Responses to Referees comments on Manuscript nhess-2020-242

An efficient modelling approach for probabilistic assessments of present-day and future fluvial flooding

We appreciate and thank both Referees for their dedicated review and constructive comments on the manuscript (MS). We have addressed all comments and revised the MS accordingly. For each comment and/or suggestion, we have provided the corresponding response below. Both our responses and the newly added text in the manuscript are shown in blue.

Thank you very much once again.

On behalf of the authors,

Hieu Ngo

Summary of responses

The two Reviewers of this manuscript have raised several key issues that we have responded to following each of those referee comments. However, we think it is important to clarify some of the main issues that were raised by the reviewers in summary form:

Comparison with previous studies - Apel et al. (2016):

The reviewers point out that the study of flood hazard/risk in Can Tho city has been done before. They recommended we compare the results with those studies. We have done this in the current version of the manuscript. Of particular interest to this is the publication by Apel et al. (2016). A key difference between that and the current study is that the former did not consider the drainage network of the city. In the case of Can Tho city, the drainage network is connected to the river via many outlets through the river reaches and the major canals. These work as an effective hydraulic connection between the river level and the water in the city, causing, for example, back flow during the high river levels. Therefore, flooding in the city happens long before the water level in the river reaches the bank height. Further, it is very likely that modelling floods without considering the drainage connections can (significantly) underestimate the flood levels (and the extent).

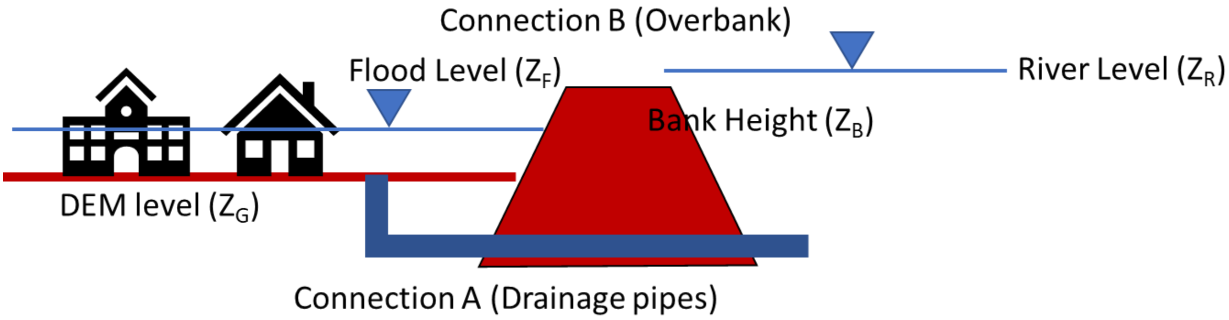


Figure 1: Urban flood water in Can Tho can be hydraulically connected to the river by two means: (A) Numerous drainage pipe outlets, (B) Surface (overbank).

Apel et al. (2016) were unable to consider this as they have not modelled the drainage network. We believe this was the reason why the flooding results were underestimated in their initial results. To address this, they artificially lowered the DEM level (ZG), until a satisfactory agreement between the observed flood level (extent) and the modelled. However, this did not address the underlying reason for the underestimation of flooding, which is the hydraulic connections created by the drainage network (A) in addition to surface hydraulic connections (B).

Therefore we do not expect the current results to match those published by Apel et al. (2016). To the best of our knowledge, there are no previous flood hazard/risk studies on Can Tho, considering drainage connections with a 1D/2D coupled model.

Period of observational data used:

Another important point raised is the fact that a short period of time was considered in generating upstream boundary conditions. We are aware that the Mekong river flow data is available for a much longer period (starting from 1924). However, statistical analysis of these data (annual maxima, extreme values) shows that these data shows a strong non-stationarity.

The climate scenario impact modelling approach we used in this study was to model the impact under the ‘present’ and ‘future’ forcings and compare the results (As opposed to a continuous simulation from ‘present’ to the future point in time). In our approach, it is important that the baseline (‘present’) indeed represent the conditions of the present state. Using data over a long period of time does not result in an accurate representation of the present state as the signals show a strong trend (non-stationarity). This was the main reason to use a short period of time with statistical generation of synthetic flow data (Fig. 20 in the MS).

Referee #1

General comments

Comment R1_1:

The proposed method is neither new nor innovative. The combination of 1D for large scale flow dynamics with 2D detailed inundation dynamics has been used in many other studies worldwide, e.g. Falter et al. (2016); Metin et al. (2018); Vorogushyn et al. (2010), the cited Davidsen et al. (2017) and many more, but also in the MKD: Apel et al. (2016).

The simplification of the 1D model to gain faster simulation times is not sufficient to claim a new modelling concept as the title suggests. This simplification has also some drawbacks like the very likely insufficient performance for the many smaller channels and the floodplains in the MKD. This has not been shown here, but the neglect of these features in the simplified model will inevitably cause this. The simplified model is thus a model that is tailored for this particularly purpose only, i.e. the simulation of water levels along the main channels of the MKD. This has not been mentioned in the MS, but should be.

Response R1_1:

We agree that the combination of the 1D model for large-scale flow dynamics with a 2D detailed inundation model has been used in many other studies. The flood hazard assessments in the previous studies are limited to either analysing dependence among multiple drivers (e.g. riverflow, sea level, storm surge), or determining bivariate joint probability and/or joint return periods, and did not provide information about the likelihood and intensity of floods that take into account the combination of multiple drivers (Ganguli and Merz, 2019), which may stem from the large computational cost.

This study presents a modelling approach to develop probabilistic fluvial flood hazard maps for the urban centre of Can Tho city (Ninh Kieu district) for present-day and future under different scenarios, taking into account the impact of climate change (future river flow, sea-level rise, storm surge). The use of the simplified 1D model for the entire Mekong Delta here provides rapid and accurate estimates of water level at Can Tho. With the assumption that the flood inundation in Can Tho city is significantly affected only by the water level in the river, we propose an approach that substantially cuts down the computational effort to develop probabilistic flood maps for the study area.

Due to its speed, our modelling approach is ideal for obtaining probabilistic fluvial flood hazard and risk maps for a location of interest, taking into account climate change driven variations in upstream river flows and downstream sea levels.

The development of the 1D simplified model for the entire Mekong Delta used here was presented in detail in Ngo et al. (2018) and is also summarized in this manuscript. The limitations of the 1D simplified model have also been mentioned clearly in Ngo et al. (2018). Following the suggestion of the reviewer, these limitations are now briefly reiterated in the current MS for completeness (Lines 185-191), as follows:

"The simplification of the model for the entire Mekong Delta leads to a degradation of the precision and accuracy of its results, but far away from Can Tho specifically at Chau Doc and Tan Chau (Ngo et al., 2018). Moreover, the simplified model is a 1D model, which cannot accurately simulate flood propagation, especially on the floodplains, even though the floodplains have been included in cross-sections and assigned appropriate roughness coefficients. Therefore, the simplified 1D model is used here as a surrogate model for simulating water levels along the main rivers, bearing in mind that it may not provid reliable information on water levels and inundation dynamics in areas that are far away from Can Tho and are located a distance to the main rivers on the floodplains."

Comment R1_2:

The authors fall short in properly citing and discussing the available literature. Apel et al. (2016) performed an almost identical study in the MKD, for the same city, even the very same district of the city, with a similar model setup (combination of a 1D model for the whole delta and a 2D model for the city), and using in parts even the same data (DEM). The study was even published in the same journal as this discussion paper.

Under this circumstances neglecting this study is a serious breach of proper scientific conduct and cannot be accepted. The authors need to address the previous study and highlight the scientific advances made by their study, or provide a comparison of the results, or address any weaknesses in the previous study, if they see any. Comparing both studies and considering comment 1, I suggest that the authors focus on the estimation of the changes in flood hazard by climate change, sea level rise and land subsidence, which is not performed in Apel et al. (2016).

Response R1_2:

In the revised MS, we have split the current "Results and Discussion" section into two separate sections including Results and Discussion. In the Discussion section, we have included a discussion related to Apel et al.´s study and some other issues (Lines 346-459). We have also now highlighted that the focus of our study is on assessing future flood hazards and damage due to climate change (Lines 355- 356 and Lines 368-370). Please see also Response R1_3 and Response 22 below for more details.

Comment R1_3:

I have serious concerns about the statistics used in the study. Firstly, the authors use an input (Kratie) discharge time series of 7 year only. This is clearly not sufficient for a statistical evaluation of return periods.

In this context it has to be noted that for Kratie almost 100 years of daily discharge values (since 1924) are publicly available through the Mekong River Commission. Why did the authors not use this valuable data source? This is not comprehensible. The authors claim that the insufficient time series for extreme value statistics is compensated by the (stochastic?) synthetic streamflow generator. I have serious doubts that this is the case.

Any streamflow generator has to make some assumptions on the discharge statistics in order to provide information about extreme events not contained in the time series used. But these statistics will be highly uncertain due to the shortness of the time series length. And if the streamflow generator if based on resampling of 7 years of data only, the extreme events will surely be highly underestimated. In any case the authors have to provide more details about the streamflow generator and the applied methods and assumptions, and provide prove or convincing arguments that the generated synthetic time series are statistically representative for the “real” time series and discharge variability at Kratie. This is crucial for the validity of the results.

Moreover, I urge the authors to use the full length of time series of Kratie. Using this will enhance the statistical soundness of the analysis, and enables an estimation of the representativeness of the generated 1000-year time series based on shorter time series, and if this approach would be comparable or even superior to the bivariate extreme value statistics by (Dung et al., 2015) used in Apel et al. (2016).

Another aspect concerning statistics is the poor fit of the Gumbel function to the synthetic water level time series at Can Tho shown in Figure 6. There is a large mismatch between the empirical quantiles and the distribution quantiles. If such a long synthetic time series is used, the distribution function should model the time series almost perfectly. Otherwise the empirical quantiles should be used. The use of the Gumbel distribution function for estimating quantiles is in this case a loss of information. See also my comment in the annotated manuscript. To sum all these comments up, I have serious doubts that the probabilities associated to the discharges (Kratie) and water levels Can Tho) are robust.

