Local-To-Regional Landscape Drivers of Extreme Weather and Climate: Implications for Water Infrastructure Resilience

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Summary

This article represents the first report by an ASCE Task Committee "Infrastructure Impacts of Landscape-driven Weather Change" under the ASCE Watershed Management Technical Committee and the ASCE Hydroclimate Technical Committee. In this first of a series of reports, it argues for explicitly considering the well-established feedbacks triggered by infrastructure systems to the land-atmosphere system through landscape changes. A definition for Infrastructure Resilience (IR) at the intersection of extreme weather and climate is also proposed for the engineering community. By providing a broader range of views and issues than what is currently in the front view of engineering practice, more robust approaches can be achieved by the engineering community by affording a greater number of scenarios in its decision making related to infrastructure design, operations and management. Although the article does not strive to seek consensus on any particular view or recommend a particular design/operations strategy for improving resilience, the issues requiring further discussion are discussed. For example, it is not entirely clear at this stage how best to impact engineering practice directly through the research that appears on land-atmosphere feedbacks triggered by infrastructure systems. Some examples related to adjusting design metrics as wholly new (atmospheric model-based) or modified current practices have appeared in recent literature. Performing a survey of actual water managers in the various water infrastructure units (such as U.S. Army Corps of Engineers district offices) would be beneficial for the engineering community. Moving forward, a key focus for the engineering community should be to understand the predictive uncertainty of changes to extreme weather and climate through integrated forcings of landscape change and planetary warming, and the implications of this uncertainty on infrastructure design and operations.

Introduction

"With many calculations, one can win; with few one cannot. How much less chance of victory has one who makes none at all!" –Sun Tzu in *The Art of War*

The previous statement made by *Sun Tz*u in his seminal book *The Art of War* more than two thousand years ago summarizes best the mission statement of the ASCE Task Committee (TC) on the topic of this article. In early 2014, the TC was tasked with providing the engineering community additional calculations for improving infrastructure resilience for securing water supply and protection against water hazards. It was set up in follow-up to a wide-audience forum article that appeared in 2012 in the ASCE *Journal of Hydrologic Engineering* (Hossain et al. 2012) and in *Civil Engineering Magazine* (Dec 2012 issue). These articles implored engineers to explicitly consider the well-established feedbacks triggered by large infrastructures on the land-atmosphere system for decision-making related to water management, better design, and operations. The goal of this article is to shed light on the findings of the initial round of dialogue within the TC to understand the role of landscape change for improving the resilience of our water infrastructure.

In particular, infrastructure that manages our water resources (such as dams and reservoirs, irrigation systems, channels, navigation waterways, water and wastewater treatment facilities, storm drainage systems, levees, urban water distribution and sanitation systems), are critical to all sectors of an economy. Yet, they are ageing beyond their lifespan and design in many parts of the world. In addition, these infrastructures are subjected to excessive wear and tear from rising water demand, increasing frequency of flooding from urbanization or human encroachment of water bodies. Such water infrastructures, by virtue of their service to society, are also directly or indirectly responsible for changes to the surrounding landscape. For example, a newly-built water supply distribution system favors a faster growth rate of urban development which then leads to landscape transforming to one that is more impervious. Similarly, a large flood control and irrigation dam can increase downstream urbanization and convert barren or forested land to irrigated landscape. Inversely, by changing a river's or lake's edge through levees and seawalls can cause naturally irrigated areas to become barren. The body of knowledge accumulated by the atmospheric science community since the early 1970s informs us that changes in extreme weather and climate can be a direct product of such landscape modification. Thus the issue of infrastructure resilience becomes directly relevant as large infrastructures are usually designed to handle worst-case or extreme weather and climate scenarios in mind. For samples of the cumulative body of work on effects of landscape change on extreme weather and climate, the reader is referred to Cotton and Pielke (2007) and Pielke et al. (2011).

The commonly observed landscape changes around water infrastructures also interact with other local, regional, hemispheric, and global-scale atmospheric forcings and can often alter the future behavior of extreme events to an amplitude or phase-space not recorded before or during the design phase of the infrastructure. According to the Clausius-Clapeyron relationship, the water holding capacity of air increases approximately 7% per 1°C of warming (at 288 K). In the Unnw2sS, the increase in water holding capacity is already evident from recorded increases in dew point temperatures over the last 40 years (Robinson 2000). If such a trend continues, then it implies that future extreme storms would occur under conditions of increased available moisture, which can result in potentially higher intensities and higher frequency of occurrence of extreme precipitation events (Kunkel et al. 2013; Trenberth 2011). It should be noted, however, that observational studies of water vapor do not indicate yet an consistent trend on water vapor (Wang et al. 2008; Vonder Haar et al. 2012).

Because the future resilience of water infrastructure is dictated by the future behavior of extreme patterns of weather and climate, and because wear and tear are a constant stressor magnified by the increasing demand for or damage from water, it is important for the engineering community to recognize these local to regional drivers of landscape change for a more robust assessment of resilience. Although there is a broader and complex impact of such landscape change, it is the local effect (or local perturbation) that is important for understanding the vulnerability or resilience of water infrastructure. Many of such local effects may warrant a relook of parameters and factors of safety for which an infrastructure is designed or operated. In this report, the local effects are referred to as a delta x–type perturbation and a random function. The important question to ask now for the engineering community is if this delta x is large enough to require a wholesale reassessment of infrastructure resilience. This concept can be demonstrated through a classic beam loading scenario, in which the standard shear force and bending moment diagram need to be derived for a known deterministic load W (Fig. 1). If the load is perturbed randomly by ΔW due to the bending of the beam itself, then the derivation of the shear force

