GENERAL

I have read the manuscript entitled "Climate or land cover variations: what is driving observed changes in river peak flows? A data-based attribution study" with interest. The topic of the manuscript is suitable for the journal. Indeed, it has been widely referenced but the need to know the significance of drivers for floods in different areas still exists.

In this case, 29 catchments in Flanders were selected for the analysis of the influence of catchment characteristics, climate and land use variables on floods. In general, the objective of the paper is clear, "to investigate the (relative) importance of climate variability and land cover changes related to changes in river peak flows", and results obtained are interesting. However, in my opinion, the authors should work further on the analysis and discussion of those results, trying to better explain the dependencies between drivers and floods, but specially the influence of interactions between drivers, that explain up to the 32% of the variability on river peak flows.

Dear reviewer

We thank you for your evaluation of our manuscript. We appreciate the constructive comments and suggestions you have made and would like to respond to them below.

Several comments deal with the lack of a discussion on the interaction effects. Hence, we investigated this further in detail and added a subsection in the results on these interaction effects. Also, we added some more discussion on the single driver effects. As such, the manuscript changed significantly, and we added a revised manuscript to this reply.

COMMENTS

Comment 1. The abstract is clear and concise but it lacks some general conclusion.

REPLY. We will add some more conclusions in the abstract, with respect to the interaction effects.

Comment 2. Introduction is well structured, follows a clear central theme and mentions many references, that could be used to enrich the text extracting some information from them that could help establishing the state of the art in the topic. Little is said in the introduction about the significance (in other studies) of one of the main drivers in this study: catchment characteristics, in my opinion some references should be included on this.

REPLY. We prefer to keep the introduction as it currently stands. With respect to the catchment characteristics: based on some of the other comments, the results section will significantly change in the revised manuscript. And the effects of single drivers will be discussed more in depth, where our results will be compared with literature.

Comment 3. The case study is not sufficiently described. In my opinion, a general description of the area, considering average climate, geology, slopes, hydrology, vegetation should be included (are they spatially variable?), in order to have a general idea on the study area characteristics and the representativeness of the selected catchments.

REPLY. We will add below paragraphs under the section Case study:

For this case study, 29 catchments are selected, evenly spread across Flanders, the Northern part of Belgium (Figure 1).

Flanders, with 6.4 million inhabitants, covers around 13,500 km2. The coastal area in the North-West of the region mainly consists of sand dunes and clayey alluvial soils in the polders. The central area, ranging between 0 and 10 mTAW, mainly consists of loamic soils. The North-Eastern part, known as the Campine region, has sandy soils at altitudes around 30 mTAW. The Southern part with silty soils has low hills op to 150 mTAW. The maximum height is 288 mTAW in the South East. The DTM in Figure 1 was taken from "Digitaal Hoogtemodel Vlaanderen" (https://overheid.vlaanderen.be/producten-diensten/digitaal-hoogtemodel-dhmv). Soil texture is available from www.dov.vlaanderen.be.

Flanders has a maritime climate (Cfb, according to the Koppen climate classification), with average temperatures of 3 °C and 18 °C in January and July, respectively. There is a small gradient present with lower temperatures in the South-East (annual average of 10 °C) towards higher temperatures in the North-West (annual average of 11 °C) (data between 1981-2010); the average temperatures in Flanders, further, has been rising over the past 30 years with 1 – 1.5 °C. Average evapotranspiration was 540 mm/year in 1980 and rose to 625 mm/year in 2010. Yearly precipitation varies between 600 mm/year to 1000 mm/year, with little variation throughout the year, and little spatial differences (Brouwers et al., 2015).

Comment 4. Table 1 includes the period and the number of years of discharge data for each gauging station. These information is repetitive and in my opinion not needed, as data used are those from 1992 to 2015 for all stations. Eliminating those columns may leave space enough for including data on fig. 3 (soil texture) in this table.

REPLY. We would like to keep table 1 as it currently stands. To estimate peak flow anomalies, we use all available data (e.g. for Grobbendonk Troon, this is 1982 – 2018). Then, the variation is explained based on the selected predictors, and due to the availability of these predictors, the period is reduced.

Further, see also the comment lower related to Fig. 3 – we wish to keep Fig. 3 as is, in order to make a visual comparison between the catchments possible (wrt soil texture).

The methods section needs to be explained further as some questions are not clear enough:

Comment 5. Is daily discharge data an adequate time resolution to explore river peak flows in catchments smaller than 100 km2? Many of the catchments included in this study are quite small, so that discharge response, especially during peak flows, could be lower than the daily scale proposed; could the authors justify that the selected scale is adequate for the analysis of high flows?

REPLY. Please note that, unfortunately, in the manuscript it was erroneously noted as daily discharge data (P3L16 and P3L21). However, the analysis has been carried out based on hourly data. This will be corrected in the revised manuscript to state hourly discharge data was used.

The hourly discharge data is freely available through https://www.waterinfo.be/default.aspx?path=NL/Rapporten/Downloaden, under section 1A Waterlevel/riverflow select: Discharge (Hourly), and you can verify this hourly data is available.

Comment 6. Using a figure/example/scheme could help understanding better the estimation of peak flow anomalies in section 3.2.

REPLY. In the revised manuscript, we will add a figure under Section 3.2 and replace the text in order to better explain the estimation of peak flow anomalies. See the revised manuscript in supplement to this reply.

Comment 7. In section 3.3. The consideration of characteristics other than climate and land use in the analysis is interesting; however, the authors should justify the inclusion of catchment characteristics on the analysis and the selection of the included characteristics. Why those and not others? The general description of the area may help on this, if the selected characteristics are the ones that show higher variability in the area...

REPLY. Soil texture taken into account as there are significant gradients in Flanders and thus differences amongst the various catchments: e.g. L01_491 has mainly a loamic soil texture, whereas L07_286 is mainly siltic, etc.

Slopes should definitely be taken into account, as this has a known/obvious impact on rainfall runoff. Similar for the river density (ratio of river length over catchment area).

Catchment area is often linked to peak flow sensitivity, and thus was initially taken into account for this study. However, later in the study, this variable is discarded, based on statistical considerations. See also the start of the discussion (P6L21).

Note that these characteristics also come back in the concepts of the hydrological model WetSpa when assigning runoff coefficients.

Comment 8. Nothing about soil is said in this section

REPLY. Soil texture is mentioned as possible drivers, P4L9. We don't see what you are missing here?

Comment 9. Some information is repeated in section 2 and section 3.3. The authors should decide where to include the completed information just once. For example: P3L7-9: "For land cover, the 30 classes from the ESA CCI Land Cover project (www.esa-landcovercci.org) were regrouped into the 6 IPCC land categories, i.e. cropland, forest, grassland, wetland, settlement and other land...". P4L19-22: "Land cover and land cover changes have been described in the past through the ESA CCI project (www.esalandcover-cci.org): . . .. The 22 land cover categories (or 30, when including 'level 2' or 'regional' labels) identified in this project are grouped into the six IPCC land categories, i.e. settlement, agriculture, grassland, forest, wetland and other area."

REPLY. Indeed, this was repeated in both sections. We would adjust the text in Section 3.3 to: "Six IPCC land categories (settlement, agriculture, grassland, forest, wetland and other area) are taken into consideration as possible drivers for this study.."

Comment 10. In table 2 soil textures are included. However, nowhere in the text or in other figures and tables the authors talk about textures. They base their analysis in soil textures or in soil classes?? This should be clarified and corrected.

REPLY. Analysis is based on soil textures – not soil classes. We will scan the manuscript and clarify/correct where needed.

Comment 11. The first part of the Results section, that referred to steps followed "Prior to the first step of the model building process", should not be included in this section but in methodology as no results are explained here (P5L26-P6L4).

REPLY. OK. This will move to the relevant paragraphs of the methods section in the revised manuscript.

Comment 12. Is it possible to consider at the same time variables that change spatially but not on time (catchment characteristics) and variables that change on space and time? How should results be considered? Catchment characteristics explain a high % of the variability in flood records, however, they are supposed to

change only spatially, from one catchment to another, not for the same catchment from one year to the next. However, climate or landuse, explain less variability, but they change from one catchment to another and also in the same catchment on time. How should these be considered when analyzing results? Some discussion on this point would be interesting.

REPLY. Yes, temporal and spatial data can be considered simultaneously – through panel data analysis.

Catchment characteristics only show a spatial variation and no temporal variation. And, indeed, they explain a high % of the variability in flood records. Meaning that the flood responses is strongly catchment specific, and in a lesser degree depending on fluctuations of the climate, and land use changes.

For the revised manuscript, we will change the first paragraphs of 3.4.1 (P4L26-29) to:

"A model is built with the techniques and ideas of panel analysis, which is widely used in social sciences, epidemiology, and econometrics where two dimensional data is analysed. Typically, in those sectors data is collected over time and over the same individuals. Here, the two dimensions are space and time – input data can show only a temporal variation (climate data), only a spatial variation (soil texture), or a combination of both (LULC). Note that, typically, climate data does show a spatial variation as well. However, we assume the area of Flanders to be homogeneous with respect to the considered climate data."

And, we would add in the conclusion (P7L13) *"[…] topography and soil texture. The high importance of these time-invariant factors (topography and soil texture) indicate flood response in Flanders is highly catchment specific, and to a lesser degree depending on fluctuations of the climate, and land use changes."*

Comment 13. P6L10: "The final model, with 26 terms in 9 predictors. . .". Which terms and predictors? The 9 predictors that in figure 5 are higher than the 50%? And terms? I would appreciate if the authors could specify a bit more.

REPLY. The predictors: indeed the 9 predictors in Figure 5 that are higher than the 50%. We believe this should be clear by P6L5-9.

We will include the coefficients of the final model in the revised manuscript (see table 3 in the revised manuscript in supplement to this reply). One should, however, be careful when interpreting these coefficients. E.g. the coefficient of Settlement in the final model is equal to -3.04. At first sight, an increase of settlement would thus correspond with a decrease of peak flow anomaly. However, the interpretation of the coefficients is more complex:

- An increased Settlement also impacts the interaction effects, and the coefficient becomes: (-3.04 – 0.85*Slope + 6.47*Loam + 17.85*Settlement);

- An increased Settlement means that Agriculture (13.08) and/or Forest (3.71) decrease – and there again, the interaction effects of Agriculture and Forest come into play.

Thus, because of the dependency between variables, the interpretation of the resulting model coefficients β is not straightforward. Therefore, we did not include this table initially. However, based on this comment, we will include it in the revised manuscript.