Response R1_3:

We thank the reviewer for this thoughtful response.

The rationale for not using long discharge data series in this study has now been described in the revised MS (Lines 348-373), as follows:

"First, it (i.e. the synthetic hydrology) is derived from the length of discharge data (2000-2006) that was freely available to the authors at the start of this study. Only recently, the longer discharge data become available at the Mekong River Commission website with 66 years of data (1924 to 1970 and 2000 to 2018).

Secondly, the purpose of this study which is to quantify climate change driven variations in the flood hazard between the present period and future time periods. Therefore, it is important to ensure that the selected baseline period (and baseline simulations), are in fact representative of the present-day period. This is important because, not only has the climate change signal emerged in several climate variables over the last 50 years or so (i.e. signal is clearly discernible from the inter-annual variability) (King et al., 2015), but also human activities (e.g. reservoirs) have led to noticeable changes in the natural regimes that may have existed earlier in the 20th century (see Ranasinghe et al., 2019 for examples in China). Both of these phenomena may change the probability distribution of climate variables over time (Chadwick et al., 2019).

To investigate the stationarity of the upstream river discharge in the Mekong River, the discharge time series at Kratie was analysed, based on the 66 years of data (1924 to 1970 and 2000 to 2018). The analysis showed that the peak discharge at Kratie has indeed noticeably decreased over time, and particularly after 2000 (Figs. 18, 19), likely due to irrigation expansion and upstream dam construction in recent years (MRC, 2010; Piman et al., 2013).

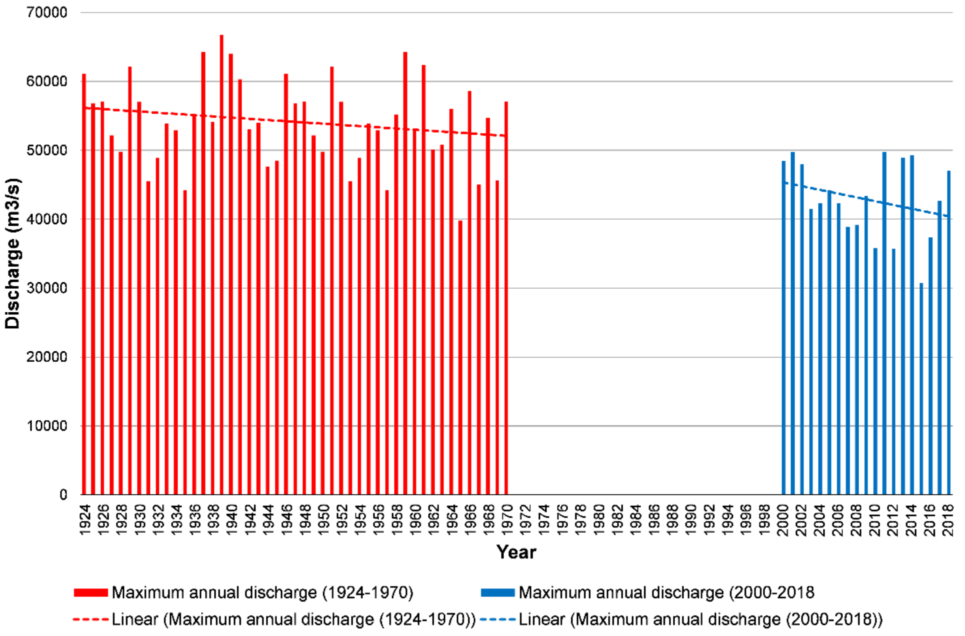


Figure 18: Maximum annual discharge at Kratie from 1924 to 1970 and 2000 to 2018

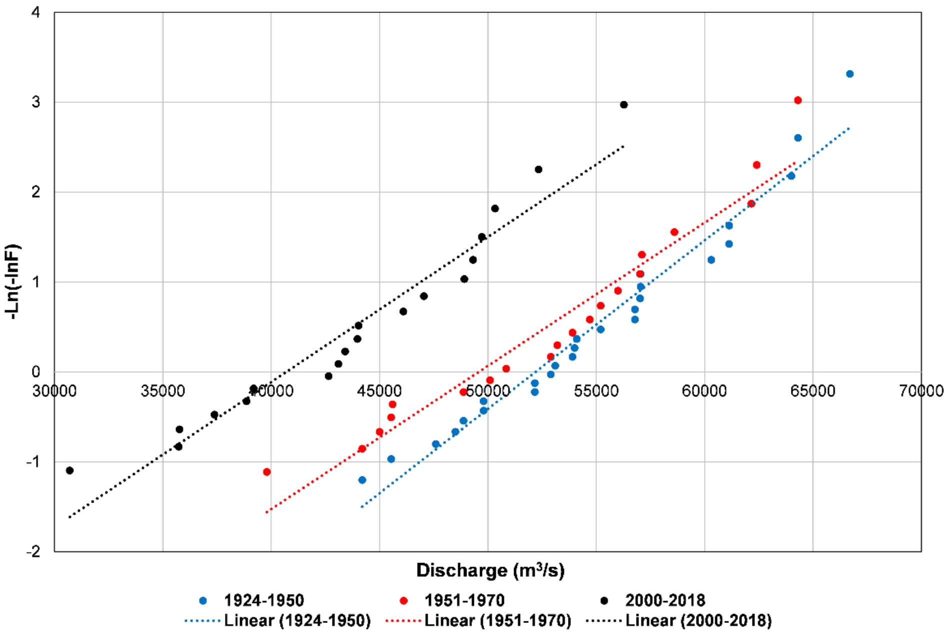


Figure 19: Gumbel distribution of discharge peaks at Kratie corresponding to three periods (1924-1950), (1951-1970) and (2000-2018)

The use of the full discharge time series at Kratie to develop flood frequency curves is therefore inappropriate in the present study which aims to quantify climate change driven variations in the flood hazard, and further, risk, relative to present-day conditions, in order to inform the development of climate resilient flood risk reduction measures for the urban centre of Can Tho city. The use of the full observed discharge data at Kratie, including pre-2000 flow with large flood peaks, can lead to an overestimation of flood hazard and risk. Therefore, for the purposes of this study, only the post - 2000 discharge data were used to represent baseline conditions."

Regarding the information on the synthetic streamflow generator, this has has been added in the revised MS (Lines 131-139), as follows:

"This synthetic streamflow generator uses the non-parametric method to re-sample flows from the recorded data, which combines the methods of Kirsch et al. (2013) and Nowak et al. (2010), wherein Kirsch's method is used to generate flows on a monthly time step, and Nowak's method is used to disaggregate these monthly flows to to daily flows by proportionally scaling daily flows from a randomly selected historical month +/- 7 days (Quinn et al., 2017)."

Additionally, in the revised MS, we have added the results of using synthetic streamflow generator to generate the 1000 synthetic river flow based on the seven years of discharge data at Kratie to assess the validity of the method (Lines 382-391), as follows:

"Figure 20 shows several representations of synthetic flow time series that are generated based on the seven years of observed discharge data used here, and their corresponding statistics and extreme values.

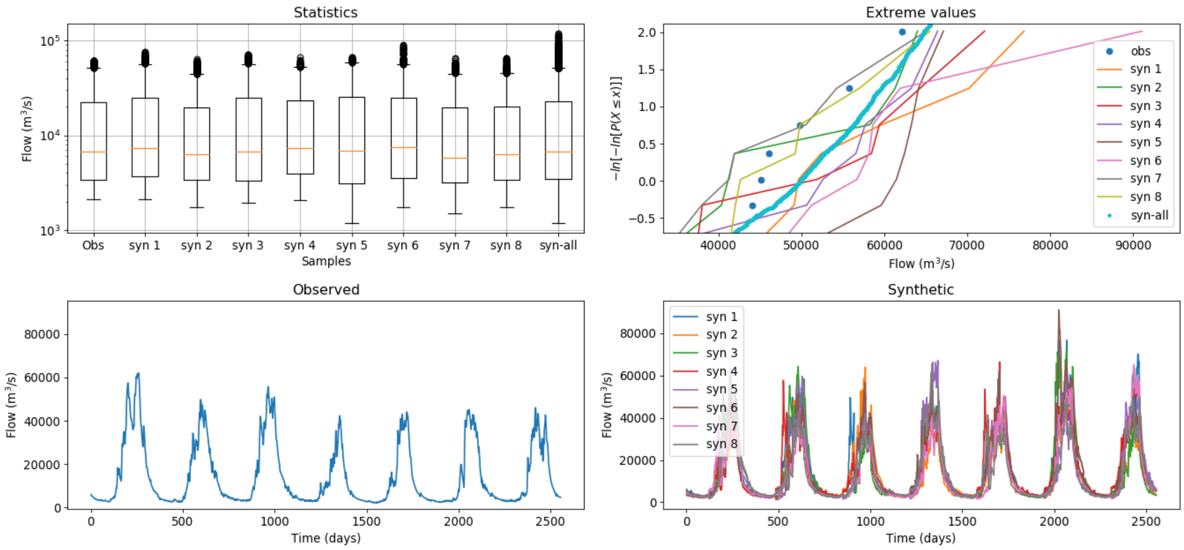


Figure 20: Representations of synthetic flow time series that are generated based on the seven years of observed discharge data, and corresponding statistics and extreme values.

In all, 1000 synthetic flow time series were created, which were then combined with 36 sea level time series to have 36000 different water level time series at Can Tho. This helps to capture the statistical variation of water level at Can Tho better, which is important in flood hazard modelling. Using these 36000 water level time series series does not add any information that was originally not present in the observed data. However, as the sea-level and river flow time series are independent of each other, these combinations of statistical realizations of streamflow with observed sea-level improve the joint-probability manifestation in the resulting longer time series. It should be noted that the synthetic generator is not the only approach to achieve this. For example, a similar statistical robustness might be achieved by time-shifting one set of series against the other."

