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In the United States, statistics suggest that building dams is outdated and considered a twentieth-century construct by the civil engineering profession (Fig. 2) Graf et al. 2010; Graf 1999).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

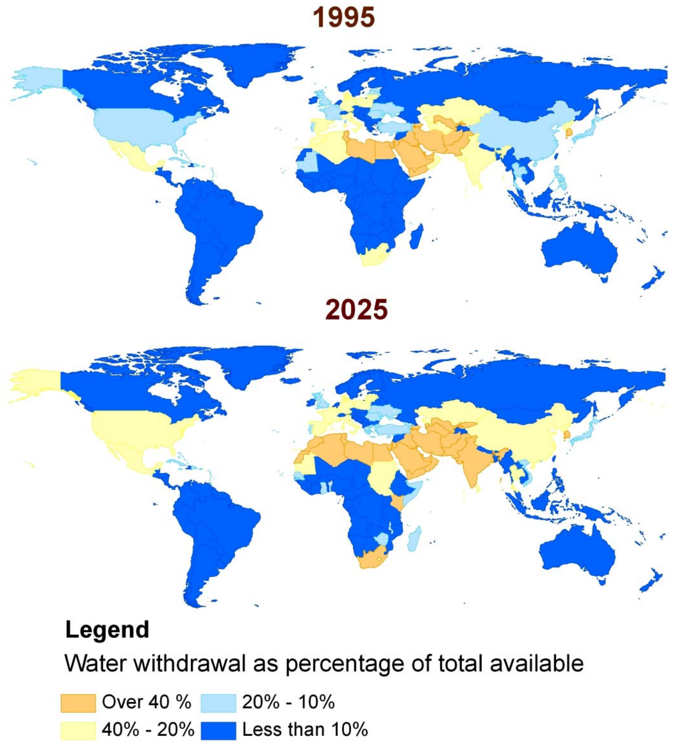

Fig. 1. Global freshwater stress projected on the basis of a report by the United Nations [data source: Global Environment Outlook (GEO)-2000, UN Environmental Program (UNEP) 2000, Earthscan, London, 1999]

observable effect on local climate (such as a change in surface temperature or precipitation) is conceived with difficulty by the conventionally trained engineer. Impacts on weather have historically received minimal consideration for postdam water management. Evaporation is only considered with respect to the resulting loss of water from the impoundment. Yet there is a rich body of research, accumulated independently over the previous few decades, that shows that the land cover changes typically caused by a dam (such as irrigation, urbanization, deforestation, and afforestation) can significantly alter the natural availability of water within the impounded river basin (Pielke et al. 2009; Cotton and Pielke 2007).

The purpose of this article is to shed light on the need for climate feedback–based considerations in dam design, operations, and water management for the 21st century. The next section provides a brief summary of the known impacts on climate caused by changes in land use and land cover that are typically experienced after dam construction is complete. This is followed by recent research on the signature of dams on local climate using observational evidence. The final section discusses the need for climate-based provisions in today's dam design and operations and in engineering education. The discussion is cast in the context of an overview of a database comprising approximately 7,000 large dams worldwide and the need for a dialogue on incorporating additional topics as prerequisites in the traditional civil engineering curriculum.

Is There a Physically Sound Rationale to Suggest Dams Can Change Local Climate?

In current dam-infrastructure literature, the impact of global climate change (which is popularly perceived as a more planetary-scale phenomenon on the basis of a globally rising temperature trend) on artificial reservoirs and water supply has been studied at regional scales for some time (e.g., Hamlet and Lettenmaier 1999; Christensen et al. 2004). This is also evident from a comprehensive literature synthesis published recently by the U.S. Bureau of Reclamation (USBR) on climate-change adaptation (USBR 2009). The converse (impact of reservoirs on local climate via feedback mechanisms), which is the focus of this paper, has not yet been explored in depth (Degu et al. 2011; Hossain et al. 2010).

To understand whether a physical rationale can be constructed to suggest that dams change the local climate, a broader view of the change that a dam typically triggers during its lifespan needs to be considered. Such a broader view, although obvious, has not received the necessary attention from the engineering profession, particularly from the dam-building community. At a minimum, a dam changes the preexisting landscape to an open body of water, which then leads to a change in surface albedo, surface roughness, and sensible and latent heat fluxes. A flood control or hydropower dam can also trigger a faster pace of urbanization of the downstream valley regions, while irrigation dams intensify agricultural production in the vicinity of the reservoir. Global data and simulation analysis by Biemans et al. (2011) report that artificial reservoirs contribute significantly to irrigation water supply in many regions around the world. The additional contribution of reservoirs to irrigation has increased spectacularly from 5% (around 1900 C.E.) to almost 40% in the 21st century (Biemans et al. 2011). When such changes to land cover and land use (LCLU) are assessed in relation to existing knowledge on their impact on climate (e.g., Pielke 2005; Feddema et al. 2005; Pielke et al. 2007; Ray et al. 2009), it becomes apparent that a typical dam-reservoir system can, in principle, change the local climate through a gradual change in the landscape. Examples of the effect of local landscape changes on precipitation include Gero et al. (2006), Lei et al. (2008), Shepherd et al. (2010), and Niyogi et al. (2011). There have also been studies that conclude that there is a global-scale impact from irrigation (Puma and Cook 2010), of which a significant fraction of this irrigation is the result of atmospheric moisture made available for vegetation from artificial reservoirs.

The change on local climate near dams is expected to be particularly noticeable in temperature and precipitation patterns during the growing season. For example, Mahmood et al. (2004) showed that irrigation in the Great Plains during growing season (May through September) may have caused regional cooling of growing-season mean maximum temperatures by 1.41°C during the post-1945 period at irrigated locations. Data and modeling studies support the notion that atmospheric moisture added by irrigation can also increase rainfall, provided that the mesoscale conditions are appropriate (Lohar and Pal 1995; Barnston and Schickedanz 1986). DeAngelis et al. (2010) have reported an increase of 10–30% of rainfall downwind of the Ogallala aquifer that has been used for groundwater-based irrigation in the Great Plains. For the most up-to-date and comprehensive review of observational evidence on the impact of land-cover changes (many of which are triggered by dams) on climate, readers should refer to Mahmood et al. (2010). In principle, there exists a defensible rationale that suggests that dams can change the local climate in their vicinity.

Having briefly reviewed the potential impact of dams on the local climate, it is now appropriate to put in context the more widely reported global climate change from anthropogenic greenhouse-gas emissions. If the climate warms, more water vapor 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, canceled, or undetectable. Although the focus of this paper is how an impounded basin may be transforming itself climatologically, such global-local interaction may exclude a large number of dams

