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Natural Hazards and Earth System Sciences
Discussions

Interactive comment on "Multivariate statistical modelling of the drivers of compound flood events in South Florida" *by* Robert Jane et al.

Robert Jane et al.

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Response to Anonymous Referee 2

he authors apply multivariate statistical analysis approaches to assess the correlation between flood drivers, particularly rainfall, ocean-side water levels, and groundwater levels, in South Florida. They then evaluate existing structural design approaches considering compound rainfall and surge and the effects of sea-level rise. Finally, they apply higher-dimensional copulas to generate estimates of joint probabilities between the three flood drivers. Overall, the paper is well-researched and written and applies a robust statistical analysis approach. It advances past assessments of compound flood drivers and is relevant

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to the scope of NHESS. Prior to acceptance, I recommend further assessing the groundwater contribution to compound events and strengthening the discussion of how the results of this analysis can inform planning/management.

Thank you for the pertinent comments. Please find our responses to each comment below including how we plan (following the NHESS review process) to adjust the manuscript.

Specific comments:

-When groundwater is incorporated, you find that "the annual exceedance event (i.e., trivariate event comprising the rainfall, Os-WL, and groundwater level with univariate return periods of 1 year) possesses return periods of 2000, 227, and 116 years" (L499). While it is important to note the likelihood of co-occurrence of these three exceedance events, co-occurrence of a high groundwater table and heavy rainfall OR extreme OsWL is also a concern for flood management. The results of bivariate analysis of these interactions would provide further insight into the potential mechanisms of flooding in the region.

Agreed, plots of the high groundwater table and heavy rainfall OR extreme OsWL associated with return periods of 10-,20-,50- and 100-years at site S22 obtained using the 10,000-year synthetic event records from the three approaches have been added to the supplementary material (see Figures 1 and 2 in this document, dotted lines represent extrapolation). The following comment has been added to the text to summarize the results:

"Similar patterns emerge when considering the co-occurrence of groundwater level and either rainfall or O-sWL, see Figures SM.32 and SM.33."

-You mention that rainfall cluster maxima "are paired with simultaneous O-sWL values and vice versa" (L185). Did you consider different time lags across the three sites? No time lags were considered at any of the sites in the multivariate

statistical modeling.

Thank you for highlighting that this was not stated as clearly as it should have been in the original manuscript. Please see the following paragraph which has been added to Section 3.1 detailing our justification for why no lag was considered in the statistical modelling.

"To ensure that temporally coherent combinations of the drivers are simulated no lags are considered in either the bivariate or trivariate analysis. For instance, applying a lag to the groundwater level will account for its maximum correlation with O-sWL and rainfall at sites S22 and S28. However, by the time the elevated groundwater level arises the high O-sWL may have dissipated and rainfall potentially ceased, thus it is possible the drivers do not produce any compounding effects."

-It would be helpful to have more information about SFWMD's planning/design approach and how groundwater levels are considered. What types of structures are designed using the full-dependence approach? Does SFWMD have existing thresholds for groundwater levels that are used in the design or operation of their facilities? Are there seasonal differences in how the system is managed given rainfall patterns and the need to limit salt-water intrusion?

Thank you for this thoughtful comment. Please see the following two paragraphs which will be added to the introduction to more thoroughly explain the original design and current work being undertaken by SFWMD to assess the level of service provided by the relevant structures.

"Water control facilities for the Central and South Florida Project (CSFP) authorized by the Flood Control Act of June 30, 1948 (Pub. L. 80-858, 46 Stat. 925) were designed by the USACE in the 1950s and 60s. The project included hydrologic and hydraulic design for canals, many of which terminate in flood/salinity control structures. The control structures are operated by the SFWMD to maintain the water level to prevent saltwater intrusion and release canal water to the sea (typically via tidally modulated channels)

alleviating potential flooding. The design of the canal required pairing a design O-sWL, typically obtained from tide tables, and a design storm under the assumption of full dependence; i.e. bivariate design event associated with a return period is obtained by pairing the O-sWL and peak rainfall with the corresponding univariate return periods. Groundwater level conditions were accounted for through the rainfall input. For instance, in the Greater Miami area, it was assumed that the first four inches of rainfall of the design storm would be used to replenish the groundwater storage.

The SFWMD is beginning to revisit the original designs of coastal water control structures. The SFWMD's Flood Protection Level of Service (FPLOS) project is examining the protection that existing coastal structures provide to urban areas, adopting a more holistic approach as compared to 1950s and 60s designs. FPLOS uses design storms, which are run through hydrologic models with initial conditions given by groundwater stages. For coastal structures, the O-sWL represents an additional downstream boundary condition described by a stage hydrograph. Peak stages in the boundary condition hydrographs are derived using frequency analysis, hence in FPLOS assessments rainfall, O-SWL and groundwater level are assumed fully dependent."