Concerning using Gumbel distribution in this study, while it is true that the empirical distribution might have resulted in less information loss, it will also include all the random artifacts in the observed (and generated) data. Therefore we prefer to have a probability distribution fitted to the trend rather than using the empirical distribution. However, we do admit that the log-log-linearity of the Gumbel distribution might introduce a bias to the very extreme values (e.g. the real data may, for example, have a flatter tail than that is fitted by Gumbel distribution.). However, such an analysis needs a long series of data that are largely devoid of non-stationarities (or them beingcarefully removed). The flow database used here, which was limited in length due to the climate change impact focus of the study (see Response R1_3 above) does not provide the necessary data quality or quantity to do such an analysis. Therefore, using the Gumbel distribution here is more reasonable in our view.

Additionally, the difference in water levels corresponding to large return periods between the empirical and distribution quantiles is small. Furthermore, Gumbel distribution was well-fitted in scenario RCP 8.5 with higher water levels.

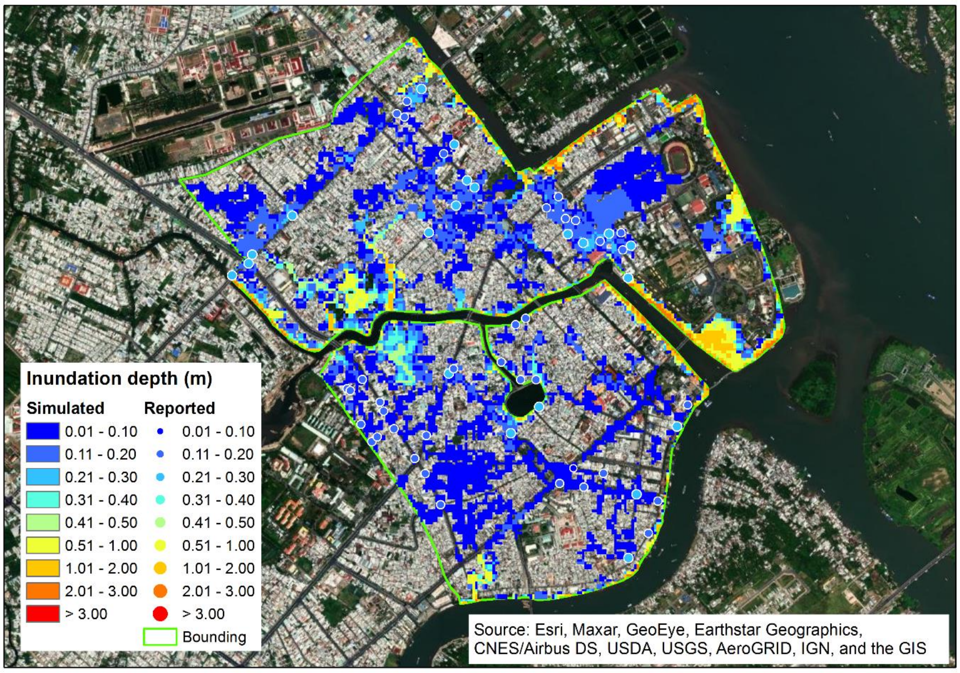
Comment R1_4

The authors try to validate of by two water depths in manholes only. I am missing a validation or at least a plausibility check of the spatial inundation simulation. The performance of the spatial inundation simulation is crucial for the hazard analysis, thus some analysis or at least arguments should be provided. As mentioned above, there are more (and mostly more specific) comments are provided in the annotated manuscript.

Response 4

Thank you for the comment. In the revised MS, we have added information on the 1D/2D coupled model validation (Lines 283-287), as follows:

"The validation results for the 1D/2D coupled model for the flood event of Oct 2016 are shown in Fig. 8. Simulated flood extent and inundation depths at many different streets in Ninh Kieu district are presented in the description of the flooding situation and observed inundation depths at the same places in the report of Can Tho Water Supply and Drainage Construction Company regarding this event. The comparison shows a good agreement between the simulated flood extent and inundation depths and observations.



Source: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS

Figure 8: Flood inundation map (flood extent and the maximum simulated inundation depth) and the measured inundation depth (filled circles) at streets in Ninh Kieu district during the Oct 2016 flood event."

Specific comment in the MS

Comment 1 in the MS – page 2

Non-stationary flood risk assessment (FRA) is still quite a challenge. But even for a proper stationary FRA, more than just two hazard maps with defined probabilities are required. Even for this a less time consuming hydraulic approach would be very beneficial.

Response 1

No action needed

Comment 2 in the MS – page 3

But also frequency, because inundation is likely to occur more often even without any change in water levels due to lower river banks.

Response 2

Thank you for the comment. We have revised the MS according to this comment as follow (Lines 66-69):

"Increases in population inevitably increases water demand, which is often satisfied by excessive groundwater extraction, which, more often than not, leads to land subsidence, further exacerbating the flood hazard due to increased inundation levels and frequency. Lowering of the inundated areas as well as the river banks due to land-subsidence can contribute to this increase."

Comment 3 in the MS – page 3

True

Response 3

No response required

Comment 4 in the MS – page 4

In the Mekong Delta these are rather distributaries

Response 4

Thank you for the correction. We have updated this in the revised MS.

Comment 5 in the MS – page 4

More detailed information about the streamflow generator are required in order to assess the validity of the method. See also the general comment Nr. 3.

Response 5

Thank you for the suggestion. In the revised MS, we have added more information about the synthetic streamflow generator (Lines 131-139 and Lines 376-383), please see in Response R1_3 above.

Comment 6 in the MS – page 5

This link does not work

Response 6

Currently, this link still works. However, when clicking the link directly in the MS, it is somehow combined with row number 135 (row contains the link in the MS) and parentheses, which results in not being able to access the link. Please use the same link here (https://github.com/julianneq/Kirsch-Nowak_Streamflow_Generator) to download the Streamflow Generator.

Comment 7 in the MS – page 6

Which is already a simplified model. For any hydraulic model of the MKD the floodplain inundation is important for the overall flood propagation and water levels. How is this considered in the ISIS and then the SWMM model?

Or to put this comment in a different frame: it needs to be mentioned that the SWMM is a surrogate model for water levels along the main rivers and is not fit for providing reliable information about water levels and inundation dynamics in the areas at some distance to the main river channels and on the floodplains.

Response 7

Thank you for the comment and suggestion. Both the ISIS model and the SWMM model (detailed SWMM model) for the entire Mekong Delta as the Referee mentioned in the MS are not simplified models yet. The simplified SWMM model used here is a model obtained after systematically reducing nodes and links in the detailed SWMM model.

The ISIS model for the entire Mekong Delta is a 1D hydrodynamic model, which was developed by HRWallingford and Halcrow (UK). In this model, floodplains were modelled by extending the cross-section to both sides of the mainstream. Like the ISIS model for the entire Mekong Delta, floodplains in the 1D simplified SWMM model are also considered as part of the cross-section, and they are assigned appropriate roughness coefficients. Although the 1D model cannot accurately simulate flood propagation, especially in floodplains, the simulated flood propagation time from Kratie to Can Tho of the 1D simplified model is realistic at around 14 days, which is consistent observed time difference in peak floods at Kratie and Can Tho.

Regarding the limitations of the simplified model, these are mentioned in detail in Ngo et al., (2018). However, following the suggestion of the reviewer, these limitations are briefly reiterated in the current MS for completeness (Lines 185-191). Also, please see in Response R1_1 above.

Comment 8 in the MS – page 6

Daily discharge data at Kratie are available since 1924!! Why don't you use the full data set? This would provide a much robust estimation of extreme events and probabilities than just using 7 years of discharge, even if errors in the measurements are considered.

The streamflow generator surely makes some assumptions/estimations of the (extreme value) the statistics and distribution of discharges. If this is based on 7 years only, the generated time series is associated with high uncertainty. This aspect is crucial for the whole work and needs more attention/discussion.

Response 8

Thank you for the comment and suggestion. We agree that using the long discharge data would provide a robust estimation of extreme events and probabilities in studies focusing on developing flood hazard maps for the present-day without considering climate change driven variations in the flood hazard. However, the main focus of this study is in fact climate change driven variations in flooding. Please see Response R1_3 above for our justification for not using the full discharge time series data in this study, and also for our detailed response regarding the use of the the synthetic streamflow generator.

Comment 9 in the MS – page 7

To get this right: only the synthetic event where the historically highest water level is exceeded was used for determining the flood hydrographs? Why this high threshold? Even below this threshold floods do occur in Can Tho. The river bank elevation seems a much better threshold for in my opinion. You need to justify your selection.

Response 9

Thank you for the comment. We agree that flooding can occur in Can Tho when the water level is below this threshold of 2.15m and even when the water level is lower than the riverbank elevation, as explained in our response to specific comment 22 below. While preparing the manuscript, we also compared the water levels of 36,000 water level time series corresponding to each scenario with 3 flood water level alarms in Can Tho (1.7 m, 1.8 m and 1.9m). The results are shown in Table 1.

Table 1: Water level alarms in Can Tho and number of time series that have at least one peak of water level higher than flood water level alarms and water level value of 2.15m corresponding to each scenario RCP 4.5 and RCP 8.5.

Alarm level	**Water level in Can Tho (m)**	**Number of time series that have at least one peak value of water level higher than compared water levels**	
		RCP4.5	***RCP8.5***
1	1.70	36000	36000
2	1.80	36000	36000
3	1.90	17859	21844
4	2.15	41	162

As here we focus on extreme floods, rather than nuisance or moderate floods, we selected a water level threshold of 2.15 m, one of the highest historical flood water levels (occurred in Can Tho in 2011). This helps to select water level time series with a water level peak value higher than a historical extreme water level that is entirely possible in the future due to the effects of climate change, which is the focus of this study.

Comment 10 in the MS – page 8

This is too short. High water levels that cause inundation in Can Tho are usually caused by the interplay of high river water levels and high tidal level. The high tidal levels, which are particularly pronounced during spring tides, typically last for a couple of days. See e.g.