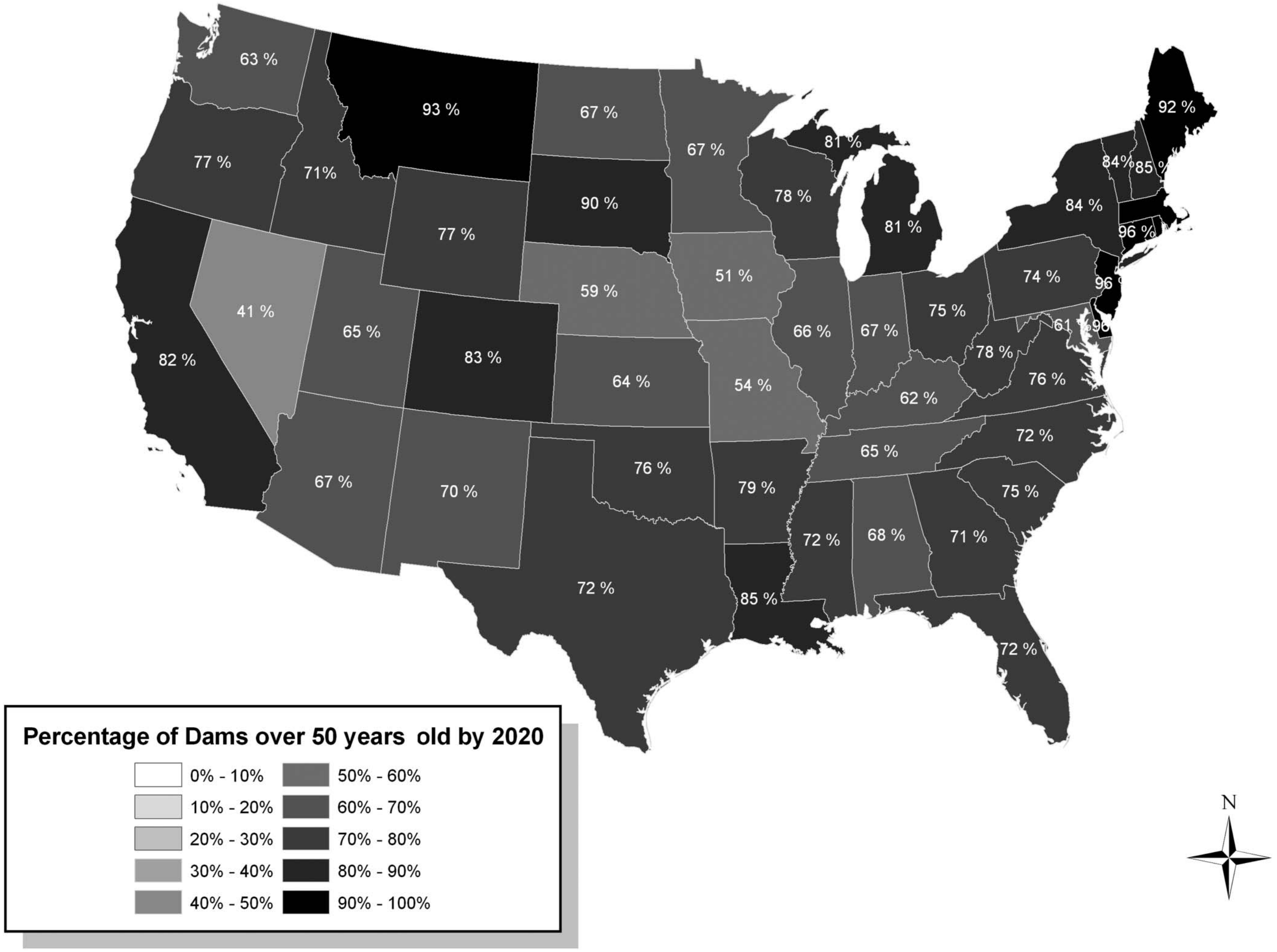

Fig. 2. Percentage of dams per state that will be over 50 years old in 2020 [Reprinted from Hossain et al. (2009), with permission; data source: National Inventory of Dams of USACE)]

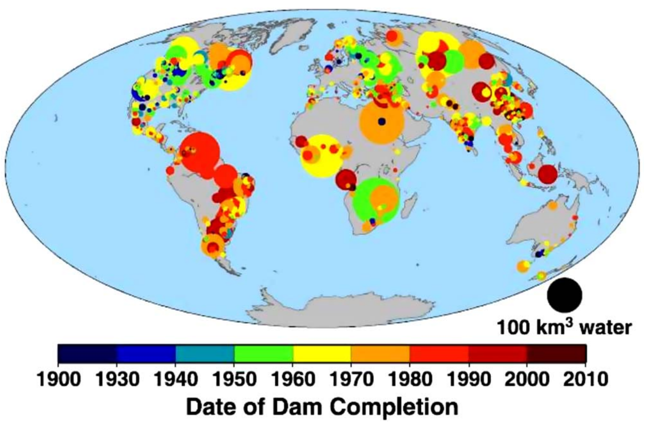

Fig. 3. Timeline of completion of some of the large dams around the world

as not directly responsible for the climate change experienced by the basin. For example, a recent study by Zhao and Shepherd (2011) points to the possibility of the larger-scale dynamics of the asian monsoon potentially masking any local effect on heavy precipitation from the Three Gorges Dam (TGD). They report that the detectable impact is on the 50th percentile rain (moderate events) rather than on the 90th (or higher) percentile rain (heavy events), and this impact is most likely attributed to the filling of the TGD reservoir.

Regardless of the nature of the global-local interaction, the engineering profession is usually more concerned about the required action 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. Herein we refer to the word "mutate" as an anomaly to the engineer's manner of considering the stationarity of the hydrologic parameters used in dam design (such as the probable maximum flood value mutating from 20,000 to 40,000 m^3/s as the dam ages because of changes in rainfall patterns and the rainfall-runoff transformation characteristics through changing land use).

Have Dams Changed Local Climate?

The question posed in the previous section was a can-type question on what a dam-reservoir system is physically capable of doing to the predam climate. The have-type question posed here dwells more on observational evidence—i.e., if dams can really change local climate in principle, can it be detected? To answer this question, it is important to note that a bulletproof cause-effect relationship attributing any change solely to a dam is nearly impossible, as is the case for any other human activity, because of numerous other (nondam-induced) interactions. For example, urbanization (Shepherd et al. 2010) and aerosols from industrialization (Rosenfield et al. 2008) are both known to affect local climate, particularly heavy precipitation patterns. To pinpoint the specific role of a dam (or dams) and the land-use change that is triggered, an integrative study that separates the other effects is required. That is beyond the scope of this forum article. The purpose in this section is to highlight the first-order and statistical understanding that climate observations alone allow us to make for dams, without considering other factors.

We studied 92 dams located in the United States and defined them as "large" according to the International Commission on Large Dams (ICOLD) in a manner similar to a recent study by Degu et al. (2011). The database of dams was available from a series of world-dam registers published by the Global Water Systems Project (GWSP) Digital Water Atlas (GWSP 2008). These dams were spread across eight distinct climate zones (Fig. 4). The classification of climate zones shown in Fig. 4 is the Koppen-Geiger scheme (Peel et al. 2007). For the observational record of climate, reanalysis data from the National Center for Environmental Prediction (NCEP) North American Regional Reanalysis (NARR; Mesinger et al. 2006; Rutledge et al. 2006) was used. NARR provides a quality-controlled, finer-resolution climate dataset over North America. Daily NARR fields spanning the period of 1979–2009 (30 years) and focusing on the daily average of the surface convective available potential energy (CAPE; J/kg) was used as a proxy signature of dams (Pielke 2001). Among the many important factors required for rainfall, CAPE can be considered an important atmospheric indicator of the presence of heavy-rainfall process. The objective was to identify detectable changes in CAPE climatology (available at 32-km spatial scales) in the vicinity of dams for a given climate zone.