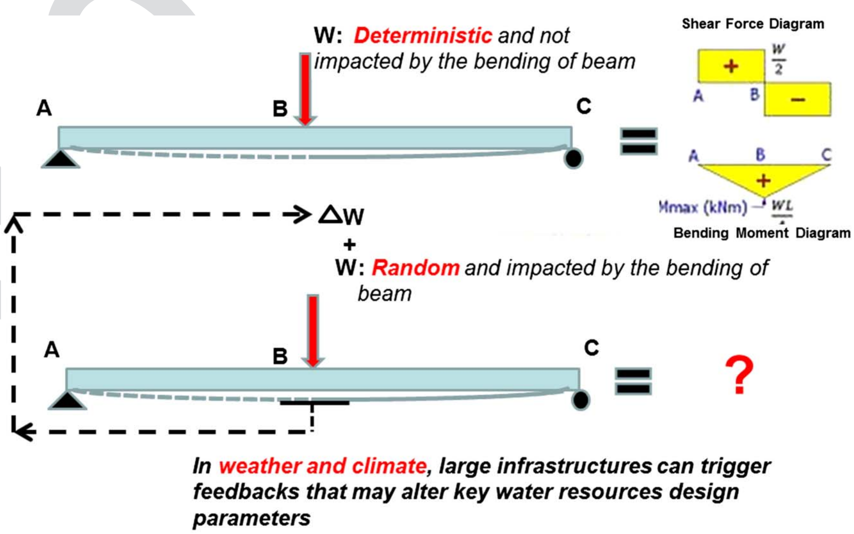


Fig. 1. Beam loading example to demonstrate the potential impact of a local random perturbation to a deterministic load in which the perturbation is triggered by the bending of the beam; the upper panel shows the conventional situation in which it is assumed that W is a deterministic variable; whereas the lower panel shows that W is now a random (stochastic or deterministic) variable due to ΔW load added through a feedback mechanism triggered when a certain amount of bending has occurred

and bending moment diagrams become a nontrivial process. The ΔW variable could also be represented as a chaotic variable due to the nonlinearity of the land-atmosphere feedbacks, as demonstrated in Zheng et al. (1993). Thus, ΔW may not be a random (stochastic) effect but a result of deterministic chaos (i.e., deterministic random variable), which consequentially may make the problem of deriving the shear force and bending moment diagrams with the ΔW feedback all the more tractable. Today, in conventional engineering practice, future design or operations changing impacts directly triggered by the infrastructure itself are not addressed proactively to estimate such local perturbations. Thus, it is now imperative to understand the importance (or the lack of) of such local perturbations triggered by local-regional landscape change on the land-atmosphere system.

The goal of this article is to summarize the findings that emerged from its first round (year 1) of TC activities from panel discussions, literature review and seeking feedback from experts in various disciplines such as atmospheric science, infrastructure building, water management, landscape architecture, hydrologic sciences and land use planning. This is particularly timely as the *Water Resources Reform and Development Act (WRRDA) 2014* was recently passed into law in June 2014. *WRRDA-2014* provides the engineering community a pathway to legislating some of the state of the art science and engineering practices as it is inclusive of the various water infrastructure systems of the nation. Although the focus is more on coastal and navigation systems, water infrastructure related to water supply, water hazard, power, and food production are explicitly recognized as in need for reform by the United States Congress.

The first round of this report by the TC does not strive to seek consensus on any particular view or recommend a universal design/operations strategy for improving resilience. It does not claim to present the most comprehensive and up-to-date synopsis of knowledge on the topic available today. Rather, the key goal of the article is to lay out the diverse perspectives and findings on the impact of landscape change that have potential implications for our current and future water infrastructure. By providing a broader range of views and issues than what is currently in the front view of engineering practice, the TC believes a higher level of empowerment can be achieved by the engineering community by affording a greater number of calculations in its decision making, particularly in understanding the possible future perturbations at the local scale due to larger-scale interactions. Hereafter, we will use the term climate as the statistics of weather events over historical (i.e., already occurred) multidecadal time periods, wherein the actual weather event in the future will dictate resilience.

Why Should Landscape Change be Important for Understanding Infrastructure Resilience?

Pielke et al. (2011) summarizes where the world currently appears to stand (as of 2011) in giving landscape drivers its due recognition for climate as follows:

"A great deal of attention is devoted to changes in atmospheric composition and the associated regional responses. Less attention is given to the direct influence by human activity on regional climate caused by modification of the atmosphere's lower boundary—the Earth's surface."

This perspective has not changed as of 2013 (Mahmood et al 2013). According to Forster et al. (2007), the direct radiative impact of global landscape change since the industrial revolution has been a reduction in the amount $0.2 \pm 0.2\ \mathrm{W\,m^{-2}}$. Being a relatively smaller number (compared to the radiative forcing from greenhouse gas emissions which is an order higher), Pielke et al. (2011) and many others (such as Narasima and Pitman 2006; Pitman 2003) have suggested that this is why landscape change is mostly omitted from the climate models used in previous Intergovernmental Panel on Climate Change (IPCC) reports up until the fourth Assessment Report (AR4). Yet this omission is a mistake as weather events that are hydrologically important result from regional and local atmospheric circulation features and are little, if at all, affected by global average forcings. More importantly, there is a local perturbation of significance to the infrastructure (as will be elaborated next from published literature). An unexpected casualty of this historical omission has been that the engineering profession was deprived of additional calculations as more reliable alternatives to highly uncertain and model-based climate change impacts that are predicted from global climate models (GCM). As an example of the current limitations of the GCMs, Stephens (2010) concluded that:

> "models produce precipitation approximately twice as often as that observed and make rainfall far too lightly . . . The differences in the character of model precipitation are systemic and have a number of important implications for modeling the coupled Earth system . . . little skill in precipitation [is] calculated at individual grid points, and thus applications involving downscaling of grid point precipitation to yet even finer-scale resolution has little foundation and relevance to the real Earth system."

A 2005 NRC report (NRC 2005) wrote:

> "Regional variations in radiative forcing may have important regional and global climatic implications that are not resolved by the concept of global mean radiative forcing. Tropospheric aerosols and landscape changes have particularly heterogeneous forcings. To date, there have been only limited studies of regional radiative forcing and response . . . .Improving societally relevant projections of regional climate impacts will require a better understanding of the magnitudes of regional forcings and the associated climate responses . . . .Several types of forcings—most notably aerosols, land-use and land-cover change, and modifications to biogeochemistry—impact the climate system in nonradiative ways, in particular by modifying the hydrological cycle and vegetation dynamics."

