A two-way street

Dam construction and its associated effects on landscape development can trigger local and regional climate responses, significantly altering the availability of water resources. This is the belief of the climate science community which has accumulated a rich body of research over the past few decades. Faisal Hossain and Roger Pielke Sr say it is now time for the engineering community to recognise this body of evidence, and realise that climate is very much a two-way street with local, regional and global impacts. The dam building community is urged to collaborate more closely with the climate and land use community for better stewardship of the earth's water resources.

In the US, dam building may be considered very '20th century' and some believe that the country's ageing dams need a fresh assessment of the role they play within the climate system.

Around the world, particularly in the under-developed or developing world, large dam construction projects are being implemented in increasing numbers for tackling the rising water deficit for emerging economies. Examples of such large dam projects are the Southeast Anatolia Project in Turkey comprising 22 dams on the Tigris and Euphrates rivers, Three Gorges dam in China, and Itaipu dam in Brazil. From a global perspective, dam operations and water management in impounded river basins remain very relevant worldwide, while dam design and building are more important to the developing world comprising Africa, South America and Asia where many of the rivers remain unregulated.

In general, the aspects of dam design and operations that have improved during the last century are those that are directly visible or have almost an instantaneous impact on the surrounding area. This is expected, as the very essence of engineering is 'hands-on'. If something can be touched or visualised immediately through cause and effect, then it can easily be accounted for in the design and operations protocol for a dam.

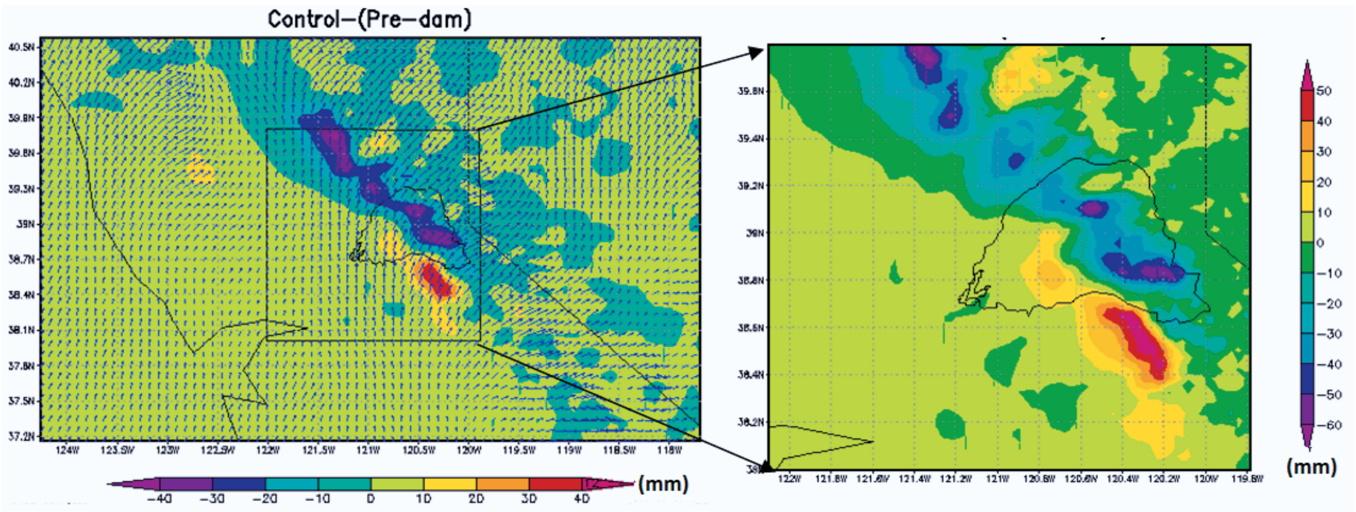
However, aspects that cannot be touched, seen and therefore hard to be visualised immediately through cause and effect, have historically not been featured in the design and operation of dams. Climate is one such example. With what we already know on how humans and nature modify its behaviour, the role of climate in dam design and operations cannot be ignored. In particular, the climatic impacts of dams and the surrounding landscape are unique areas that need consideration from the engineering profession. Such climatic impacts include:

- Weather forcing: The term 'forcing' is usually defined as the set of initial drivers of the weather or climate system that result in a change. Derived from the word 'force', the term is generally implied as strength or energy to initiate motion.
- Weather feedbacks: This usually refers to processes that change as a result of an earlier change in the forcing, and cause additional change (amplified or diminished) in the climate or weather system.

Climate, by virtue of one of its definitions as the long term statistics of weather, represents anything but a 'hands-on' phenomenon. Unlike day-to-day weather, climate impacts cannot be measured instantaneously. Weather, which is the time-specific behaviour of climate, features in the design and operations mostly during the pre-dam planning stage. For example, most high risk dam projects that are planned upstream of a major population centre, are mandated in the US to be designed according to the probable maximum precipitation (PMP) and probable maximum flood (PMF) criteria. Almost all accepted methods practised in the engineering community computes this design parameter based on historical records of extreme storm events.

