CITIES, DAMS, AND EXTREME WEATHER

Dams have long played a critical role in fostering urban growth, a trend that is expected to continue throughout the developing world. As the interplay between large dams and local weather patterns becomes better understood, civil engineers must lead the way in ensuring that large dams and the urban areas that rely on them remain as resilient as possible, even in the face of changing patterns of extreme weather.

By Faisal Hossain, Ph.D., A.M.ASCE, and
Alfred Kalyanapu, Ph.D., A.M.ASCE

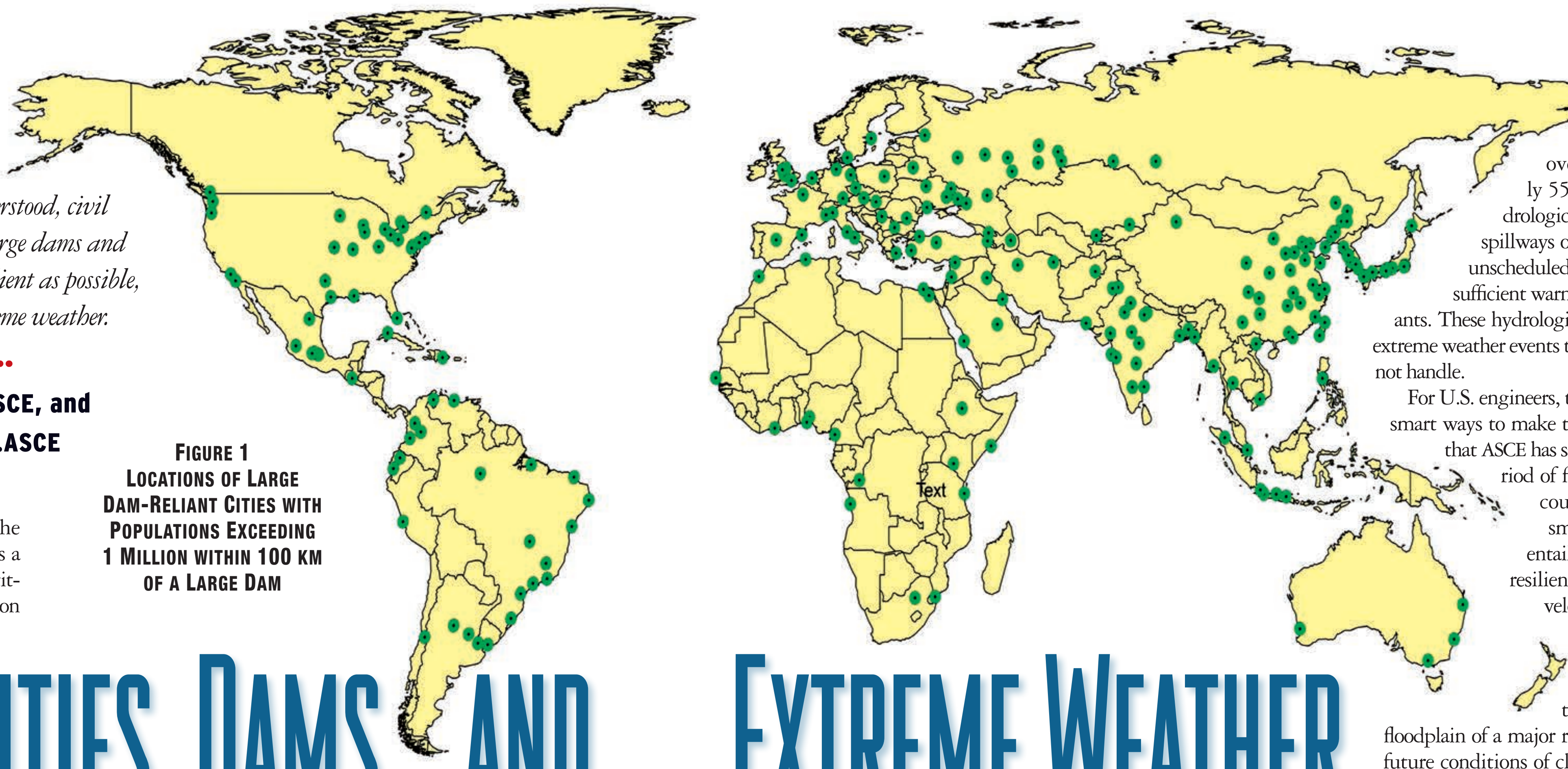

FIGURE 1 LOCATIONS OF LARGE DAM-RELIANT CITIES WITH POPULATIONS EXCEEDING 1 MILLION WITHIN 100 KM OF A LARGE DAM

WITH AN INCREASING percentage of the world's population living in urban areas as a result of migration and economic growth, cities are becoming larger and more dependent on such key resources as energy, water, and food. In addition to the trend of rural-to-urban migration, rising demand for skilled labor and the increasing globalization of the world's economies are the leading forces shaping the future of cities. According to one estimate, 70 percent of the world's population will reside in large cities by 2050, and many of these will have populations of more than 1 million.

It is worth noting that most large cities are located near a freshwater source, either a river or a lake. Because of urban growth, demand for freshwater has systematically risen as a result of increased consumption, energy generation, and food production. In the United States and much of the world, when naturally available supplies of freshwater have failed to satisfy anthropogenic demand, human regulation of surface water has emerged as the typical solution. Historically, one common engineering solution for regulating surface flows has involved constructing dams and artificial reservoirs. By retaining sufficient flows from the local water cycle, dams and reservoirs balance shortfalls that occur when demand exceeds the variable supply afforded by nature. Large dams play another critical role by protecting downstream urban infrastructure from the effects of extreme meteorological events, including severe storms and significant floods.