The interactions between local-to-regional drivers of climate (such as landscape change) with hemispheric or planetary forcings (such as rising greenhouse gas emissions and other changes in atmospheric composition) have also not received the attention they should have. Another reason often cited for this is that the impact of planetary scale greenhouse gas emissions is consistently unidirectional (i.e., an increase in positive radiative forcing) whereas the role of landscape change can result in both cooling and warming depending on other ambient conditions of the region. For example, Narasima and Pitman (2006) explored the relative role of land cover change in the context of increasing greenhouse gas concentrations and warming for the Australian climate. Their study clearly showed the interaction of the unidirectional warming with bidirectional landscape change wherein reforestation resulted in a 40% reduction in temperature increases, whereas deforestation had the effect of amplifying warming. These interactions were found to be highly localized. There appears to have been little research reported until 2011 on local-regional landscape interactions with global forcings with a view to guiding the engineering community for improving infrastructure resilience against future change in extreme weather.

The more localized and variable sensitivity of landscape change to extreme weather reported in more recent literature should be a strong reason why engineers need to be aware this landscape change is an additional driver. Engineering practice concerning design and operations is never geographically universal. One size does not fit all. Infrastructure has variable factors of safety that are driven by the ambient environmental risks, which are spatially variable. A perfect example of this can be found in reservoir sizing. The dust bowl of the 1930s and the ensuing high rates of soil erosion led to a necessary oversizing of reservoirs built in the 1940s in the Great Plains and midwest of the United States. Another appropriate example of how engineering practice has inadvertently accepted the variable response of landscape to extreme weather is probable maximum precipitation (PMP). According to the American Meteorological Society (AMS 1959), PMP, which is a design parameter for storm and flood drainage infrastructure, is defined as, "the theoretically greatest depth of precipitation for a given duration that is physically possible over a particular drainage area."

In the United States, the currently practiced PMP values reported in hydrometeorological reports (HMRs) are derived from maximum persisting humidity records for storms east of the 105th meridian or from sea surface temperature (SST) for storms west of the 105th meridian (Stratz and Hossain 2014). The argument for this differential approach has been that storms on the west coast are due to large synoptic-scale moisture originating in the Pacific Ocean, and thus, they are not as sensitive to landscape change effects as heavy storms in the Southeast or Eastern seaboard. Overall, the TC suggests that the impacts of landscape change on extreme weather should be considered with other issues that are currently in front of the engineering profession.

The civil engineering community is not yet harnessing very effectively the vast body of knowledge that has accumulated in the field of local to regional drivers of extreme weather and climate. This is despite the fact that the first field campaign to study the impact of urbanization on weather occurred in the 1970s in St Louis (MO) called METROMEX (Chagnon 1979). A rich history of observational and modeling studies that followed METROMEX the last three decades have reported a wide array of attributable impacts of land use change, such as increasing precipitation intensity (e.g., Barnston and Schikendanz 1984; Shepherd et al. 2002, 2010), frequency of convective storms (e.g., Pielke and Avissar 1990; Taylor 2010; Pielke et al. 2007; Pielke and Zeng 1989), and tornado activity around urban areas (Kellner and Niyogi 2013).

For example, recent research using mesoscale numerical models has shown that PMP, which is a legally mandated design parameter in the United Dates for high hazard dams (those upstream of a population center), can change in the ranges of 2% to 7% due to postdam changes to landscape such as irrigation and urbanization (Woldemichael et al. 2012). Such studies also report that the nature of change is dependent on the surrounding terrain and underlying moisture convergence conditions (leeward or windward side of orographic mountains) and geographic location (Woldemichael et al. 2014). Beauchamp et al. (2013) have hypothesized a 6% increase in PMP values by 2070 from projected increases in atmospheric humidity based on simulations by a global climate model (GCM) for a local watershed in Canada. Several GCMs forecast a 20% to 30% increase by 2100 A.D. in maximum precipitable water due to greenhouse gas emissions (Kunkel et al. 2013).

Landscape changes have also been known to alter probable maximum flood (PMF) not just through increased runoff due to reduced infiltration, but also through the atmospheric pathway of PMP changes. In the *Design of Small Dam* manual produced by the U.S. Bureau of Reclamation (USBR), the case of a Texas reservoir that experienced eight times the design PMF inflow due to rapid urbanization effects is a well-known example to engineers of the nonatmospheric effects of landscape change on water infrastructure resilience (USBR 1987). Recent research now indicates that the terrestrial hydrologic effects can be compounded by PMP modifications through land-atmosphere feedbacks. A recent study on the American River in California and Folsom Dam by Yigzaw et al. (2013) reports the need to estimate and perhaps account for future land cover changes upfront during the dam design and operation formulation phase by considering the gradual climatic effects on PMF through PMP modifications. This compounding effect can also manifest in sedimentation rates. Soil erosion, which is usually dictated by rainfall intensity and landscape change, results in reservoir sedimentation through inflow and a gradual loss of reservoir storage. With changing patterns of extreme precipitation through landscape change, the engineering community needs to understand how reservoir storage would be impacted to address the multiple objectives (such as flood control, water supply, and hydropower).

Fig. 2. Floodplain zone for a 10 year, 100 year flood and PMF; critical infrastructure is usually placed outside the boundaries of the PMF floodplain (reprinted from Queensland Government Australia 2011, courtesy of WMAwater)

Another implication for infrastructure resilience is on land use zoning for placement of critical infrastructure. Many, if not all, of the most critical infrastructures (Biringer et al. 2013) (such as large schools, hospitals, waste treatment facilities, and nuclear power plants) for society are often placed outside the PMF floodplain. The PMF floodplain has historically been treated as an absolute boundary in land use planning (Fig. 2). If this PMF floodplain is deemed no longer absolute and can potentially encroach on the previously designated safe zone for critical infrastructures, then the quantification of future risks associated with a changing PMF through PMP and landscape change becomes urgent.

