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REVIEWS

Design Flood Estimation in a Warming Climate—Issues, Challenges and the Way Ahead

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Abstract | Flooding is the biggest and severest natural disaster faced by humanity year after year worldwide. In spite of advances in technology, data availability and computing power, the loss of life and property from flooding continues unabated. To add to this is the new challenge of climate change, a challenge that forces us to ask whether existing norms and approaches for estimating the design flood still apply in this warming world. This paper reflects on the issue of design flood estimation in a warming world, addressing questions such as—why is it that floods are changing—and what is it we need to do to estimate the changed values to both secure existing and plan new water infrastructure with. The paper poses a lot of questions, and lays down some thoughts on what could be done to prepare us better to reduce miscalculated risks in our designed infrastructure as we head deeper into this new century.

Key Words: *Climate Change; Hydrologic Design; Design Flood Estimation; Design Storm; Evaporation*

1 Introduction

"Stationarity is dead—whither water management".[1] The title of this recent summary paper aptly catches the dilemma facing hydrologists and engineers today. Climate change poses new challenges to estimating the design flood, with traditional alternatives such as flood frequency analysis or derivations using an equivalent design storm being increasingly questionable as the climate (and hence the hydrologic) system changes.

This paper reflects on some of the issues facing design flood estimation, and summarises recent research on this topic. The paper is split into reflections on a number of questions, all of which need to be addressed before we can formulate intelligent alternatives to address the design flood estimation problem for this changing climate. So let us start off with the very first question that needs to be answered—are floods really changing?

2 Are Floods Changing?

In a recently published study, an attempt was made to answer the above question using one of the longest and densest records of annual maximum floods used till date for a comprehensive stationarity assessment.[2] Results from this study are summarised in Figure 1. Some of the notable features of this study that are relevant to addressing the question this section focuses on are:

1. There exist a statistically significant number of stations exhibiting trends in annual maximum flows in Australia. This point is all the more noteworthy when we take into consideration the fact that all the above stations are checked and found free from anthropogenic influences.
2. Of these stations, a majority exhibit a decrease in the annual maximum flood.
3. The number of such significant trend stations decreases when the effect of climatic covariates (such as the El Nino Southern Oscillation (ENSO) or the Interdecadal Pacific Oscillation (IPO)) is taken into consideration. As the above mentioned covariates are known to impact extremes, any asymmetric sampling of records towards one phase of the climatic anomaly (such as a negative IPO phase in contrast to a positive phase) can lead to an artificial trend in the overall record.

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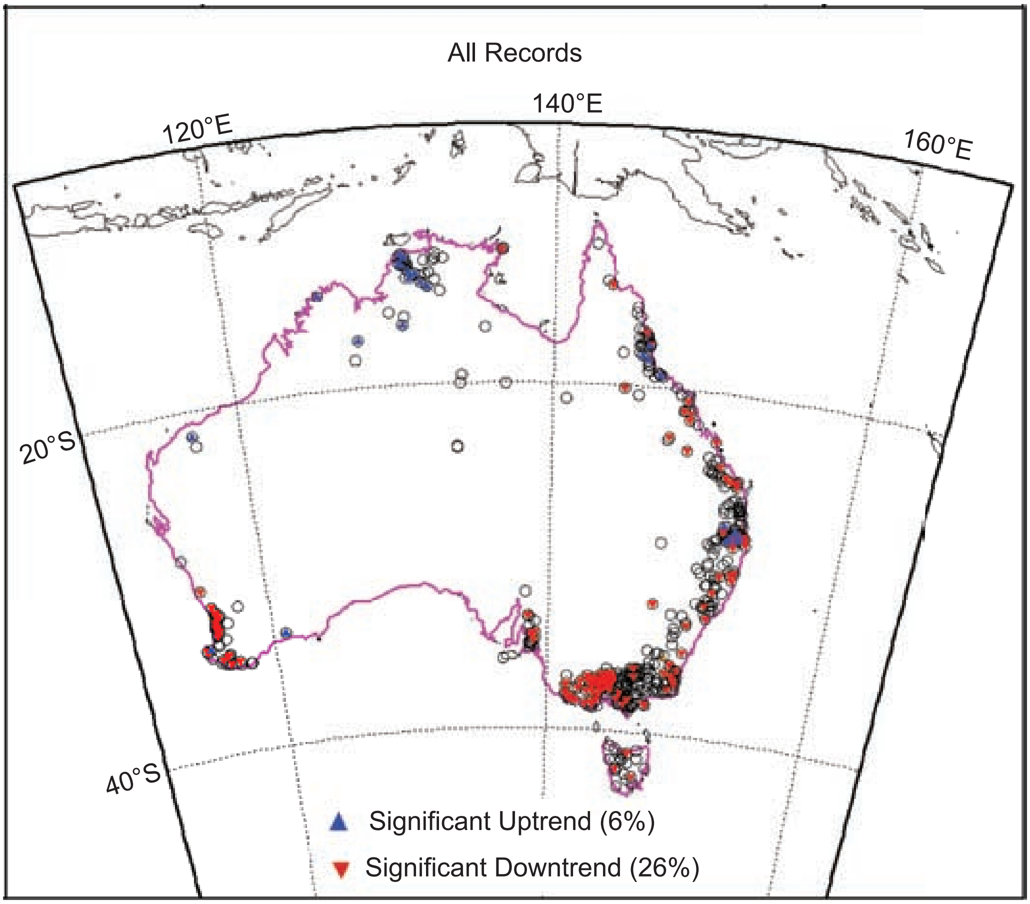

