Responses to Referee #1 for the Manuscript ID: hess-2012-522

Title: "ASSESSING THE HYDROLOGIC RESTORATION OF AN URBANIZED AREA VIA INTEGRATED DISTRIBUTED HYDROLOGICAL MODEL" by D.H. TRINH and T.F.M. CHUI

We would like to thank the referee for the helpful comments and suggestions. Please see our detailed responses to each query and comment below.

1. About the language issue:

The manuscript needs some editorial work because some phrases sound awkward:

- Page 4100, line 21: … be intervened…'. I would rephrase this.

- Page 4100, line 24: '…impervious surfaces enhances…'

- Page 4101, lines 2-3: I would rephrase this.

- Page 4101, line 29: '…canals'. This sounds awkward.

- Page 4102, line 16: 'The model included…'

- Page 4102, line 18: 'and detailed the spatial…'

- Page 4103, lines 5-6: '…truly reflective'. This phrase also sounds awkward.

- Fig. 5: 'Hybird' should be 'Hybrid'.

[Response] We will edit all the phrases as suggested in the revised manuscript.

2. About the lumped model:

Page 4103, lines 5-6: lumped models can have more than one parameter.

[Response] We agree with the referee that lumped models can have more than one parameter. However, lumped models are not able to describe the spatial distribution of one parameter. Taking soil hydraulic conductivity of a catchment as an example: actual hydraulic conductivity is not homogeneous throughout the catchment. However, the model can only have one value of soil hydraulic conductivity. Thus only one "representative hydraulic conductivity" value is used as model input, which might not reflect the actual spatial variation within the catchment.

We will revise to make it clearer in the revised manuscript.

3. About the green roof:

- Green roof: the description of green roofs lacks some details. It is said that green roofs function as micro-catchments; however, it looks like the only effect of green roofs is to delay peak runoff. What is the soil depth of the modeled green roof? This would determine the ability of roofs to store water; also, the type of vegetation is important to estimate evapotranspiration. How are these features embedded in the model? I could not understand it from Section 2.1. I do not think that imposing a constant delay of 3h is accurate, because the delay should depend on the time between rainfall events. This choice should be discussed and justified more in depth, maybe suggesting possible consequences if this assumption were relaxed or a model accounting for green roof soil depth were used.

- Page 4104, line 12: the Authors should provide a reference for the statement 'improving runoff quality'. In some environment, green roofs need to be fertilized to maintain healthy vegetation; this would cause pollutant leaching, thereby reducing runoff water quality.

[Response]

- We agree with the referee that imposing a constant delay of 3 hours for green roofs without considering the water storage and evapotranspiration is not highly accurate as green roofs not only delay the peak runoff but also reduce the runoff discharge and retain certain amount of rain water depending on the green roof specifications and rainfall intensity (Mentens et al., 2006, Bengtsson et al., 2005, VanWoert et al., 2005). Therefore, we acknowledge that this is a limitation of our current model. However, the assumed average delay of 3 hours is chosen with reference to the results from Moran et al. (2004) and Rowe et al. (2003). In term of water storage, previous studies show that there is only small amount of retention during large rainfall events (VanWoert et al., 2005, Carter and Rasmussen, 2006). Our current model assumes no retention which is conservative but acceptable as tropical rainfall is of high intensity and we are interested in large rainfall events that potentially cause flooding problem. For evapotranspiration, we performed measurement on a plot-scale green roof in Singapore and found that evapotranspiration accounts for 5% of total water balance (results not yet published). So, we consider it as insignificant and therefore also neglect it in this study. In addition, this study aims to develop general idea on the effectiveness of catchment-scale green roof implementation without focusing on the detailed behaviour of each individual green roof. Therefore, we believe that simplifications made at individual green roof level would not affect the overall catchment-scale results and conclusions.

We will add the above discussion on our model limitation in the revised manuscript.

- Page 4104, line 12: Regarding runoff water quality, we are aware that fertilization is one of the key issues. However, the requirement of fertilization and its influences on water quality greatly depends on the design specification. Study of Czemiel Berndtsson (2010) indicate that fertilization may be replaced by watering during the dry period for the same aesthetic result. Palla et al. (2010) even use green roofs to reduce stormwater pollution via the substrate layer. Hathaway et al. (2008) applies media with nutrient removal to improve water quality at the outlet discharge.

We will provide these references in the revised manuscript.

4. About the elements of the model:

Page 4107, line 8: I cannot understand how the Authors have 89900 elements, when the catchment is 160 km^2, each cell is 60 m by 60 m with 45 layers.