Many large cities are located within 100 km of a large dam, which is defined here as one with a height of more than 15 m from the foundation or having a reservoir volume of more than 3 million m³ (see figure 1). These large cities may often be categorized as dam-reliant, meaning that they simply could not exist in their current form without the steady supply of water and the flood control services provided by the nearby dam. For civil engineers and other members of the infrastructure community, it is of cardinal importance that the increasingly critical interplay between large cities and dams be recognized. Only by understanding this connection will engineers and others succeed in improving the future resilience of the dam-reliant infrastructure of large cities, particularly in the face of changing patterns of extreme meteorological events.

From an existential standpoint, two overwhelming reasons exist for studying cities and dams together. First, dams supply water for 40 percent of the world's irrigation, 20 percent of global food production, and 10 percent of power generation (see figure 2). All of these processes play a key role in maintaining the integrity and functional resilience of nearby downstream cities. Second, even though dam building may seem a thing of the past in the developed world (see figure 3), large dams continue to be built near major cities at a significant rate in developing nations (see figure 4). For the sake of global sustainability, participants in these new and proposed dam projects urgently need to draw on the experience of those who developed the aging infrastructure and gain an insight into practices that have proved highly effective ("best practices"). From a research standpoint, dams and nearby cities must be studied together because future patterns of extreme weather are expected to differ from the records that have been used in designing and operating dams and assessing the potential flood risks faced by downstream infrastructure.

The term "infrastructure resilience" refers to efforts to maximize the extent to which large civil infrastructure continues functioning even if some of its elements fail or are not equipped to handle conditions that exceed the design criteria and operational guidelines. Physical infrastructure is considered resilient if it has been designed to account for various potential scenarios so that it can survive and can adapt to and recover from external disruptions. These disruptions can encompass normal wear and tear, acts of nature, and such man-made forces as population pressures, extreme overuse, landscape changes, and terrorist attacks. For large infrastructure, attention has commonly been focused on extreme events associated with meteorological processes, particularly severe storms and the ensuing flooding.

