve this situation. Below we consider three approaches – global monitoring, large field experiments and new modeling and assessment tools. These activities should all work towards enhancing our understanding of the intensity, location and causes of change in the water system. A particularly important task is to identify “hot spot” areas in the world of rapid change or particular sensitivity. (See Figure 2 for an example estimate of hot spots.)

Expand the scope of remote earth observations of the global water system. The past decades have seen enormous progress in the use of satellites and aircraft to collect data about the global environment. An effort particularly relevant to the global water system is the “Soil Moisture and Ocean Salinity” (SMOS) Mission of the European Space Agency. Beginning in 2008, SMOS will collect planet-wide data on soil moisture, a key parameter of the earth’s water cycle. While being very useful, the SMOS and other space-based missions tend to concentrate on the physical side of the global water system despite the urgent need for planet-wide data on ecological, biogeochemical and anthropogenic variables (e.g. spatial variation of water quality, state of aquatic ecosystems, and locations of human appropriation of water resources). Collecting these data will certainly pose technical challenges, but the scientific community has already shown that satellite sensors can meet these challenges.

Conduct new large-scale field experiments and surveys. While remote earth observations are ideal for giving us an overview of changes in the water system, intensive field experiments can provide better understanding about processes and feedbacks in the system. Programs such as the “African Monsoon Multidisciplinary Analyses” (AMMA) collect vast amounts of hydrological and climatological data by concentrating the capacity of scientists in an efficient way over a short period of time. From the perspective of global water research, AMMA-type experiments bring us further along in understanding large scale teleconnections between land use, climate and the hydrologic cycle. Another useful type of field campaign are flow manipulation experiments (as conducted on the Colorado, Snowy, and other rivers) in which experimental flows are released from dams in order to study their downstream ecological effects. Data from these campaigns provide valuable new insights into the flow requirements of aquatic and riparian ecosystems. Not only the natural sciences, but also the social sciences need more large scale field campaigns to acquire data. Social science surveys up to the planetary scale would provide new knowledge about the spatial variability and variety of human vulnerability to changes in the water system. This knowledge would help researchers match locations of expected rapid change with particularly vulnerable populations.

Develop and use new tools for simulating the global water system. Collecting new data is important but these data must also be analyzed by novel types of analytical tools. A new generation of global- and continental-scale water models is required for comprehending and anticipating future changes in the global water system. To be useful for addressing policy-relevant questions, these models must be able to integrate a very wide range of global scale information about the socioeconomic system, land use, climate, hydrology and aquatic ecosystems. Model builders will have to team up with groups collecting data to identify the current and future "hot spots" of changes in the global water system. Considering the importance of simulating the global water system, the new generation of water models must be hooked into world-wide internet-based "user support systems" that store key model outputs and make them widely available to researchers, policy analysts and interest groups. New integrated assessment procedures are needed for systematically tracking the state of the global water system and computing scenarios of future changes and response options, and especially for communicating this information to society. The water community can build on the experience of the Intergovernmental Panel on Climate Change which periodically assesses and interprets the state of understanding of climate change issues in a way relevant for policymakers and other stakeholders.

Intervention Number Two: Expanding Governance of the System

As compared to global monitoring, field experiments, and the like, a more direct intervention would be to expand the global governance of water. "Water governance" is defined by the United Nations Development Programme as "the political, economic and social processes and institutions by which governments, civil society and the private sector make decisions about how best to use, develop and manage water resources." The first steps towards global water governance were already taken back in 1921 with the adoption of the "Convention and Statute on the Regime of Navigable Waterways of International Concern" which prohibits states from impeding the navigation of important international waterways passing through their territory. Two years later, a convention concerning "Hydraulic Power" established guidelines for states to negotiate about hydropower projects affecting international waters. The much more recent "Convention on the Law of the Non-Navigational Uses of International Watercourses" (1997) also intervenes in international waters by urging the prevention, reduction and control of pollution, by hindering the further introduction of alien species, and by fostering cooperation between states in management of water resources.