Engineers need to recognize that there has been massive but gradual redistribution of water through artificial reservoirs, numerous irrigation schemes, land cover change, and urbanization since the early 1900s. Such a redistribution has altered the regional and global water cycle with local and regional implications of the change. For example, numerous irrigation schemes have contributed to an increased moisture availability and altered atmospheric convergence patterns overland in the US (Puma and Cook 2010; DeAngelis et al. 2010). The United States Geological Survey (USGS) records (Kenny et al. 2009) indicate an increase in irrigation acreage from 35 million acres (1950) to 65 million acres (in 2005) — enabled through water infrastructure. Similarly, there are approximately 75,000 artificial reservoirs built in the United States during the last century with a total capacity almost equaling one year's mean runoff (Graf 1999, 2006; GWSP 2008). The cumulative effect of this extensive impoundments has been to triple the average residence time of surface water from 0.1 years (in 1900) to 0.3 years in 2000 (Vorosmarty and Sahagian 2000), an aspect that clearly has not received the attention of the global change community and on what it means for local perturbations to extremes that engineers design and operate infrastructure for.

The research findings summarized previously clearly exemplify infrastructure-sensitive impact of landscape change on extreme weather through land-atmosphere feedbacks. A more relevant question for the engineering community now is if the sensitivity (i.e., the local perturbations or delta x) observed in the landscape's impact on extremes and whether the associated uncertainty are within the margins of safety practiced in conservative engineering design of very large and high hazard infrastructures. The TC believes this is a topic of timely research for the engineering community to secure the future health of water infrastructure systems.

Water Infrastructure Resilience at the Intersection of Weather and Climate

It is important, given the mounting body of research, to propose a definition for infrastructure resilience (IR) at the intersection of weather and climate for the engineering community. The definition proposed by the TC is as follows:

> "A Weather-Climate Resilient Water Infrastructure is defined as an infrastructure that can to a degree anticipate or adapt and recover from external disruptions due to severe weather and climate and carry on providing the essential services the infrastructure is designed for with managed interruption to nonessential services, while balancing tradeoffs among social (e.g., security), environmental and economic factors."

The term anticipate in the aforementioned definition requires elaboration as it may appear counter-intuitive term to the engineering community. With the complex land-atmosphere modeling capability that is now available, it is now possible to model the future impact of landscape change on extreme weather that are likely to be triggered by an infrastructure change. For example, the proposed Grand Renaissance Dam on the Blue Nile in Ethiopia, that is expected to be completed in 2020, will irrigate vast areas of land for agricultural production. Clearly, the expected impact of this irrigation on the local-regional climate can be modeled to consider if the anticipated local perturbations to extreme weather (during post-dam phase) need to be explicitly addressed in infrastructure design as the dam is being built and later in operations. Such an exercise is akin to a life cycle assessment and if performed, may make the infrastructure anticipate better the possible future changes to extreme weather.

Herein, a point to keep in mind is the trade-off between the three bottom lines that are currently practiced for sustainability — social, environmental, and economic factors. In the United States, the ongoing failure to adequately address the state of the nation's existing infrastructure makes infrastructure resilience all the more critical for the engineering community. For example, between 1889 and 2006, a total of 1,133 dams in the United States were overtopped, according to a database maintained by Stanford University's National Performance of Dams Program. Of the structures that were overtopped, 625 dams, or roughly 55 percent, experienced a hydrologic performance failure triggered by extreme weather events that the dam spillways or downstream levees could not handle. A challenge now is to find smart ways to address the trillions of dollar that ASCE has estimated is needed to rehabilitate infrastructure across the nation. One smart, cost-effective approach entails understanding the future resilience of infrastructure and developing procedures for adapting infrastructure so as to manage expected risks (Vugrin et al. 2011). In other words, the traditional notion of demolishing existing infrastructure and rebuilding it as necessary is not an option. For example, this approach relies on uninterrupted economic growth and abundant resources, an outcome that cannot always be counted on to occur, as shown by the recent fiscal crisis facing the United States and the world. Meanwhile, cement production's global contribution to greenhouse gas emissions cannot be ignored.

The TC has suggested that although making the present infrastructure stronger and bigger may be appropriate in some cases, there will be situations in which it may mean abandoning existing solutions and considering others that are less expensive with similar results. Infrastructure resilience must weigh affordability in selecting infrastructure solutions against structural resilience. It may be that in order to build infrastructure that is financially feasible and create neighborhoods that are affordable, engineers may have to design infrastructure that can fail safely rather than to expend a greater amount of funds to withstand the changing patterns of extreme weather. Engineers may also find that so-called natural solutions are more affordable over solutions that demand excessive construction interventions, for instance by exploring natural water storage systems over manmade reservoirs.

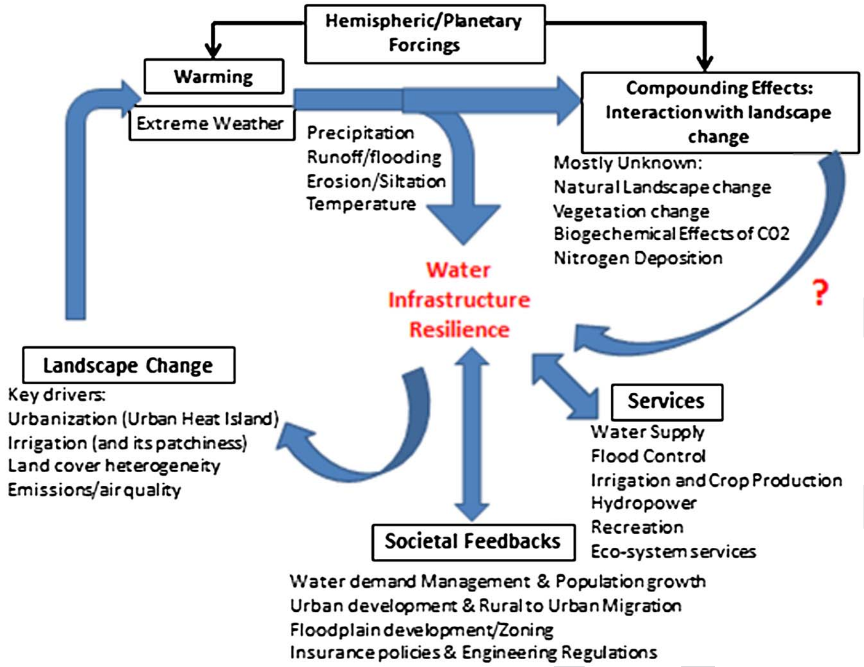
Itemizing the Key Landscape Drivers of Importance to Engineers

It is worthwhile at this stage to itemize the various landscape drivers referred to previously that have implications for infrastructure resilience. The list provided is by no means exhaustive. The list highlights the landscape changes most commonly known to impact extreme weather and climate.