Because the NARR record of CAPE does not date before the construction of most large dams in the United States, the ergodic assumption was invoked to answer the "detection" and "have"-type question posed in this section. The spatial average of CAPE over a region distant from dams (referred to as a no-dam region) was considered a substitute for the temporal average of CAPE during the predam era. In other words, the average CAPE over the no-dam region was used to represent the predam climatology of convective atmospheric instability. Similarly, the average CAPE over the dam region was used as a proxy for the postdam climatology. Herein, the no-dam region was defined as the annular region 100 km outside a dam's spillway having the same area as the dam region (Fig. 5). To attribute the unique and local impact of the dam alone, a dam region was defined as a circular area having a 50-km radius around the dam location (Fig. 5). The 50-km influence zone is a statistical, as well as a mesoscale, attribute that was derived from a preprocessing sensitivity study. Mesoscale (or local) impacts of climate, which are the focus of this study, are usually confined

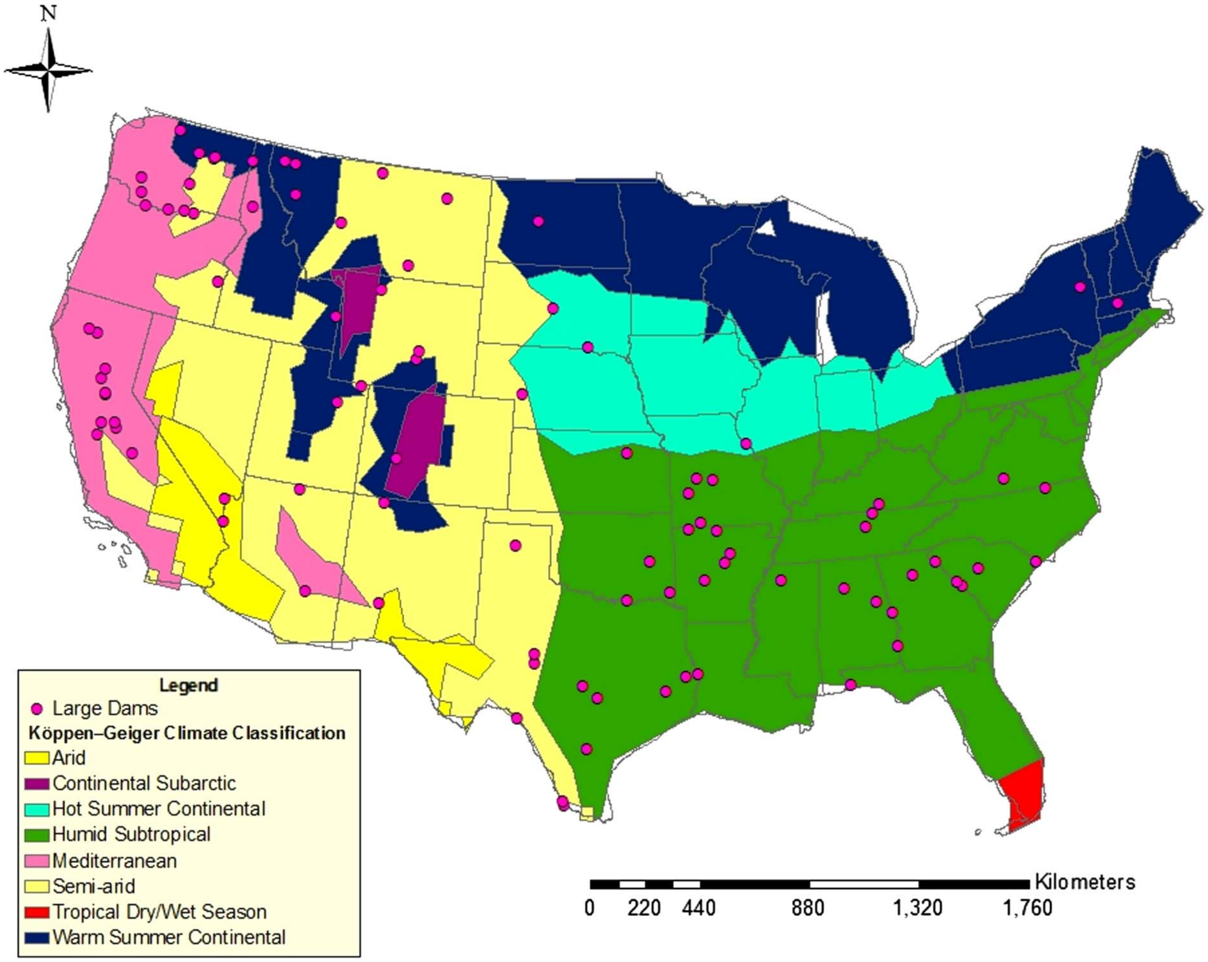

Fig. 4. Location of 92 large dams according to the Koppen climate map

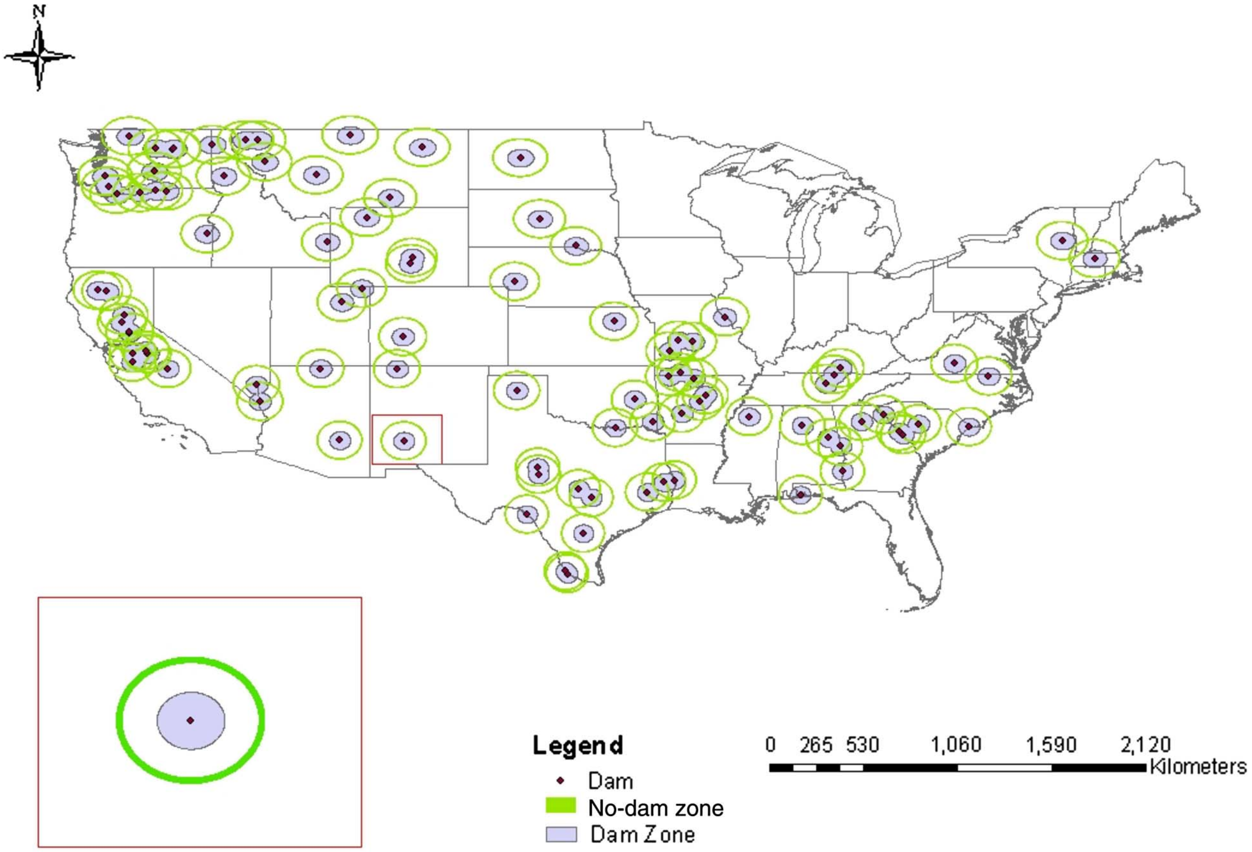

Fig. 5. The 50-km buffer zone showing the dam and the 100-km-distant annular region as the no-dam region

to 25–100 km. In the sensitivity study, other influence radii up to 100 km were also considered, wherein most of the zones larger than 50 km overlapped extensively with neighboring dams. It was found that 50 km offered the best compromise for identifying a statistically significant standalone mesoscale effect (with minimal overlap from neighboring dams) and yet was compatible with the spatial scale of NARR data.