Comment 14. Figure 6 needs more explanation and discussion in the text. Which are the most problematic catchments? Can those worse results be related to some specific aspect/characteristic of the catchment?

REPLY. Observed peak flow anomalies in catchments L07_289 (Mark at Viaene) and L08_233 (Zuunbeek at Sint-Pieters-Leeuw) have a bad correspondence with their modelled results. The Mark catchment has a long history of flooding – as from the 2000s, the local authorities have installed several mitigation measures (hydraulic structures, retention basins etc.), effectively decreasing the flood risk. This is visible in the observed peak flow

anomaly, however, the regression model used in this study cannot capture such management changes. Further, for the Zuunbeek catchment at Sint-Pieters-Leeuw, increased peak flow anomalies are observed as from the middle of the period. This is due to the extreme flood season in the winter of 2001-2002 where 7 events were observed with peak discharges exceeding 6 m³/s, corresponding to empirical return periods larger than 1 year, based on data between 1978 and 2016.

We will add the above paragraph in the Results section of the revised manuscript.

Comment 15. What about interactions between variables? How do they work? Which are the most significant? Does the same landuse change have same results in different climatic conditions? And for different catchment characteristics? And what about climate variability? Has the same effect under forest or under agricultural land? What else can be extracted from figures 7 and 8?

REPLY. A section on interaction effects will be added in the revised manuscript.

Comment 16. Figure 8 footnote should be corrected: "Increasing settlement area will, in most cases, lead to increased 5 peak flows". This is not what the figure shows but what the authors read from the figure. The figure shows boxplots shoing the results given by the model for all the catchments when increasing (or reducing?? See the text of P6L18) settlement percentage to reduce (or increase?) forest. . ..

REPLY. We will change the caption in the revised manuscript to: "Figure 8. Peak flow changes by increasing settlement area trough decreasing forest, grassland or agriculture."

Comment 17. What does figure 8 really show? Contradictions are found in the text: P6L18: "1% of the total area from settlement to forest, grassland and agriculture, respectively" P7L17: "1% increase in urbanization could lead in some cases to a 5% increase in river peak flows"

REPLY. We would replace the word 'urbanisation' on P7 to 'settlement'. We further don't see the contradiction? Ref. also comment higher on the caption of this figure.

Comment 18. In this figure (8) it can be observed that changes in peak flows vary depending on which type of landuse is reduced to increase settlements. Could the authors say something about that? What do other authors say about it?

REPLY. Indeed, we specifically quantified the changes in peak flows for increased urban area depending on the type of LULC that is reduced. In literature, we did not find similar studies where the independent effects were quantified. Most of the references look at the total picture by comparing the situation for two distinct periods in time and, as such, observing/modelling the integral response of a catchment due to e.g. the simultaneous decreases in forested area and agricultural area in favor of urban area.

Comment 19. The discussion and conclusion section repeats 3 times that the model explains the 60% of the flood variability, but it does not discuss which could be the reasons why in some catchments the fitting or the consistency is not good. In P6L29-30 the authors say "Since the explanatory variables all have a smooth variation over time, it is a priori almost impossible for any simple regression model to mimic these step changes". However, there are important changes in landuse around the year 2002.

REPLY. Ref. comment 14, and reply on this comment, higher. We now looked deeper into the reasons why we see a bad fit for some catchments. For the revised manuscript, we will further take out the comment on the explanatory variables and their smooth variation over time.

Comment 20. The comment on the time span used in the analysis (P6L32-P7L3) is not a conclusion and in my opinion, should not be included neither as a discussion.

REPLY. Okay, we will delete this paragraph in the revised manuscript.

Comment 21. As the author say "Obviously, given the complexity of these environmental systems,the simple linear model will not be able to capture/describe all effects – indeed, it was seen that interaction effects between catchment characteristics, land cover and climate variability are equally important in explaining changes in river peak flows." In my opinion a deeper analysis of results and discussion on this part would notably improve the impact of the paper.

REPLY. A section on interaction effects will be added in the revised manuscript.

Comment 22. P7L16-17: "The model also showed that, for most of the considered case studies, deforestation indeed leads to increased peak flows" where can this effect be seen? Deforestation? Or decreasing forest to increase settlement, agriculture or others?. "Moreover, 1% increase in urbanization could lead in some cases to a 5% increase in river peak flows". Can these results be analyzed a bit more? In which cases? Which characteristics have those catchments??

REPLY. Correct, the use of the term "deforestation" might be out of place here, as, indeed, it is rather decreasing forest to increase settlement and others. Will replace this sentence to: "The model also showed that, for most of the considered case studies, a decrease in forested area to increase settlement area indeed leads to increased peak flows."

The catchment with the strongest influence are flat catchments with a high loamic content. In this case: L01_491, L01_492, L01_496 and L05_404 have the highest impacts. This confirms the results from the interaction effects, which will be described in a separate subsection of the revised manuscript.

Other comments:

Comment 23. Which is the resolution of the DTM mentioned in section 3.3? In P4L6 the authors say "The slope at every point in the catchment are calculated", which is the resolution of those points? (1x1; 5x5, meter?)

REPLY. Resolution of the DTM is 100x100m. Will add this on P4L5 of the original manuscript.

Comment 24. P4L15. "W; (NW, N), (NE; E; SE), (S; SW); U; C; A, with N, E, S and W referring to wind directions". Please consider re-writing this sentence. Comma and semi-colon are arbitrary used. Parenthesis do not help understanding groups.

REPLY. Correct, comma and semi-colon were unfortunately arbitrarily used. Groups are separated by parentheses and semi-colons. Weather types within each group are separated by commas. We hope the following is more clear:

"The remaining weather types are: W; (NW, N); (NE, E, SE); (S, SW); U; C; A, with N, E, S and W referring to wind directions, C and A to cyclonic and anticyclonic atmospheric patterns, respectively, and U to an unclassified weather type."

Comment 25. In figure 3 the word fraction should be replaced or accompanied by classes not to create confusion with soil fractions (sand, silt and clay)

REPLY. Okay, will be replaced by "Figure 3. Relative areas of soil texture classes (arenic, loamic and siltic) for the selected catchments. Data from: www.dov.vlaanderen.be" in the revised manuscript.

Comment 26. Figure 3. Information included in this figure can be moved to table 1.

REPLY. Correct, this could be included in Table 1. However, we specifically opted for this graphical representation. In this way, the reader can more easily see what the dominant soil class is for that particular catchment. The order of the catchments is the same as in Figure 2 and Figure 6, which makes a comparison between these figures easier. Also, with the current graphical representation, it is easier to compare two (or more) catchments among each other – in table format, this is a bit more difficult.

Reference list needs revision. For example:

Comment 27. "IPCC, 2014": review formatting. Doi included corresponds to: IPCC, 2013: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535pp, doi:10.1017/CBO9781107415324.

REPLY. Indeed, doi is referring to the wrong document. In the revised manuscript, this reference will be updated and formatted according to guidelines mentioned on http://www.ipcc.ch/report/ar5/syr/.

Comment 28. "Blöschl, G., Ardoin-bardin, S., Bonell, M., Dorninger, M., Goodrich, D., Gutknecht, D., Matamoros, D., Merz, B., Shand, P. and Szolgay, J.: At what scales do climate variability and land cover change impact on flooding and low flows ?, Hydrol. Process., 1247(March), 1241–1247, doi:10.1002/hyp, 2007." doi is not complet. https://doi.org/10.1002/hyp.6669 and journal volume is 21.

REPLY. This will be corrected in the revised manuscript.

Comment 29. Mediero et al., 2015. Last author surname is not complete, lacks first letter.

REPLY. This will be corrected in the revised manuscript.

I decided to review this manuscript because the title was quite enticing. The manuscript was interesting overall, but it is simply too short the work done. Each of the figures regarding results should carry a paragraph, but most of them do only a sentence. I entirely agree with the comments by Reviewer 1, so thankfully I don't have to repeat here. Reviewer 1 questions the variability by space of some variables and that by time of other variables. I understand that's why the authors used the panel data analysis, but it seems explained/discussed inadequately. I do not personally know the analysis method, and I still do not understand either.

I would like to point out that there are many paragraphs that are too short for a paragraph (e.g. line12-13onpage3). Please make them a complete set of thoughts. I also recommend that the authors separate discussion from conclusion. To me, the biggest problem with the manuscript is a lack of a general conclusion.

Dear reviewer

Thank you for reading our manuscript and providing us feedback. As you generally agreed with the comments raised by reviewer 1, we would like to refer you to our reply on the comments of reviewer 1; and we invite you to read the revised and significantly expanded manuscript.

In general, this manuscript covers an interesting topic and makes some conclusions leading to new thinkings regarding the impacts of climate change and land use/cover change on water resources. However, to the manuscript itself, I made a few suggestions and comments as a potential reader.

Dear reviewer

Thanks for your evaluation of our manuscript. We appreciate your comments and suggestions and would like to respond to them below.

Comment 1. Page 1 Line 7 - "increased urbanization": Not only urbanization but also some other land use/cover categories can have a great impact on the hydrological cycle. This word is recommended to be revised.

REPLY. OK. This will be changed to "land use/land cover changes" in the revised manuscript.

Comment 2. Page 1 Line 19 - "...it is very likely that further changes will...": You have to give a citation here or tell readers why you can make this conclusion.

REPLY. The reason why we make this conclusion, is expressed further in that paragraph: climate change projections from IPCC (2014) and impact analysis from Tabari et al. (2015), and UN (2018), Poelmans (2010) and Ruimte Vlaanderen (2017) talk about future changes in the built environment.

Comment 3. Page 2 Line 1 - "...knowledge on some driver-effect mechanisms is still limited (Blöschl et al., 2007; Merz et al., 2012)": When you make the conclusion of the limitation in this study, recent articles should be cited in order to inform the reader that the conclusion is not out of date.

REPLY. Okay, we will add more recent references in the revised manuscript: Van Loon et al (2016) and Dey and Mishra (2017).

Comment 4. Page 2 Line 15 - "...mainly because of the heterogeneity in catchments globally and the scale of the river basin/catchment considered": What kind of heterogeneity catchments have? (heterogeneity of land use/cover change or heterogeneity of hydrological responses) Moreover, citations should be given to the conclusion here if this result is not a part of your research.

REPLY. Here, we mean the heterogeneity of hydrological responses of the catchments, partially originating in the heterogeneity of lulc changes. We will clarify this in the revised manuscript, and give the reference to Zhang et al (2017) as an example.

Comment 5. Page 2 Line 30 - Use Section instead of Sect.

REPLY. OK. This will be changed in the revised manuscript.