1. Irrigation and crop production resulting in altered, surface temperature, humidity, moisture flux, and precipitation patterns.
2. Urbanization and urban heat islands (concretization, upward expansion, and densification leading to change in albedo, turbulence, and convergence patterns) resulting in precipitation anomalies over and downwind regions of cities.
3. Urban Archipelago (note – this is a newer concept that has emerged from the concept of large cities joining through corridors to alter the regional dynamics of extreme weather and climate).
4. Deforestation and forest fire impacts (which also impact soil erosion, landslides, and infiltration rates).
5. Afforestation resulting in altered infiltration and moisture fluxes.
6. Overgrazing & desertification resulting in drought and altered local climate.
7. Dry land farming.
8. Industrialization (aerosols/air quality impacting cloud condensation nuclei) resulting often in altered precipitation rates and the ability of clouds to precipitate.
9. Reservoir creation (upstream of dams) resulting in lake effect rain, snow and fog, and altered evaporation and precipitation rates in adjacent lands.
10. Wetland shrinkage (downstream or upstream of dams; tragedy of commons or urban encroachment).
11. Emissions (carbon dioxide, nitrogen deposition impacts water quality for water infrastructure systems).

As discussed previously, the aforementioned landscape drivers are compounded by the hemispheric or planetary forcings of climate and weather. At this stage, it appears that much less is known about the compounding factors due to the historical focus mostly on global atmospheric composition changes and the effect on the global average temperatures. The list that follows itemizes a few potentially compounding factors that the engineering community would benefit from knowing, particularly for water management.

1. Salinity of stream flow reaching the ocean: Due to increasing withdrawal, diversion and redistribution of water in



F3:1 **Fig. 3.** Schematic of landscape change drivers on extreme weather and climate, its compounding effect in context of societal feedbacks and services

infrastructure systems from the natural pathways, freshwater flux to the ocean is likely to become increasingly saline. This trend can have significant impact on ocean circulation which in turn impacts climate.

2. Location/terrain (Woldemichael et al. 2014; Knutsmann and Knoche 2011; Mahmood et al. 2010).
3. Large scale regulation, inter-basin transfers and redistribution (replumbing) of watersheds through interconnected water infrastructure systems (e.g., this topic is recently coined as hydromorphology by Vogel 2011)
4. Season/climate type (Mahmood et al. 2010; Pielke et al. 2011)
5. Synoptic scale moisture convergence pattern (e.g., Asian Monsoon has been reported to mask any local-to-regional-scale impact of Three Gorges Dam on heavy precipitation pattern — see Zhao and Shepherd 2011)
6. Dewpoint temperature trends [e.g., a study by Robinson (2000) indicate average dew point having risen one degree over the last 40 years in most parts of the United States] and some, or even all of this, could be due to landscape conversion [e.g., see Fall et al. (2010)].
7. The biogeochemical effects of added CO_2 (and its radiative forcing) and nitrogen deposition (Galloway et al. 2004).

To put the landscape drivers and its potential compounding effect in context of infrastructure resilience, societal feedbacks, and essential services, the TC proposes the following schematic (Fig. 3) as a platform for considering the additional calculations for the engineering community.

Integrating Additional Calculations from Landscape Change in Current Engineering Practice

As stated previously, the goal of this first round of report by the TC is not to recommend any particular approach for considering the landscape drivers of change for engineering practice. Nevertheless, the TC believes that the engineering profession can still benefit from a few suggestions on how the additional calculations from landscape drivers might be addressed in current engineering practice for improving infrastructure resilience.

The first suggestion pertains to an extensive use of historical observations on weather events and extreme climate spanning the pre and post construction phase of large water infrastructure projects. In the developed world, such as the United States and Europe, such data is available. Therefore, engineers are uniquely positioned to perform data-based observational studies (or hypothesis testing) of the statistical difference in extreme weather and climate processes due to infrastructure-triggered changes in landscape. Examples of such observational studies may be found for the case of large dams of the world in Hossain (2010) and Hossain et al. (2010). Degu et al. (2011) and Degu and Hossain (2012) provide an observational study of 92 large dams in the United States by observing the statistical difference in atmospheric proxies for heavy storms [e.g., convective available potential energy (CAPE), precipitation intensity and frequency downwind and upwind of reservoirs]. Pizarro et al. (2013) have reported that the inland water bodies of Chile may have intensified precipitation intensity at higher elevations. For sedimentation effects, Graf et al. (2010) provides a comprehensive synopsis of how the large dams in the Western US have lost storage.

The use of satellite remote sensing appears to have considerable potential in regions lacking in situ measurements as demonstrated by a recent study by Taylor (2010) over the Niger Delta. Although not directly related to infrastructure issues, Taylor (2010) reported that the 24 years of cloud imagery from satellites indicates the favoring of convection when the inner delta is inundated (which has implications to regional water supply and upstream dam operations for the riparian nations of Senegal, Nigeria, and Mali). It should be noted that most of the current method today focus on using historical data to define design criteria The focus on trend detection or discrete shifts is not new but needs more attention by the engineering community.