FAISAL HOSSAIN, *ALL FIGURES*

In the United States, the ongoing failure to adequately address the state of the nation's infrastructure makes the concept of infrastructure resilience all the more critical for the engineering community. This claim is particularly true in the case of dams. Between 1889 and 2006, a total of 1,133 U.S. dams were overtopped, according to our investigation of databases archived by Stanford University's National Performance of Dams Program. Of the dams that were overtopped, 625, or roughly 55 percent, experienced a hydrologic performance failure; that is, spillways or gates had to be opened in unscheduled fashion without providing sufficient warning to downstream inhabitants. These hydrologic failures were triggered by extreme weather events that the dam spillways could not handle.

For U.S. engineers, the main challenge is to find smart ways to make the $2.2-trillion investment that ASCE has said will be needed over a period of five years to rehabilitate the country's infrastructure. One smart, cost-effective approach entails understanding the future resilience of infrastructure and developing procedures for adapting infrastructure in such a way as to manage expected risks. For example, better estimates of the size of the floodplain of a major river in an urban area under future conditions of climate change could justify relocating development outside the zone at risk of flooding. Additional efforts could also be made with respect to zoning and postdisaster management and to improving systems for flood warning. In other words, the traditional notion of demolishing existing infrastructure and rebuilding it as necessary is no longer tenable for financial and environmental reasons. For example, this approach relies on uninterrupted economic growth, an outcome that cannot always be counted on to occur, as shown by the ongoing fiscal crisis facing the United States and the world. Furthermore, cement production's large contribution to greenhouse gas emissions cannot be ignored.

A major component of future smart approaches will probably involve educating a new breed of civil engineer who will be equipped with the skills and the mind-set to handle the multifaceted issues of infrastructure resilience, particularly those issues involving human effects on climate. To accomplish this objective, changes will have to be made to the bachelor of science curricula. For example, we contend that civil engineering majors should be required to take at