Apel, H., Martínez Trepat, O., Hung, N. N., Chinh, D. T., Merz, B., and Dung, N. V.: Combined fluvial and pluvial urban flood hazard analysis: concept development and application to Can Tho city, Mekong Delta, Vietnam, Nat. Hazards Earth Syst. Sci., 16, 941-961, 10.5194/nhess-16-941-2016, 2016.

or

Triet, N. V. K., Dung, N. V., Fujii, H., Kummu, M., Merz, B., and Apel, H.: Has dyke development in the Vietnamese Mekong Delta shifted flood hazard downstream?, Hydrol. Earth Syst. Sci., 21, 3991-4010, 10.5194/hess-21-3991-2017, 2017.

During this period the city is typically repeatedly inundated periodically during high tides (or completely if the river water level is constantly above bank level). This has an impact on the damage caused by the inundation (higher water levels, larger area flooded and longer duration of ponding water). You need to justify this short simulation time.

Comment 11 in the MS – page 8

In this lowland low relief environment the duration of inundation might, or very likely also plays an important role for flood damage. This should be mentioned/discussed. See e.g.

Dung, N. V., Merz, B., Bárdossy, A., and Apel, H.: Handling uncertainty in bivariate quantile estimation – An application to flood hazard analysis in the Mekong Delta, Journal of Hydrology, 527, 704-717, http://dx.doi.org/10.1016/j.jhydrol.2015.05.033, 2015.

Response 10 and 11

Thank you for the comment and suggestion. We agree that flood duration is also an important factor affecting flood hazard and damage. This is also mentioned in the current MS, which has been updated in the revised MS (Lines 235-243), as follows:

"*Several different flood parameters can be used to quantify the flood hazard, including inundation level, flow velocity, frequency of flooding, and flood duration, etc. (Ramsbottom et al., 2006; Ward et al., 2011; Moel et al., 2015). Of these, inundation level (water depth) and flow velocity are considered the most important parameters (Penning-Rowsell et al., 1994; Wind et al., 1999; Merz et al., 2007; Kreibich et al., 2009). However, due to the relatively flat terrain combined with small inundation depths in Can Tho, the effect of the flow velocity is expected to be small compared to that of the flood inundation depth (Dinh et al., 2012). While in agricultural contexts as well as indirect damages (e.g. loss of livelihoods, nuisance), the flood duration may play an important role in the context of urban property damage (e.g. buildings, furniture, road), inundation depth is much more important than the duration. Hence, this study considers inundation levels as the main indicator of the flood hazard in the study area*."

Additionally, in agricultural contexts as well as indirect damages (e.g. loss of livelihoods, nuisance), the flood duration may play an important role in the context of urban property damage (e.g. buildings, furniture, road), inundation depth is much more important than the duration.

The water level in Can Tho varies following the downstream tidal fluctuation (semi-diurnal tide), because the urban centre of Can Tho (Ninh Kieu district) is connected with the Hau River and Can Tho River via the open sewer channel and urban drainage system. Therefore, for e.g., if during the flood phase of tide, the river water level rises above the lowest elevation of the top of the manholes in the city, although without necessarily being higher than the crest elevation of the river embankment, this will lead to flooding in the city centre due to backwater flow through the urban drainage/sewer systems. This is consistent with the flood situation in Can Tho, which was described in Nguyen (2016) (http://www.cantholib.org.vn:84/Ebook.aspx?p=27B9F975353796A6E64627B93B65654746C6B65637B91B857557). When the river water level drops during the ebbing phase of the tide, the inundation level is also reduced mostly as flood water is drained through the urban drainage/sewer systems. Representing these processes correctly is very important for flood modelling in Ninh Kieu district, and our modelling approach does capture this. The spring-neap cycle will have only secondary effect at the microtidal Can Tho region (Takagi et al., 2014), and therefore reasonable approximation of the flood hazard in the Ninh Kieu district can be obtained with a short simulation time of 24h.

Comment 12 in the MS – page 8

What about the calibration or performance of the 2D inundation model? You don't make any statement about the procedure, data, or performance measures or at least a plausibility check of this model part. This needs to be addressed.

Response 12

Please see Response R1_4 above.

Comment 13 in the MS – page 9

Figures 6 and 7 could be merged to a single figure with 4 panels.

Response 13

Thank you for the suggestion. In the revised MS, we have merged them into one figure.

Comment 14 in the MS – page 9

What about the inefficiency and malfuntioning of the sewer system, as highlighted by Huong and Pathirana (2013). Is this considered in the model (explicitly, implicitly and not at all?). Or did the situation change since then?

Response 14

Thank you for the comment. We agree that the inefficiency and malfunctioning of the sewer system is a main contributor to flooding in Can Tho. Since the current approach explicitly models the sewer system, it indeed considers this issue in the modelling system. Possible malfunctionings of the system was apparent during the model calibration and validation (for example in some locations pipes had to be artificially narrowed to reflect the observed water levels – providing strong indications of system malfunctioning like blockages.

The consideration of the drainage system in the coupled 1D/2D model for Ninh Kieu district demonstrated that in the centre of Can Tho, there are still inundated areas even when the water level in the river is lower than the crest level of the protective embankment.

Comment 15 in the MS – page 9

This figure is not required at this position. The maps are repeated in later figures. I suggest to delete this figure and insert a figure showing the differences in maximum inundation depths at present to future inundation depths at a later point in the MS.

Response 15

Thank you for the suggestion. However, the intention of Fig. 10 is to compare the flood extent and inundation depth corresponding to two flood hydrograph patterns (Pattern 1 and 2) leading to the choice of Pattern 1, which has a greater effect on the flood extent and inundation depth than Pattern 2. In addition, none of the others flood hazard maps included in the paper correspond to water level hydrograph Pattern 2 to support this decision. Therefore, we believe that Fig. 10 is needed.

Comments 16, 17 in the MS – page 11

Minderhoud et al. 2017 or 2020 are even better and more recent references for this.

Minderhoud, P. S. J., Erkens, G., Pham, V. H., Bui, V. T., Erban, L., Kooi, H., and Stouthamer, E.: Impacts of 25 years of groundwater extraction on subsidence in the Mekong delta, Vietnam, Environmental Research Letters, 12, 064006, 2017.

Minderhoud, P. S. J., Middelkoop, H., Erkens, G., and Stouthamer, E.: Groundwater extraction may drown mega-delta: projections of extraction-induced subsidence and elevation of the Mekong delta for the 21st century, Environmental Research Communications, 2, 011005, 10.1088/2515-7620/ab5e21, 2020.

Comment 17 in the MS – page 16

Use the appropriate ISI journal references of this work, i.e.

Minderhoud, P. S. J., Erkens, G., Pham, V. H., Bui, V. T., Erban, L., Kooi, H., and Stouthamer, E.: Impacts of 25 years of groundwater extraction on subsidence in the Mekong delta, Vietnam, Environmental Research Letters, 12, 064006, 2017.

and/or

Minderhoud, P. S. J., Middelkoop, H., Erkens, G., and Stouthamer, E.: Groundwater extraction may drown mega-delta: projections of extraction-induced subsidence and elevation of the Mekong delta for the 21st century, Environmental Research Communications, 2, 011005, 10.1088/2515-7620/ab5e21, 2020.

Responses 16 and 17.

Thanks for your suggestion. Up to now, there is no study on the land subsidence specifically at the Can Tho city; therefore, in this study, we used an average land subsidence rate of 1.6

cm yr^{-1} for the entire Mekong Delta (Erban et al., 2014; Minderhoud et al., 2015) in scenarios considering the effect of land subsidence on the flood hazard at Ninh Kieu district. In recent studies by Minderhoud et al, the average subsidence rate in the Mekong Delta was estimated to be 1.1 cm yr^{-1} (Minderhoud et al., 2017) and 1.31 cm yr^{-1} corresponding to the B2 scenario (no-mitigation with a steady annual increase of 4% of the 2018 volume) (Minderhoud et al., 2020). However, according to the authors, this subsidence rate is likely to increase in the future due to increased groundwater demand. Thus, we would like to keep using a subsidence rate of 1.6 cm yr^{-1} in considering the effect of land subsidence on the flood hazard in the future. We have now added these references mentioned by the Reviewer in the manuscript.

Comment 18 in the MS – page 25

The Gumbel function is inadequate for the data. For such a large data set (36000 entries!) you should strive for a better fitting distribution. Although the deviation in terms of water level are small, there is big difference in probabilities between the empirical and distribution quantiles. E.g. for the present state 2.0 m water level has an empirical return period of 100 years, while the Gumbel distribution estimates the probability of occurrence much higher with a return period of about 30 years. Considering The large amount of data, the empirical quantiles are more reliable than those derived from the distribution function. Using the probabilities of the Gumbel function will bias/impair the hazard analysis!

Thus use either the empirical quantiles or use another extreme value distribution function. The GEV might be a good option.

Response 18

Thank you for the comment and suggestion. Please see the Response R1_3 above.

Comment 19 in the MS – page 28

What is actually the pattern 1, that is finally used for creating the synthetic hydrographs? Here you only show the group of similar patterns, but not the (mean?, maximum?, ...?) pattern used for scaling the maximum water levels. How was this pattern then normalized? In order to scale the maximum water level to a flood event, this needs to be done. Please explain how the "characteristic" pattern 1 was derived and normalized.

Response 19

In this study, Pattern 1 is a group of similar water level hydrograph shapes (Fig 9 in the MS), which was identified after comparing with a threshold value of 2.15m. The highest 24-h long water level time series of all the water level hydrograph shapes corresponding to Pattern 1 was selected as a typical water level hydrograph shape, which was then scaled to the maximum water level with calculated water levels corresponding to each return period to create the 24-h boundary condition time series for the 1D/2D flood model. This information has now been included in the revised MS (Lines 291-295) and (Lines 298-300), as follows:

"The highest 24-h long water level time series of all the water level hydrograph shapes corresponding to Pattern 1 and Pattern 2 were selected as a typical water level hydrograph shape for each pattern respectively. These were scaled to the maximum water level with calculated water level corresponding to 100-year return period to create the 24-h boundary condition time series for the 1D/2D flood model in order to examine the response of different river water level hydrograph shapes on flooding." and

"Therefore, in this study, the typical water level time series following Pattern 1 above was scaled to the maximum water level with calculated water levels corresponding to each return period for each scenario to create the 24-h boundary condition time series for the 1D/2D".