The next suggestion for the engineering community is to explicitly embrace high resolution numerical models that can model the land-atmosphere processes and feedbacks due to landscape changes down to the mesoscale (~500 m, hourly). Models widely used today, such as the weather research and forecasting (WRF) and the regional atmospheric modeling system (RAMS; Pielke 1992; Pielke et al. 1992), are some examples that have seen use in this regard. For example, Georgescu et al. (2014) have looked into the effect of albedo changes (through artificial whitening of urban canopy) on the heat signature in major cities of the United States using WRF. Burian (2006) has reported on how urbanization impacts of rainfall can impact a city's storm drainage infrastructure. Knutsmann and Knoche (2011) have applied a numerical model to track the precipitation recycling effects for Lake Volta dam in Ghana. A series of studies reported in Woldemichael et al. (2012, 2014), Ohara et al. (2011), Tan (2010), Yigzaw et al. (2013, 2013), and Yigzaw and Hossain (2014) provide examples on the use of atmospheric models for estimation of PMP and a hydrological model [variable infiltration capacity (VIC); Liang et al. 1994] for deriving the consequential PMFs for modeling the resilience of large dams in the western United States. Given that GCMs, which operate on significantly coarser space-time resolutions, are not yet ready for prime time (Kundewicz and Stakhiv 2010), the TC cautions the direct use of GCMs for any infrastructure resilience. To date, research based on GCMs has yet to reveal findings on local perturbations of relevance that can impact current engineering practice.

Another suggestion by the TC is to partially modify standard engineering practice that allow a swapping with more recent climate-driven data or methods (Rackecha et al. 1999). A good example of this is the HMR approach to estimating PMP (Schreiner and Riedel 1978). The HMR approach is a relatively straightforward and linear method based on using a historical storm and maximizing it according to the ratio of historical maximum precipitable water to the storm precipitable water (Rakhecha and Singh 2009). The engineering assumptions behind this HMR approach are: (1) the precipitation is linearly related to the precipitable water; (2) the precipitation efficiency of the storm does not change as the moisture available to the storm increases; and (3) terrain modulates the distribution of the precipitation but does not affect the synoptic-scale dynamics of the storm. Abbs (1999) has investigated the validity of these assumptions and has identified possible reasons why certain accepted-PMP values have been exceeded by recently observed extreme storm events (such as the 1996 flood in Sydney, Australia). Thus, such standard procedures can be easily modified where the precipitable water data can be extracted from more climate-informed approaches (based on newer observations or models). Stratz and Hossain (2014) have demonstrated this approach in two ways: (1) using RAMS derived humidity profiles to update HMR PMP and (2) using Robinson (2000) data on dewpoint temperature trends over the last 40 years to project future HMR PMP. In both cases, considerable changes to PMP were found.

Currently, engineering risk assessment is already practiced from a multicriteria decision making approach that includes sustainability metrics. This approach, known as the triple bottom line (TBL), usually includes socioeconomic, social, and environmental components, and is standardized by the U.S. Army Corps of Engineers (USACE) and USBR (Kalyanapu et al. 2011), to identify a balanced alternatives. The TBL is therefore an ideal framework to add the impact of additional calculations (such as from landscape change). Applying the TBL framework that also includes the local perturbations expected from land-atmosphere feedback effects should yield more resilient alternatives (as an adaptation policy) for water infrastructures in terms of not only the economic benefits (e.g., damage reduction), but also societal benefits (e.g., realistic perception of flood risk, increase in land value, and improved health) and environmental benefits (e.g., minimal disruption of riparian ecology, water quality, and natural conditions).

Conclusion: The Road Ahead

This article explored the importance of the well-established feedbacks triggered by infrastructure systems to the land-atmosphere system. Such feedbacks and the consequential implications serve as additional calculations for decision-making related to infrastructure management, design and operations. The TC has shed light on the findings of the initial round of dialogue initiated to understand various issues in its first year. A definition for infrastructure resilience (IR) at the intersection of extreme weather and climate has been proposed for the engineering community. By providing a broader range of views and issues than what is currently in the front view mirror of engineering practice, the TC believes a higher level of empowerment can be achieved by the engineering community by affording a greater number of calculations in its decision making.

As noted previously, the timing of the TC report is critical for *WRRDA-2014* that is now signed into law and had the full endorsement of ASCE. The onus is on the engineering and science community to communicate the state of the art science and new engineering practices to this legislative body so that methods for managing water infrastructures can be improved. As a future goal, performing a survey of actual water managers in the various water infrastructure units (such as U.S. Army Corps of Engineers district offices) could be beneficial.

Although the article does not strive to seek consensus on any particular view or recommend a particular design/operations strategy for improving resilience, there are several open issues that require work in the near future. For example, it is not entirely clear how best to impact engineering practice directly through the research that appears well-established on land-atmosphere feedbacks triggered by infrastructure systems. Some examples related to adjusting PMP and PMF as wholly new (model-based) or modified current practices have appeared in recent literature. However, more work is required in this area and for exploring acceptance as the field of engineering practice for design/operations/risk assessment is much broader (e.g., intensity duration frequency (IDF), curves; return periods, flood frequency, design storm; envelope curves).

A precursor to devising effective ways to impacting current engineering practice is to first identify knowledge gaps on landscape change that currently prevent the engineering community from formulating practical solutions to more resilient water infrastructure building or management. For example, the interaction at regional to global scale with atmospheric composition (a planetary forcing) is not sufficiently well known. Also, GCMs do not provide the skill required at the spatial scale that impacts engineering practices at the infrastructure scale. Thus, such gaps need to be identified and recommended as new research areas. A key focus should be to understand the predictive uncertainty of changes to weather and climate, and the implications of this uncertainty on infrastructure design and operations. The TC hopes to work on these important issues and provide further reports as updates in the coming years for the engineering community.

References

Abbs, D. J. (1999). "A numerical modeling study to investigate the assumptions used in the calculation of probable maximum precipitation." *Water Resour. Res.*, 35(3), 785–796.

Barnston, A. G., and Schickedanz, P. T. (1984). "The effect of irrigation on warm season precipitation in the Southern Great Plains." *J. Appl. Meteorology Clim.*, 23(6), 865–888.

Beauchamp, J., Leconte, R., Trudel, M., and Brissette, F. (2013). "Estimation of the summer-fall PMP and PMF of a Northern watershed under a changed climate." *Water Resour. Res.*, 49(6), 3852–3862.

Biringer, B. E., Vugrin, E. D., and Warren, D. E. (2013). *Critical infrastructure system security and resilience*, CRC Press, Boca Raton.

Burian, S. J. (2006). "Urbanization effect on rainfall: Implications for drainage infrastructure performance and design." *Smart growth and climate change: Regional development, infrastructure and adaptation*, M. Ruth, ed., Edward Elgar, Northampton, MA, 207–242.