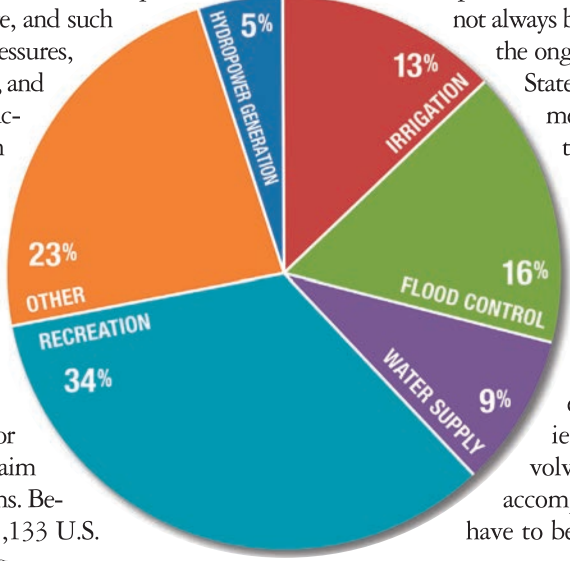

FIGURE 2 PERCENTAGE DISTRIBUTION OF LARGE DAMS ACCORDING TO MAIN APPLICATION

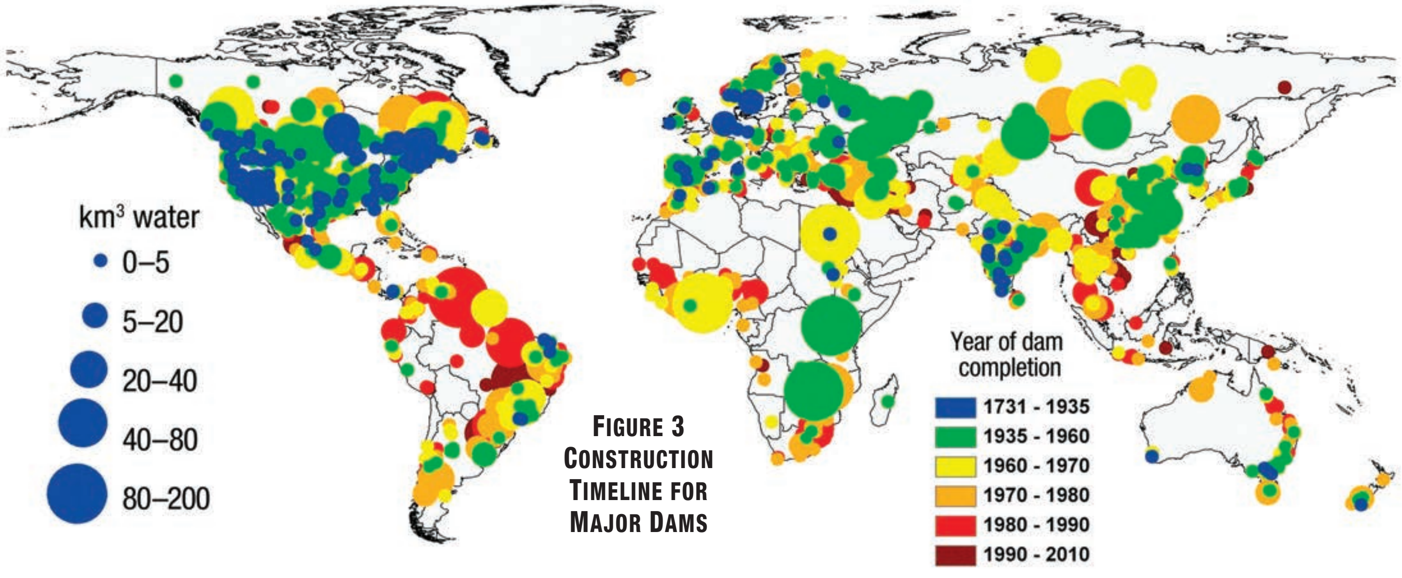

FIGURE 3
CONSTRUCTION TIMELINE FOR MAJOR DAMS

least one or two courses on climate and weather. The specific goal of this effort should be to ensure that students understand the extent to which infrastructure, urban areas, land use changes, and greenhouse gas emissions can affect patterns of extreme weather.

At present the literature on infrastructure resilience and on adapting to extreme meteorological events in the future is focused on the anticipated effects from just one source: climate change. However, this source is more of a planetary-scale phenomenon, in contrast to the local processes of interest to those who must make decisions regarding particular infrastructure elements and adaptation. Focusing solely on climate change may lend a false impression of simplicity to problems relating to infrastructure resilience. For example, for some time the infrastructure resilience community has based its assessments of how climate change will affect dams, water supplies, and urban water infrastructure on the coarse-scale projections of future climate based on various scenarios of greenhouse gas emissions developed as part of a general circulation model (GCM). Such models are used to project climate change decades into the future and formulate a basis on which to develop plans for mitigating or adapting to the changes.