Reference: Flood Control Act of 1948, Pub. L. 80-858, 46 Stat.925, 1948.

Other passages such as: *"structures, operated by SFWMD to maintain the water level to prevent saltwater intrusion and release canal water to the sea (typically via tidally modulated channels) alleviating potential flooding."* (L118-119) are removed to avoid repetition.

With regards to seasonality, the design of stormwater control facilities submitted as part of the Environmental Permitting requirements at the SFWMD are required to consider high seasonal groundwater stages in the hydrologic and hydraulic design. These more typically occur during the wet season period of June through October.

-You state in the abstract that this analysis "leads to recommendations for revised future design frameworks able to capture and represent dependencies be-

tween different flood drivers," but you provide little discussion of how this information could be incorporated into SFWMD's planning or what changes would be appropriate given the study results. How should the design guidelines be modified, if at all, especially considering future sea-level rise?

The authors agree that the phrase used in the abstract is not consistent with the content of the remainder of the manuscript. The work represents the first steps towards the development of a new framework that accounts for the dependencies between flooding drivers as part of assessing the level of service provided by coastal water control structures rather than providing explicit recommendations. To reflect these points the sentence quoted in the comment above has been rephrased as follows:

"The work represents the first steps towards the development of a new framework capable of capturing dependencies between different flood drivers that could potentially be incorporated into future FPLOS assessments for coastal water control structures."

The authors are happy to report a second phase of this project has recently been funded by SFWMD. The second phase will see District staff given tutorials to further their understanding of the statistical techniques used in the new framework and additional training on how to use the R package, thus representing the next step in potentially modifying design/risk analysis guidelines.

Technical corrections:

-The abstract should include more information about the results obtained.
The abstract has been amended to provide more details on the results obtained. For instance, the sentence starting on L16 now reads:
"A two-dimensional analysis of rainfall and O-sWL showed that the magnitude of the conservative assumption in the existing structural design assessment is highly sensitive to the regional sea-level rise projection considered."

-L26: No need to capitalize "state".

Thank you for the comment. The grammar been corrected.

-L35: Miami is spelled incorrectly.
Thank you. The spelling has been corrected.

-L411: Rephrase "probability density is located along other parts of the line". For example, you could say "probability density is non-zero [or above a certain threshold] along other parts of the line."
Agreed, the text has been changed in line with the recommendation.

-L421: This sentence is a bit confusing.
The sentence has been amended and now reads as follows: *"The conservative nature of the current design approach is further explored by assessing how long it will take under a given SLR for the 100-year design events selected with the two different methods (i.e. full dependence assumption vs bivariate dependence modelling) to intersect."*

-L441: Looks closer to 30 years for the 100-year return period.
Correct, the text has therefore been amended to reflect this. Thank you for pointing this out.

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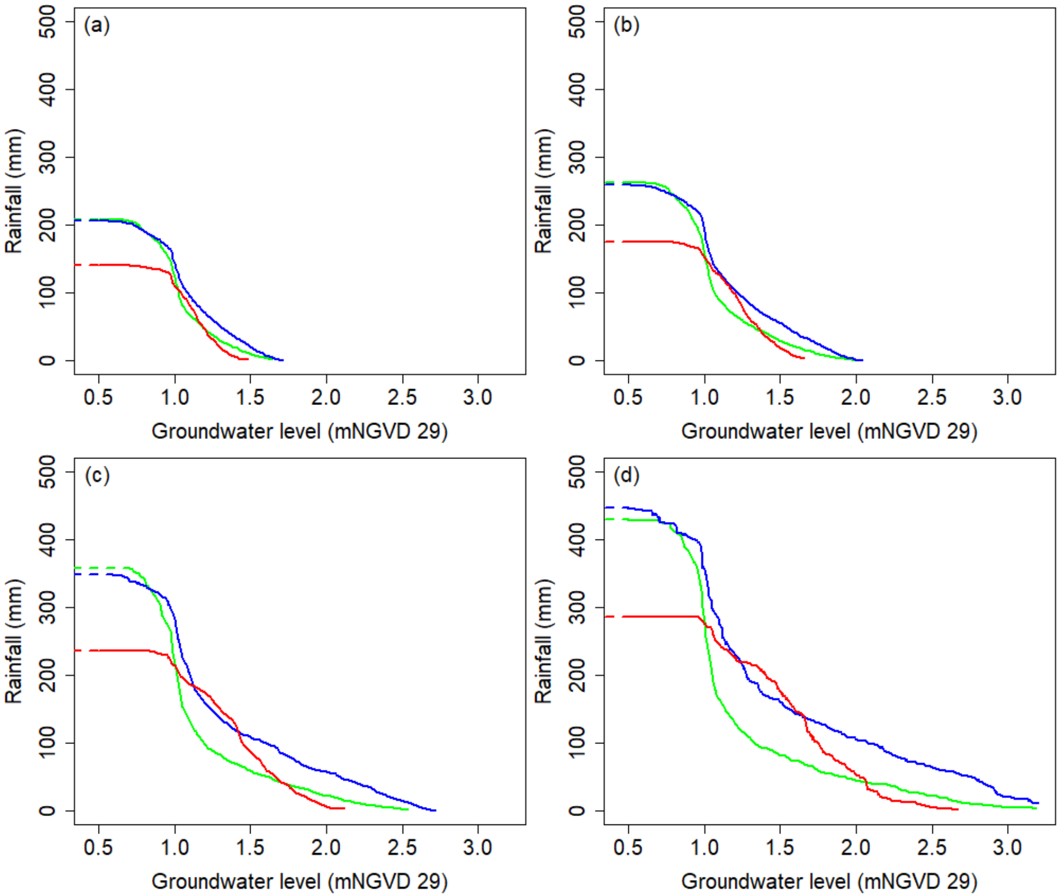