[Response]: The model domain is rectangular consisting of 290 cells in east-west direction and 310 cells in north-south direction; each cell has a size of 60 meters by 60 meters. Thus, the number of horizontal elements is 89,900 (290 x 310). Together with 45 vertical layers, the total number of elements is 4,045,500 (89,900 x 45). We will revise this part to avoid confusions.

5. About accounting for green roof and bio-retention systems in one gird cell:

How are green roofs and bio-retention systems accounted for in an area of 60 m by 60 m?

[Response] For an integrated hydrological model at catchment scale (area of 160 km^2), one approach to model green roofs and bio-retention systems is to resolve the catchment down to the scale of a single green structure system or even finer. However, this requires high computational efforts and detailed input data. Within the scope of this paper, we aim to develop a general idea about the effectiveness of catchment-scale green structures on restoring the hydrological condition of an urban area by considering one grid cell as an aggregated system of green roof or bio-retention. Study of Elliott et al. (2009) about aggregation of on-site stowmwater control devices concludes that aggregation of green structures have little effects on model predictions and therefore aggregation can be used to reduce computational and input data requirements, with little penalty on prediction accuracy. Thus, we believe aggregating the green structure systems to each grid cell of 60m by 60m is reasonable in our study.

6. About the hydraulic conductivity of the soils in bio-retention systems:

- Page 4108, line 23: the hydraulic conductivity of the soil is very similar to that of soil in bio-retention systems; I would have expected bio-retention systems to have larger hydraulic conductivities, of the order of 150-200 mm per hour (instead of about 40 mm per hour as used by the Authors).

- Page 4115, lines 9-14: according to the chosen parameters, the hydraulic conductivity of bio-retention systems is similar to that of the surrounding soil. This allows water to percolate into the surrounding soil, without accumulating in the systems. I would consider to increase the soil hydraulic conductivity of bio-retention systems to see the effect of recharge.

[Response] Authors would like to thank the referee for the valuable comment and suggestion.

- Firstly, we would like to explain further about the hydraulic conductivity of the bio-retention system and the surrounding soil. Soil information in Marina catchment is collected from different sources. The information about the top soil layer (1 to 2 meters) is based on the Singapore soil survey (Wells, 1977, Ives, 1977) (Table 1). Below the top layer, the soil is assumed to be loamy sand. The bio-retention system is only within the first meter of the top soil surface. Thus, when compared to the native soil, the hydraulic conductivity of the bio-retention system is approximately 5 to 10 times higher.

Table 1. Soil texture and properties (*added soil hydraulic conductivity compared original manuscript*)

Soil Type	Depth (cm)	Soil Texture (%)			K (m/s)	Soil Type	Depth (cm)	Soil Texture (%)			K (m/s)
		Sand	Silt	Clay				Sand	Silt	Clay	
REMGAM	0 - 8	78	2	20	1.76E-5	TAMPOI	0 - 6	81.2	2.1	16.7	1.94E-5
	8 - 34	61	1	38	3.97E-6		6 - 13	72.5	1	26.5	3.70E-6
	34 - 68	57	3	40	4.04E-6		13 - 44	69.6	0	30.4	2.69E-6
	68 - 160	55	2	43	3.13E-6		44 - 100	61.7	0	38.3	2.69E-6
JERANGAU	0 - 5	35.7	6.1	58.2	1.42E-6	BEDOK	0 - 10	Clay Loam			9.47E-7
	15 - 30	38	4	58	1.55E-6		10 -100	Silt Clay			1.11E-6
	30 - 82	30	4	66	1.25E-6	CHOWBOONLAY	0 - 10	Silt			5.06E-6
	82+	28	3	69	1.26E-6		10 - 100	Silt Clay			1.11E-6
AYERTERJUN	0 - 7	24	47	29	7.11E-6	CHANGI	0 - 100	Sand			7.44E-5
	7 - 24	23	44	33	1.53E-6	HOLYROOD	0 - 100	Loam Sand			1.22E-5
	24 - 60	13	33	54	1.58E-6	JURONG	0 - 100	Silt Clay			1.11E-6
	60 - 135	9	29	62	1.78E-6	KRANJI	0 - 100	Silt Clay			1.11E-6
HARIMAU	0 - 14	77.8	4	18.2	1.68E-5	MATAIKAN	0 - 100	Sand Clay Loam			1.53E-6
	14 - 28	73.5	4.1	22.4	5.74E-6	MASAI	0 - 100	Clay			1.71E-6
	28 - 35	69.8	3.1	27.1	3.41E-6	TENGAH	0 - 100	Loam Sand			1.22E-5
	53 - 94	57.8	1.2	41	2.16E-6						

