WATER SECURITY

Coping with the curse of freshwater variability

Institutions, infrastructure, and information for adaptation

By J. W. Hall,[1]* D. Grey,[1] D. Garrick,[2] F. Fung,[3] C. Brown,[4] S. J. Dadson,[1] C. W. Sadoff[5]

Coping with variable and unpredictable freshwater resources represents a profound challenge to climate adaptation. Rainfall, snowmelt, soil moisture, and runoff can vary from zero to large quantities, over a range of time scales and in ways not well predicted by climate models. Extreme floods and droughts are the most obvious manifestations, but hydrologic variability can also have chronic impacts. Water security involves managing these risks so that they do not place an intolerable burden on society and the economy (*1*). We discuss interlinked roles of institutions, infrastructure, and information in managing those risks.

Economic output [Gross Domestic Product (GDP)] can be sensitive to hydrologic variability (*2*), especially in agriculture-dependent societies. Droughts, floods, and extreme variability affect output directly and have ripple effects through the economy, depending on the severity of the hydrologic hazard and the vulnerability of socioeconomic systems. For example, hydrologic variability in Ethiopia accounts for there having been 38% less economic growth than would have been expected based on average rainfall (*3*). Multiyear drought in Syria has triggered migration into cities by unemployed farmers, contributing to conflict (*4*).

POLICY

Even the perceived risk of future losses can create disincentives for investment, which inhibits growth. The $43 billion in economic losses and $16 billion insured losses due to the 2011 flooding in Thailand (see the photo) shook the insurance industry and threatened continued foreign direct investment (*5*).

UNDERSTANDING VARIABILITY. With hydrologic variability poorly understood (*6*), extreme events can be hard to predict. Future changes in variability are highly uncertain. At least three dimensions of hydrologic variability can cause harm: intra-annual (seasonal and monthly), interannual (year-to-year), and unpredictable timing and intensity of extremes. Strong seasonal variability, experienced in monsoonal and tropical climates, limits the productive portion of the year. In parts of India, 50% of annual precipitation falls in just 15 days, and over 90% of annual river flows are concentrated in only 4 months of the year (*7*). Arid regions, like the southwestern United States, Australia, Middle East, North Africa, and Central Asia, are characterized by strong interannual variability, increasing the likelihood of multiyear droughts and also of intense rainfall that far exceeds the average and can lead to catastrophic flash flooding.

When these dimensions are combined, the situation is most challenging—a wicked combination of hydrology that confronts the world's poorest people. Of the 35 river basins with a population greater than one million that are classified by the World Bank as "low income," 19 have variability of runoff that is greater than both the interannual and intra-annual medians (across all populous river basins globally), and only two have variability of runoff that is less than both the interannual and intra-annual medians (see supplementary materials).

The scale of economic losses depends on factors that are difficult to isolate. Coping capacity increases with wealth (*8*), with more resources invested to manage risk. Yet, increasing wealth can increase economic exposure to extreme events, with more assets in harm's way. The Intergovernmental Panel on Climate Change (IPCC) reports that losses from climate-related hazards were 1% of GDP for middle-income countries during the years 2001–2006, but only 0.1% of GDP for high-income countries (*8*). Major investments in risk reduction, often triggered by catastrophic losses, e.g., the 1926–27 Mississippi River floods and 1953 floods in the Netherlands, have proved to be effective in managing economic impacts of climate hazards. Yet deteriorating infrastructure and changing frequency of extreme events can push losses beyond the tolerability threshold, as seen from U.S. impacts of hurricanes Katrina and Sandy.

Countries have little control over their hydrologic endowment: when and where it rains and how much water evaporates, infiltrates, and runs off. Countries that have managed to grow economically, notwithstanding complex hydrology, have invested heavily to reduce risk. In river basins where there has been low investment to cope with complex hydrology, economic output is overwhelmingly low (see the chart, lower right) (Fig. 2). By contrast, countries along river basins with benign hydrology are more wealthy, even though investments in water management have sometimes been quite modest (see the chart, left side). Additional investment required to transition from water-insecure to secure is greatest in river basins with highly variable hydrology (see the chart, right side). This is least affordable and hardest to deliver in the poorest countries. Although investment in institutions and infrastructure can shift river basins upward in the chart, reflecting improved water security, climate change may shift them rightward, adding to the threat in societies already underequipped to cope with risk.

PATHWAYS TO WATER SECURITY. Adapting to hydrologic variability, building resilience to risk, involves "the three 'I's": institutions, infrastructure, and information. Institutions and governance (including river basin organizations, legal systems, national governments, and nongovernmental organizations) support proactive planning and development of legal and economic in-

Floods in Thailand in 2011 caused $43 billion in losses (*5*). Rojana Industrial Park, Ayutthaya, Thailand, October 2011 (*14*).