For a statistical generalization of the 92 dams, Table 1 shows the relative ranking of the dams in terms of the percentage change (increase or decrease in the climatologic average of CAPE) between the dam and no-dam regions for a particular dam. Here, the percentage change in CAPE is defined as

$$\text{Percent increase} = \frac{(\text{mean of dam region} - \text{mean of no-dam region})}{\text{mean of no-dam region}} \times 100\% \quad (1)$$

Herein, the mean refers to the 30-year climatologic average for the period 1979–2009. It is clear from Table 1 that dams in the Mediterranean climate (Koppen class name is "dry summer subtropical") consistently experience the highest alteration of CAPE near the reservoir (dam) region. This change is matched by dams located in hot or cold arid climates. Dams in humid or arctic climates exhibit spatially insignificant increases ($< 5\%$) in CAPE near the reservoir. An important aspect to note is the likely absence of irrigation in humid and arctic climates that may be a contributing factor for the spatial uniformity of CAPE near and away from the reservoir. As an example, Fig. 6 shows the time series of 30-year CAPE climatology for two dams in contrasting climates (Walter dam in Alabama and Coolidge dam in Arizona). Two possible reasons may be attributed for the intensification of CAPE by dams in arid and Mediterranean climates: (1) more widespread irrigation, and (2) stronger spatial gradients in humidity and surface evaporation around the reservoir-shoreline interface.

Global Implications on Design of New Dams and Operation of Existing Dams

If the local climate is found to be impacted near dams through systematic change in land use and land cover, what does this mean for the engineering profession for dam design and operations? On the basis of research on land-cover impact, it appears that precipitation is one of the likely consequences of dam-building under many circumstances. To highlight the engineering importance of an understanding of how certain artificial reservoirs may modify climate, particularly the water aspects, three case stories are presented as representative of numerous anectodal studies that have accumulated on impounded basins during the postdam era.

Case Story 1 (Folsom Dam). When the Folsom Dam was built in 1955 to impound the American River and provide flood control for Sacramento, California, the hydraulic and structural-design features of the spillway and embankment were assumed to be 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 (Roos 2003) have led to a revision of the design-recurrence interval from 500 to 70 years [National Research Council (NRC) 1999]. Today, approximately 440,000 people and 110,000 structures are at risk downstream of Folsom Dam, and the Sacramento metropolitan area is

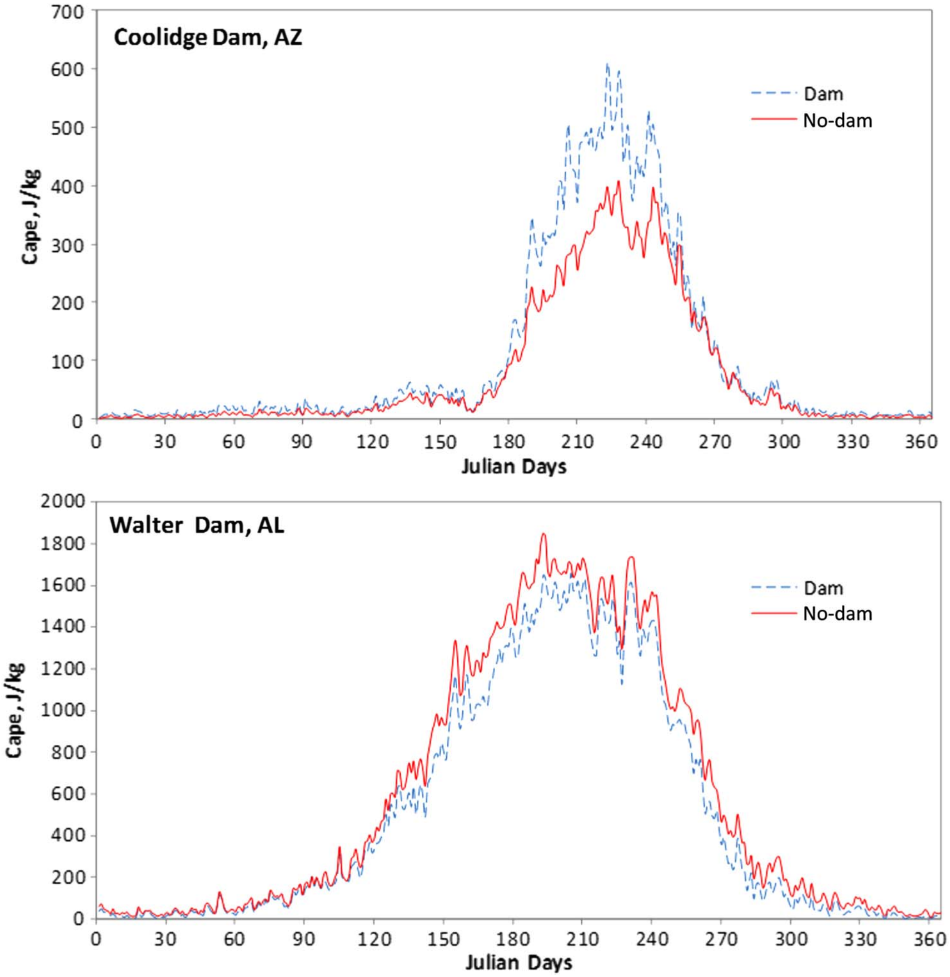

Fig. 6. Comparison of CAPE climatology (30-year) for dam and no-dam regions for the Coolidge (in arid climate) and Walter (in humid climate) dams

considered among the greatest flood-risk regions in the nation by the U.S. 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 (SAFCA 1994; Larry Hobbs, personal communication, March 21, 2011). Interestingly, a recent atmospheric modeling study by Woldemichael et al. (unpublished data, 2011) reports a clear and positive correlation between reservoir size and the magnitude of probable maximum precipitation (PMP) for the orographic environment of the Sierra Nevada region. This is not to suggest that the Folsom Dam 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.

Case Story 2 (Tennessee Valley Authority). On September 30, 2009, the Tennessee Valley Authority (TVA) announced that it would raise the height of four large dams because of increasing rainfall projected this century (TVA 2009). In its official press release, TVA stated, "TVA will place temporary, wall-like structures on top of earthen embankments of the Fort Loudoun, Tellico, Cherokee, and Watts Bar dams in East Tennessee, raising the top elevation of each embankment about four feet. The extra height would prevent water from overtopping and damaging the earthen embankments.… A recent update of TVA's river modeling program determined that the maximum floodwater elevations could be higher than previously calculated if a highly unlikely, worst-case winter rainfall were to occur in the upper part of the Tennessee Valley watershed."

Case Story 3 (National Performance of Dams). Investigation of databases archived by the National Performance of Dams Program (NPDP; http://npdp.stanford.edu) reveals that historically, the number of reported incidences of embankment overtopping far exceeds that of structural failures. According to the NPDP survey, a total of 1,133 dams have overtopped hydrologically between 1889 and 2006. Of these, 625 experienced a complete hydrologic-performance failure. Herein, it is important to note that the land-use changes can amplify the surface-runoff generation mechanism in two ways: (1) through modification of precipitation rates leading to increased infiltration-excess runoff, and (2) through enhancement of rainfall partitioning as runoff because of increased imperviousness. The former cause is akin to a strategic cause that occurs through gradual change in the local climate in the postdam era, while the latter is a more tactical (instantaneous) cause (of increasing imperviousness). Both causes may be equally important and may work in tandem to compound the problem of increasing upstream runoff as the dam ages.