Study Period	Number of Stations	Unconditioned MK	Conditioned MK on SAM	Conditioned MK on Niño 3.4	Conditioned MK on Filtered IPO
30-year	330	7 (75)	3 (45)	7 (49)	5 (49)
40-year	77	2 (16)	0 (1)	2 (11)	2 (13)
50-year	21	1 (6)	0 (0)	1 (6)	0 (3)

Figure 1: Locations of study catchments having atleast 30 years of unregulated annual maximum streamflow data, along with a summary of the Mann Kendall (MK) test results with and without conditioning on a range of climatic co-variates. SAM = Southern Annular Mode; Niño 3.4 = an index of the El Nino Southern Oscillation; IPO = Interdecadal Pacific Oscillation.[2]

4. The fact that the number of stations exhibiting significant trends is more than 10% after the climatic covariates are taken into consideration, forces one to consider that this may be a result of climate change.
5. The above consideration becomes even stronger when we acknowledge that the climatic covariates are themselves significantly correlated to the global warming trend, suggesting the "true" number of stations that exhibit significant trends is closer to that reported under the unconditional case (column 2).

Consequently, one can conclude that annual maximum floods are changing, atleast across Australia (infact there have been a number of papers documenting the same in other parts of the world—readers referred to the references and citations to the above study). What could possibly be the reason behind these changes remains elusive, but given all other significant causative factors have been addressed in deriving the above results, the most likely reason behind the change is changes to the climate. Which brings us to our second question—should we expect floods to change due to global warming?

3 Should Floods Change Due to Global Warming?

Global warming is a result of an increase in (mostly anthropogenic) greenhouse gas emissions and concentrations, which lead to an intensification of the energy cycle, specifically an increased entrapment of the longwave radiation fluxes in the earth's atmosphere. This continued entrapment leads to an increase in the overall temperature of the planet, that then goes on to result in a range of changes, including an increase in the amount of water that can be stored in an atmospheric column at any instant of time.

This leads us to ask the question this section focusses on—whether floods should be different because of the above changes? As flood extremes are rare and occur as a result of a number of factors coinciding by chance, this question is not simple to answer. However, a broad assessment allows us to suggest that floods should change if either of the following three conditions are created:

1. Pre-extreme event antecedent conditions change because of warming.
2. Extreme precipitation event volume and intensity change because of warming.
3. Warming leads to a change in the catchments response to rain—something that can happen when there is a trend towards a new or a different vegetation regime.

The question that now arises is whether there exists any evidence to suggest that either of these have changed or are changing based on the observational records we have access to?

4 Are Antecedent Conditions Changing?

In a recent study assessing the reasons for changes in annual maximum floods between opposing phases on the Interdecadal Pacific Oscillation (IPO), it was found that while floods were remarkably different between the two IPO phases, the causative rainfall leading to the flood was not.[3] Further investigation revealed that the differences in floods were a result of markedly different antecedent conditions preceding the flood causing rainfall. These antecedent conditions were clearly linked with the IPO, even when the extreme rainfall was not.