Comment 20 in the MS – page

This should read "boundary"

Response 20

Thank you for the suggestion. We have adjusted this in the revised MS.

Comment 21 in the MS – page 29

If you have to save figures, you could present this result in a table listing the flooded areas, mean, and max inundation depths

Response 21

Thank you for the suggestion. However, we would like to keep these flood hazard maps as they can help readers easily visualise the flood extent and inundation depth at all locations in the study area.

Comment 22 in the MS – page 30

The inundation areas and depths appear to be much smaller compared to Apel et al. (2016). This needs to be discussed. Is it the impact of the sewer system, which is considered in this study, but not in Apel et al.? Or is it due to the different statistics, or the mismatching Gumbel function (my first guess)? Or is there maybe an error in DEM elevation? Apel et al. (2016) detected a mismatch between the vertical datum of the river water level and of the DEM (which is identical to the one used in this study). Or is it due to the longer simulation period (6 days in Apel et al. vs. 1 days here)?

It is surely to much to ask for a complete and detailed comparison or search for the reason, but the mismatch needs to be addressed in order to provide some guidance for readers and particularly flood risk managers in Can Tho to understand the results.

The results of Apel et al. are, by the way, available for download as an electronic supplement to the paper.

Response 22

Thank you for the comment. In the revised MS, we have added a discussion part, in which we have placed our study in the context of Apel et al.´s study (Lines 396-459), as follow:

*"****5.3 Comparison with a previous study on flood hazard for Ninh Kieu district***

Computation of present-day flood hazard and probabilistic flood maps using 2D models for Ninh Kieu district has also been done before by Apel et al., (2016). However, the approach adopted in the present study differs from that adopted in previous studies and has added value by improving the computation of flood hazard of Ninh Kieu district. Furthermore, this study takes a step forward from previous studies, being the first study to probabilistically compute future flood hazard in the study area under climate change. The main value additions of this study, compared to Apel et al.'s study, are discussed below.

Difference in using flood probabilities to develop probabilistic fluvial flood hazard maps

One of the biggest differences between the present study and that reported by Apel et al. (2016) is the length of the river discharge time series used for flood frequency analysis. This difference is, in part, due to the different aims of the two studies: Apel et al.'s (2016) aim was to develop flood hazard maps for the present-day while the focus of the present study is to quantify climate change driven variations in the flood hazard.

Consistent with the aim of their study, and following traditional modelling practice, Apel et al. (2016) used flood frequency curves at Kratie of Dung et al. (2015), which were constructed based on the longest possible time series of river discharge at Kratie, spanning 88 years (1924 – 2011). In contrast, as mentioned in Section 5.1, the purpose of this study is to quantify climate change driven variations in the flood hazard between the present period and future time periods. Therefore, it is important to ensure that the selected baseline period (and baseline simulations), is in fact representative of the present-day period.

Another noteworthy difference between the approaches adopted by the present study as opposed to Apel et al.'s (2016) study arises from the fact that the probabilistic fluvial flood hazard maps for the Ninh Kieu district presented by Apel et al. (2016) were obtained by introducing upstream flood probabilities at Kratie into a combined large-scale inundation model for the entire Mekong Delta developed by Dung et al., (2011), together with a detailed 2D model for the Ninh Kieu district. Flood probabilities at Kratie were then determined *based on a bivariate flood frequency analysis using annual extreme discharge and flood volume at Kratie (Dung et al., 2015). However, floods strongly vary over space (Nied et al., 2017; Vorogushyn et al., 2018). This spatial variability of flooding would influence the flood levels at Can Tho which is about 430 km downstream of Kratie. This important aspect is not taken into account by Apel et al. (2016). Moreover, the river water level at Can Tho and the resulting flood extent and inundation depth in the Ninh Kieu district are affected by the downstream sea level, especially high tides and storm surge (Huong and Pathirana, 2013). Thus, using flood probabilities at Kratie to develop probabilistic fluvial flood hazard maps for the Ninh Kieu district without considering the effect of downstream sea level could lead to some uncertainties in the flood hazard computed at Can Tho. The present study overcomes these shortcomings by undertaking 2D flood modelling for Ninh Kieu district based on flood frequency analysis at Can Tho (as opposed to Kratie) and by taking into account both river discharges and downstream sea level in computing river water levels at Can Tho*

The difference in flood extent

Comparison of the results between the two studies shows substantial differences in the flood extent corresponding to different RPs for present-day. The inundated area corresponding to 2 yr, 5 yr, 10 yr, 20 yr, 50 yr and 100 yr RP in Apel et al.'s study are 2.37, 3.33, 3.71, 4.30, 4.98, 5.29 km2, respectively. In contrast, the inundated area for the present-day in this study are 0.42, 0.49, 0.54, 0.60, 0.74, 0.85 km2, respectively. Apart from the two key methodological differences between the two studies highlighted above, there are also two other reasons that may have led to these differences in estimated present-day flood extents.

While the present study explicitly accounted for the effect of the urban drainage system in Ninh Kieu district on flooding, Apel et al (2016) considered the entire district to be impervious. This has significant implications in terms of flood hazard estimations. The river water level in Can Tho varies following the downstream tidal fluctuation (semi-diurnal tide), as the urban centre of Can Tho (Ninh Kieu district) is connected with the Hau River and Can Tho River via the open sewer channel and urban drainage system. Therefore, for e.g., if during the flood phase of tide, the river water level rises above lowest elevation of the top of the manholes in the city, although without necessarily being higher than the crest elevation of the river embankment, this will lead to flooding in the city centre due to backwater flow through the urban drainage/sewer systems (note: no-return valves are largely dysfunctional in Ninh Kieu district). This is consistent with the flood situation in Can Tho, which was described in Nguyen (2016) (http://www.cantholib.org.vn:84/Ebook.aspx?p=27B9F975353796A6E64627B93B65654746C6B65637B91B857557). When the river water level drops during the ebbing phase of the tide, the inundation level is also reduced mostly as flood water is drained through the urban drainage/sewer systems. Hence, incorporating the effects of the flood drainage system, as done in the present study is crucial for correctly estimating flooding in this study area.

Both studies used the DEM presented by Huong and Pathirana (2013) for the study area as the input data of the 2D model. However, stemming from the above mentioned lack of consideration of the effects of the urban drainage/sewage systems, Apel et al. (2016) adjusted the elevation of the DEM data by subtracting 0.5m from the original DEM in order to achieve an acceptable validation of their 2D model. Apel at al. (2016) justify this decision referring to the two large fluvial flood events that occurred in 2011, with "extraordinary" peak water levels, but "the banks as given in the DEM were not overtopped, and thus no inundation would occur". However, revisiting the data of water levels at Can Tho station in 2011, used in Chapter 2 to validate the 1D simplified model for the entire Mekong Delta, the peak water levels of these two events occurred on the 28th of September and 27th of October with peak water levels of 2.04m and 2.15m, respectively. Both these water levels are higher than the bank elevation extracted from the original DEM data (approximately 1.9 - 2.0 m) at the surveyed point in Apel et al. (2016). Thus, these two flood events would, in reality, have caused flooding in the Ninh Kieu district by both backflow through the urban drainage system and by direct overtopping of the river embankment. The lowering of the entire DEM is therefore the likely cause for the substantially larger present-day flood extents estimated by Apel et al. (2016), relative to those computed in the present study.”

Referee #2

The paper presents a probabilistic modelling approach for flood hazard maps applied at the Can Tho city in the Mekong Delta. The flood hazard was analyzed for a present scenario and climate change scenarios. Additionally, land subsidence has been taken into account. The approach is based on 1D hydraulic model for the Mekong Delta, coupled with a detailed 1D/2D Model, covering the city drainage network and overland flow, to simulate the inundation depth and flow velocity in the area of interest (city center).

In a first step the 1D model was simplified to optimize calculation times, due to computational restraints. This was achieved by an iterative generalization procedure while keeping track of model performance against the observed data. For the upstream boundary condition, a streamflow generator is used to synthesize large amounts of one-year runoff series (1000) for a present and two future scenarios (RCP4.5 and 8.5). The generated runoff series are combined with 36 years of simulated extreme sea levels as downstream boundary condition, resulting in 36 000 combinations for each scenario (present, RCP4.5 and 8.5). Climate change was accounted for in terms of projected annual changes in river runoff and projected sea level rises for the corresponding climate projections.

Subsequently, the Gumbel distribution was fitted to the maximum water level for each scenario. The fitted distribution was applied to determine the water level in the study area for each return period (0.5-100 years). The shape of the corresponding flood hydrograph was approximated by analyzing the simulated flood hydrographs above a threshold for each scenario (present, RCP4.5 and 8.5). The coupled 1D/2D model was calibrated and finally used to simulate the inundation for each return period and scenario based on 15m resolution digital elevation model. To account for land subsidence effects, a subsidence rate of 1.6 cm/year was applied for the future scenarios. The results indicate a strong increase of the inundation extent for future climate scenarios. The increase, however, is explained to a large extent by the applied land subsidence.

The study addresses an important topic. Today, flood hazard maps are still mostly based on single scenario calculations without the consideration of a wider range of possible alternative scenarios. The manuscript fits well within the scope of the journal. However, I see a number of shortcomings which need to be addressed in the presented manuscript.

General Comments:

Comment R2_1:

A major concern is the generation of long time series of streamflow data based on 7 years of observed data. As researchers, we often face the challenge of limited input data and the stochastic methods can help to overcome these limitations. However, to fit these models, sufficient data are needed to fit the underlying distribution functions. In my opinion, 7 years of input data seems a rather short time period to derive meaningful distributions for the upper tails in which the authors are interested. Furthermore, the method to generate daily data is based on a non-parametric resampling procedure (Nowak et al. 2010), which is only able to scale the given data. This means that only observed daily patterns of the series will be present in the generated data, and no additional variability is introduced. Also, it is unclear if daily or hourly time series were generated?