Yet there is a rich body of research accumulated independently by the climate science community over the last few decades that shows that land cover changes due to the construction of a dam, with its impoundment of water and the associated effect on landscape development (such as irrigation, urbanisation, deforestation and afforestation), can significantly alter the natural availability of water in the region. It is now time to recognise this body of evidence and become wiser by moving away

Atmospheric simulation of extreme storm for Folsom dam. This shows how atmospheric models could be used to study the difference between pre and post-dam periods



from focusing solely on climate as only a one-way phenomenon, ie without considering the local climate forcings and feedbacks from the infrastructure-relative activity.

It is now time for the engineering community to realise that climate is very much a two-way street with local, regional and global impacts that occur due to natural and human activity around dams.

Can dams alter the local and regional climate?

In current dam infrastructure literature, the impact of alterations in climate from human activities is popularly perceived as a more planetary scale phenomenon based on a globally rising temperature trend primarily due to added greenhouse gases (global warming). This top-down impact on artificial reservoirs and water supply has been studied at the regional scale for some time. This is evident from a comprehensive literature synthesis published recently by the US Bureau of Reclamation (USBR) on climate adaptation (USBR, 2009). The converse (impact of reservoirs on local and regional climate via local and regional climate forcings and feedback mechanisms), which is what the engineering community engaged with dam building and operations must understand, has not been explored in depth yet.

Firstly, engineers need to consider a broader view of the change a dam can typically trigger during its lifespan. Such a view, although obvious, has not received the needed attention. At a minimum, a dam changes the pre-existing land cover to an open body of water which then leads to a change in surface albedo, surface roughness, sensible and latent heat fluxes. A flood control or a hydropower dam can also accelerate a faster pace of urbanisation of the downstream valley regions, while irrigation dams promote agricultural expansion in the vicinity of the reservoir.

The change in climate near dams is expected to be particularly noticeable on temperature and precipitation patterns during the growing season. For example, irrigation in the Great Plains during growing season (May through September) may have caused about 1˚C of cooling during the post-1945 period (ie the same time most dam construction was completed in the US).

Data and modelling studies also support the notion that atmospheric moisture added by irrigation can also increase rainfall, provided that the local ambient conditions are appropriate. Data used for such attribution studies often include rainfall, temperature and humidity that are available from meteorological stations since organised record keeping began early in the 20th century. Many of the modelling studies often involve the use of rigidly constrained numerical models that can simulate the atmospheric processes over a region and allow sensitivity studies on the impact of land cover change on rainfall. So in principle, there exists a clear physical rationale that suggests that dams can change the local and regional climate in their vicinity.

What does all this mean in the context of the more popularly known global warming? If the climate warms, more water vapour can be held in the atmosphere and the local effect of dams may interact with the global trend and result in the local climate impact being amplified, cancelled or undetectable. Regardless of the nature of the global-local interaction, the engineering profession is usually more concerned about the needed action to take in terms of adaptation, rather than better dam building practice and water management for those specific dams/reservoirs that 'mutate' the local climate around them in the post-dam period. [In this context mutate refers to an anomaly in the engineer's way of considering stationarity of the hydrologic parameters used in dam design. For example the design probable maximum flood value mutating from 20,000m^3/sec to 40,000m^3/sec as the dam ages due to changes in rainfall patterns and the rainfall-runoff transformation characteristics through land development.]

Implications on design and operation

Based on research on land cover impact, it seems that precipitation is one of the likely dominant climatic consequences of dam building under many circumstances. For example, when the Folsom dam was built in 1955 to impound the American River and provide flood control for Sacramento City, California, the hydraulic and structural design features of the spillway and embankment were assumed adequate to withstand a flood with a recurrence interval of 500 years. Repeated flooding and unscheduled release of heavy flow beginning from the late 1950s until the mid 1980s have now led to a revision of the design recurrence interval from 500 years to 70 years. Today, approximately 440,000 people and 110,000 structures are at risk downstream of Folsom dam, and the Sacramento metropolitan area is considered among the greatest flood risk regions in the nation by the US Army Corps of Engineers (USACE). A large part of this vulnerability from flooding actually arises from the inadequate height of the existing levees (currently being upgraded) along the Sacramento River near Sacramento city.

Interestingly, a recent atmospheric modelling study by Woldemichael et al (2012) reports a clear and positive correlation between irrigation extent and magnitude of probable maximum precipitation (PMP) in the orographic environment of the Sierra Nevada region. This is not to suggest that the Folsom dam activity is directly responsible for the intensification of flooding (as there are other factors) but rather, when such change in flood frequency is likely to be known a priori, dam design and operations must proactively consider the possibility.

