Climate Feedback–Based Provisions for Dam Design, Operations, and Water Management in the 21st Century

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Introduction

As the world's population increases, the rising demand for water will be compounded further by the need to sustain economic growth (Vörösmarty et al. 2000). According to one report by the United Nations Environment Program (UNEP), the stress on freshwater resources is expected to significantly magnify and spread to other regions of the world by 2025 (see Fig. 1; UNEP 2002). Historically, one of the common engineering solutions to guarantee a steady water supply against a rising demand has been to construct surface water impoundments on rivers. Such large-scale infrastructure, commonly known as dams and artificial reservoirs, trap a sufficiently large amount of water from the local hydrologic cycle to make up for a shortfall when demand exceeds the variable supply from nature. In other words, dams can be regarded as a strategic (long-term) solution to resolve the tactical (short-term) challenges of balancing the water deficit compounded by population growth and economic activity.

In the United States, statistics suggest that building dams is outdated and considered a twentieth-century construct by the civil engineering profession (Fig. 2) Graf et al. 2010; Graf 1999). However, for vast regions of the underdeveloped or developing world, large dam-construction projects are being implemented in increasing numbers for tackling the rising water deficit in emerging economies (Fig. 3). Examples of such large dam projects are the Southeast Anatolia Project, or GAP (Turkish acronym) project, in Turkey, comprising 22 dams on the Tigris and Euphrates rivers (Unver 1997), the Three Gorges Dam (TGD) in China (Shen and Xie 2004), Itaipu Dam in Brazil (Pierce 1995), and the proposed Indian River Linking Project (Misra et al. 2007). From a global perspective, dam operations and water management in impounded basins remain relevant worldwide, while dam design and building are pertinent mostly to the developing world, comprising Africa, South America, and Asia, where most of the rivers remain unregulated.

The heritage of modern dam building is nearly a century old. For example, the construction of the oldest dam in the Tennessee River Valley, called the Wilson Dam in Alabama, began in 1918 (Gebregiorgis and Hossain 2012). With a long heritage built on knowledge gained from previous failures and success stories, the civil engineering profession has made tremendous progress in dam safety against hazards of earthquakes (e.g., Marcuson et al. 1996), piping/seepage (e.g., Casagrande 1961; Sherard 1987), structural instability (e.g., Terzaghi and LaCroix 1964; Vick and Bromwell 1989), and optimization of dam operations to serve multiple, but competing, applications (Dai and Labadie 2001; Datta and Burges 1984). Similarly, much is now known about the management of postdam effects on aquatic ecology (e.g., Ligon et al. 1995; Richter et al. 1996), riparian vegetation (e.g., Merritt and Cooper 2000), geomorphology (e.g., Graf 2006), and dam removal as a result of sedimentation (Morris and Fan 1998; Graf et al. 2010).

In general, the aspects of dam design and operations that have improved during the last century are those that are directly visible or have instantaneous impact on the land surface. This is not surprising, as the essence of engineering is hands-on in nature. What can be touched, sensed, and immediately visualized in the real world can be accounted for in the design and operation of an infrastructure. For example, the importance of fish ladders to minimize the disturbance to predam fish-migration paths was quickly appreciated by the engineering community during the early history of dam building. Now fish ladders are a common provision during the planning of a dam along a river. Similarly, when the Teton Dam failed (Sherard 1987), the importance of design provisions to minimize seepage, particularly in karstic geology, has now become a standard engineering practice. The Wolf Creek Dam, the largest artificial reservoir east of the Mississippi River, has periodically undergone grouting of seepage holes throughout its existence (Boynton and Hossain 2010). With increased fluctuation of flows downstream of dams, it did not take long for the concept of environmental flow (Tharme 2003) and indicators of hydrologic alteration (IHA) (Richter et al. 1996) to be devised for better ecosystem-centric dam operations in impounded basins. When more residential and commercial development is planned in an impounded river basin, it is intuitive to the engineer that the increase in imperviousness of the land surface may require larger detention basins at select locations to account for the increased runoff and erosion from excess rainfall.

The climatic impacts (i.e., feedbacks) of dams, however, are unique areas that have received little consideration by the engineering profession for dam building and operations. Climate, by virtue of its definition, represents anything but a hands-on phenomenon. Unlike weather, climate impacts are not measured instantaneously. Given the current breadth of engineering curricula that exclude atmospheric and climate-science subjects as prerequisites at the freshmen and sophomore levels, a large artificial lake having an