Furthermore, I could not find information regarding the validation of the generated data. Are the statistics of the observed data well captured? I also wonder if there aren´t any longer time series (2000-2006) available nowadays? One possibility to overcome the limitation of lacking stream flow data (maybe not feasible as a short time solution), would be to generate data based on meteorological data (if available for longer time spans) including a rainfall-runoff simulation (see e.g. Falter et al. 2014; Winter et al. 2019).

Response R2_1:

Thank you for the comment and suggestion. The most obvious reason to use synthetic hydrology is if there is little or no data for the system (Lamontagne, 2015). There are two approaches to generate synthetic hydrology: indirect and direct. Generating discharge data based on meteorological data, including a rainfall-runoff simulation as the Referee mentioned, is the indirect approach. However, this approach is not always effective because this also depends on the recorded meteorological data, and it may not describe hydrologic shifts at a resolution or precision that is useful.

In this study, we used the direct approach to generate synthetic hydrology based on seven years of discharge data at Kratie by using the synthetic streamflow generator. This is explained in the MS (Lines 195-197), as follows:

"*As seven years of data is not sufficient to derive probabilistic results, here a synthetic streamflow generator developed by Giuliani et al. (2017) was used to generate 1000 synthetic flow time series (each one year long) for each scenario in Table 2 (current and future)".*

The rationale for using this short data series to generate long data series in this study has now been added to the revised MS (Lines 350-373), as follows:

"First, it (i.e. the synthetic hydrology) is derived from the length of discharge data (2000-2006) that was freely available to the authors at the start of this study. Only recently, the longer discharge data become available at the Mekong River Commission website with 66 years of data (1924 to 1970 and 2000 to 2018).

Secondly, the purpose of this study which is to quantify climate change driven variations in the flood hazard between the present period and future time periods. Therefore, it is important to ensure that the selected baseline period (and baseline simulations), are in fact representative of the present-day period. This is important because, not only has the climate change signal emerged in several climate variables over the last 50 years or so (i.e. signal is clearly discernible from the inter-annual variability) (King et al., 2015), but also human activities (e.g. reservoirs) have led to noticeable changes in the natural regimes that may have existed earlier in the 20th century (see Ranasinghe et al., 2019 for example in China). Both of these phenomena may change the probability distribution of climate variables over time (Chadwick et al., 2019).

To investigate the stationarity of the upstream river discharge in the Mekong River, the discharge time series at Kratie was analysed, based on the 66 years of data (1924 to 1970 and 2000 to 2018). The analysis showed that the peak discharge at Kratie has indeed noticeably decreased over time, and particularly after 2000 (Figs. 18, 19), likely due to irrigation expansion and upstream dam construction in recent years (MRC, 2010; Piman et al., 2013).

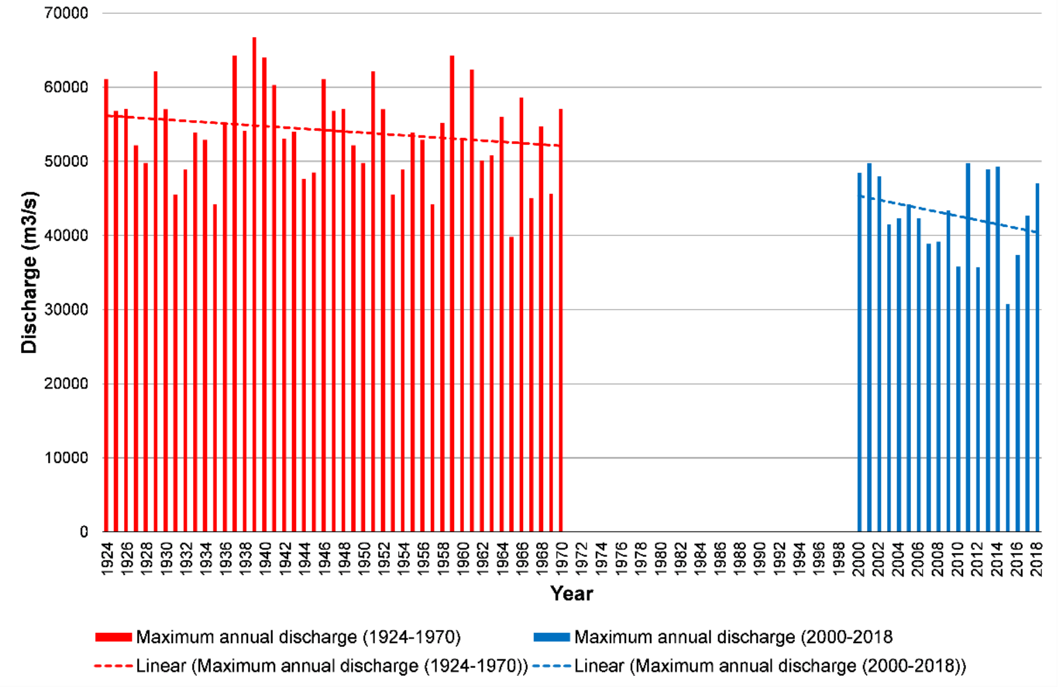


Figure 18: Maximum annual discharge at Kratie from 1924 to 1970 and 2000 to 2018

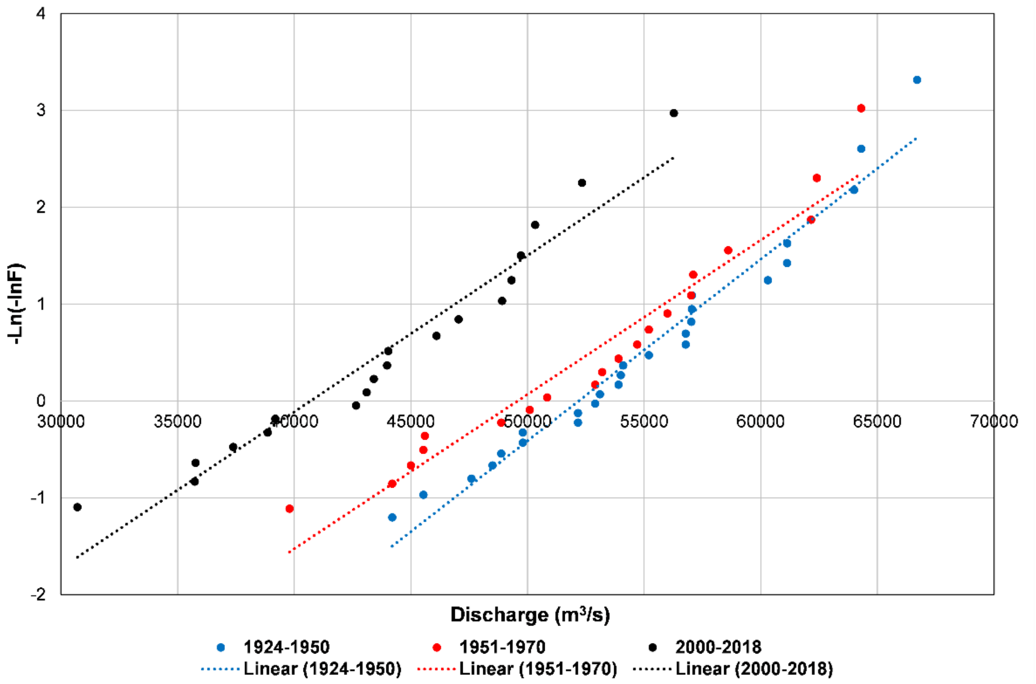


Figure 19: Gumbel distribution of discharge peaks at Kratie corresponding to three periods (1924-1950), (1951-1970) and (2000-2018)

The use of the full discharge time series at Kratie to develop flood frequency curves is therefore inappropriate in the present study which aims to quantify climate change driven variations in the flood hazard, and further, risk, relative to present-day conditions, in order to inform the development of climate resilient flood risk reduction measures for the urban centre of Can Tho city. The use of the full observed discharge data at Kratie, including pre-2000 flow with large flood peaks, can lead to an overestimation of flood hazard and risk. Therefore, for the purposes of this study, only the post - 2000 discharge data were used to represent baseline conditions."

In the revised MS, we also have added the results of using synthetic streamflow generator to generate the 1000 synthetic river flow based on seven year discharge data at Kratie to assess the validity of the method (Lines 374-383), specifically as follows:

"Figure 20 shows several representations of synthetic flow time series that are generated based on the seven years of observed discharge data used here, and their corresponding statistics and extreme values.

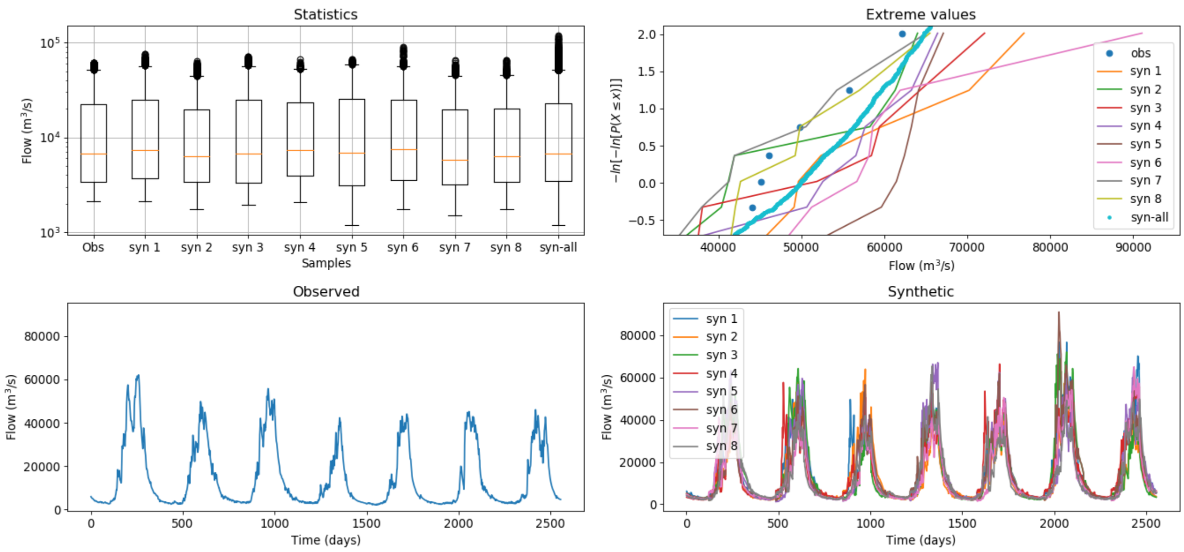


Figure 20: Representations of synthetic flow time series that are generated based on the seven years of observed discharge data, and corresponding statistic and extreme values.