Comment 6. Page 2 Line 32 - As you are talking about the study area. "Study area and data" is suggested to be used for this section.

REPLY. OK. This will be changed in the revised manuscript.

Comment 7. Page 2 Line 35 - Give the full explanation of mTAW.

REPLY. mTAW is the local height datum, equal to the height, in meters, above local mean seal level. This will be added in the revised manuscript.

Comment 8. Page 3 Line 9 - You have to make the consistent on the numeric format. Please be advised to use 29 instead of Twenty-nine.

REPLY. According to the "manuscript preparation guidelines for authors", numbers are spelled out when they begin a sentence. Therefore, we use "Twenty-nine" here. Therefore, we suggest to leave this as it currently stands.

Comment 9. Page 3 Line 14&15 - " For soil texture, taken from www.dov.vlaanderen.be, 3 domina...": Minor grammar suggestion. You can use "soil texture data is obtained from..."

REPLY. OK. We will adjust the revised manuscript accordingly.

Comment 10. Page 3 Line 21 - "The aim of the study is to find the (main) drivers ...": You have to make a decision whether including the word in the bracket or not.

REPLY. OK. The brackets will be left out in the revised manuscript.

Comment 11. Page 4 Line 6 - "...based on the DTM, the slope at every point in the catchment...": You do not have to say at every point; this sentence is suggested to be revised to "the slope in the catchment".

REPLY. OK. This will be left out in the revised manuscript.

Comment 12. Page 5 Line 14 - Equation 2: What is captalized T?

REPLY. Capitalized T is the transpose of the vector/matrix. This will be added in the revised manuscript.

Comment 13. Page 6 Line 12 - "...the model did not improve (not shown)...": The model did not improve what?

REPLY. We will change this to " … model performance did not improve …".

Comment 14. Page 7 Line 11 - "...as seen in Figure 9:": Figure 9 or Figure 10?

REPLY. Figure 9. The idea is here that we link conclusions from Figure 9 with the Wetspa model (Figure 10). We will change this sentence to: "As such, findings with respect to the potential runoff coefficient from Wetspa can be related with the conclusions based on Figure 9".

Comment 15. Page 13 - Figure 2: You don't have to give the data source here.

REPLY. OK. We will delete the reference in the revised manscript.

I read the revised manuscript which the author provided in the first referee's comment place. Although there are many places have been strengthened, I think this manuscript needs to be improved in grammar checking and make clear meanings in some sentences as well.

The manuscript has gone through a major revision. Therefore, we would like to refer to the "track changes" version to see all changes made. Below is a summary of the main changes made, based on the comments from the reviewers.

- Added conclusions in the abstract.
- Added description of the study area.
- Added details on the methodology, e.g. how we select peak flows and assign peak flow anomalies
- Added more details on the final results, incl. deeper analysis and interpretation, additional analysis of interaction effects, and comparison with an existing hydrological model (WETSPA) which is able to take LULC classes explicitly into account.
- Added data availability and author contribution section.

Climate or land cover variations: what is driving observed changes in river peak flows? A data-based attribution study

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Abstract. Climate change and land cover changes are influencing the hydrological regime of our rivers. The intensification of the hydrological cycle caused by climate change is projected to cause more flooding in winters and ~~an increased urbanization~~land use/land cover changes could amplify these effects by e.g. a quicker runoff on paved surfaces. The relative importance of both drivers, however, is still uncertain and interaction effects between both drivers are not yet well understood.

10 In order to better understand the hydrological impact of climate variability and land cover changes, including their interaction effects, we fitted a statistical model to historical data over three~~3~~ decades for 29 catchments in Flanders, covering various catchment characteristics. It was found that the catchment characteristics explain up to 18% of changes in river peak flows, climate variability 6% and land cover changes 8%. Steep catchments and catchments with a high proportion of loamic soils are subject to higher peak flows and an increase in urban area of +1% might cause increases in river peak flows up to +5%.

15 Interaction terms explain up to 32% of the peak flow changes~~in the model~~, where flat catchments with a low loamic soil content are more sensitive to land cover changes with respect to peak flow anomalies. ~~An increase in urban area of +1% might cause increases in river peak flows up to +5%.~~

1   Introduction

Our environment has undergone unprecedented changes over the past decades, and it is very likely that further changes will 20 take place in the coming decades. With respect to the climate system, increases in frequency, intensity and/or amount of heavy precipitation are globally reported for the majority of the land areas (IPCC, 2014); for Flanders (Belgium) in particular, extreme precipitation might increase with +50% in winter and +100% in summer by the late 21st century (Tabari et al., 2015). With respect to the built environment, the world continues to urbanize, with nowadays 55% of the world's population living in urban areas. This is in shear contrast with 1950, where only 30% of the world's population was urban (United Nations, 2018). For 25 Flanders, this is translated into a 300% increase in built-up area over the past four decades (Poelmans, 2010; Ruimte Vlaanderen, 2017).

Changes in climate and urbanization both cause changes in the hydrological regime of catchments in general and changes in flood frequencies in particular. Here, we aim to attribute observed changes in river peak flows to drivers related to the climate and to a changed land use/land cover. Previous attribution studies related to trends in flood hazards faced several challenges. 30 These were, among others, summarized by Merz et al. (2012). The attribution process typically involves two steps: detection of change and attribution of that change to its various drivers. In the first step, the detection of change is often challenging: the signal of flood time series (or river peak flows in general) typically shows a high natural variability, with a low signal-to-noise ratio. Moreover, floods form part the larger hydrological system and, as such, show a quite complex behavior. With respect to the attribution issue in the second step: in a complex hydrological system, different drivers act in parallel, with interactions 35 between them. The integral response of the system to all these drivers and interactions governs the changed hydrological behavior. And, finally, the power of attribution studies often lies in a deep process knowledge related to the proposed driver-

effect mechanisms (Hegerl et al., 2010); unfortunately, knowledge on some driver-effect mechanisms is still limited (Blöschl et al., 2007; Dey and Mishra, 2017; Van Loon et al., 2016; Merz et al., 2012).

On the driver-effect mechanism between climate variability and river peak flows, many studies have shown there is a link between weather types and flooding, sometimes through the intermediate variable of precipitation (Brisson et al., 2011; Hirschboek, 1991; Mediero et al., 2015; De Niel et al., 2017; Pattison and Lane, 2012; Pfister et al., 2004; Prudhomme and Genevier, 2011; Santos et al., 2015; Smith et al., 2011; Wilby and Quinn, 2013). For the area of Flanders, westerly atmospheric fluxes would, in general, cause an increased winter precipitation amount and intensity, leading to increased river peak flows (Brisson et al., 2011; De Niel et al., 2017; Willems, 2013).

On the driver-effect mechanism between land use/land cover and river peak flows, most studies hypothesize that deforestation and increased urbanization cause increased surface runoff. (Bronstert et al., 2002; Cheng and Wang, 2002; Cuo et al., 2009; Galster et al., 2006; Hamdi et al., 2011; Hundecha and Bárdossy, 2004; Miller et al., 2014; Misra, 2011; O'Driscoll et al., 2010; Pfister et al., 2004; Poelmans et al., 2011; Reynard et al., 2001; Siriwardena et al., 2006; Trudeau and Richardson, 2016; Zope et al., 2016). Most of these studies look at the integral response of the catchment due a changed land use/land cover, and do not aim to attribute the changes to the specific type of changes that occur: e.g. an increase in settlement at the expense of agricultural land. HoweverAlso, a lot of uncertainty remains, mainly because of the heterogeneity of hydrological responses in catchments globally and the scale of the river basin/catchment considered (see e.g. (Zhang et al., (2017).

Next to the independent driver-effect mechanisms of climate variability on river peak flows, and land use changes on river peak flows, both drivers should be analyzed jointly in a multiple-driver attribution study (e.g. Hall et al., 2014; Merz et al., 2012). As an example, for the Meuse river, it was concluded that changes in flood frequency and magnitude over the past century could mainly be attributed to climate variability rather than to deforestation and urbanization (Tu et al., 2005). Similarly, for the Rhine and Meuse basins, increased flooding probability was found to be correlated to an observed increase in westerly atmospheric fluxes (causing an increase in winter precipitation amount and intensity) and not to observed land use changes (Pfister et al., 2004). For a smaller catchment such as the Grote Nete (385 km^2, located in the North-East of Flanders), and for the future conditions, both climate change and urban growth are projected to have a considerable impact on river peak flows (Tavakoli et al., 2014; Vansteenkiste et al., 2014).

With this paper, we investigate the (relative) importance of climate variability and land cover changes related to changes in river peak flows, based on 29 catchments throughout Flanders. For the historical dataset covering the past three decades (Section. 22), a data-based approach is followed where peak flow anomalies are explained based on a set of maximum 24 drivers. These drivers are grouped into three categories: catchments specific drivers, climate variability and land use/land cover changes. A model is built based on panel data regression, with a top-down approach (Section. 33). Results are presented in Sect.ion 44 and overall conclusions are given in Sect.ion 5.

2   Case studyStudy area and data

For this case study, 29 catchments are selected, evenly spread across Flanders, the Northern part of Belgium (Figure 1).

Flanders, with 6.4 million inhabitants, covers around 13,500 km^2. The coastal area in the North-West of the region mainly consists of sand dunes and clayey alluvial soils in the polders. The central area mainly consists of loamic soils and ranges between 0 and 10 mTAW, with mTAW the height, in meters, above the local mean sea level. The North-Eastern part, known as the Campine region, has sandy soils at altitudes around 30 mTAW. The Southern part with silty soils has low hills op to 150 mTAW. The maximum height is 288 mTAW in the South East.. The DTM in Figure 1 was taken from the Digital Elevation Model Flanders "Digitaal Hoogtemodel Vlaanderen" (https://overheid.vlaanderen.be/producten-diensten/digitaal-

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hoogtemodel-dhmv). Soil texture data were ~~is~~ obtained ~~available~~ from the Flanders underground database (www.dov.vlaanderen.be). ~~.~~

Flanders has a maritime climate (*Cfb*, according to the Koppen climate classification), with average temperatures of 3 °C and 18 °C in January and July, respectively. There is a small gradient present with lower temperatures in the South-East (annual average of 10 °C) towards higher temperatures in the North-West (annual average of 11 °C) (based on ~~data between~~ the period 1981-2010); the average temperatures in Flanders, further, has been rising over the past 30 years with 1 – 1.5 °C. Average evapotranspiration was 540 mm/year in 1980 and rose to 625 mm/year in 2010. Yearly precipitation varies between 600 mm/year to 1000 mm/year, with little variation throughout the year, and little spatial differences (Brouwers et al., 2015).