Recommended design storm criteria for dam building in various states of the US

State	Recommended Design Storm Criteria
Alaska	IDF (Intensity Duration Frequency) equal to PMF or based on Incremental Damage Assessment (IDA)
Arizona, Connecticut, Oregon, Pennsylvania, South Carolina, Tennessee, Virginia	0.5 PMF to PMF depending on persons-at-risk downstream
Colorado, Florida, Indiana, Iowa, Kentucky, Vermont, West Virginia	PMP
Georgia	25, 33, 50, 100 % PMP based on height and storage
Idaho	Small Dam =100 year, Intermediate = 0.5 PMF, Large= PMF
Illinois	Small=0.5 PMF; Intermediate= PMF; Large= PMF
Kansas	40% PMP
Maryland, Minnesota, Nevada, New Jersey, Puerto Rico, Texas, Ohio	PMF
Michigan	1/2 PMF over 40 ft high 200 yr or flood of record under 40 ft high
Missouri	75% PMP
North Carolina	small-1/3 PMP, Medium-1/2 PMP, Large-3/4 PMP, Extra large-PMP
Oklahoma	50-100% PMF with 1-3 feet freeboard
Utah	IDF
Washington	3000-year flood to PMF
Wisconsin	1000 year
Wyoming	PMF or Paleoflood Data

Challenging mindsets

Originally trained as a civil engineer, Faisal Hossain has been trying to challenge the traditional mindset of engineers that, once built, it is acceptable to treat public infrastructure as being 'static', and assumed as having no impact bottom-up on climate or weather systems. About three years ago, Hossain began studying the role of large dams and the surrounding landscape change due to human activity on the climate system. This has been morphed while experiencing first-hand tremendous heavy rains near the shorelines of two closely located run-of-river dams (Kentucky dam and Barkley dam located a little north from his residence near Nashville, Tennessee).

Hossain's approach is in stark contrast to the usual top-down approach embraced by the infrastructure and engineering community on climate, where only the larger scale impacts projected from global warming are cascaded down to the smaller infrastructure-related footprint, albeit with tremendous uncertainty. To support the notion, he uses extensive observational data on atmospheric records (hydrometeorological and thermodynamic) as well as numerical models, such as the Regional Atmospheric Modelling Systems-RAMS, that can simulate atmospheric processes. He also has the help of his climate scientist colleagues such as Roger Pielke Sr, Dev Niyogi, Marshall Shepherd and many others.

Hossain presented his work to the US Congress Natural Resources Committee and Water and Power Subcommittee in 2011 where discussion is on-going about revising rule-curves for better management of the US' ageing dam infrastructure.

Conventional dam and reservoir planning over the last century has been 'one-way', without acknowledging the possible feedback mechanisms on precipitation recycling due to local and regional evaporation. For example, dam design protocol continues to assume as 'static' (or stationary) the statistical parameters of extreme precipitation events during the life span of a dam. In a review of the National Dam Safety Programme Act (passed in 1972 and Public Law 92-367) and various design/operations manual made available by USACE, USBR and Association of State Dam Safety Officials (ASDSO), there seems to be no 'unified' building and operations code followed in the US. Rather the practices recommended (see Table for an example of design storm criteria) appear to be state-specific and cognizant of the historical regional hydrology.

Closer collaboration

The engineering profession needs to look at local and regional climate forcings and feedbacks once large infrastructure like a dam is built. While studies have predicted the impact of the changing climate on region-specific dams in the coming decades based on global climate models, it is equally important now to focus on the local and regional effects attributable directly to the landscape changes triggered by the dam. This effect is likely to be unique and location-specific.

Many of the large dams built during last century in the US now have long observation records of their local and regional climate. These provide a platform to observationally understand the physics behind the modification of local and regional climates and the implications on water management, including better dam design. Using numerical models currently available for simulating the atmospheric processes (climate forcings and feedbacks), we now have an opportunity to consider different scenarios of landscape change and perform a life cycle assessment before even building a dam.

For example, a numerical model could be set up over a larger region that includes the proposed impoundment and the dam project. This model would first need to be constrained against high quality observational data so that it can simulate accurately an actual extreme weather event (that would typically be of interest to an engineer as a design storm and flood). Next, various scenarios of potential land use/land cover change that are likely during the post-dam period over many decades, could be simulated with their impact on the behaviour of the extreme weather event and flooding pattern. Such a model set up can help the dam community answer questions such as:

- If the river basin and surrounding region undergoes an increase in irrigated agriculture, will the PMP and PMF change appreciably to warrant checking the spillway and embankment design or can the change be ignored with the safety factor adopted?
- Is this change in PMF likely to be larger than that expected purely from urban land development which creates more surface imperviousness and surface runoff?
- Which type of landscape change is likely to intensify extreme weather events in the region?

In short, the use of numerical models in the design stage is analogous to forecasting how a dam may alter the local and regional water cycle within the impounded basin as it ages before building it, then verifying if the factor of safety that is standard in design (such as 'freeboard') is adequate to handle the expected alteration. Without considering the effect on climate of these local and regional landscape changes when a dam is constructed, there can be a significant risk of improper design.

Now that numerical models and long records of observational data are easily available, the dam building community should collaborate more closely with the climate and land use community for better stewardship of our planet's water resources. ■

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Acknowledgement

A substantial portion of this article has been reproduced, with kind permission of the American Society of Civil Engineers, from an article written by the authors which appeared in The Journal of Hydrologic Engineering (vol 17(8)). IWP&DC would like to thank ASCE for its collaboration.