In all, 1000 synthetic flow time series were created, which were then combined with 36 sea level time series to have 36000 different water level time series at Can Tho. This helps to capture the statistical variation of water level at Can Tho better, which is important in flood hazard modelling. Using these 36000 water level time series does not add any information that was originally not present in the observed data. However, as the sea-level and river flow time series are independent of each other, these combinations of statistical realizations of streamflow with observed sea-level improve the joint-probability manifestation in the resulting longer time series. It should be noted that, the synthetic generator is not the only approach to achieve this. For example, a similar statistical robustness might be achieved by time-shifting one set of series against the other."

Comment R2_2:

The headline of Chapter 4 is named Results and Discussion, however I think it mainly contains the description of the results with little to no critical review and reflection about assumptions and limitations of the presented methodology and results. The uncertainties and limitations need to be discussed in detail. Furthermore, if available, results or parts of it should be compared to existing studies. In my opinion a sound discussion chapter is missing.

Response R2_2:

Thank you for the comment and suggestion. In the revised MS, we have split this section into two separate sections including Results, and Discussion. In the Discussion section, we have added detailed discussions regarding issues such as the rationale for using the 7-year data series, comparison with results of previous studies, etc (Lines 346-459). Since the rationale for using 7-year data series was presented in Response R2_1, here we only provide the remaining additional information in the new Discussion:

"*5.2 Limitation of probabilistic distribution function*

"In this study, Gumbel distribution was used to model this distribution of the maximum water levels of the water level time series to select design water levels corresponding to each return period. However, there is a difference in probabilities between the empirical and distribution quantiles corresponding to the present and RCP 4.5 scenarios. Using the log-log-linearity of the Gumbel distribution might introduce a bias to the very extreme values. In contrast, using the empirical distribution might result in less information loss. However, it will include all the random artifacts in the observed (and generated) data. Additionally, such an analysis needs a long series of data that are largely devoid of non-stationarities (or them being carefully removed). The flow database used here, which was limited in length due to the climate change impact focus of the study does not provide the necessary data quality or quantity to do such an analysis. Therefore, using the Gumbel distribution here is more reasonable in our view. Additionally, the difference in water levels corresponding to large return periods between the empirical and distribution quantiles is small. Furthermore, the Gumbel distribution was well-fitted in scenario RCP 8.5 with higher water levels.

5.3 Comparison with a previous study on flood hazard for Ninh Kieu district

Computation of present-day flood hazard and probabilistic flood maps using 2D models for Ninh Kieu district has also been done before by Apel et al., (2016). However, the approach adopted in the present study differs from that adopted in previous studies and has added value by improving the computation of flood hazard of Ninh Kieu district. Furthermore, this study takes a step forward from previous studies, being the first study to probabilistically compute future flood hazard in the study area under climate change. The main value additions of this study, compared to Apel et al.'s study, are discussed below.

Difference in using flood probabilities to develop probabilistic fluvial flood hazard maps

One of the biggest differences between the present study and that reported by Apel et al. (2016) is the length of the river discharge time series used for flood frequency analysis. This difference is, in part, due to the different aims of the two studies: Apel et al.'s (2016) aim was to develop flood hazard maps for the present-day while the focus of the present study is to quantify climate change driven variations in the flood hazard.

Consistent with the aim of their study, and following traditional modelling practice, Apel et al. (2016) used flood frequency curves at Kratie of Dung et al. (2015), which were constructed based on the longest possible time series of river discharge at Kratie, spanning 88 years (1924 – 2011). In contrast, as mentioned in Section 5.1, the purpose of this study is to quantify climate change driven variations in the flood hazard between the present period *and future time periods. Therefore, it is important to ensure that the selected baseline period (and baseline simulations), is in fact representative of the present-day period.*

Another noteworthy difference between the approaches adopted by the present study as opposed to Apel et al.'s (2016) study arises from the fact that the probabilistic fluvial flood hazard maps for the Ninh Kieu district presented by Apel et al. (2016) were obtained by introducing upstream flood probabilities at Kratie into a combined large-scale inundation model for the entire Mekong Delta developed by Dung et al., (2011) together with a detailed 2D model for the Ninh Kieu district. Flood probabilities at Kratie were then determined based on a bivariate flood frequency analysis using annual extreme discharge and flood volume at Kratie (Dung et al., 2015). However, floods strongly vary over space (Nied et al., 2017; Vorogushyn et al., 2018). This spatial variability of flooding would influence the flood levels at Can Tho which is about 430 km downstream of Kratie. This important aspect is not taken into account by Apel et al. (2016). Moreover, the river water level at Can Tho and the resulting flood extent and inundation depth in the Ninh Kieu district are affected by the downstream sea level, especially high tides and storm surge (Huong and Pathirana, 2013). Thus, using flood probabilities at Kratie to develop probabilistic fluvial flood hazard maps for the Ninh Kieu district without considering the effect of downstream sea level could lead to some uncertainties in the flood hazard computed at Can Tho. The present study overcomes these shortcomings by undertaking 2D flood modelling for Ninh Kieu district based on flood frequency analysis at Can Tho (as opposed to Kratie) and by taking into account both river discharges and downstream sea level in computing river water levels at Can Tho

The difference in flood extent

Comparison of the results between the two studies shows substantial differences in the flood extent corresponding to different RPs for present-day. The inundated area corresponding to 2 yr, 5 yr, 10 yr, 20 yr, 50 yr and 100 yr RP in Apel et al.'s study are 2.37, 3.33, 3.71, 4.30, 4.98, 5.29 km^2, respectively. In contrast, the inundated area for the present-day in this study are 0.42, 0.49, 0.54, 0.60, 0.74, 0.85 km^2, respectively. Apart from the two key methodological differences between the two studies highlighted above, there are also two other reasons that may have led to these differences in estimated present-day flood extents.

While the present study explicitly accounted for the effect of the urban drainage system in Ninh Kieu district on flooding, Apel et al (2016) considered the entire district to be impervious. This has significant implications in terms of flood hazard estimations. The river water level in Can Tho varies following the downstream tidal fluctuation (semi-diurnal tide), as the urban centre of Can Tho (Ninh Kieu district) is connected with the Hau River and Can Tho River via the open sewer channel and urban drainage system. Therefore, for e.g., if during the flood phase of tide, the river water level rises above lowest elevation of the top of the manholes in the city, although without necessarily being higher than the crest elevation of *the river embankment, this will lead to flooding in the city centre due to backwater flow through the urban drainage/sewer systems (note: no-return valves are largely dysfunctional in Ninh Kieu district). This is consistent with the flood situation in Can Tho, which was described in Nguyen (2016) (http://www.cantholib.org.vn:84/Ebook.aspx?p=27B9F975353796A6E64627B93B65654746C6B65637B91B857557). When the river water level drops during the ebbing phase of the tide, the inundation level is also reduced mostly as flood water is drained through the urban drainage/sewer systems. Hence, incorporating the effects of the flood drainage system, as done in the present study is crucial for correctly estimating flooding in this study area.*

Both studies used the DEM presented by Huong and Pathirana (2013) for the study area as the input data of the 2D model. However, stemming from the above mentioned lack of consideration of the effects of the urban drainage/sewage systems, Apel et al. (2016) adjusted the elevation of the DEM data by subtracting 0.5m from the original DEM in order to achieve an acceptable validation of their 2D model. Apel at al. (2016) justify this decision referring to the two large fluvial flood events that occurred in 2011, with "extraordinary" peak water levels, but "the banks as given in the DEM were not overtopped, and thus no inundation would occur". However, revisiting the data of water levels at Can Tho station in 2011, used in Chapter 2 to validate the 1D simplified model for the entire Mekong Delta, the peak water levels of these two events occurred on the 28th of September and 27th of October with peak water levels of 2.04m and 2.15m, respectively. Both these water levels are higher than the bank elevation extracted from the original DEM data (approximately 1.9 - 2.0 m) at the surveyed point in Apel et al. (2016). Thus, these two flood events would, in reality, have caused flooding in the Ninh Kieu district by both backflow through the urban drainage system and by direct overtopping of the river embankment. The lowering of the entire DEM is therefore the likely cause for the substantially larger present-day flood extents estimated by Apel et al. (2016), relative to those computed in the present study."

Comment R2_3:

I think the overall results of the study are associated with very large uncertainties. Due to the lack of critical discussion this is not clearly laid out in the presented study. Furthermore, as stated in the manuscript, the main influencing factor for the future flood hazard is based on the applied land subsidence rate. This is, however, only threated as a minor issue in the manuscript. How is the subsidence rate considered in detail? The way I understood the article, the rate is linear interpolation by 1.6 cm per year up to 2050, however is this a valid assumption? Is the subsidence rate homogeneous over space and time? Is the methodology for considering the subsidence rate by simply modifying the DEM solid and common?

Response R2_3:

Thank you for the comment. In the revised MS, we have added some discussion related to the uncertainties associated with results of this study (Lines 346-459). Please also see Responses R2_1 and R2_2 above.