- Secondly, in response to the referee's comment, we have also carried out two more simulations using bio-retention systems with soil hydraulic conductivity of 5 x 10^{-5} m/s (180 mm/hr) and 10^{-4} m/s (360 mm/hr) which are higher than the original value of 10^{-5} m/s (36 mm/hr). The results show that the difference in outlet discharge among the scenarios is insignificant. Taking a bio-retention system at the centre of the catchment as an example, Fig. 1 presents the groundwater table, infiltration rate and groundwater recharge across the system 12 hours after the largest rainfall event in the simulated year. This event has a rainfall depth of 130 mm and an intensity of 26 mm/hr. The infiltration rates of the different scenarios are the same, as the rainfall intensity is lower than all the soil hydraulic conductivity values. There is more recharge to the saturated zone at that particular moment leading to a higher groundwater table in the scenario with higher soil hydraulic conductivity. However, the total recharges of all scenarios reach the same values eventually. The temporal difference in groundwater recharge is because rain water requires different duration to travel through the unsaturated zone to reach the saturated zone depending on the soil hydraulic conductivity. Therefore, we believe the original soil hydraulic conductivity of bio-retention system is reasonable as increasing soil hydraulic conductivity does not affect the overall recharge amount.

We will add the information above in the revised manuscript.

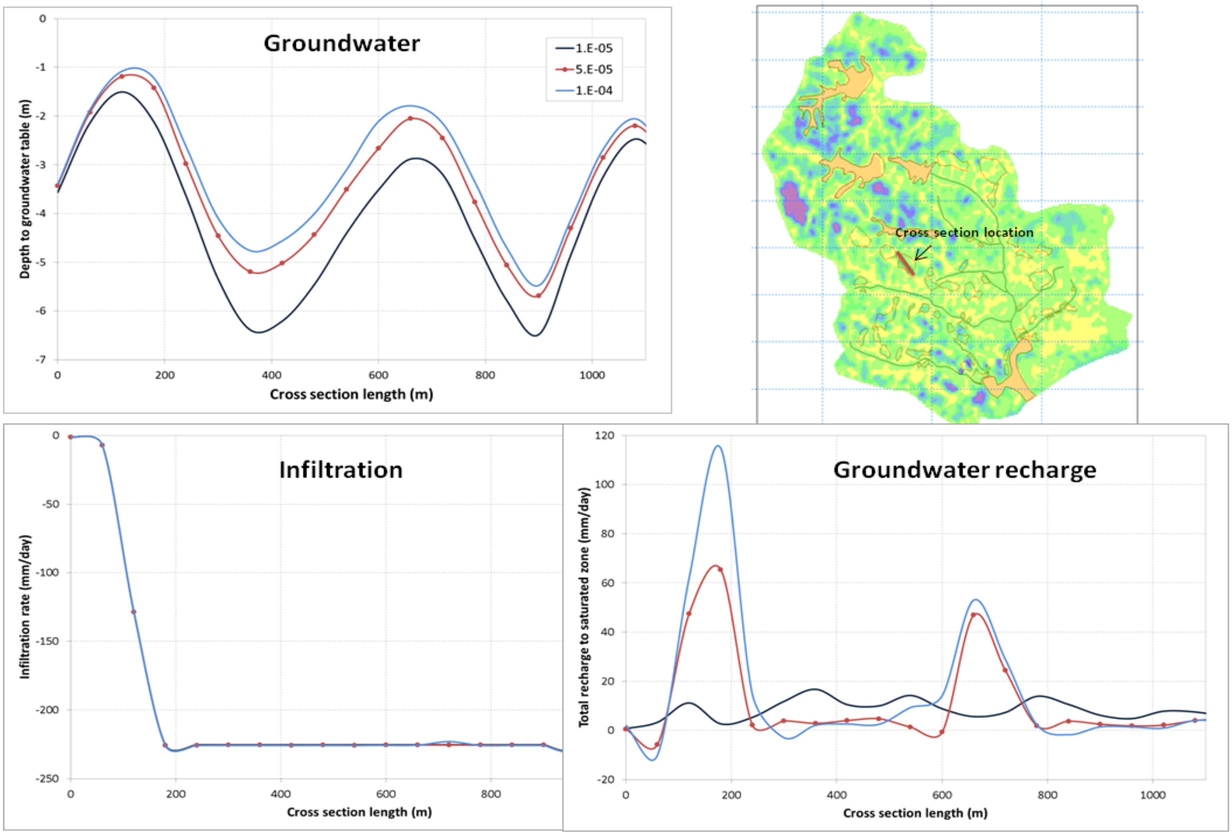

Fig. 1 Groundwater depth, infiltration rate and groundwater recharge across bioretention systems with different soil hydraulic conductivities. Results are from 12 hours after largest rainfall event (130mm) on 8th December 2005

7. About the evapotranspiration equation:

Eq. 1: how is G calculated?