The preceding three cases highlight the dangers posed by the commonly accepted assumption of stationarity that is fundamental to dam design and operations (Milly et al. 2008). Conventional dam and reservoir planning over the last century has been unidirectional,

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Table 1. Ranking of Dams Studied According to Percentage Change in CAPE Climatology between Dam and No-Dam Region

Köppen-Geiger Climate	Dam	State	% Increment
Dry summer subtropical	New Bullards Bar	California	105.01
Dry summer subtropical	Oroville	California	99.00
Dry summer subtropical	New Exchequer	California	80.91
Dry summer subtropical	Shasta	California	66.89
Dry summer subtropical	Folsom	California	56.86
Dry summer subtropical	Don Pedro	California	56.06
Dry summer subtropical	Trinity	California	42.41
Dry summer subtropical	Monticello	California	33.79
Dry summer subtropical	Pine Flat Lake	California	31.31
Dry summer subtropical	Swift	Washington	27.22
Warm summer continental	Conklingville	New York	26.36
Dry summer subtropical	Dworshak	Idaho	25.73
Cold semiarid	Kingsley	Nebraska	21.27
Cold semiarid	Yellowtail	Montana	20.61
Humid subtropical	Hartwell	Georgia	20.42
Warm summer continental	Albeni Falls	Idaho	18.01
Warm summer continental	Hungry Horse	Montana	16.66
Warm summer continental	Kerr	Montana	15.35
Cold arid	Hoover	Nevada	14.16
Humid subtropical	Smith Mountain	Virginia	13.45
Humid subtropical	Pensacola	Florida	13.09
Warm summer continental	Seminoe	Wyoming	12.13
Warm summer continental	Palisades	Idaho	11.19
Hot arid	Davis	Arizona	11.17
Humid subtropical	Center Hill	Tennessee	10.87
Hot semiarid	Robert Lee	Texas	7.86
Humid subtropical	Little River	South Carolina	7.49
Continental subarctic	Blue Mesa	Colorado	7.26
Dry summer subtropical	Mossyrock	Washington	6.13
Humid subtropical	Sardis	Mississippi	5.97
Cold semiarid	Owyhee	Oregon	5.47
Cold semiarid	Pathfinder	Wyoming	4.78
Dry summer subtropical	New Melones	California	4.24
Humid subtropical	Richard B. Russell	Georgia	4.02
Humid subtropical	Wolf Creek	Kentucky	3.97
Humid subtropical	Eufaula	Oklahoma	3.75
Humid subtropical	Dale Hollow	Tennessee	3.38
Continental subarctic	Oahe	South Dakota	3.35
Cold semiarid	Coolidge	Arizona	3.28
Cold semiarid	Buffalo Bill	Wyoming	3.03
Warm summer continental	Libby	Montana	2.98
Humid subtropical	Stockton	Missouri	2.79
Cold semiarid	Tiber	Montana	2.23
Hot semiarid	Twin Buttes	Texas	2.19
Cold semiarid	Fort Peck	Montana	1.86

Note: Only a percentage change of greater than 1% is reported in the table.

without acknowledging possible feedback mechanisms on precipitation recycling caused by local evaporation (Hossain et al. 2010). For example, dam-design protocol continues to assume that the statistical parameters of extreme precipitation [more appropriately termed probable maximum precipitation (PMP)] events are static (or stationary) during the life span of a dam (Abbs 1999). In the exhaustive review of the National Dam Safety Program Act (passed in 1972 and Public Law 92–367) and various design/operations manuals made available by USACE, USBR, and the Association of State Dam Safety Officials (ASDSO), it was found that there is no unified building and operations code followed in the United States. The practices that are recommended (see Table 2 for an example of design-storm criteria) appear to be state-specific and cognizant of regional hydrology. However, the assumption of stationarity is implicit in the design values that were adopted for design (Table 2).

It is thus clear that the civil engineering profession needs to look at local climate feedbacks in the context of how it is impacted locally once a large infrastructure such as a dam is built. While studies have reported the impact of large-scale climate change on region-specific dams for operations (USBR 2009), it is equally important to focus on the local effect attributable directly to the LCLU changes triggered by the dam. This effect is likely to be unique and location-specific. Many of the large dams built in the last century in the United States now have long observation records on local climate which provide a platform to observationally understand the physics behind the modification of local climate and the implications on water management or better dam design. Using numerical models for simulating climate feedbacks, we now have an opportunity to consider different scenarios of LCLU change and perform a life-cycle assessment before building a dam. This is analogous to forecasting how a dam may alter the local water cycle within the impounded basin as it ages before building it, then verifying whether the factor of safety that is standard in design (such as “freeboard”) is adequate to handle the expected alteration. Moreover, this also provides an opportunity to verify whether urban drainage and flood-control designs in cities near dams are resilient to dam-altered extreme-weather patterns. Urban watershed studies and drainage-design assessments similar to those quantifying impacts from urban-induced rainfall modification (Yang et al. 2010; Reynolds et al. 2008; Burian 2006) are needed to determine the robustness of existing drainage systems and develop changes to drainage-design standards in response to dam-altered precipitation.

For example, if a higher frequency of heavy flooding is expected from upstream regions because of the compound effects of increased imperviousness and rainfall-intensifying LCLU change (such as irrigation), then greater allocation for the flood-control pool (or a greater margin of error through a bigger surcharge pool) will be required [Fig. 7(a)]. Accounting for such changes during the postdam stage would imply that other equally important pools (such as a conservation pool for water supply) will have to be compromised. A consistently compromised conservation pool may impact irrigation or hydropower generation (because of the reduced level of the reservoir) in the long run [Fig. 7(b)].

In the plethora of work studying the impact of global climate change on dams on the basis of projections from a general circulation model (GCM) (for a summary, refer to USBR 2009), the outcome on the dam/reservoir strategy is often reactive and not proactive. Such GCM-based projections can only have an implication on water management and operations on existing dams (i.e., during the postdam era), as the literature indicates. However, because of the coarse scale and incomplete model physics (e.g., NRC 2005; Stephens 2010), such GCM-based projections are unlikely to have any value for a specific dam design (i.e., during the predam era). Rainfall and temperature changes projected by

Table 2. Recommended Design Storm Criteria for Dam-Building in Various States of the United States

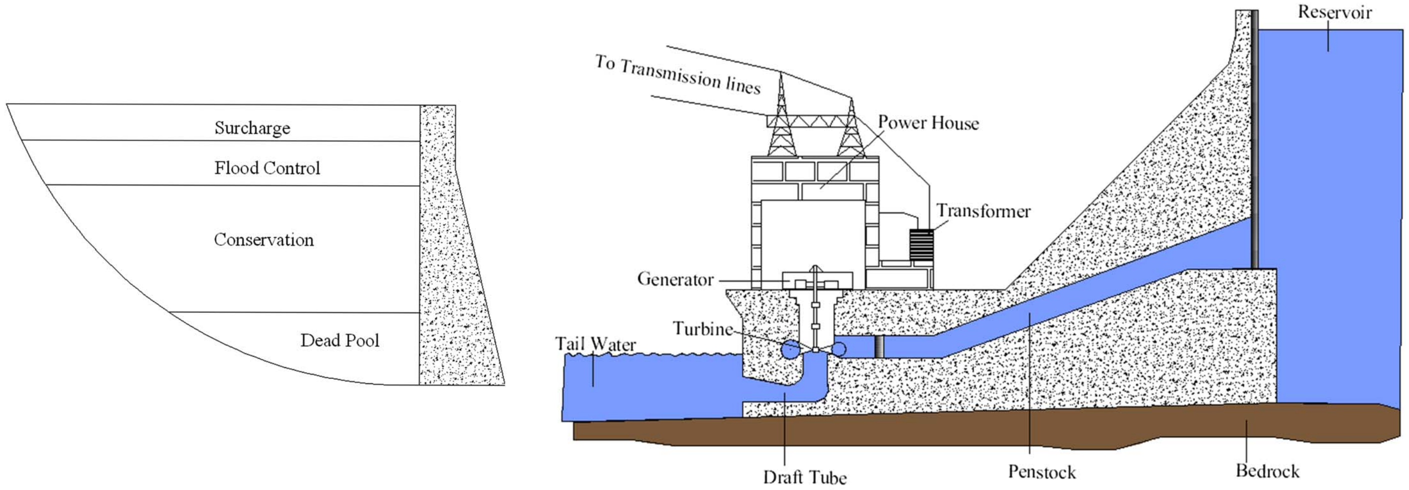
State or territory	Recommended design storm criteria
Alaska	Intensity duration frequency (IDF) equal to probable maximum flood (PMF) or determined on the basis of incremental damage assessment (IDA)
Arizona, Connecticut, Oregon, Pennsylvania, South Carolina, Tennessee, Virginia	0.5 PMF to PMF depending on persons-at-risk downstream
Colorado, Florida, Indiana, Iowa, Kentucky, Vermont, West Virginia	PMP
Georgia	25, 33, 50, 100% PMP on the basis of height and storage
Idaho	Small dam = 100 years; 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-year; 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	3,000-year flood to PMF
Wisconsin	1,000-year
Wyoming	PMF or paleoflood data

GCM scenarios may be used for future planning, but to date no such guidelines are available. GCMs also do not provide an estimate of design parameters, such as PMP and the corresponding PMF, that are needed for operations and design at a specific basin (Woldemichael et al., unpublished data, 2011).