The aim of the preceding three conventions was to influence the development and management of international watercourses. But what about the rest of the global water system? The Ramsar Convention (1971) ("Convention on Wetlands of International Importance Especially as Waterfowl Habitat") established the fundamental right of the international community to intervene *even if a particular issue does not involve international waters*. Ramsar promulgated international guidelines for protecting wetlands *within the borders of countries* because these wetlands are internationally significant to "ecology, botany, zoology, limnology or hydrology". As an example of "international significance", the convention argues that wetlands are vital to migrating waterfowl whose habitat can include many other countries outside of the wetlands locations.

As noted in the above definition, water governance is also carried out by non-political or quasi-political institutions. Examples at the global level are the Global Water Partnership, the World Water Council, the World Water Forums, the World Conservation Union, and the World Bank. These institutions, and especially the political conventions noted above, have established the basic legitimacy of governing water globally. How should we now build on this experience?

Establish an international convention on environmental flows – A timely follow-up to the Ramsar Convention would be an international convention promoting universal compliance with environmental flows. Such a convention would set up international guidelines for the natural flow regimes needed for protecting or restoring aquatic ecosystems and would require that these flows be protected in undeveloped river basins and re-established where possible in developed basins. These guidelines would have to be quite general and flexible because of the large differences between flow requirements of different ecosystems. The convention would cover both international and non-international rivers following the precedent established by the Ramsar Convention. Rivers within country borders would be covered by the agreement because of their "international importance" in providing vital ecosystem services such as regulation of the global nutrient cycle and provision of food. Of course such a convention could not provide full protection for aquatic biota since it would not address the physical modification of aquatic and riparian habitats, nor the degradation of water quality, nor other factors endangering ecosystems. Nevertheless, taking universal action to protect natural flow regimes where they still exist, and restoring some semblance of these patterns where they do not, would be important steps in protecting the biological side of the global water system.

Introduce international water labeling – Product labeling falls somewhere between consumer protection and public education; it is used to inform consumers about the performance of a product with the aim to reduce the use of products that are dangerous or environmentally-harmful. Advocates of this approach believe that well-informed consumers will voluntarily seek out ecologically-sound merchandise. A prominent example dealing with water is Australia's national water labeling program. Under this program notices are placed on dishwashers and other appliances that show their water use intensity and whether they conform to minimum water efficiency standards. Arjen Hoekstra at UNESCO and others have proposed that water labeling be tried internationally to stimulate global water conservation. Although international water labeling does not yet exist, the forest industry has set a valuable precedent that could be built upon – Internationally-traded wood products carry a certification label of the Forest Stewardship Council if they comply with "responsible forest management" criteria. The water community could adopt a similar approach and carry out its own certification of the water performance of internationally-traded appliances. Alternatively, labeling could be introduced by governments through a convention of the type described above. Either way, a labeling program would require information on water use efficiency to be placed on all internationally-traded products that use significant amounts of water and this could turn out to be a powerful tool to stimulate worldwide water conservation.

Enforce international water efficiency standards – The international community could go a step further than labeling and pass a law specifying a limit to the allowable water use of internationally-traded appliances. Agreement would be needed on the definition of "reasonable water consumption" for different technologies and the law would have to be updated periodically to keep up with technological improvements in water use efficiency. Such a statute could require that major technology exports, such as power plant turbines, are water efficient and this would encourage not only industrialized countries but also developing countries to use the most up-to-date water-saving equipment. A disadvantage of this approach is that water-saving technology could have higher capital costs than less water-efficient alternatives. Hence measures may have to be taken to reduce the extra financial burden on developing countries caused by their compliance with international water efficiency standards.

Guarantee the human right to water – Many individuals and organizations advocate an explicit international declaration of the human right to adequate water supply and sanitation.