Twenty-nine~~These~~ catchments were selected based on a minimum of 20 years of available discharge data (www.waterinfo.be). Some of the main characteristics of these catchments are listed in Table 1.

Further, Figure 2 and Figure 3 show details on land cover and soil texture of these catchments, respectively. For land cover, the 30 classes from the ESA CCI Land Cover project (www.esa-landcover-cci.org) were regrouped into the 6 IPCC land categories, i.e. cropland, forest, grassland, wetland, settlement and other land. This was done in order to reduce the total degrees of freedom for this study. ~~For s~~Soil texture~~, taken~~ is obtained from www.dov.vlaanderen.be~~,~~; 3 dominant soil textures ~~classes~~ (~~a~~Arenic, ~~l~~Loamic and ~~s~~Siltic) cover 99.3% of the total area of the selected catchments. Therefore, further in this study, only these 3 dominant soil textures ~~classes~~ were taken into account ~~for this study~~.

Climatic conditions in the past are based on the NCEP/NCAR reanalysis data, available online through https://www.esrl.noaa.gov/psd/ (Kalnay et al., 1996).

3   Methods

3.1   General

The aim of the study is to find the ~~(main)~~ drivers behind changes in river peak flows. Therefore, the ~~daily~~ hourly discharge series of each catchment is first transformed to peak flow anomalies (Sect. 3.2). Then, possible drivers are derived from the data introduced in Sect. 2 and further split into separate categories, see Sect. 3.3. Finally, a regression model is fitted to the data (Sect. 3.4).

3.2   Peak flow anomalies

The methodology to estimate peak flow anomalies is schematized in Figure 4.~~For quantification of peak flow anomalies, t~~ The ~~daily~~ hourly discharge data (Figure 4a) is first split into independent events and extremes are extracted (see Figure 4b), based on the method proposed by (Willems, 2009). Empirical probabilities (or equivalent return periods) are assigned to these extremes, based on the full time series (reference period) on the one hand, and based on subsets of extremes in subperiods/blocks of 10 years length on the other hand (Figure 4c). The quantiles in a particular subperiod/block are then compared with the corresponding quantiles based on the ~~full timeseries~~reference period and the ratio of these two empirical quantiles defines an anomaly factor (Figure 4d). Finally, per subperiod/block of 10 years, all anomaly factors corresponding to a return period larger than one year are averaged in order to get one value per subperiod of 10 years (Figure 4d). As such, one can plot and/or investigate peak flow anomalies for a given catchment over time (Figure 4e). Note that, when investigating these anomalies over time, a detected signal is only considered robust if it persists for a period longer than the selected block period (here: 10 years). If, e.g. an increased anomaly is found for 4 consecutive years and afterwards falls back to the values prior to this increase, this increase is only an artefact of the anomaly method.

3.3 Possible drivers

The data introduced in Sect. 2 generally relate to one of the following three categories: catchment characteristics (*CAT*), climate variability (*CLIM*) and land cover changes (*LULC*).

Catchment characteristics are considered time invariant in this study and are derived from following sources: digital terrain model (DTM) with a spatial resolution of 100m x 100m, river map and soil texture. From the DTM, the river map and locations of the outlet stations, catchment delineations are defined. Further, based on the DTM, the slope ~~at every point~~ in the catchment ~~are~~ is calculated, as well as the average slope over the whole catchment. A river density is defined as the ratio of total river length in the catchment over the total area of the catchment. Finally, the relative area of the soil textures ~~classes~~ are being used in the further analysis. For these soil textures, Arenic, Loamic and Siltic were found to cover 99.3% of the area of Flanders; and when Arenic is seen as the complement of (Loamic + Siltic), only two variables remain to describe soil textures. The absence of an explicit variable Arenic is compensated through the constant α in the model (see ~~lower in~~ Section 3.4.1).

Climate variability is derived from the NCEP/NCAR reanalysis data (Kalnay et al., 1996). Here, weather types are derived based on the daily mean sea level pressure from this reanalysis dataset. Different classification methods exist (Philipp et al., 2010); here, the Jenkinson Collison system (Jenkinson and Collison, 1977), a modified version of the Lamb-weather type classification method (Lamb, 1972) is used to convert sea level pressure into one of 28 weather types. These 28 weather types are reduced to 11 by combining all types with the same directional component (see also e.g. (Demuzere et al., 2009)) and further reduced based on the link between river peak flows and weather types (De Niel et al., 2017). The remaining groups of weather types are: W; (NW, N), (NE; E; SE), (S; SW); U; C; A, with N, E, S and W referring to wind directions, C and A to cyclonic and anticyclonic atmospheric patterns, respectively, and U to an unclassified weather type. This reduction ~~again~~ aims to limit the degree of freedom in the final model. ~~The remaining weather types are: W; (NW, N), (NE; E; SE), (S; SW); U; C; A, with N, E, S and W referring to wind directions, C and A to cyclonic and anticyclonic atmospheric patterns, respectively, and U to an unclassified weather type~~ In the further analysis, relative frequencies of these daily weather types are considered, based on a rolling window of 5 years (Figure 5~~Figure 4~~), and U is considered as the complement of the other groups of weather types.

Six IPCC land categories (settlement, agriculture, grassland, forest, wetland and other area)~~Land cover and land cover changes have been described in the past through the ESA CCI project (www.esa-landcover-cci.org) : annual global maps of land cover are available between 1992 and 2015. The 22 land cover categories (or 30, when including 'level-2' or 'regional' labels) identified in this project are grouped into the six IPCC land categories, i.e. settlement, agriculture, grassland, forest, wetland and other area.~~ are taken into consideration as possible drivers for this study. ~~With respect to *LULC*, it~~ It ~~was~~ is seen that the maximum proportion of Wetland and Other area in the considered catchments is equal to only 0.2% and 1.5% respectively. Therefore, ~~it is suggested to not take~~ these *LULC*-classes will further not be taken into account. In addition~~Further, t~~the *LULC* class Grassland is considered as the complement of (Forest + Agriculture + Settlement). Because ~~Finally,~~ the *LULC* database does not show any significant changes after 2005 (Figure 2), ~~and therefore,~~ the analysis is limited to 1992-2005.

Table 2 summarizes the possible drivers considered in this attribution study.

3.4 Regression model

3.4.1. Panel data analysis

A model is built with the techniques and ideas of panel analysis, which is widely used in social sciences, epidemiology, and econometrics where two dimensional data is analysed. Typically, in those sectors data is collected over time and over the same

individuals. Here, the two dimensions are space and time – input data can show only a temporal variation (e.g. climate data), only a spatial variation (e.g. soil texture), or a combination of both (e.g. LULC). Note that, typically, climate data does show a spatial variation as well. However, we assume the area of Flanders to be homogeneous with respect to the considered climate data.

~~the data is also collected over time; the individuals should be seen here as the different catchments, with certain heterogeneous characteristics which may also further vary over time.~~ The typical panel data regression model can be described as follows:

$$y_{it} = \alpha + \boldsymbol{\beta X}_{it} + \epsilon_{it}, \tag{1}$$

with y the output of interest, i the individual (or catchment), and t the time; α and $\boldsymbol{\beta}$ are constants, of dimension (1 x 1), and (1 x n) respectively, with n being the number of inputs/observations considered. Note that both α and $\boldsymbol{\beta}$ are catchment independent, as no index i appears here. $\boldsymbol{X}$ represents the input/observations as explanatory variables, with dimension (n x 1) for each individual (or catchment) at a particular time t and ϵ is an error term. In this study, the output of interest is peak flow anomaly, and inputs can be split into three categories: catchment specific characteristics *CAT*, climate variability indicators *CLIM* and land cover *LULC*, as described in Table 2. As such, $\boldsymbol{X}_{it}$ from Eq. (1) becomes:

$$\boldsymbol{X}_{it} = (\boldsymbol{CAT\ CLIM\ LULC})_{it}^{T}. \tag{2}$$

with superscript T indicating the transpose of a matrix. Next to the linear model (Eq. (1)), combined effects of (changes in) observed variables might also play a role in explaining the changes in the output of interest.. Therefore, an interaction term is added to the model:

$$y_{it} = \alpha + \boldsymbol{\beta X}_{it} + \boldsymbol{\rho}\, \boldsymbol{X}_{it}^{T}\, \boldsymbol{X}_{it} + \epsilon_{it}. \tag{3}$$

The interaction matrix $\boldsymbol{\rho}$ is of dimension (n x n) and is constant, hence time and catchment independent. This matrix is a strictly upper triangular matrix, meaning all entries on and below the main diagonal are all equal to 0. Furthermore, for our study, we added the restriction that there cannot be any interaction between explanatory variables from within the same category: e.g. $\rho_{area,slope} = 0$.

3.4.2.   Model building

Model building happens based on a top down approach. Starting from a simple constant model, with $\boldsymbol{\beta} = \mathbf{0}$ and $\boldsymbol{\rho} = \mathbf{0}$, explanatory variables are added to the model based on changes in the value of the Bayesian information criterion *BIC* (Kass and Raftery, 1995). BIC is a general criterion for model selection, where models with the lowest BIC are preferred. It takes into account the likelihood of a model, the sample size and the number of parameters estimated by the model. In a first step, only the linear model (Eq. (1)) is considered. Once the linear model is fixed, interaction terms are added in a similar way. Note that we only consider interactions between variables present in the linear model. E.g. if β_{arenic} would be equal to 0 in the linear model, then all $\rho_{arenic,X}$ in the model including interaction terms are, a priori, set equal to 0.

In order to build a robust model, 100 linear models are tested based on (100 times) 20 random calibration catchments. Based on this set of 100 models, significant variables are selected, i.e. variables which appear in the majority of the models.

4   Results and discussion

4.1   Final model

~~Prior to the first step of the model building process, a reduction of the number of variables is carried out. With respect to soil texture, it was seen that for all catchments combined, Arenic, Loamic and Siltic describe 99.3% of the total area. Hence, the~~

analysis will further only consider these three dominant soil texture classes. Furthermore, when the class Arenic is seen as the complement of (Loamic + Siltic), this further reduces to only two variables. The absence of an explicit class Arenic is compensated through the constant α in the model. Similarly, with respect to the climate variability, the weather type U is considered as the complement of the other classes. Similar to the considerations in the soil texture classes, After the above

5   reduction in number of variables, 100 models are built, each based on 20 random catchments. Variables are only included in the model if they are found to be significant. The proportion of the models including the various variables are summarized in Figure 5 and, based on this The final model has 26 terms in 9 predictors (see Table 3). During model building, it was decided to not further consider, following variables will further not be considered (Figure 6):

- Catchment characteristics: Area;

10   • Climate variability: W; (NW, N); (NE,E,SE); A and U.