In the context of the present discussion, the question that arises from the above finding is whether antecedent conditions corresponding to the extreme floods recorded on the catchment, exhibit any trend that would indicate that these are affected by global warming. To our knowledge, this is a question that has not been investigated in significant detail as of yet. However, for antecedent conditions to be different, one would need to see a difference in the incident rainfall, and also in the evaporation associated with this rainfall. Alternately, one would be able to spot such changes in soil moisture, a variable that global records for exist through advances in satellite remote sensing.

In a recent study to investigate trends in satellite derived soil moisture across the world, 27% of the area sampled indicated significant trend, with roughly 3/4th of these locations exhibiting negative trends.[4] Figure 2 reproduces results from the mentioned paper, indicating the locations where significant trends were identified.

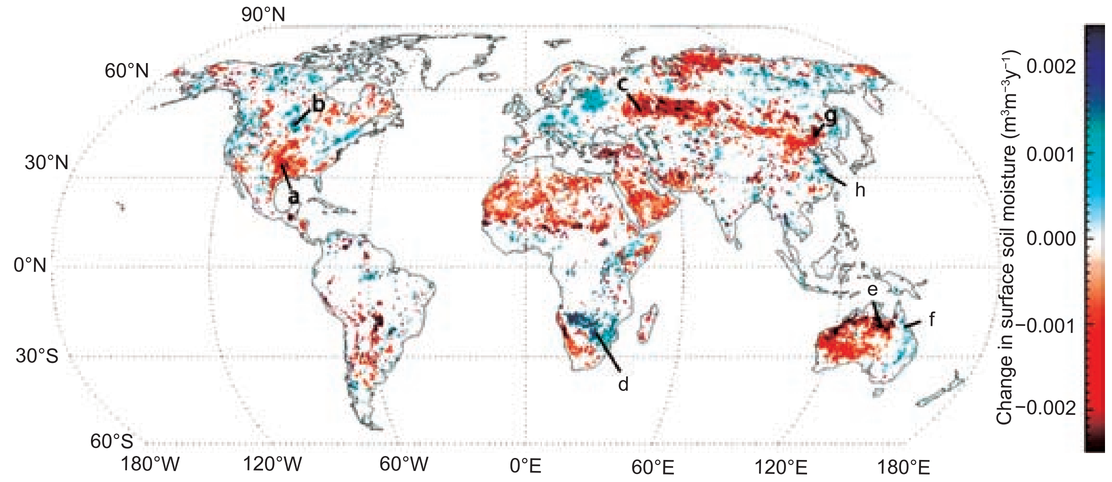

Figure 2: Mann Kendall test results on global reconstructed satellite derived soil moisture estimates. These estimates cover a time period from 1988–2010. Locations a-h indicated on the plot are explored further in the supplementary material included in the paper.[4]

The results in figure 2 are possible only if there has been an overall increase in evaporation for the continent, something that is to be expected with increase in global air temperature. In a recent paper, an assessment of the changes in pan evaporation in the instrumented record, an assessment of whether pan evaporation decreases (associated with the so called "pan evaporation paradox") can be reconciled with the overall increases one would expect in a warming climate, and an assessment of the evaporation that is simulated across a range of General Circulation Model (GCM) simulations representing likely future climates are presented.[5] The paper clearly shows that even if there is a question about pan evaporation decreases in the current climate, caused due to the win-forced (or aerodynamic) component of the evaporation decreasing over certain segments of our instrumented record, the radiation forced component (or the radiative component) of evaporation will overshadow any such decreases through the added energy that will be available in the atmosphere as the full impact of global warming unfolds.

A related question to ponder on is whether one should expect antecedent condition changes to impact extreme flood events or not? While this point was discussed in reference to the flood study mentioned above,[3] it should be pointed out that antecedent conditions will impact floods more in larger catchments than in smaller (possibly urbanised) ones. This is an issue that was investigated in some detail, clearly illustrating the importance of antecedent moisture conditions preceding extreme rainfall events across a range of catchments in Australia, varying in size from 65 to 1600 square km.[6] While urban catchments were not considered in this study, the results do point to possible impacts in small catchments, such as may be present within an urban locale. But if antecedent conditions are of lesser relevance when it comes to design floods in urban catchments, does that imply that urban catchments are safe from future changes to design floods? This is a question we evaluate next.