[Response] According to FAO (Food and Agriculture Organization) document (Allen, 1998), soil heat flux (G) is calculated by equation below:

$$G = c_s \frac{T_i - T_{i-1}}{\Delta t} \Delta z$$

where *G* is soil heat flux [$MJm^{-2}day^{-1}$], c_s is soil heat capacity [$MJm^{-3}{}^{o}C^{-1}$], T_i and T_{i-1} is air temperature at time i and i-1 [^{o}C], Δt is length of time interval [day], and Δz is effective soil depth [m]. The depth of penetration of temperature wave is determined by the length of time interval. The effective soil depth, Δz, is only 0.1 – 0.2 m for a time interval of one or few days. Thus the magnitude of soil heat flux is relatively small. For this model, we assume that G to be negligible.

We will comment about G value in the revised manuscript.

8. About the model boundary:

- Page 4110, lines 11-12: is setting a constant boundary at sea level correct? Are tidal effects important in the studied catchment? I would add a comment to acknowledge that tidal fluctuations are neglected.

- Page 4110, lines 15-16: assuming flat bedrock at a constant depth below the ground affects groundwater movement. Is this a reasonable assumption in the studied catchment? I would add a comment in this regard.

[Response]

- Page 4110, line 11-12: Authors would like to further describe the situation at the sea boundary of the domain. Downstream of Marina catchment is Marina reservoir connecting with open sea through Marina barrage of about 6 meters height. The operation of this barrier depends on the water level in the reservoir and the tide outside, and the water level in the reservoir is often independent from the tidal fluctuations. Therefore, setting a sea boundary constant at sea level should be a reasonable assumption.

- Due to the lack of detailed geology data, we assume the bedrock to be at a constant depth below the ground. However, this study focuses on shallow subsurface environment. Thus, the bedrock level of 30 m below the ground should be sufficient and this assumption will not affect the shallow groundwater movement in the top few meters.

We will add comments regarding boundary conditions in the revised manuscript.

9. About the trickle channel:

- Page 4110, lines 20-22: '…assumed to be rectangular…'. What is 'trickle channel'?

[Response] Trickle channel (also known as dry weather flow channel) is usually a longitudinal channel constructed along the centre and lowest part of a channel to carry low flows. They are usually shallow, narrow and concrete lined (Guo, 2006). The capacity of trickle channel is usually about 1 to 3% of the major design flow.

10. About the model results:

- Section 3.1: I would indicate precisely in the area of the catchment where the location of the results in Fig 4 is.

- Page 4113, lines 15-20: why is the flow in the scenarios with green roofs and bioretention systems lower than that in pre-urban conditions? Is that due to the larger infiltration rates of bio-retention systems?

- Fig. 5: Why is subsurface storage only in the urbanized and green roof scenarios?

[Response]

- Section 3.1: We would indicate precisely the location of results in Fig. 4 in the revised manuscript.

- Page 4113, line 15-20: The peak flow in the scenario with green roofs and bio-retention systems (Hybrid) is lower than that in the pre-urban scenario because of the combined effect of green structures: the delay of rainfall by green roofs and the enhancement of infiltration by bio-retention systems.

- Fig. 5 Explain the subsurface storage change in different scenarios: The storage changes in the model (subsurface storage change and surface storage change) are in fact changes of storage from one year to the next. As we repeat the simulations for 5 years with the same climatic input, the model should reach a dynamic steady state and the storage changes in the reporting year, which is the last year of the simulation run, should be minimal. The total storage changes in all the scenarios are in fact less than 1% of total water balance which is considered insignificant.

11. About the problems of infiltration in shallow groundwater area:

Section 3.2.2: one of the problems of infiltration systems in urban areas with shallow groundwater is localized recharge that might damage urban underground infrastructure. I would suggest the Authors to check the groundwater levels in the elements of their model where bio-retention systems are installed to see whether there are localized groundwater mounds.

[Response] Authors would like to thank the referee for the suggestion. The locations where the bio-retention systems are installed have local groundwater mounds. The groundwater table is about 1 to 2 meters higher than the surrounding area depending on the groundwater table and rainfall conditions. As a result, groundwater level at those locations is close to the land surface. However, this should not affect the main underground infrastructure in Singapore, the underground transport system which is approximately 30 meters below the ground. Other infrastructures (e.g. pipes) within the shallow subsurface environment are also often below the groundwater table and are designed for submerged conditions. Therefore, a groundwater table mound of 1 or 2 meters due to bio-retention systems should not damage these structures.