Chagnon, S. A (1979). "Precipitation changes in summer caused by St. Louis." *Science*, 205(4404), 402–404.

Cotton, W. R., and Pielke, R. A., Sr. (2007). *Human impacts on weather and climate*, 2nd Ed., Cambridge University press, Cambridge, U.K.

DeAngelis, A., Dominguez, F., Fan, Y., Robock, A., Kustu, M. D., and Robinson, D. (2010). "Evidence of enhanced precipitation due to irrigation over the Great Plains of the United States." *J. Geophys. Res.*, 115, D15115.

Degu, A. M., et al. (2011). "The influence of large dams on surrounding climate and precipitation patterns." *Geophys. Res. Lett.*, 38, L04405.

Degu, A. M., and Hossain, F. (2012). "Investigating the mesoscale impact of artificial reservoirs on frequency of rain." *Water Resour. Res.*, 48(5), in press.

Fall, S., Niyogi, D., Gluhovsky, A., Pielke, R. A., Sr., Kalnay, E., and Rochon, G. (2010). "Impacts of land use land cover on temperature trends over the continental United States: Assessment using the North American Regional Reanalysis." *Int. J. Climatol.*, 30(13), 1980–1993.

Forster, P., et al. (2007). "Radiative forcing of climate change." *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the 4th Assessment Report of the Intergovernmental Panel on Climate Change*, S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor and H. L. Miller, eds., Cambridge University Press, Cambridge, 129–234.

Galloway, J. N., et al. (2004). "Nitrogen cycles: Past, present, and future." *Biogeochemistry*, 70(2), 153–226.

Georgescu, M., Morefield, P. E., Bierwagen, B. G., and Weaver, C. P. (2014). "Urban adaptation can roll back warming of emerging megapolitan regions." *Proc. Nat. Acad. Sci.*, 111(8), 2909–2914.

Graf, W. L. (1999). "Dam nation: A geographic census of American dams and their large-scale hydrologic impacts." *Water Resour. Res.*, 35(4), 1305–1311.

Graf, W. L. (2006). "Downstream hydrologic and geomorphic effects of large dams on American rivers." *Geomorphology*, 79(3–4), 336–360.

Graf, W. L., Wohl, E., Sinha, T., and Sabo, J. L. (2010). "Sedimentation and sustainability of western American reservoirs." *Water Resour. Res.*, 46(12), W12535.

GWSP (Global Water System Project) Digital Water Atlas. (2008). "Map 41: Dams and capacity of artificial reservoirs (V1.0)." ⟨http://atlas.gwsp.org⟩ (Mar. 9, 2015).

Hossain, F. (2010). "On the empirical relationship between the presence of large dams the alteration in extreme precipitation." *Nat. Haz. Rev.*, 10.1061/(ASCE)NH.1527-6996.0000013, 97–101.

Hossain, F., et al. (2012). "Climate feedback-based considerations to dam design, operations and water management in the 21st century." *J. Hydrol. Eng.*, 10.1061/(ASCE)HE.1943-5584.0000541, 837–850.

Hossain, F., Jeyachandran, I., and Pielke, R. A., Sr. (2010). "Dam safety effects due to human alteration of extreme precipitation." *Water Resour. Res.*, 46, W03301.

Kalyanapu, A. J., Judi, D. R., McPherson, T. N., and Burian, S. J. (2011). "Monte Carlo-based flood modeling framework for estimating probability weighted flood risk." *J. Flood Risk Manage.*, 5, 37–48.

Kellner, O., and Niyogi, D. (2013). "Land-surface heterogeneity signature in Tornado climatology? An illustrative analysis over Indiana 1950-2012." *Earth Interact.*, 18, 1–32.

Kenny, J. F., Barber, N. L., Hutson, S. S., Linsey, K. S., Lovelace, J. K., and Maupin, M. (2009). "Estimated use of water in the United States in 2005." *U.S. Geological Survey Circular 1344*, Reston, VA.

Kundzewicz, Z. W., and Stakhiv, E. Z. (2010). "Are climate models 'ready for prime time' in water resources management applications, or is more research needed?" *Hydrol. Sci. J.*, 55(7), 1085–1089.

Kunkel, K. E., et al. (2013). "Probable maximum precipitation and climate change." *Geophys. Res. Lett.*, 40(7), 1402–1408.

Kunstmann, H., and Knoche, H. R. (2011). "Tracing water pathways from the land surface through the atmosphere: A new RCM based evapotranspiration tagging method and its application to the Lake Volta Region in West Africa." *J. Geophys. Res*., 118(22), in press.

Liang, X., Lettenmaier, D. P., Wood, E. F., and Burges, S. J. (1994). "A simple hydrologically based model of land surface water and energy fluxes for GSMs." *J. Geophy. Res.*, 99(D7), 14415–14428.

Mahmood, R., et al. (2010). "Impacts of land use land cover change on climate and future research priorities." *Bull. Am. Meteorol. Soc.*, 34(4), 37–46.

Mahmood, R., et al. (2013). "Land cover changes and their biogeophysical effects on climate." *Int. J. Climatol.*, 34(4), 929–953.

Narasima, T., and Pitman, A. J. (2006). "Exploring the sensitivity of the Australian climate to regional land-cover-change scenarios under increasing CO_2 concentrations and warmer temperature." *Earth Interact.*, 10, 1–27.

NRC (National Research Council). (2005). "Radiative forcing of climate change: Expanding the concept and addressing uncertainties." *Committee on Radiative Forcing Effects on Climate Change, Climate Research Committee, Board on Atmospheric Sciences and Climate, Division on Earth and Life Studies*, The National Academies Press, Washington, DC, 208.

Ohara, N., Kavvas, M. L., Kure, S., Chen, Z. Q., Jang, S., and Tan, E. (2011). "A physically based estimation of maximum precipitation over American River Watershed, California." *J. Hydrol. Eng.*, 10.1061/(ASCE)HE.1943-5584.0000324, 351–361.

Pielke, R. A., Sr. (1992). "A comprehensive meteorological modeling system—RAMS." *Meteorol. Atmos. Phys.*, 49, 69–91.