Fig. 1. Isolines of rainfall and groundwater level from the Gaussian copula (blue), Vine copula (green) and HT04 model (red) for return periods (a) 10- (b) 20- (c) 50- and (d) 100- years.

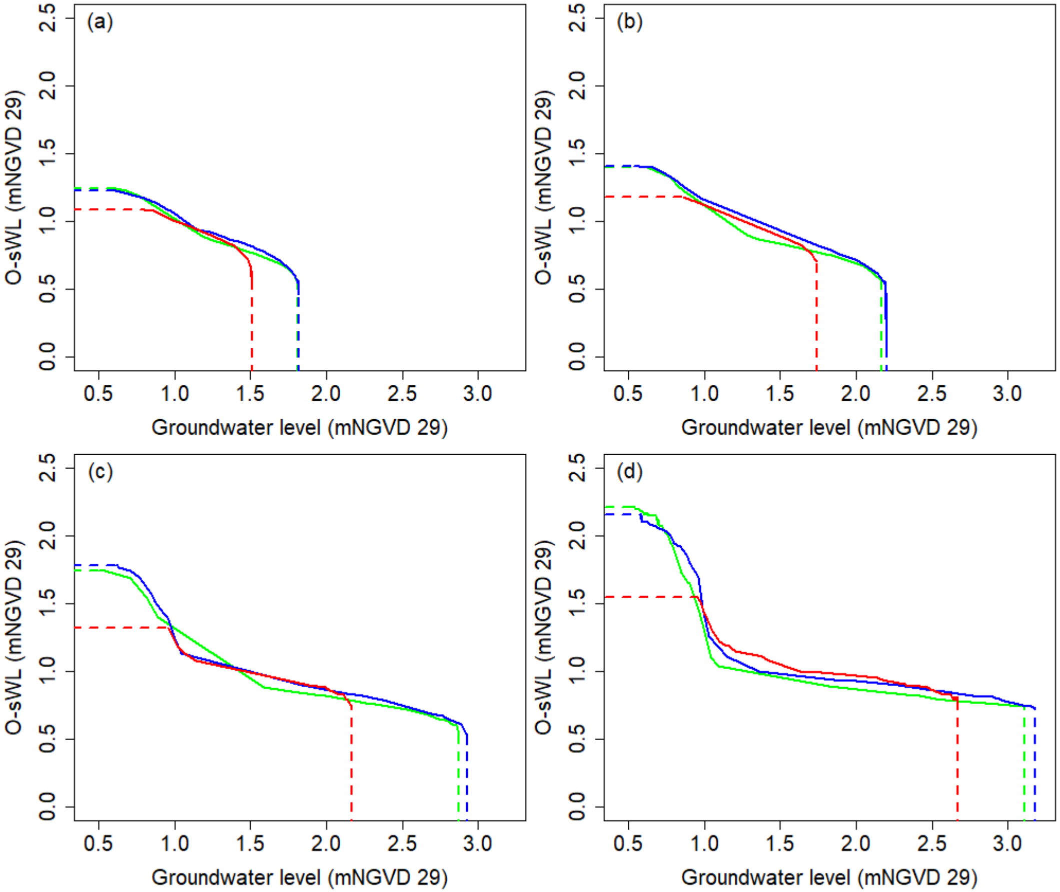

Fig. 2. Isolines of O-sWL and groundwater level from the Gaussian copula (blue), Vine copula (green) and HT04 model (red) for return periods of (a) 10- (b) 20- (c) 50- and (d) 100- years.

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