12. About the root depths of vegetation:

Table 1: the root depths are well below the water table; this is unlikely, since many species would suffer under such conditions. The Authors should provide a reference to justify this choice.

[Response] According to Singapore National Parks Board (Npark), tree height in Singapore varies in the range from 4 meters to more than 20 meters (NPark, 2011). Based on the relationship between tree height and root depth from Štofko (2010), the root depth is approximately 3.5 meters for a 4.0 meter tree. In addition, a recent survey in Singapore shows that the root of vegetation can be more than 3 meters (Ngo et al., 2013). Thus, we believe that our assumption on root depth is reasonable. Furthermore, most of the vegetation with deep roots locates in the upstream of the catchment where the groundwater table is mostly below 5 meters (Fig 2). The rest, locating in the downstream area, either has shallower root or is wetland vegetation that is more resistant to flooding conditions.

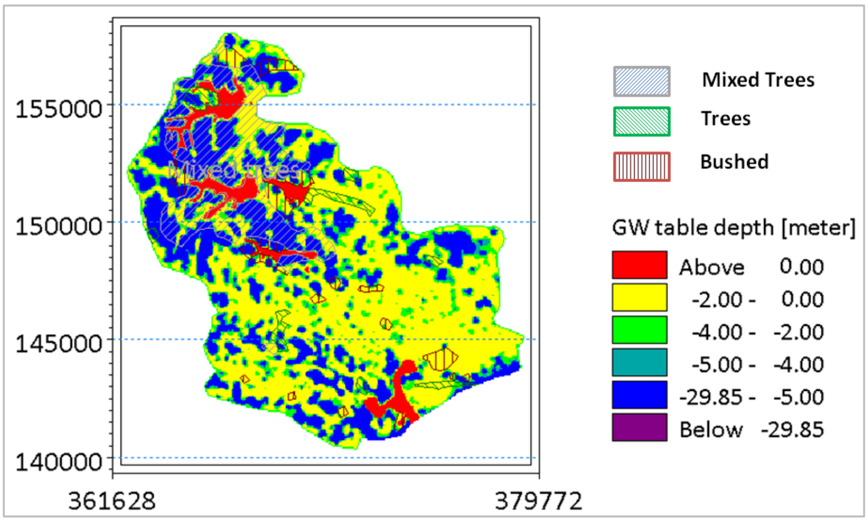

Fig 2. Groundwater (GW) table depth and vegetation distribution Marina-like catchment

13. About the evaporation process from groundwater:

Fig. 1: I do not think that there should be evaporation from groundwater.

[Response] We apologize for the mistake, as it should be evapotranspiration from groundwater instead of evaporation. We will correct it in the revised manuscript.

For the model used in this study, soil evapotranspiration only takes place when water table is above the extinction depth (i.e., the summation of roof depths and thickness of capillary fringe) and is calculated follow:

$$ET_{SZ} = ET_{rate} F_{ETSZ} \Delta t$$

where $ET_{rate} = ET_{ref} k_c$ (ET_{ref} is reference evapotranspiration and k_c is crop coefficient), F_{ETSZ} is 1 when water table is in the root zone and decreases linearly from 1 to 0 when the water table is below the roof zone, but above extinction depth.

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Responses to Dr. Olga Barron (Referee) for the Manuscript ID: hess-2012-522

Title: "ASSESSING THE HYDROLOGIC RESTORATION OF AN URBANIZED AREA VIA INTEGRATED DISTRIBUTED HYDROLOGICAL MODEL" by D.H. TRINH and T.F.M. CHUI

We would like to thank Dr. Barron for her helpful comments, especially about the influences of soil properties, rainfall data interval and simulation time steps on rainfall partitioning and river discharge. We have carried out a sensitivity analysis on the above three factors. The results, reassuringly, lead to the same main conclusions that were drawn previously. Please see the detailed responses below.

1. Models do not allow developer to influence recharge, runoff coefficients, etc, but only the catchment and subsurface characteristics, the conceptualisation of the catchment water balance has to be well defined, particularly when those characteristics have to be spatially distributed.

[Response]

We apologize for not stating it clearly in the original manuscript. In terms of rainfall partitioning between direct runoff, infiltration and groundwater recharge, we cannot explicitly specify the proportions as the model simulates the infiltration and subsurface water movement according to the different soil properties and rainfall conditions. However, in terms of direct runoff from paved vs unpaved areas, we can specify a "paved runoff coefficient" that defines the fraction of ponded water that drains to the drainage system. Thus, if 25% of surface area is paved, then a paved runoff coefficient of 0.25 removes 25% of the ponded water and drains it directly to the river network. The remaining 75% will be available for infiltration and those that does not infiltrate will flow as overland flow to the adjacent cells. For our case study, the paved runoff coefficient is respectively set as 0.3 and 0.7 for pervious and impervious surfaces, as specified in the manuscript.