One of the most interesting findings during the model building and evaluation process, The catchment area does not have a significant contribution in explaining observed peak flow changes. Furthermore, when including interaction factors between catchment area and the other variables, model performance did not improve (not shown). This might seem surprising at first, since Bloschl et al. (2007), among others, hypothesize that land use impact on hydrological response is depending on the

15   catchment scale. However, all selected case studies are considered to be of the same scale, despite the differences in catchment area and thus, the hypothesized effect of catchment scale on land use impacts is not applicable here.

One should be careful when interpreting the coefficients from the final model in Table 3. E.g. the coefficient of Settlement in the final model is equal to -3.04. At first sight, an increase of settlement would thus correspond with a decrease of peak flow anomaly. However, the interpretation of the coefficients is more complex:

20   ▪ An increased Settlement also impacts the interaction effects, and the coefficient becomes: (-3.04 – 0.85*Slope + 6.47*Loam + 17.85*Settlement);

    ▪ An increased Settlement means that Agriculture (13.08) and/or Forest (3.71) might decrease – and there again, the interaction effects of Agriculture and Forest come into play.

The model is able to explain 60% of the changes in river peak flows over time (Figure 7 Figure 7). This performance is further

25   broken down into linear effects of the three separate groups and their interactions (Figure 8 Figure 8). Linear effects (28%) are found to be of equal importance as interaction effects (32%). Within the linear effects, catchment characteristics are most important as they explain the highest portion (18%) of the river peak flow changes, followed by land use/land cover (8%) and climate variability (6%). These percentages were obtained by only considering the models that include the variable considered. Note that 18% + 8% + 6% is only slightly larger than 28%, which is due to a small interdependency between land use/land

30   cover, and soil texture and catchment slope.

Observed peak flow anomalies in catchments L07_289 (Mark at Viaene) and L08_233 (Zuunbeek at Sint-Pieters-Leeuw) have a bad correspondence with their modelled results (Figure 7). The Mark catchment has a long history of flooding – as from the 2000s, the local authorities have installed several mitigation measures (hydraulic structures, retention basins etc.), effectively decreasing the flood risk. This is also visible in the observed peak flow anomaly. However, the regression model used in this

35   study cannot capture such management changes. Further, for the Zuunbeek catchment at Sint-Pieters-Leeuw, increased peak flow anomalies are observed as from the middle of the period. This is due to the extreme flood season in the winter of 2001-2002 where 7 events were observed with peak discharges exceeding 6 m^3/s, corresponding to an empirical return periods larger than 1 year, based on data between 1978 and 2016.

4.2 Effect of single drivers

Firstly, the dependency of peak flow anomalies to catchment characteristics is investigated. This is done by only considering those factors of the model, solely consisting of catchment characteristics. It is seen, from Figure 9, that peak flow anomalies go up with an increased slope, lower proportion of loamic soil textures and higher proportions of siltic soil textures in the catchments. With respect to density, the results show less clarity.

These findings correspond to an analysis done on the potential runoff coefficient as used in the hydrological model Wetspa (Liu and De Smedt, 2004). The potential runoff coefficient of a catchment is defined as the ratio of runoff volume to rainfall volume. A simple and practical technique was developed in Wetspa to estimate this runoff coefficient as a function of land use, soil texture and slope, based on reference values from literature (Browne, 1990; Chow et al., 1988; Fetter, 1980). See e.g. Figure 10 for potential runoff coefficients in Wetspa for different combinations of LULC, slope and soil texture. Note that they use slightly different LULC classes, but these differences are insignificant for the purpose of this discussion. From a hydrological point of view, relative changes in potential runoff coefficient can serve as a proxy for peak flow anomalies. As such, findings with respect to the potential runoff coefficient from Wetspa, can be related with the conclusions based on Figure 9:

- Figure 10a shows that potential runoff coefficients increase, with increasing slope. Moreover, the rate of this increase is lower for higher slopes. This corresponds with our findings on catchment slope.
- Figure 10b and c show that potential runoff coefficients are generally lower for a loamic soil texture compared with a siltic soil texture. This corresponds with our findings on the impact of soil texture classes.

Secondly, with respect to the climate system, it was seen that the relative frequencies of S+SW, combined with the relative frequencies of A give the most information to the model explaining peak flow anomalies (Table 3 and Figure 6). This, however, does not mean that the hydrological cycle is mostly/only depending on these weather types. Correlations exist between the various weather types; for example frequencies of anticyclonic and cyclonic weather show a negative correlation of -0.79. Because of these correlations, we do make any statements on the effect of increasing/decreasing frequencies of S+SW or A on peak flow anomalies.

Finally, based on the model, the overall impact of increased urbanization can be investigated. This is done by changing, for each catchment, 1% of the total area from settlement to forest, grassland and agriculture, respectively. This results for most catchments in increased peak flows (Figure 11), with disappearing grassland in favour of settlement area causing the biggest changes. These results are in line with (Hundecha and Bárdossy, 2004), who found an increase of 7 – 10% in river peak flows for a 15% increase in urban area at the expense of agricultural land. The strongest changes were found for catchments L01_491, L01_492, L01_496 and L05_404. These catchments are all quite flat and have a high proportion of loamic soil texture. This finding will further be discussed by investigating interaction effects below.

4.3 Interaction effects

The total amount of interaction effects (32%) is largely carried by three terms only: interaction between LULC and soil texture classes (% loamic) (10%), between LULC and slope (6%) and between soil texture classes (% loamic) and slope (6%) (see Figure 12):

- Figure 12a shows effects of LULC changes on peak flow anomalies as a function of the slope (three particular slopes are shown: flat (0.40), medium (2.83) and steep (5.26)). Note that this graph was obtained by averaging out effects of other predictors and, as such, the absolutes values of the effects should be interpreted carefully. For the purpose of interaction effects, results of Figure 12 should be interpreted in a relative way. It is seen that, with increasing slope, the effect of LULC changes on peak flow anomaly goes down. A steeper slope, typically, already results in increased

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peak flows but the: LULC changes will influence these peak flow anomalies in a lesser degree, compared with more flat catchments. Note that, although different in magnitude, these trends are consistent for each LULC class.

- Similar to this interaction between slope and LULC, catchments with a low proportion of loamic soil textures are less influenced by LULC changes with respect to peak flow anomalies, compared to catchments with a high proportion of loamic soils (Figure 12b). Again, trends are consistent for each LULC class.

- And finally, the catchment slope has a larger effect with respect to peak flow anomalies in catchments with a high proportion on loamic soil textures, compared to catchment with a lower proportion on loamic soil textures (Figure 12c).

Comparison with the analysis on the potential runoff coefficient from Wetspa (Figure 10) learns the following on the three main interaction effects:

- Slope and LULC:- One can see in Figure 10a that the range of potential runoff coefficients between the four LULC classes is significantly larger at a near-zero slope, compared with a slope of 100%. Or, iIn other words, (relative) changes in the potential runoff coefficient with changing LULC are smaller for catchments with a steeper slope.

- Soil texture and LULC:- For catchments with a pure loamic soil texture, the potential runoff coefficient at a near-zero slope increases with a factor 4.4 from a forested area (0.14) to mixed urban (0.62). For catchments with a pure siltic soil texture (thus, with a very low contribution of loam), this is only a factor 3.1 (0.21 vs. 0.66) (Figure 10b). Or, iIn other words, loamic catchments are more sensitive to LULC changes with respect to potential runoff coefficients.

- Soil texture and slope:- For catchments with a pure loamic soil texture, the potential runoff coefficient in forested area increases with 42% between a slope of 1% (0.14) and 5% (0.20). For catchments with a pure siltic soil texture (thus, with a very low contribution of loam), this is only 29% (0.21 vs. 0.27) (Figure 10c). Or, iIn other words, loamic catchments are more sensitive to the catchment slope with respect to potential runoff coefficients.

Interaction terms between LULC and climatic conditions holds only 2% of explanatory power in the models. Figure 13 shows these (minor) interactions.: Pperiods in time rich on anticyclonic weather types show a decreased sensitivity on changes in agricultural and forested land, and an increased sensitivity on settlement area. Moreover, also, a decreased sensitivity to agricultural land is seen for periods rich on S and SW weather types. However, as the confidence intervals for the different climatic conditions overlap in all four cases of Figure 13, these interactions might not be significant.

The remaining interaction terms from Table 3 further explain an additional 8% of the variation in peak flow anomalies, but will further not be discussed here. Note that no significant interaction terms were found between catchment characteristics and climate conditions. This would mean that each catchment responds in a similar way to climatic oscillations.

Based on this model, the impact of increased urbanization can further be investigated. This is done by changing, for each catchment, 1% of the total area from settlement to forest, grassland and agriculture, respectively. The resulting changes in river peak flows are summarized for all catchments in Figure 8.

75 Discussion and Ceonclusion

The regression model is able to explain 60% of the changes in peak flow extremes. For some individual catchments, however, the model is not able to mimic observed step changes, e.g. for catchments L07_289 (Mark at Viaene) and L09_145L08_233 (Zuunbeek at Sint-Pieters-Leeuw). On the other hand,For the other 27 considered catchments, the direction and the overall

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trends simulated by the model are~~is~~ found to be accurate. ~~Since the explanatory variables all have a smooth variation over time, it is a priori almost impossible for any simple regression model to mimic these step changes.~~

~~The model was built for selected catchments and based on a selected time window. The selected catchments are considered to be a good representation of the spatial heterogeneity within Flanders with respect to land cover and soil texture. For the peak flow anomalies, the reference period spans the total period where discharge data is available and ranges between 31 and 47 years (depending on the catchment considered). However, due to the lower availability of land cover images, the regression model was fitted based on a shorter time window. Nevertheless, clear changes in peak flow anomalies could be identified for this period and these could be explained for 60% by explanatory variables describing topography, density, soil texture, weather types and land use/land cover.~~

With respect to the estimation of the regression model, ideally, one would carry out a split-sample test (in space and in time); however, because of data availability and spatial heterogeneity, this approach would fail in this case. Alternatively, the robustness of the model is tested here by fitting multiple models with different calibration data. It is seen from Figure 7~~Figure 7~~ that this approach results in consistent estimations for the peak flow anomalies – only for catchment L11_518 this consistency was not always found.