The climate feedback-based provisions that are now needed should consider the unique climate and surrounding geographical changes that the dam can produce using regional-scale models. The Global Reservoir and Dam (GRAND) (Lehner and Doll 2004) database provides a useful summary on the location and main purpose of the dams. On the basis of 6,862 records of large artificial reservoirs archived in GRAND, Table 3 shows the distribution of dams in various climates. Table 4 summarizes the distribution by continent. While GRAND does not include all of the dams in the world, it provides a reasonable picture of the wide-ranging types of climate, locations, and applications with which a dam is associated. Fig. 8 shows the variability of dam density within a given Koppen climate class. Close-up maps of the locations of large dams in Africa (Fig. 9), Asia (Fig. 10), and South America (Fig. 11) reveal that a dam needs to be treated uniquely for the required climate-based feedback provisions in its design (for new dams) or management strategy (for existing dams). Such an approach should be bottom-up by considering the dynamics of change in the local water cycle (caused by the dam, as well as other factors, such as anticipated rates of urbanization and industrialization) in

Table 3. Number of Dams in the GRAND Database by Major Koppen Climate Class and Main Dam Purpose

Climate	Hydropower	Irrigation	Others	Unknown	Total
Arid	2	37	17	22	78
Semiarid	29	358	117	125	629
Tropical	122	268	44	222	656
Temperate	705	925	1,122	991	3,743
Continental	582	190	410	484	1,666
Polar	58	3	2	11	74



(a)

(b)

Fig. 7. (a) Typical pools allocated during dam design, planning, and operations; (b) hydropower generation plant showing how power generation can be reduced by lowering the reservoir level to make way for other pools

Table 4. Number of Dams in the GRAND Database by Continent and Main Purpose

Continent	Hydropower	Irrigation	Others	Unknown	Total
Africa	56	383	129	153	721
Asia	228	574	151	979	1,932
Australia	66	72	92	11	241
Europe	563	262	306	180	1,311
North America	506	461	1,032	242	2,241
South America	70	18	10	201	299

the context of an underlying larger change (such as global climate change and socioeconomic factors; Hossain et al. 2011).

Suggested Changes to the Baccalaureate Curriculum for Civil Engineering

A significant change in the baccalaureate curriculum for civil engineering is now required to train the next generation of civil engineers to tackle the aforementioned challenges resulting from climate change that is likely attributable to large infrastructures,

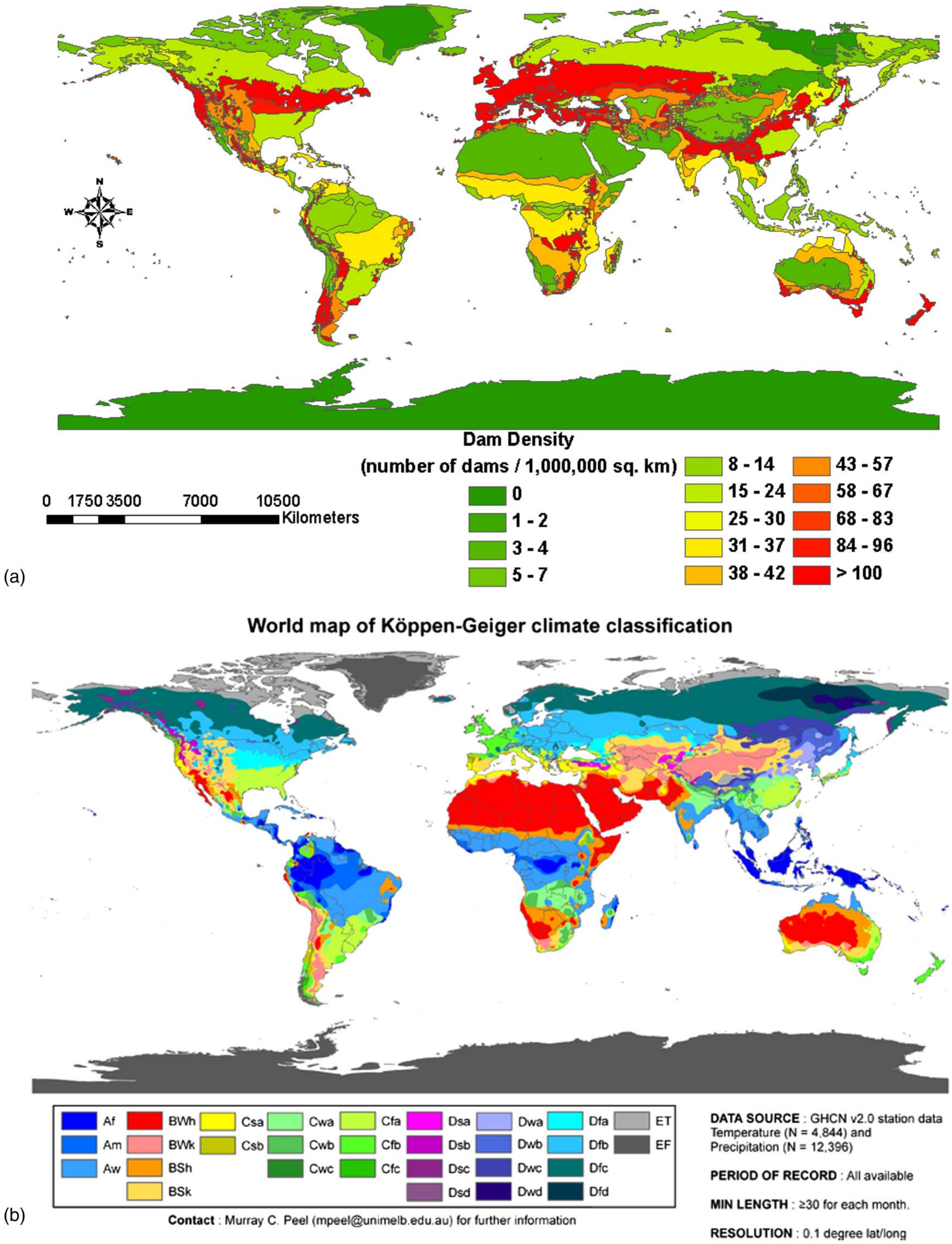


Fig. 8. (a) Dam density (number of dams per 1 million square kilometers) for each major Koppen climate zone (climate class not shown) on the basis of the GRAND database of 6,682 dams; (b) the major Koppen climate classes reproduced from Peel et al. (2007) with permission