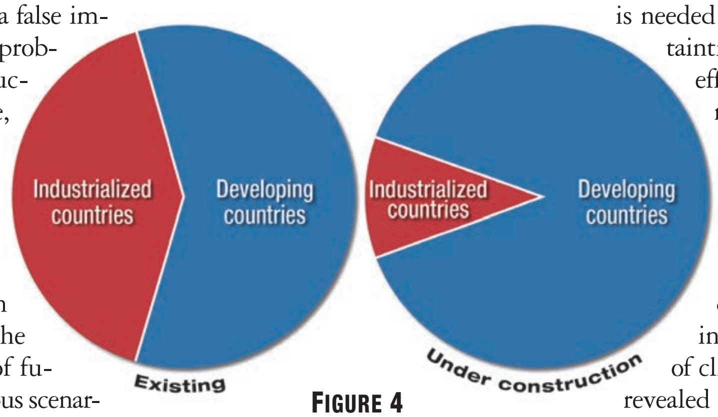

FIGURE 4
RELATIVE SHARE OF DAM INFRASTRUCTURE AMONG INDUSTRIALIZED AND DEVELOPING NATIONS

The outcome of such research is at best reactive rather than proactive. Because of the exclusive focus on how greenhouse-gas-based, top-down planetary effects will influence local climate, adoption of GCM-based projections can do no more than suggest certain implications relating to water management, operations, and resilience for existing infrastructure. So far such research has yet to reveal insights relating to new and proposed dams and emerging dam-reliant urban infrastructure in the developing world. (For more details, see the article "Climate Feedback–Based Provisions for Dam Design, Operations, and Water Management in the 21st Century," by F. Hossain, A.M. Degu, S. Burian, D. Niyogi, J.M. Shepherd, and R. Pielke, Sr., which appeared in the August 2012 issue of ASCE's *Journal of Hydrologic Engineering*.)

However, a more serious problem exists regarding the use of GCM climate projections. Because of their coarse scale and the incomplete nature of the modeling used to describe their underlying physics, projections based on GCMs offer tremendous uncertainty and little of value with regard to decision making at the local scale, that is, approximately 100 km² in relation to dam-reliant city infrastructure. For example, some experts have suggested that more research is needed to address climate uncertainties before GCM outputs can effectively be used for planning and designing water resource projects. In fact, others have argued that the accuracy of climate predictions is limited by the fundamentally irreducible uncertainty deriving from the chaotic nature of climate. Recent research has revealed that GCMs, in contrast to regional-scale, high-resolution weather models, cannot provide an estimate of such infrastructure design parameters as probable maximum precipitation, which is needed for addressing infrastructure resilience and managing flood risks.

As a result of criticism on using GCM-based projections to guide projects at the local level, some researchers have recently sought to "downscale" the projections spatially so that they match the scale of interest to decision makers. However, almost all such approaches in downscaling have an inherent uncertainty that renders the resulting projections even less reliable. In response, in a paper entitled "Decision Scaling: Linking Bottom-Up Vulnerability Analysis with Climate Projections in the Water Sector," which appeared this year in *Water Resources Research* (volume 48), C. Brown, Y. Ghile, M. Laverty, and K. Li proposed the concept of decision scaling, which aims to downscale the decision about local infrastructure rather than the climate projection and to align the coarse-resolution projections of GCMs to a greater extent to the local-scale factors affecting the infrastructure.

Finally, the most critical factor regarding infrastructure resilience involves the process through which development causes bottom-up, human-driven changes to extreme weather at the local and regional scale. As a large dam-reliant city grows, the preexisting landscape is converted to open bodies of water, impervious surfaces, and deforested land, some of which is now irrigated. Such changes alter surface albedo, surface roughness, and fluxes of sensible and latent heat to such an extent that they can change patterns of extreme weather (see figure 5). For example, dams built to provide flood control or hydropower can accelerate urbanization within the downstream city or region, while a dam built for irrigation intensifies nearby agricultural production. When such changes to land use and land cover are assessed in terms of their potential effects on extreme weather, a large dam-reliant city can be viewed as a potential trigger for altered weather patterns. Recent research regarding the effects of Folsom Dam on weather in the nearby city of Sacramento, California, has demonstrated that changes in land use and land cover have altered local weather patterns to the extent that estimates pertaining to the area's probable maximum precipitation and probable maximum flood have had to be modified. Of course, these estimates are critical factors in efforts related to managing flood risks.