It was seen that for these case studies, changes in land cover and climate variability play an equally important role in explaining changes in river peak flows. These effects, however, are of a lower importance than catchment specific factors, such as topography and soil texture: higher peak flow can be expected for catchments with a high average slope, a low proportion of loamic soil texture and high proportions of siltic soil. The high importance of these time-invariant factors (topography and soil texture) indicate that flood response in Flanders is highly catchment specific, and to a lesser degree depending on fluctuations of the climate, and land use changes.

Obviously, given the complexity of these environmental systems, the simple linear model will not be able to capture/describe all effects – indeed, it was seen that interaction effects between catchment characteristics, land cover and climate variability are equally important in explaining changes in river peak flows. It was shown that the sensitivity with respect to peak flow changes caused by LULC changes is lower for catchments with a steep slope and a low proportion of loamic soil textures.

The model also showed that, for most of the considered case studies, ~~deforestation~~ a decrease in forested area to increase settlement area indeed leads to increased peak flows. Moreover, 1% increase in ~~urbanization~~ settlement could lead in some cases to a 5% increase in river peak flows.

These findings provide important new findings in support of urban planning and flood management. Firstly, the link between slope, soil texture and peak flows can help in developing catchment specific flood management plans. Also, the land use changes should be planned taking catchment characteristics into account since it was shown that land use change impacts on peak flows differ significantly in catchments with different slopes and soil textures.

Data availability

All data were obtained via publicly available sources. The DEM was obtained from "Digitaal Hoogtemodel Vlaanderen" (VMM, Watlab and Agiv), available from https://overheid.vlaanderen.be/producten-diensten/digitaal-hoogtemodel-dhmv. The river network and catchment delineation was obtained from "Vlaamse Hydrografische Atlas" (www.geopunt.be). Land cover was obtained from the ESA CCI Land Cover project (https://www.esa-landcover-cci.org/). Soil texture data is available on www.dov.vlaanderen.be. The NCEP/NCAR Reanalysis data were provided by the NOAA/OAR/ESRL PSD, Boulder Colorado, USA, from their website at https://www.esrl.noaa.gov/psd/. The discharge data were obtained from www.waterinfo.be.