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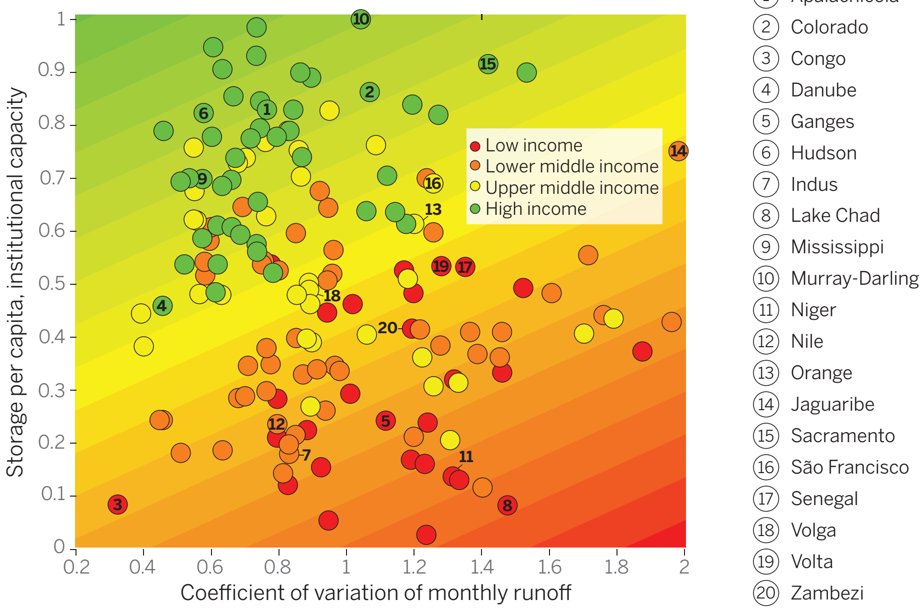
Linking economic growth, hydrologic variability, and investment in risk mitigation



Linking economic growth, hydrologic variability, and investment in risk mitigation. The world's river basins with a population >2 million, colored according to GDP per capita of the population in the basin. The horizontal axis summarizes hydrologic variability. The vertical axis is a composite indicator of investment in infrastructure and institutional capacity. The colored contours are a linearly interpolated surface reflecting the association between variability, water security investments, and GDP. See supplementary materials for details.

struments to manage and share risks (water allocation and property rights, land zoning, watershed protection, water pricing and trading, insurance, and food trade liberalization) (*9*). Investments in infrastructure buffer variability and minimize risks (storage, transfers, groundwater wells, levees, wastewater treatment, and desalination). Information collection, analysis, and transfer (monitoring, forecast and warning systems, expert know-how, simulation models, and decision-support systems) are essential for operating institutions and infrastructure.

Coping with variability involves combinations of the three I's—seldom do they yield their full benefits in isolation. Thus, although individual projects have typically been the "unit of currency" in investment decision-making, this needs to be replaced by a more systemic view of the pathway to water security, sequencing investments along a pathway that can most cost-effectively and equitably reduce risk. Benefits of water security may not fully materialize until some way along the pathway when systems are nearing completion. Unwise choices can lock in unsustainable pathways, storing up future costs, for example, of environmental restoration.

Investment in hydraulic infrastructure is not consistently productive. Investments may be wasteful and inefficient, and perhaps socially and ecologically harmful, causing political disruption and undermining the catchment's capacity to deliver ecosystem services (*10*). A transformation in investment appraisal is therefore required, focused on risks, trade-offs, and uncertainties associated with alternative investment pathways. There are promising cases of analysis of costs and benefits of water resources management in a changing climate [e.g., in the Great Lakes (*11*) and the Dutch Delta Programme] and of long-term planning for water security in a rapidly urbanizing world (e.g., in Singapore). Even in these advanced-economy settings, the analysis of risks, exploration of uncertainties, and development of long-term investment plans have generally not been integrated in the way that we believe water security requires.

In practice, this requires (i) accounting for what is known about variability (from the observed record and model evidence) and taking proportionate risk-based decisions (*12*), (ii) extensive sensitivity testing of residual uncertainties (known and unknown) to identify key vulnerabilities and select robust options, and (iii) promotion of adaptive approaches and system resilience that can cope with unexpected change (*13*).

There is increasing capability for modeling runoff, water resources, and extreme events, but there has been disinvestment in observation systems that are essential for validation of simulations and to provide evidence for risk managers on the ground (*6*). Embracing nonstationarity requires more observations over space and time, not fewer, exploiting the possibilities of new sensors and data sources—from crowd-sourcing to Earth observation.

Understanding the evolution of risk also means tracking and predicting processes of demographic, economic, social, institutional, and environmental change. Global socioeconomic data sets and scenarios are an exciting advance but provide a limited picture of vulnerability and exposure, often at coarse resolution. Records of impacts of risks rely heavily on reported events, which provide an incomplete picture. Scarcest of all are the data to quantify the effectiveness of investments in institutions and infrastructure to reduce risk. We know that successful investments are path dependent, i.e., that context matters. But we do not know, for different basins and development paths, what are the critical balance and sequencing of investments in institutions, infrastructure, and information.

[1]University of Oxford, Oxford OX1 3QY UK. [2]Department of Political Science and Walter G. Booth School of Engineering Practice, McMaster University, Hamilton, Ontario L8S 0A3, Canada. [3]Environment Agency, Bristol BS1 5AH, UK. [4]Department of Civil and Environmental Engineering, University of Massachusetts, Amherst, MA 01003, USA. [5]World Bank, Washington, DC 20433, USA. E-mail: jim.hall@eci.ox.ac.uk

SUPPLEMENTARY MATERIALS

www.sciencemag.org/content/346/6208/429/suppl/DC1

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ACKNOWLEDGMENTS

The analysis described in this article forms part of the Global Water Partnership/Organisation for Economic Cooperation and Development global dialogue on Water Security and Sustainable Growth and the Oxford Martin Programme on Resource Stewardship.

10.1126/science.1257890