We will make it clearer in the revised manuscript.

2. The main concern about the reviewed paper is related to an absolute lack of any observation data (apart from meteorological data), and all presented results and discussion are solely based on the model outcome. This is the main limitation of the suggested results: the model doesn't seem to be validated at all. In couple models, rainfall partitioning to recharge and runoff is depended on the soil properties, and it is very sensitive to unsaturated zone parameters. Incorrect partitioning, resulting from inadequate parameters selection propagates the error to simulated river flow. How much trust one can put in the model outcomes, when no evidences were offered on whether the model treats the rainfall

partitioning correctly? Even in relative terms, the analysis of difference between selected scenarios on baseflow or peak flow could be wrong.

[Response]

We understand and acknowledge that our models, without calibration and validation, are not producing the exact and precise responses of any particular system. Instead, we are hoping to develop general understandings on the overall effects of green structures using the physically based models with realistic choice of parameters, and that the generic results and insights are more widely applicable, as we have stated on p. 4105 lines 19-26 and on p. 4118 lines 1 to 5.

We also agree with Dr. Barron that rainfall partitioning to recharge and runoff is sensitive to soil properties. We therefore simulate the different scenarios with a soil hydraulic conductivity that is one order of magnitude lower. For the aggregated water balance over one year (Fig.1), the rainfall partitioning still follows the same patterns as the original simulation. For example, when compared with the pre-urbanized scenario, there is still close to a 10% increase of direct runoff and 10% decrease in evapotranspiration in the urbanized and hybrid scenarios. There is also more baseflow in the hybrid scenario when compared to the urbanized one due to the green structures.

In terms of peak outlet discharge (Fig.2), the low hydraulic conductivity leads to an increase of peak discharge by 50 m^3/s in the pre-urbanized scenario. Similarly, the decrease in hydraulic conductivity also results in a higher peak discharge in the hybrid scenario. However, the amount of increase, 100 m^3/s, is higher than pre-urbanized one. This is because the low hydraulic conductivity of the native soil not only reduces rainfall infiltration but also limit the exfiltration of the bio-retention system. The change in hydraulic conductivity however does not significantly affect the peaks in the urbanized scenario due to the low percentage of pervious area. Although the absolute values of peak discharges change with the hydraulic conductivity, the relative differences among the scenarios are still the same. In other words, there is still a drastic increase of peak discharge in the urbanized scenario and a partial recovery in the hybrid one.

In conclusion, although the change in hydraulic conductivity leads to some changes in the model results in terms of the aggregated water balance as well as the absolute values of outlet peak discharge; the main observations of how urbanization influences hydrological conditions and how green structures restores it are still the same. Thus, we believe that the model outcomes are reliable for drawing the main conclusions of this study.