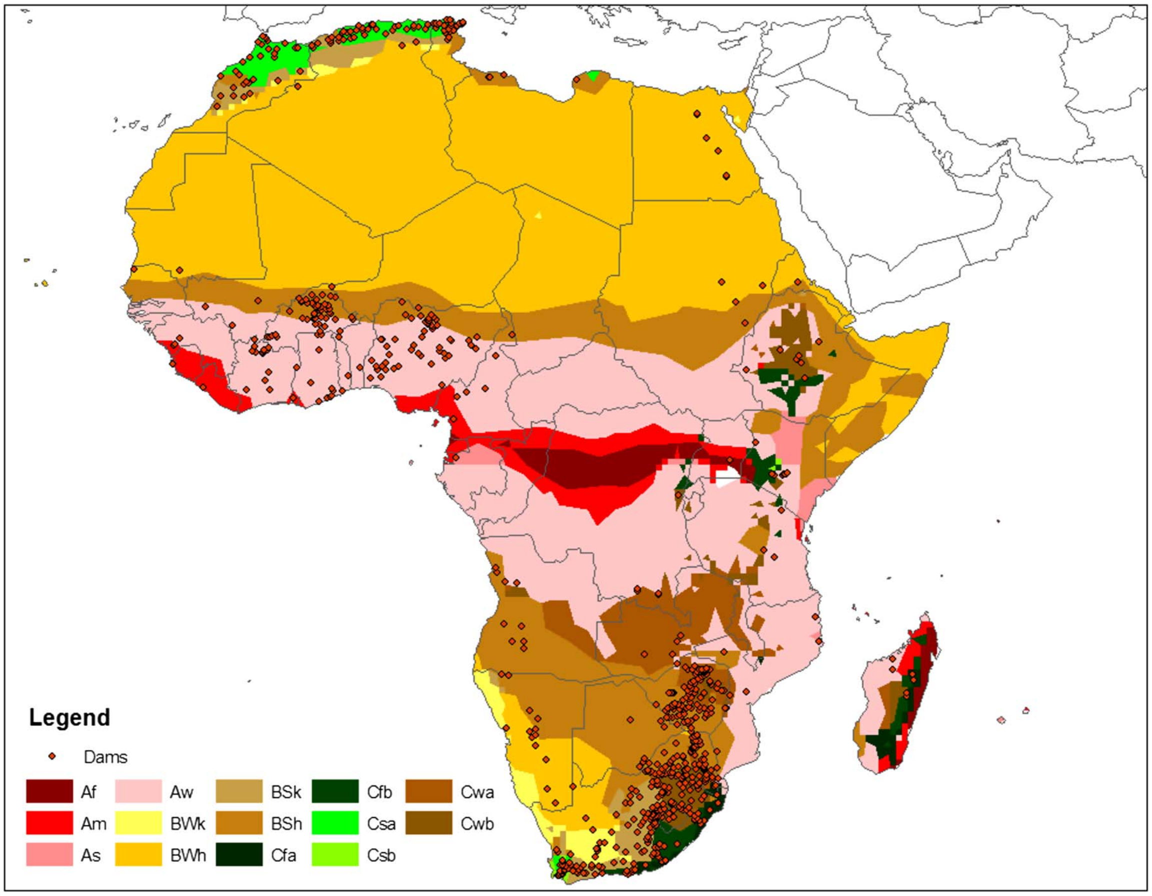


Fig. 9. Dam locations in Africa in the GRAND database

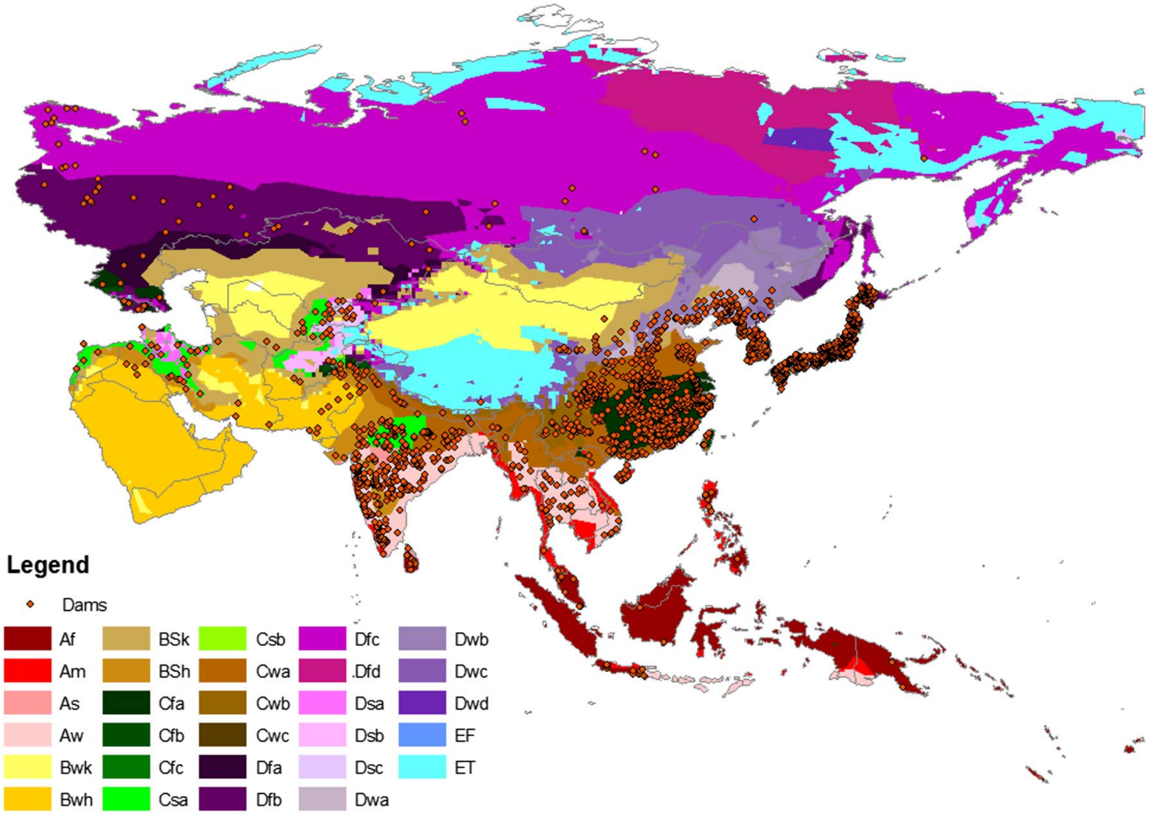


Fig. 10. Locations of dams in Asia in the GRAND database

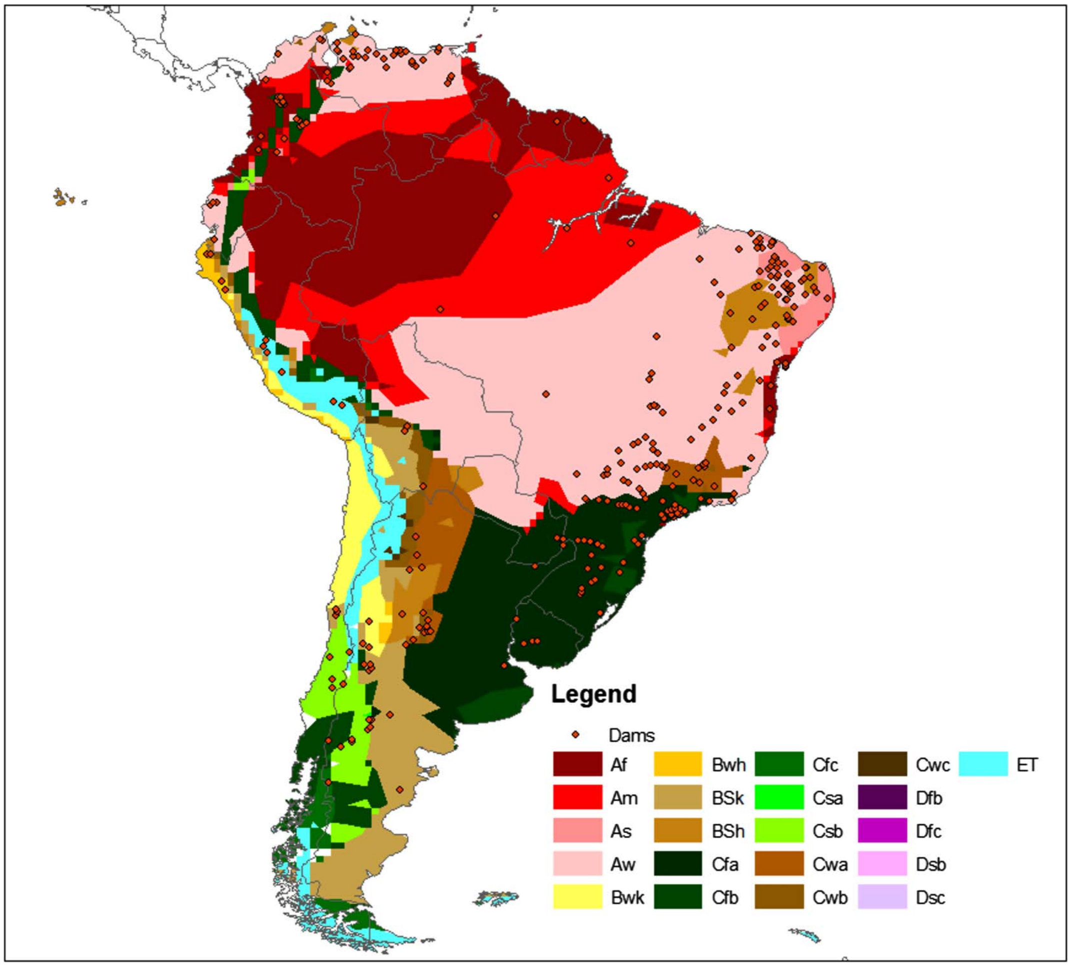


Fig. 11. Location of dams in South America in the GRAND database

such as dams. Currently, there exists sufficient provision to specialize on climate and atmospheric science–related topics at the senior level (fourth year of the bachelors program) or at the graduate level of a civil engineering program. However, the current setup does not guarantee that all civil engineers will graduate with a reasonable knowledge of topics such as climate, meteorology, and atmospheric sciences, and knowledge of how human activities related to infrastructure design and maintenance—the cornerstone of the profession—directly impact the local climate. This is because not all civil engineers are required to prepare for such a specialization at the senior level (as the courses are mostly electives) or pursue an advanced degree with a strong research component.

If civil engineers and the accreditation body for North America [Accreditation Board for Engineering and Technology (ABET, Inc.)] both agree that, no matter the specialization, all 4-year degree programs must have sophomore and junior-level prerequisite courses on statics, mechanics of materials, and structural design, then there is no compelling reason in the 21st century not to implement measures that can help students understand the implications of what they build, maintain, and operate. Large dams and their associated LCLU change are clearly the beneficiaries of this needed provision. This argument is analogous to the rising environmental awareness during the 1960s that eventually led most civil engineering departments of North America to embrace an environmental outlook and modify their name to Civil and Environmental Engineering. It is again time for a similar wave of awareness concerning climate impacts attributable to the civil engineering profession that can make engineers more environmentally responsible.

An example of such a change affecting the civil engineering profession is the response to urban heat islands (UHI). Knowledge of UHI impacts has recently inspired planning and policy that encourages developers to consider the urban-heat-island impacts of their projects, as well as consider its control as an adaptation tool for regional climate (Oberndorfer et al. 2007; Akbari et al. 2009). Such ideas currently drive incentives for developers to achieve certification in the Leadership in Energy and Environmental Design (LEED). In a similar way, an increased knowledge and understanding of climate modification from dams helps to inspire new climate-resilient policies in design and operations and perhaps incorporation of sustainability goals and certifications.