5 Is Design Rainfall Changing?

Given that antecedent conditions are less likely to impact urban flooding, the next question we need to ask is whether there is likely to be a change in extreme rainfall due to global

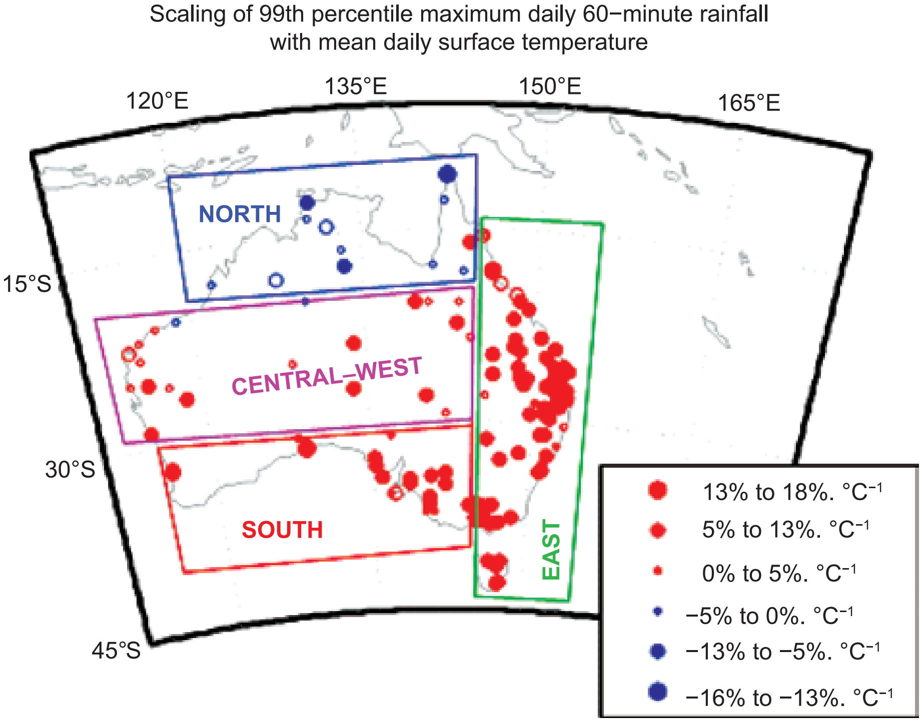

Figure 3: Variations in the 99th percentile 60-minute extreme rainfall across Australia. The red dots represent locations which indicate increases, and the blue dots decreases. The increase in the extreme rainfalls is clear from the above figure, whereas the decreases are most likely a result of additional moisture sources contributing to the extreme rainfall.[8]

warming? General Circulation Model (GCM) simulations of likely future climates, in general, predict that the wetter latitudes will get wetter, and the drier latitudes drier. But there general changes may not have much relevance when the rainfall intensity associated with extreme events is under question.

The key physical change that is likely in a future warmer climate is related to the atmosphere being capable of holding a greater volume of moisture that what is the case now. This extra holding capacity of the atmosphere is explained through the Clausius-Clapeyron law, and has been used to argue that an atmospheric column will have a greater holding capacity of moisture, and consequently, can lead to greater extreme events if the moisture source is constrained to fall within this column.[7] In related work using extensive sub-daily rainfall data across Australia, clear intensification of sub-daily rainfall with increased temperatures was identified, with the increase becoming less significant as the rainfall duration became larger.[8] Selected results from this study are presented in Figure 3.

Given that these increases are more likely to be associated with shorter duration extreme rainfall events, the implications of this result are likely to be felt in the smaller urban catchments most. While the same arguments hold for the larger catchments too, the assumption that the moisture source is constrained to the atmospheric column is more likely to be violated.