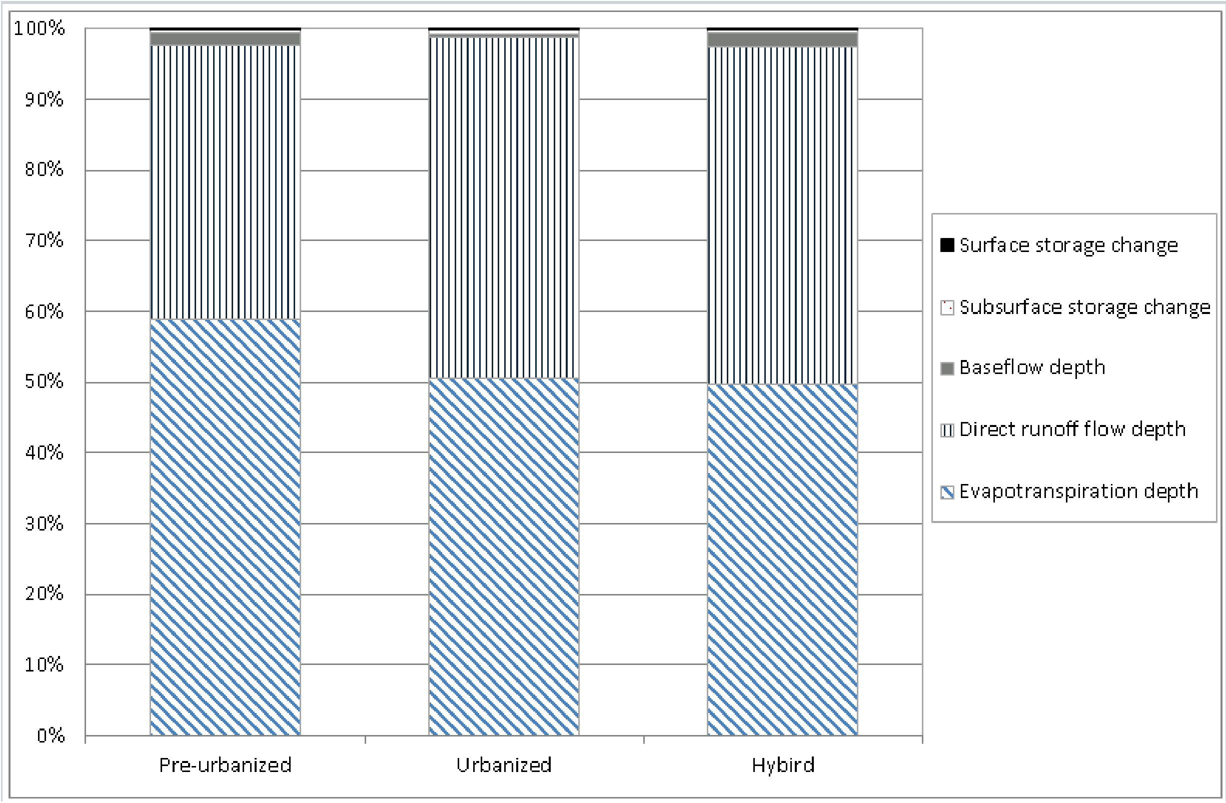

Fig 1. Water balance aggregated over one year for different scenarios with a lower soil hydraulic conductivity

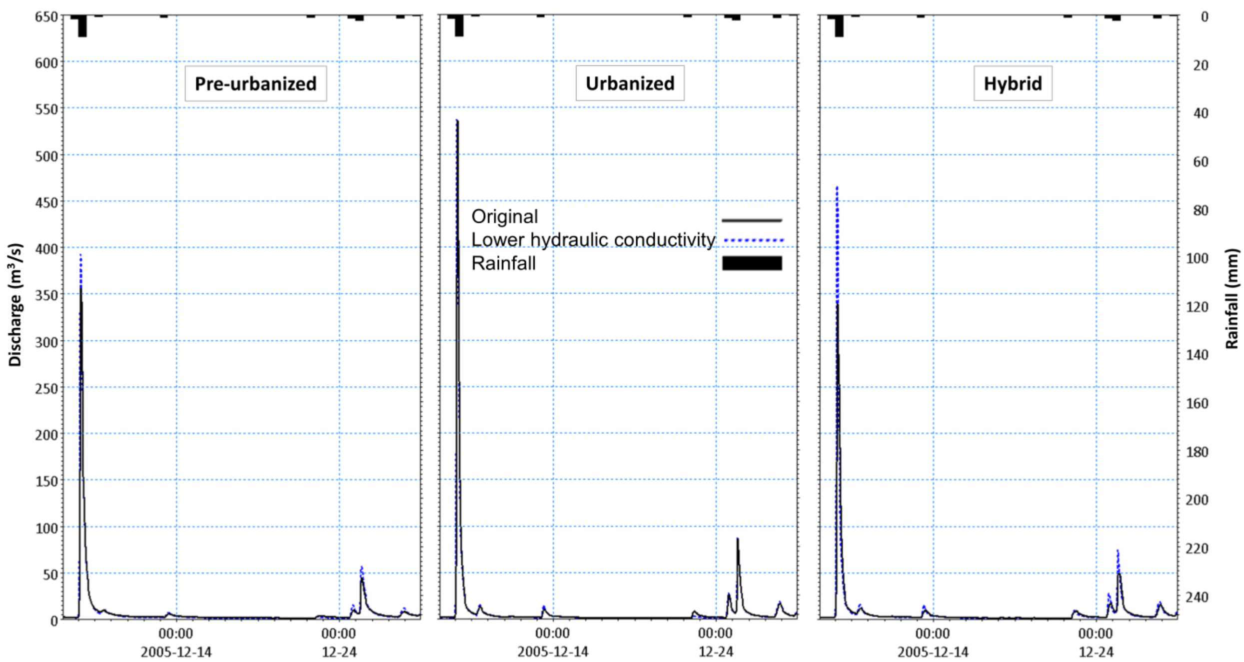

Fig 2. Comparison of peak discharges under different scenarios

3. About the simulation time step and rainfall input resolution:

If the input data was hourly rainfall, how these data were used for when the river routing was model with time step of 1 min, while other components of the water balance – 0.25 and 0.5 hours?

[Response]

When the time steps taken are finer than the data input, the model would then linearly interpolate the data for the simulated time step. The simulation time steps of the several components can be different given that they meet their individual model requirement. Also, to simulate the flow exchanges between the components, their time steps have to be even multiples of each other (e.g., overland flow time step is even multiple of river routing one; saturated zone is even multiple of unsaturated zone).