The specific suggestion in this forum is that the civil engineering profession, represented by ASCE and ABET, include adequate provisions during the freshman and sophomore years for prerequisite courses on climate, atmospheric science, and the role played by human activities such as infrastructure building. Currently most 4-year civil engineering programs require a certain number of credit hours in general education and humanities. A discussion is now needed as to how much of that requirement can be modified to include climate feedback–based provisions so that civil engineers are aware of the climate implications of the infrastructure with which they will be involved. To maximize the success of such a curriculum change, it is equally important to ensure that new courses are taught such that the science of climate and the atmosphere can be related directly to the real-world infrastructure activities in which students will engage as professional engineers.

Conclusion

The purpose of this article is to shed light on the need for climate feedback–based considerations in dam design, operations, and water management for the 21st century. It first overviewed the known impacts on climate from changes in land use and land cover that are typically anticipated once a dam is constructed. Recent research was presented on the first-order signature around dams on local climate using observational evidence. A global overview of the location of large dams was presented to highlight the need to treat each dam uniquely according to its location and the larger setting. It is now obvious that the observational data associated with current dams, combined with the rich body of research of LCLU impact on climate, can provide the planning and engineering professions with insightful guidance for both operations and more robust dam building in the 21st century as well as modifications of local design guidelines to account for climate feedback.

For existing dams, the hydraulic and structural features can be wide-ranging (Fig. 12). Incorporating climate-based structural provisions (such as the TVA example in case 2) will remain a major challenge for the engineering profession because of the difficulty in anticipating or perceiving local climate impacts. One way to maximize the ability of future generations of engineers to assimilate knowledge on climate modification for dam design and operations is to enhance the baccalaureate curriculum by adding prerequisite courses on atmospheric sciences and climate. The most effective way to achieve this is to start with a suggestion for revision of the ASCE's Body of Knowledge (BOK). According to the ASCE, the purpose of the Civil Engineering BOK for the 21st century is to define the following:

1. What are the knowledge, skills, and attitudes needed to enter into professional practice?
2. How can the Body of Knowledge be fulfilled by tomorrow's aspiring engineers?
3. Who should guide the learning of the engineering student and engineer intern?

The BOK committee at ASCE should consider incorporating language suggesting climate science courses be included as an additional natural science in foundational outcome 2 (ASCE-BOK 2008). Moreover, engineers should be exposed to the general concept of climate feedbacks from civil infrastructure systems in the introductory course, similar to the incorporation of sustainability concepts. It is now time for climate feedback–based provisions to be discussed and explicitly incorporated within civil engineering practice, given that infrastructure building and resilience is a cornerstone of the profession.

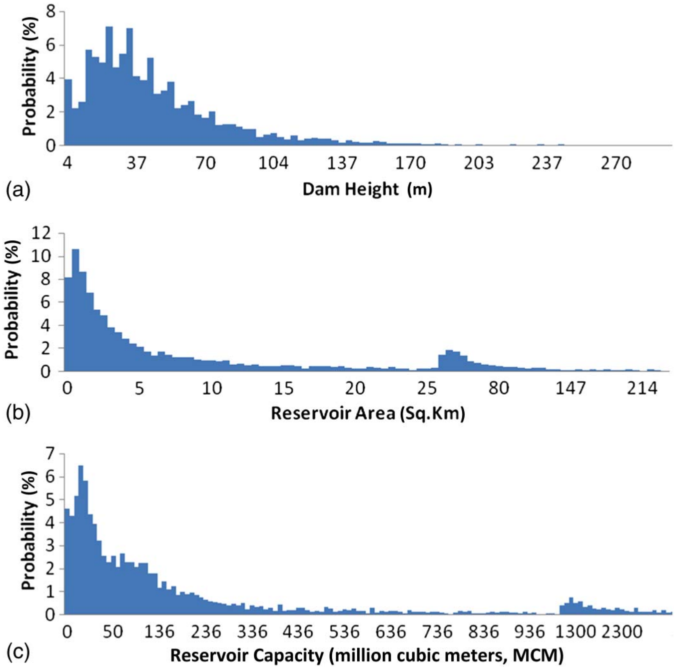


Fig. 12. Probability distributions on the basis of the GRAND database; (a) dam spillway crest height; (b) surface area; (c) reservoir volume

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