Regarding land subsidence, up to now, there is no study on the land subsidence specifically at the Can Tho city; therefore, this study used an average land subsidence rate of 1.6 cm.yr^{-1} for the entire Mekong Delta (Erban et al., 2014; Minderhoud et al., 2015) in scenarios considering the effect of land subsidence on the flood hazard at Ninh Kieu district, even though land subsidence in the Mekong Delta is not uniform, with the rates of (1~4 cm.yr^{-1}) (Erban et al., 2014; Minderhoud et al., 2015). Land subsidence is here considered to be linear at a rate of 1.6 cm.yr^{-1}, the ground level at a specific time in the future is determined by adjusting the DEM which is indeed common practice (Tiggeloven et al., 2020; Shirzaei et al., 2021). While we acknowledge that this treatment of land subsidence is simplistic, the lack of spatio-temporally varying land subsidence projections at the study site precludes the consideration of more sophisticated approaches to address this issue.

Specific Comments:

Comment 1:

P4 L.114 I understand that performance is critical, but why must the calculation time be 1 minute? Is this not a rather subjective assumption and will it not always be depending on the individual case?

Why do you speak of hourly time steps? I thought the generator is based on daily values, or did you produce hourly values?

Response 1:

Thank you for the comment. Among the key features of our non-stationary fluvial flood hazard modelling approach, the simplified model for the entire Mekong Delta was presented in Ngo et al. (2018), which can complete the simulations in the span of a minute. In this study, we summarised this feature with the aim to provide information to readers. The 1 minute is strictly in reference to this specific application and is not intended to be taken as standard for applications in other river systems.

Regarding hourly time steps, this was a mistake while preparing this MS. In the revised MS, “hourly time step” has been corrected to “daily time step” (Line 114).

Comment 2:

P6. L183 Are the skill values based on the total time series? Do they also capture the extremes well? Maybe you could add a validation plot to the manuscript. On what basis do you judge the skill values as “very good” and “excellent”?

Response 2:

Thank you for the comment. In the “Model reduction” section of this MS, we tried to provide as much information as possible to readers about our approach in developing a simplified model for the entire Mekong Delta. The details of the results given in this section have been presented in Ngo et al. (2018). Therefore, in this section, we only summarise and emphasize that the simplified model was calibrated and validated by comparing simulated and observed water levels at Can Tho gauging station for 2000, 2001, 2002, and 2011. The results indicated that the performance of the simplified model is acceptable. Even with the year 2011, which had an extreme flood event on 27th October, the model's performance is classified “good” by two indicators, NSE (0.77) and RMAE (0.04) for October 2011. And “Very good” and “excellent” ratings are given based on the classification of each indicator by Nash and Sutcliffe (1970) and Sutherland et al. (2004).The detailed classification of these indicators was presented in detail in Ngo et al. (2018) and is therefore not repeated here.

Comment 3:

P6. L186 Aren´t longer time series available than 2006 nowadays? In my opinion this is a very poor data basis for the applied usage.

Response 3:

Please see Response R2_1 to Comment R2_1 above.

Comment 4:

P7. L197 As I understand the statement, a %-change is sampled out of the given range and applied to the generated data. What about the dynamic? I think there may be more complex changes in the system than only a percentage change and, more importantly, an annual change does not necessarily say something about possible extreme events. These assumptions and limitations need to be at least addressed in the discussion.

Response 4:

Thank you for the comment and suggestion. We agree that an annual change cannot say anything about possible extreme events in the future. Accurate prediction of extreme events (e.g., time, magnitude) is always difficult and uncertain. In this study, we relied on Hoang et al.'s prediction for the change in riverflows (magnitude) at Kratie due to the effects of climate change, including extreme events, as a detailed analysis on changes in extremes in the study area is outside the scope of this study.

Comment 5:

P7. L215 If you produced 36.000 series, would it not also be possible to derive the boundary conditions directly from the generated full hydrographs? Then you would not need to make any assumptions about the hydrograph. The shape of the hydrograph may change between different return periods. Also, by only looking at the water level, you may miss the important factor of flood volume for the hydraulic modelling exercise (e.g. Grimaldi et al. 2013).

Response 5:

Thank you for the comment. We agree that flood hydrograph shape may change for different return periods, even for a single return period event there may be different flood hydrograph shapes. There are many hydrograph shapes of water level in 36000 water level time series containing at least one water level corresponding to a specific return period. Therefore, selecting an appropriate flood hydrograph for a return period is not trivial.

In this study, we performed a detailed analysis of the flood hydrograph shapes and selected the highest hydrograph shape of water level in all hydrograph shapes corresponding to Pattern 1 as the typical flood hydrograph shape, which was then scaled to the maximum water level with calculated water levels corresponding to each return period to create the 24-h boundary condition time series for the 1D/2D flood model. As such, in this regard, we believe our approach could be considered as an advancement compared to previous studies.

In addition, we would also like to emphasize that hydrograph shapes of water level at Can Tho are obtained from the combination of downstream sea levels and upstream riverflows, including flood peak and hydrograph shape (i.e. flood volume).

Comment 6:

P7. L220 There might be a much broader variability of possible flood hydrograph shapes. Even if all 36k scenarios are analyzed, the interday variability is based on 7 years of input data. The resampling algorithms of the generator will not introduce further variability. This needs to at least be addressed in the discussion.

Response 6:

We agree with the the Reviewer that there are limitations to our study which we hope are now better described in the manuscript. The decision to use only seven years of discharge data was due to a combination of the data that were available to the authors at the time of this study and importantly due to the climate change focus of the study. Please see our detailed response to R1_3 on these issues

Comment 7:

P8. L249 I think it is not necessary to explain how exactly the inundation grids are produced by telling which ArcGIS Tools were applied.

Response 7:

Thank you for the comment. This information was added into the MS following an editorial request. Additionally, we also thought that providing this information would help readers understand more our methodology.

Comment 8:

P9. Headline "Results and Discussion" I think these are mainly results without a sound discussion. I would advise to add a separate discussion section.

Response 8:

Thank you for the comment and suggestion. In the revised MS, we have split it into two separate parts including Results and Discussion. The Discussion section contains detailed discussions regarding issues such as the rationale for using 7-year data series, comparison with results of previous studies, etc. Please see our detailed response to R2_2

Comment 9:

P9. L268 I cannot identify two patterns in Fig 9a). Only two cases differ in all plotted simulations for 9a), which I would not call "a pattern".

Response 9:

Thank you for the comment. In the MS, we used a water level threshold of 2.15m to identify water level time series that have at least one peak water value greater than 2.15m for both scenarios RCP 4.5 and RCP 8.5. Then 24 h long time series around each peak value (12 h earlier to 12 h later) were extracted. For scenario RCP 4.5, although the number of water level time series with flood hydrograph shape of Pattern 1 is limited (two time series) (Fig. 9a), they have the same shape as flood hydrograph shapes of Pattern 1 in Fig. 9b corresponding to scenario RCP 8.5. Therefore, we called it "Pattern 1" to distinguish it from the other flood hydrograph pattern (Pattern 2).

Comment 10:

Fig. 3 I think calibration/validation plot for the events (see comment P6. L183) would be of more interest to the reader.

Response 10:

Thank you for the suggestion. However, there appears to be a misunderstanding here. Figure 3 in the MS was presented to show the highest observed flood water levels in Can Tho since 2000 and official flood water level alarms in Can Tho following Decision No.632/QĐ-TTg issued on May 10th, 2010 to describe the flooding situation in Can Tho.

Regarding calibration/validation plot for the events related to comment P6. L183, calibration and validation of the simplified model with the measured water levels of the year 2000, 2001, 2002, and 2011 is presented in detail in Ngo et al., (2018) and not repeated here.

Comment 11:

Fig. 4 is close to identical to Fig. 1. I think it is really helpful to understand the workflow, but it may be combined with Fig. 1

Response 11:

Thank you for the comment. We agree that there are many similarities between Fig. 1 and Fig. 4 in the MS; however, we would like to retain them as they are because these figures help readers understand the general methodology adopted versus specific case study applications (this study).

Comment 12:

Fig. 6. The fitted distributions seem to be biased for higher return periods. This is probably related to the short input time series.

Response 12:

Thank you for the comment. Usually, the fitted distributions are more biased for large return periods (at the tail of the distribution). This is because the length of recorded data is smaller than the value corresponding to large return periods. However, in this study, to say that the bias is related to short input data is not entirely correct. This is demonstrated in Figure 9c in the MS, which shows that empirical quantiles and the distribution quantiles compare quite well.

Comment 13:

Fig. 8 I am not an expert on drainage simulations, but I do not understand the plot. Is the red line the simulated line? Why is it higher at the beginning of the simulation than the observed one? Is the plotted elapse time window appropriate?

Response 13:

Thank you for the comment. The red lines are the simulated water depths at two manholes. Fig. 9 shows the comparison between the simulated water depths and measured water depths in manholes at the time of conducting the water depth survey in the sewer; however, the starting time of the simulation is 9 hours earlier than the time shown in this figure. This is why simulated water depths are higher than measured water depths at the beginning of the comparison.

Comment 14:

Fig. 9 see comment P9. L268

Response 14:

Please see our response to the specific comment 9 above.

Technical Notes:

Comment 1:

P.2 L.62 Either use "e.g." or "etc."

P.4 L.104 Either use "e.g." or "etc."

Response 1:

Thank you for the correction. We have adjusted this in the revised MS (Line 61 and 104).

Comment 2:

P4. L109 Possible alternative: "not always sufficient"

Response 2:

Thank you for the suggestion. In the revised MS, we have updated this (Line 109).

Comment 3:

P5. L135 The link doesn't work

Response 3:

Currently, this link still works. However, when clicking the link directly in the MS, it is somehow combined with row number 135 (row contains the link in the MS) and parentheses, which results in not being able to access the link. Please use the same link here (https://github.com/julianneq/Kirsch-Nowak_Streamflow_Generator).

Comment 4:

P5 L.135 - This could be moved to the “Code availability”-section at the end of the manuscript.

Response 4:

Thank you for the suggestion. However, since the synthetic streamflow generator has been developed by Matteo Giuliani, Jon Herman, and Julianne Quinn, we think it is reasonable to mention the link of the synthetic streamflow generator at the place when it was first introduced in the MS.

Comment 5:

P10 L301 “inundated area” instead of “flood hazard”

Response 5:

Thanks for your comment. We have adjusted this in the revised MS (Line 326).

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