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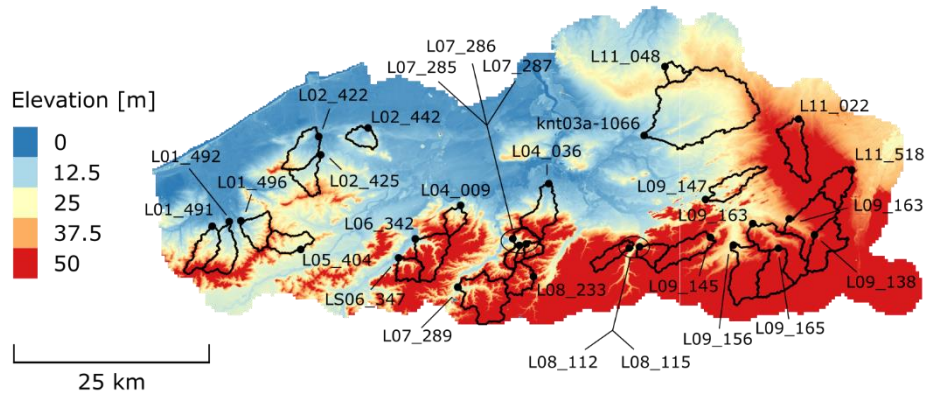
Figure 1. Selected catchments in the Flanders area of Belgium.
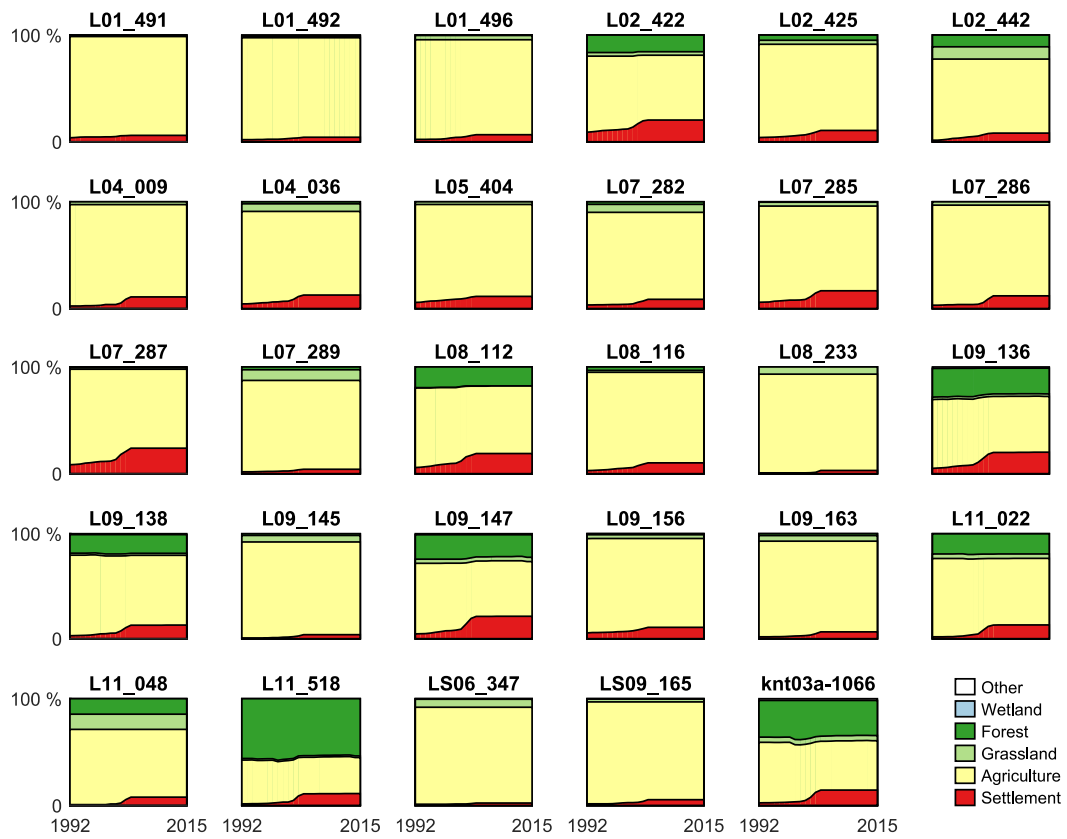
5   **Figure 2. Land cover and land cover changes over time (1992 – 2015) for the selected catchments.** ~~Data from: www.esa-landcover-cci.org.~~
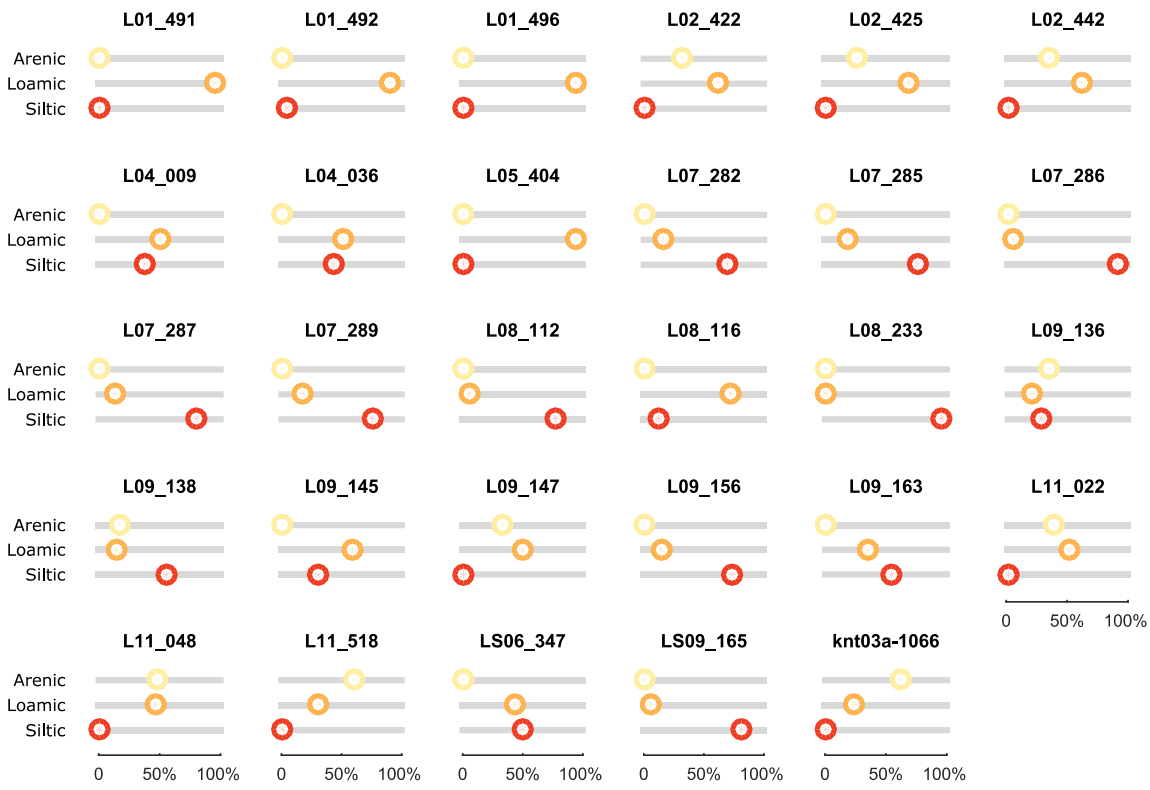
Figure 3. Relative areas of soil texture (Aarenic, loamic and siltic) fractions (WRB units) for the selected catchments. Data from: www.dov.vlaanderen.be
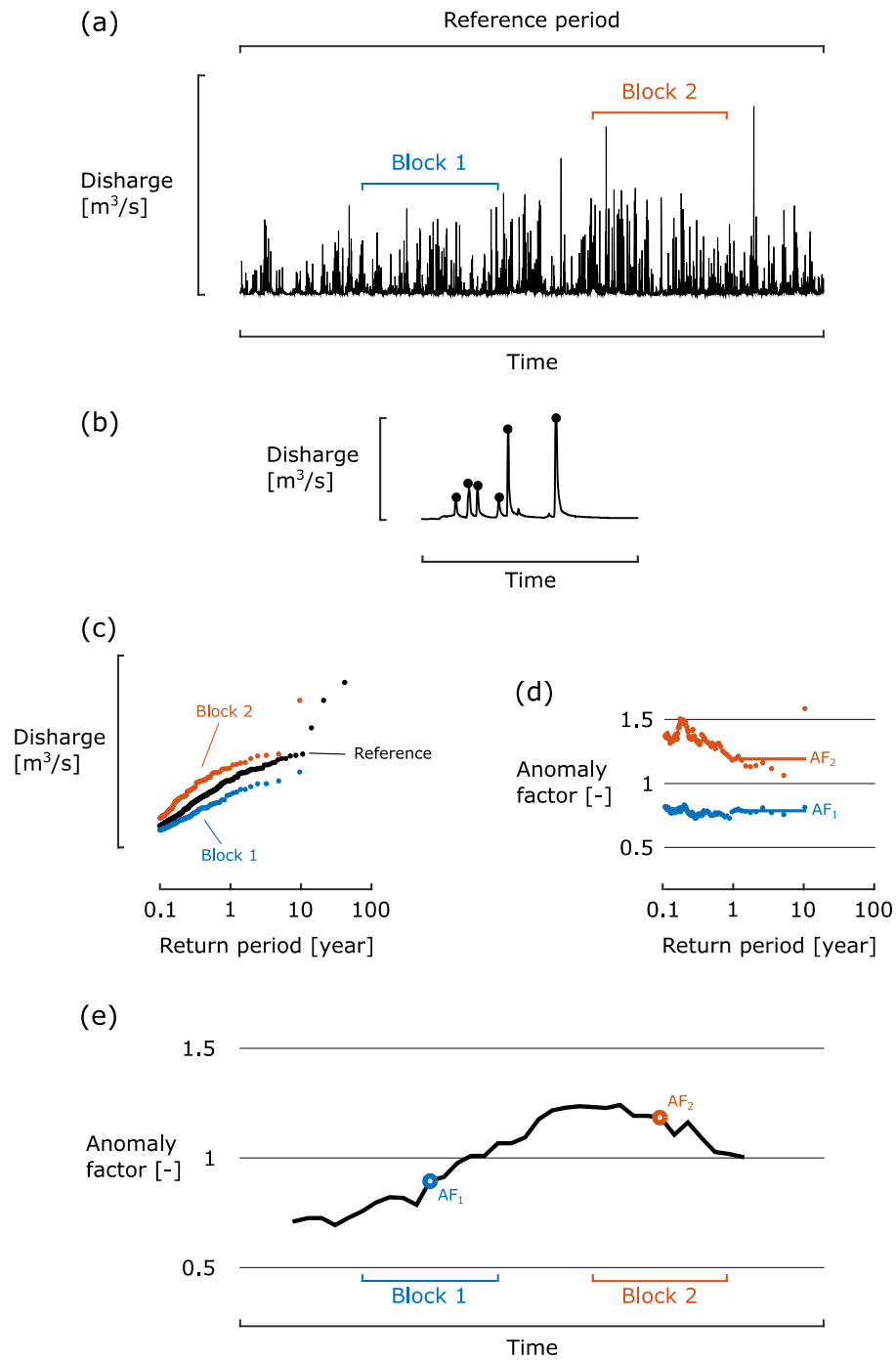
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Figure 4. Schematic overview of methodology to estimate peak flow anomalies for two specific block periods over a reference period.
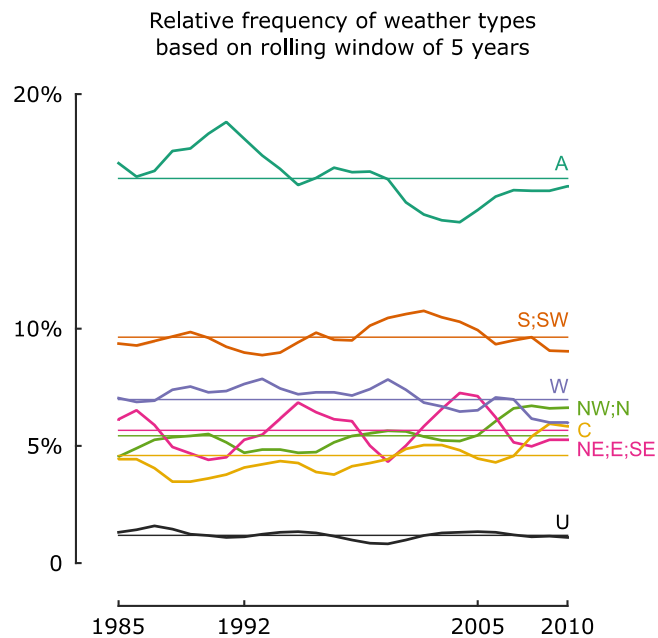
Figure 54. Relative frequency of Lamb weather types over the years.
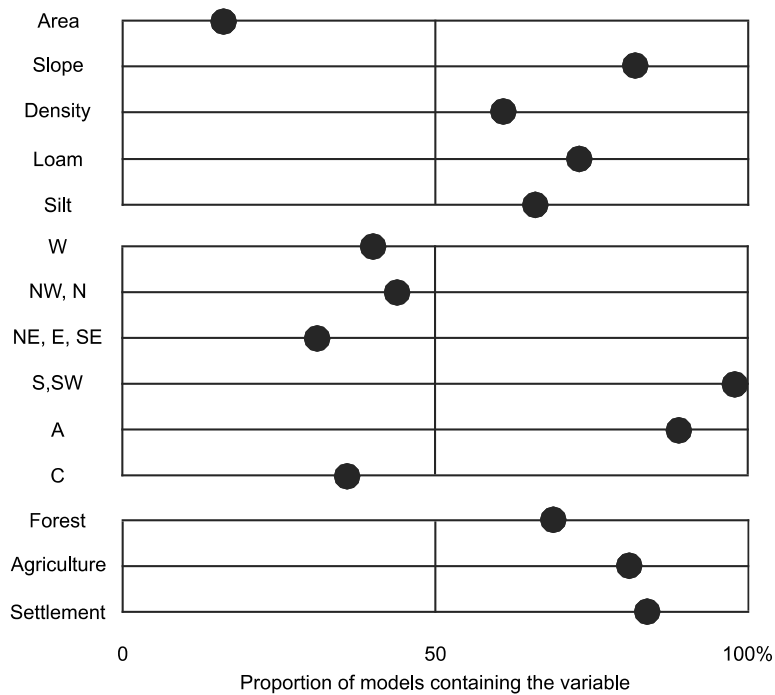
Figure 65. Variables appearing in >50% of the calibrated models are selected to explain changes in river peak flows.
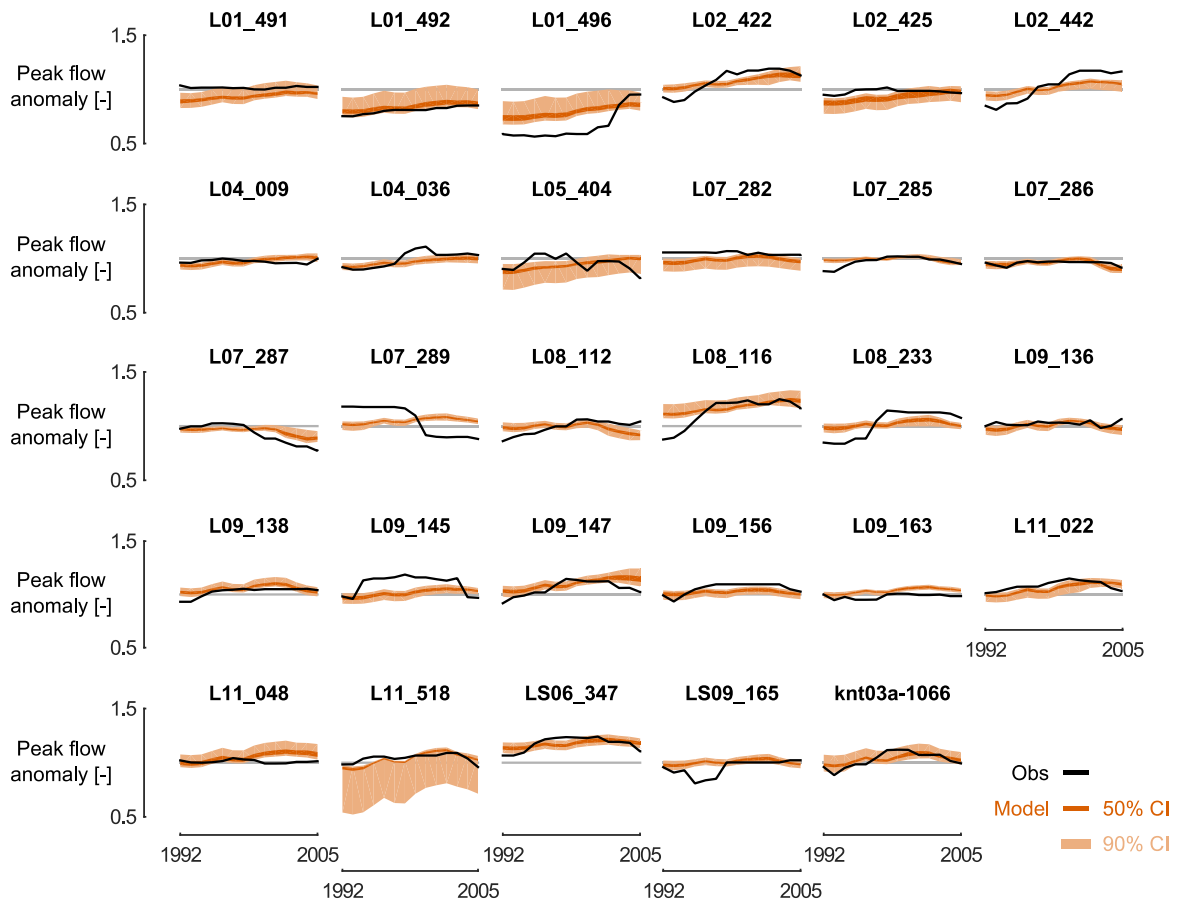
17

Figure 76. Regression model combining catchment characteristics, climate variability and land cover changes to explain streamflow variability.
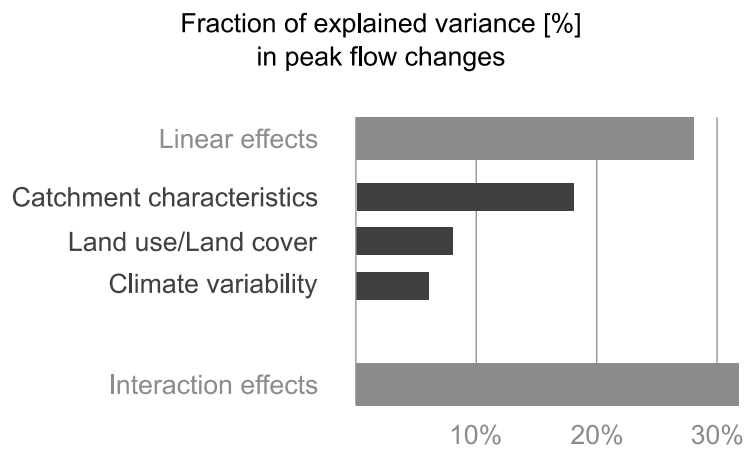