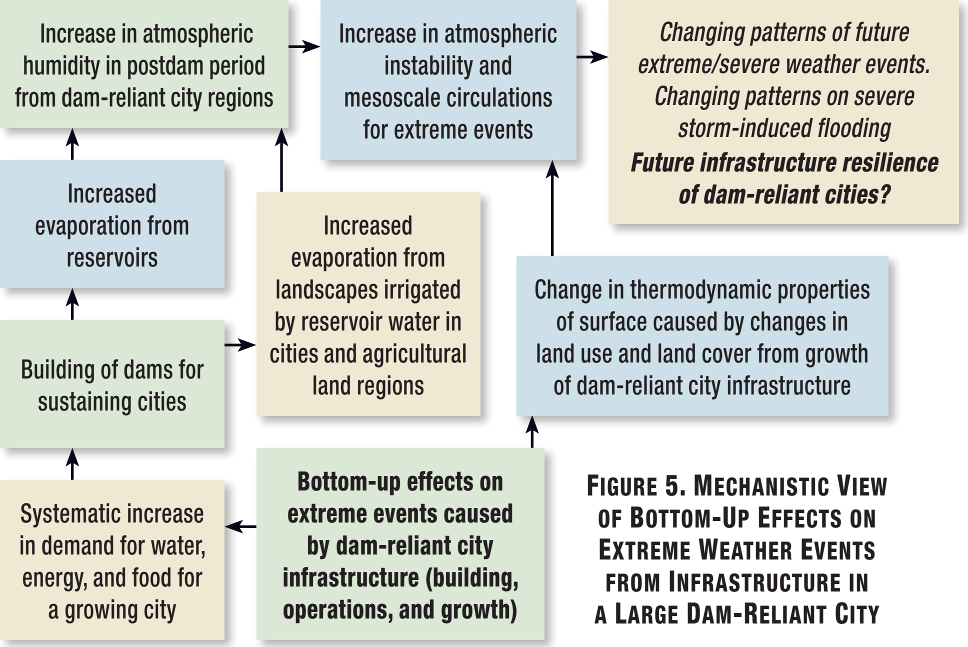

FIGURE 5. MECHANISTIC VIEW OF BOTTOM-UP EFFECTS ON EXTREME WEATHER EVENTS FROM INFRASTRUCTURE IN A LARGE DAM-RELIANT CITY

To be cost effective, efforts to assess the future resilience of urban infrastructure under changing patterns of extreme weather must recognize the following key issues:

- The fundamental, irreducible uncertainty and problems of scale associated with GCM climate projections must be considered in the light of bottom-up approaches of higher accuracy. Such approaches must begin at the local scale with locally relevant infrastructure in mind, evaluating various scenarios that could lead to changes in land use and land cover that in turn could alter extreme weather locally. Gradually, these analyses would widen to include such larger-scale threats as hurricanes or monsoons.
- By causing significant changes in the landscape, a large dam-reliant city can potentially modify local extreme weather conditions.
- Accurate, high-resolution modeling of extreme weather events can be combined with flood modeling of higher resolution to provide decision makers with information of superior value regarding infrastructure resilience, risk management, and adaptation.

In developing nations, large dams will continue to be built near major cities at a significant rate. For the sake of global sustainability and improved infrastructure resilience, the developers of all such dam projects urgently need to learn the practices developed from the experience of those who have built and operated large U.S. dams. More detailed studies of the infrastructure resilience of large dam-reliant cities in the United States could help educate a new breed of civil engineer who would be equipped with the skills and mind-set needed to handle the multifaceted issues of resilience, particularly those at the intersection of climate change and human activity.

In the United States alone, more than 85 percent of large dams will be more than 50 years old by 2020. Cities located downstream of these critical structures are confronted with the possibility of higher flood risks resulting from three main factors: sedimentation and the resulting loss of storage, an increase in flood magnitude, and more frequent unscheduled releases of flows over spillways. Therefore, research aimed at understanding and improving infrastructure resilience under changing patterns of extreme weather must aim to inspire the younger generation of engineers. This inspiration is necessary to initiate training within the infrastructure community to better understand the interplay of infrastructure and extreme weather and to improve the state of the nation's dam-reliant city infrastructure. **CE**


Hossain


Kalyanapu

Faisal Hossain, Ph.D., A.M.ASCE, is an associate professor and Alfred Kalyanapu, Ph.D., A.M.ASCE, an assistant professor in the civil and environmental engineering department at Tennessee Technological University.