With around 1.1 billion people lacking access to safe water and 2.4 billion to basic sanitation it is hoped that such a declaration would pressure governments to comply with the Millennium Development Goal mentioned above, to provide adequate water supply and sanitation to the needy. But the international acceptance of this human right is unclear. To date, the strongest official statement is General Comment No. 15 published in 2002 by the Committee on Economic, Social and Cultural Rights of the United Nations. This statement decrees that "the human right to water entitles everyone to sufficient, safe, acceptable, physically accessible and affordable water, for personal and domestic uses" and makes important statements about the obligations of governments to deliver clean water and adequate sanitation to their citizens. While the World Water Council considers the Comment "decisive progress" on the human rights question, they also point out that it is a recommendation rather than a legal document. An unfinished task of the international community is to make an unequivocal, legally-binding declaration about the human right to water. It is also time to think about how such a declaration can be enforced. A first step could be for UNESCO and UNICEF (already busy monitoring the adequacy of water supply and sanitation in different countries) to assess how well nations are complying with basic human rights to water.

Intervention Number Three: Challenging the Goals for the System

The educator and systems theorist, Donella Meadows, conjectured that systems have particular "leverage points" where humans can intervene most effectively to alter the system's behavior. Further, she claimed that the most sensitive leverage point was to challenge the goals for the system and their underlying assumptions. How does this idea apply to the global water system? What does it mean to challenge its goals? From the human standpoint, these goals are to provide humanity with adequate water for its perceived requirements or aspirations. To challenge these goals would be to ask: Do we really need the volume of water we now use or aspire to use? In the following paragraphs we discuss two ways to address this fundamental question.

Stimulate a public and institutional debate on water needs – Just as the many impacts of conventional energy use have stimulated a debate about how much energy we really need, so too the consequences of human abstraction of water justify serious reflection about the volume of water really needed by humanity and nature. The bottom line is our physical requirement for water. The United Nations High Commission on Refugees recommends a minimum allocation of 15 liters per day for each person in a refugee camp, but regards 7 liters per day as the "minimum survival allocation". Beyond survival, the United Nations suggests 20 liters per day as a guideline for "reasonable access to water". In the "World Water Vision Scenarios" the World Water Commission assumed that 40 liters per day per person was the minimum needed for basic personal and household use. Another widely quoted figure is 100 liters per day per person which Falkenmark and Lindh call a "fair level of domestic supply". Hence the range of minimum personal needs outside of crisis situations is around 20 and 100 liters per day per person. Looking at the actual situation, the average daily water use of a sub-Saharan African is about 25 liters, which is not much above minimum personal needs. At the other extreme, the current European lifestyle requires 233 liters per person per day, while North Americans use 638 liters per person per day, very far above minimum personal requirements. In the face of these data, we need to seriously consider: What is an equitable level of domestic water use and how can this be universally achieved and complied with? It is equally urgent to apply this question to water used by industry and agriculture.

Reform water education and training – If our aim is to make a lasting change in society's attitudes about water, we will have to train the new generation of researchers, engineers and managers to think in a new way about water. The reality is that conventional training tends to reinforce current assumptions about water resource development. Students learn how to design water infrastructure and develop water management plans, but learn much less about competition between water sectors or the long term impacts of river basin developments. An exception to this rule, called "integrated water resources management" is slowly finding its way into university curricula. This is a management approach that "integrates" many different aspects of river basin development by promoting a long-term perspective to planning, by encouraging the participation of diverse interest groups in the planning process, by reconciling the water needs of many different human users together with needs of aquatic ecosystems, and by advocating a strengthening of water use efficiency as an alternative to expanding water supply.

Incorporating the ideas of integrated water resources management into the routine training of water researchers and professionals would be a major step in encouraging new thinking about water. But a further step is needed. It is just as urgent to expand university curricula in ecology, economics, hydrology, water and wastewater management, and other water-related disciplines to encompass the global perspective. The new generation of water researchers and professionals must understand that water is no longer just a local or river basin issue. On the contrary, research has uncovered wide-spread and large-scale connectivities that show that water is also a global system. Moreover, pervasive changes going on in this system pose risks to humanity and the rest of nature that require global attention. Summing up, a major challenge for the new generation of water specialists is to enlarge the scope of water research and management from the local, watershed and regional level to include the global scale.

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