6 Is the Rainfall-Runoff Transformation Changing?

The last part of the puzzle lies in pondering on whether a warmer climate may lead to a change in the rainfall-runoff transformation mechanism. The key reason this transformation may change is through the change in transpiration properties associated with the catchment. Transpiration, on its own, should change for two reasons. The first reason is the change in the overall atmospheric temperature, leading to an increased humidity, causing possibly a tendency to reduce the transpiration that would occur. The second reason is more related to the change in vegetative attributes, brought on because of a change in climate (rainfall and evaporation). It is this latter change that may make the biggest impact when it comes to the rainfall-runoff transformation.

Has this change already been noted to be occurring? To the best of knowledge, statistically conclusive evidence to this effect are not clearly available, especially if the region being considered is large and remains beyond the influence of other changes such as anthropogenic impacts. However, this is an area that needs further investigation, along with an assessment how this change could be modelled for warmer, more humid climates.

7 So How Should We Estimate the Design Flood in a Nonstationary Climate?

The above discussion establishes two key points. First, antecedent conditions are changing and will continue to change with time. These will have impacts on the design flood that is estimated. And second, incident extreme rainfall will increase for shorter durations, and change for longer durations possibly dependent on the overall change to rainfall for the region. How these changes could be used to ascertain the design flood is what we discuss now.

Before formulating a new approach for design flood estimation in a nonstationary climate, it is prudent to assess what problems may exist in the procedures that already exist. Most design flood estimation problems are addressed using two approaches—flood frequency analysis, and the design storm approach. Flood frequency analysis, in itself, is not suitable if the flood data is nonstationary. As regards the design storm approach, for it to be used for a warmer climate, new design storms need to be ascertained at the very least. However, given that these new design storms will still assume that pre-storm antecedent conditions are unchanged, their transformation to a corresponding flood may not be appropriate.

In the absence of these traditional alternatives, readers are pointed to the lesser used option of continuous simulation as the basis of design flood estimation. The continuous simulation procedure was recently extended to all ungauged locations in Australia.[9,10] While this procedure assumed the climate was stationary, and hence was not appropriate for application in a warmer setting, a later paper presented a simple framework for extending the continuous simulation for a warmer climate.[11] This new framework assumed that for use in a warmer climate, the user must have access to daily rainfall sequences that could be obtained through the use of suitable downscaling alternatives.[12,13] These daily sequences can then be disaggregated into sub-daily sequences by resampling the sub-daily fragments conditional to suitably selected covariates (such as temperature and humidity). As a result, an assumption is made that the daily to sub-daily rainfall relationship shifts spatially from the target location to another location, the extent of the shift being controlled by the change in the relevant covariate. Simplistically, generating continuous rainfall sequences for a semi-arid location for a future climatic setting, may involve obtaining these sequences from a wetter location (in todays climate) as the covariate simulated by an appropriate GCM for the future, may indicate that humidity is likely to go up.

While this idea is simple, further work is needed to establish its merits and drawbacks more clearly. Specifically, which covariate to choose, whether the aggregate period should be daily or longer, the form of the daily downscaling model, biases in the GCM simulations of covariates, and the form of the rainfall-runoff model to convert the associated sequences to flow, are all legitimate research topics that need to be carefully assessed.

8 Summary

This paper reflected on some of the challenges facing design flood estimation in a warming climate. It recognised that traditionally followed approaches such as flood frequency analysis or the use of a design storm to estimate the flood, become especially flawed when used in a knowingly nonstationary setting. It suggested that any approach that be used, needs to recognise three key changes associated with future extremes—that antecedent rainfall preceding the extreme rainfall event will change, that the design storm itself is going to intensify especially for the shorter design durations, and that catchment response to the rainfall event may be different in the future because of changes in humidity and vegetation.

The paper went on to propose that continuous rainfall simulation for a warming climate may offer a means to address many of the difficulties noted in the traditional alternatives above. Continuous sequences could be formulated based on daily rainfall sequences, with the daily sequences being designed to accommodate the changes altered antecedent conditions might bring. They may then be further disaggregated in a manner that ensured that the extreme subdaily rainfall exhibited greater extremes corresponding to change in the climate, again possible to accommodate as long as the disaggregation model is structured to do so. While this approach will still use an existing rainfall-runoff transformation to generate flows, this issue can be addressed too through carefully designed studies. The framework described, on the whole, will be capable of simulating design floods for future warmer climates, something that is highly needed across the world as we protect our existing and planned infrastructure against the extremes of tomorrow.

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