Pielke, R. A., Sr., et al. (2002). "The influence of land-use change and landscape dynamics on the climate system- relevance to climate change policy beyond the radiative effect of greenhouse gases." *Phil. Trans. A*, 360, 1705–1719.

Pielke, R. A., Sr., et al. (2007). "An overview of regional land use and land cover impacts on rainfall." *Tellus B*, 59(3), 587–601.

Pielke, R. A., Sr., et al. (2011). "Land use/land cover changes and climate: Modeling analysis and observational evidence." *WIREs Clim. Change*, 2, 828–850.

Pielke, R. A., and Avissar, R. (1990). "Influence of landscape structure on local and regional climate." *Landscape Ecol.*, 4(2–3), 133–155.

Pielke, R. A., and Zeng, X. (1989). "Influence on severe storm development of irrigated land." *Natl. Wea. Dig.*, 14(2), 16–17.

Pitman, A. J. (2003). "The evolution of, and revolution in, land surface schemes designed for climate models." *Int. J. Climatol*., 23(5), 479–510.

Pizarro, R., et al. (2013). "Inland water bodies in Chile can locally increase rainfall intensity." *J. Hydrol.*, 481(25), 56–63.

Puma, M. J., and Cook, B. I. (2010). "Effects of irrigation on global climate during the 20th century." *J. Geophys. Res.*, 115, D16120.

Rakhecha, P. R., Clark, C., and Lane, S. (1999). "Revised estimates of one-day probable maximum precipitation (PMP) for India." *Meteorol. Appl.*, 6(4), 343–350.

Rakhecha, P. R., and Singh, V. P. (2009). *Applied hydrometeorology*, Springer, Netherlands.

Robinson, P. J. (2000). "Temporal changes in United States dew point temperatures." *Int. J. Climatol.*, 20(9), 985–1002.

Schreiner, L. C., and Riedel, J. T. (1978). "Probable maximum precipitation estimates." *United States East of the 105th Meridian (HMR No. 51)*, National Weather Service, National Oceanic and Atmospheric Administration, United States Dept. of Commerce, Washington, DC.

Shepherd, J. M., Carter, W. M., Manyin, M., Messen, D., and Burian, S. (2010). "The impact of urbanization on current and future coastal convection: A case study for Houston." *Environ. Plan.*, 37(2), 284–304.

Shepherd, J. M., Pierce, H., and Negri, A. J. (2002). "On rainfall modification by major urban areas: Observations from space-borne radar on TRMM." *J. Appl. Meteorol.*, 41, 689–701.

Stratz, S. A., and Hossain, F. (2014). "Probable maximum precipitation in a changing climate: Implications for dam design." *Hydrol. Eng.*, 10.1061/(ASCE)HE.1943-5584.0001021, 06014006.

Tan, E. (2010). "Development of a methodology for probable maximum precipitation estimation over the American River watershed using the WRF model." Ph.D. dissertation, Univ. California-Davis, Davis, CA.

Taylor, C. M. (2010). "Feedbacks on convection from an African wetland." *Geophys. Res. Lett.*, 37, L05406.

Trenberth, K. E. (2011). "Changes in precipitation with climate change." *Climate Res.*, 47(1–2), 123–138.

USBR (U.S. Bureau of Reclamations). (1987). *Design of small dams*, Water Resources Technical Publication.

Vogel, R. M. (2011). "Hydromorphology." *J. Water Res. Plan. Manage.*, 10.1061/(ASCE)WR.1943-5452.0000122, 147–149.

Vonder Haar, T. H., Bytheway, J., and Forsythe, J. M. (2012). "Weather and climate analyses using improved global water vapor observations." *Geophys. Res. Lett.*, 39(15), in press.

Vorosmarty, C., and Sahagian, D. (2000). "Anthropogenic disturbance of the terrestrial water cycle." *Bioscience*, 50(9), 753–765.

Vugrin, E. D., Warren, D. E., and Ehlen, M. A. (2011). "A resilience assessment framework for infrastructure and economic systems: Quantitative and qualitative resilience analysis of petrochemical supply chains to a hurricane." *Process Safety Progress*, 30, 280–290.

Wang, J-W., Wang, K., Pielke, R. A., Lin, J. C., and Matsui, T. (2008). "Towards a robust test on North America warming trend and precipitable water content increase." *Geophys. Res. Letts.*, 35, L18804.

Woldemichael, A. T., Hossain, F., and Pielke, R. A., Sr. (2014). "Impacts of post-dam land-use/land-cover changes on modification of extreme precipitation in contrasting hydro-climate and terrain features." *J. Hydrometeorol.*, 15(2), 777–800.

Woldemichael, A. T., Hossain, F., Pielke, R. A., Sr., and Beltrán-Przekurat, A. (2012). "Understanding the impact of dam-triggered land-use/land-cover change on the modification of extreme precipitation." *Water Resour. Res.*, 48, W09547.

Yigzaw, W., and Hossain, F. (2014). "Land use land cover impact on probable maximum flood and sedimentation for artificial reservoirs: A case study in Western US." *J. Hydrol. Eng.*, 18(9), 1180–1190.

Yigzaw, W., Hossain, F., and Kalyanapu, A. (2013). "Comparison of PMP-driven PMFs with flood magnitudes from increasingly urbanized catchments: The case of American River Watershed." *Earth Interact.*, 17(8), 1–15.

Yigzaw, W., Hossain, F., and Kalyanapu, A. (2013). "Impact of artificial reservoir size and land use/land cover patterns on estimation of probable maximum flood: The case of Folsom dam on American River." *J. Hydrol. Eng.*, 10.1061/(ASCE)HE.1943-5584.0000722, 1180–1190.

Zhao, F., and Shepherd, J. M. (2011). "Precipitation changes near three Gorges Dam, China-part I: A spatio-temporal validation analysis." *J. Hydrometeor.*, 13, 735–745.

Zheng, X., Pielke, R. A., and Eykholt, R. (1993). "Chaos theory and its applications to the atmosphere." *Bull. Amer. Meteor. Soc.*, 74, 631–644.