This study examines the rapid response of peak outlet discharge (in time scales of minutes), as well as the long-term groundwater response (in time scales of days and months). Thus, we believe that our original choices of data resolution and simulation time steps (i.e., 1 min for river routing, 0.25 hours for overland flow, 0.5 hours for unsaturated zone and 12 hours for saturated zone) are good compromises. It should also be noted that other than river routing, the time steps specified are maximum allowed ones. During periods of heavy rainfall, the actual time steps are reduced to maintain model stability as well as accuracy.

We will provide more information about rainfall input interval and choice of time step in the revised manuscript.

4. About sensitivity analysis:

Was any sensitivity analysis applied to assess 1 hourly rainfall data distribution with that hour on the simulated river flow and particularly the peak flow analysis?

[Response] We thank Dr. Barron very much for the suggestion. We have carried out a sensitivity analysis with two additional simulations:

1) **Original rainfall data interval (1 hour) but coarser simulation time steps (5 min for river routing, 0.5 hours for overland flow, 1 hour for unsaturated flow, and 12 hours on groundwater flow)**
2) **Rainfall data of smaller interval (5 min) with the original simulation steps**

The peak outlet discharges (i.e., highest peak, medium peak and small peak) of the above two simulations are presented in Fig. 3 together with those from the original simulation. The increase in simulation step sizes does not affect the time and the magnitude of the peak discharges. The more detailed rainfall input increases the peak discharges at most 20 m^3/s, and changes the time of occurrence by at most 1 hour. However, the changes are not significant enough to affect the main conclusions of this study. Thus, we think the original rainfall data interval and the simulation step sizes are reasonable for this study.

We are happy to add the above findings to the revised manuscript.

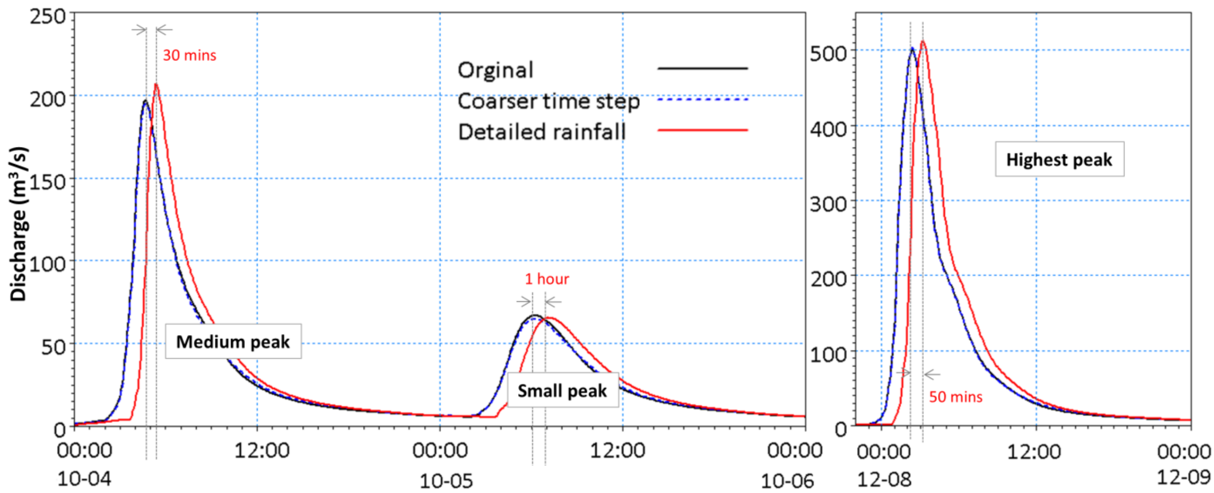

Fig 3. The influences of time step and rainfall data resolution on peak outlet discharges in Bio-retention scenario

5. About vertical model discretisation:

What was the reason for vertical model discretisation for 45 layers? It is not particularly clear why such discretisation required.

[Response] The vertical discretisation is chosen to match with the soil profile description and the required resolution of the simulation. The information on the soil profile in the studied catchment is relatively detailed in the top layer. In addition, the Richards equation is used to accurately simulate the infiltration process in the unsaturated zone. The vertical discretisation should ideally vary from 10-25 cm in the uppermost grid points to 50-100 cm in the bottom of the top soil profile. Therefore, we apply a vertical discretization of 20 cm for the first 1 m depth, 50 cm for the following 5 m depth, and then 100 cm for the rest of the domain. This discretisation results in 45 vertical layers.