Figure 87. Linear effects and interaction effects between catchment characteristics, climate variability and land cover changes play an equal role in explaining streamflow variability.
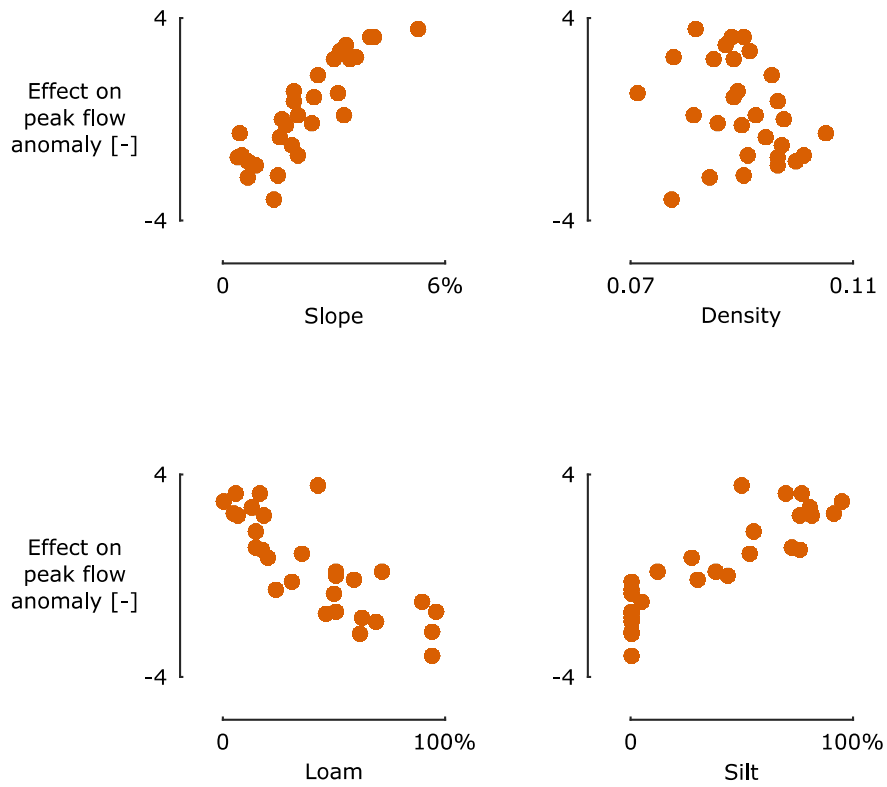
Figure 9. Effect of catchment characteristics on peak flow anomalies for the 29 selected catchments.
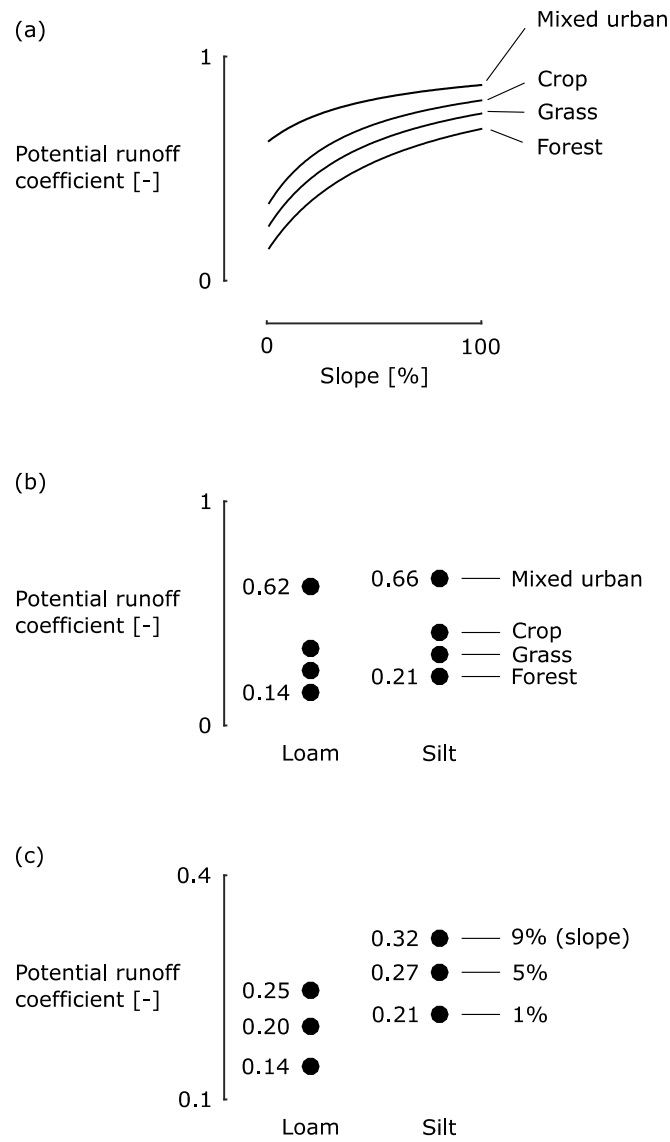
Figure 10. Potential runoff coefficient from the Wetspa hydrological model (Liu and De Smedt, 2004)**, (a) as a function of slope, for different LULC categories (loamic soil texture), (b) as a function of soil texture class for different LULC categories (near-zero slope) and (c) as a function of soil texture class for different slopes (forested area).**
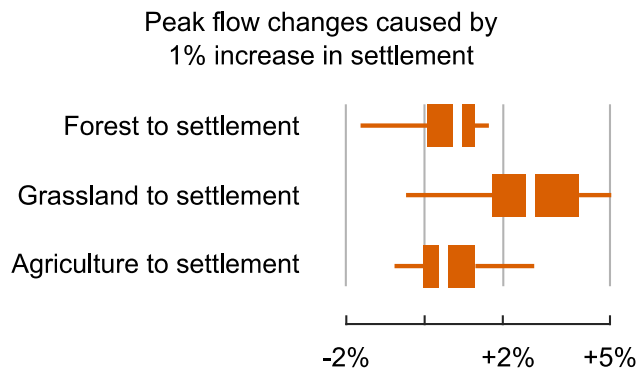
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Figure 11. Peak flow changes by increasing settlement area through decreasing forest, grassland or agriculture.
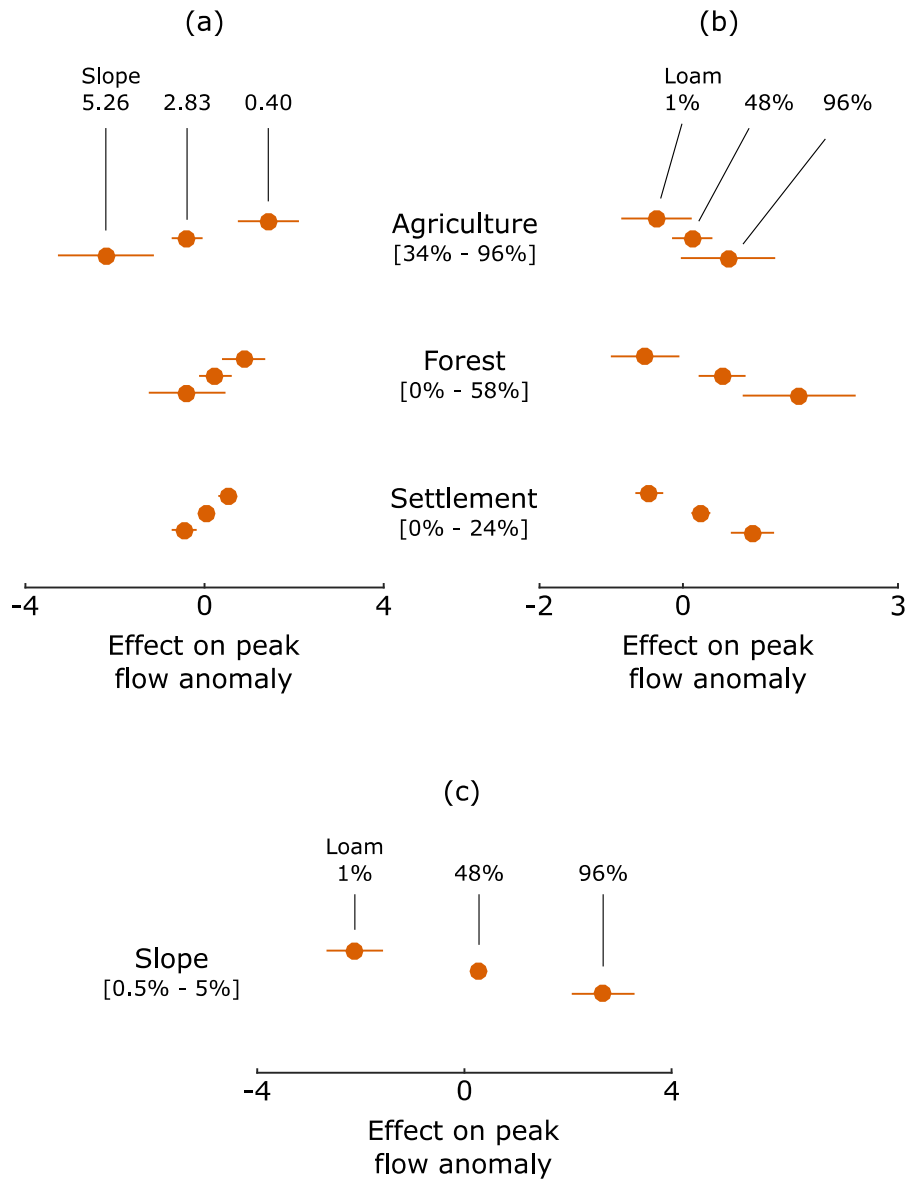
(a)

(b)

(c)

Figure 12. Estimated effect on peak flow anomalies from changing (a) slopes and LULC, (b) soil texture (loamic content) and LULC and (c) slopes and soil texture (loamic content), averaging out the effects of the other predictors. Horizontal bars indicate confidence intervals for the estimated effect.

5

Agriculture
[34% - 96%]

Forest
[0% - 58%]

Settlement
[0% - 24%]

Agriculture
[34% - 96%]

A
15%
16%
18%

A
15%
16%
18%

A
15%
16%
18%

S+SW
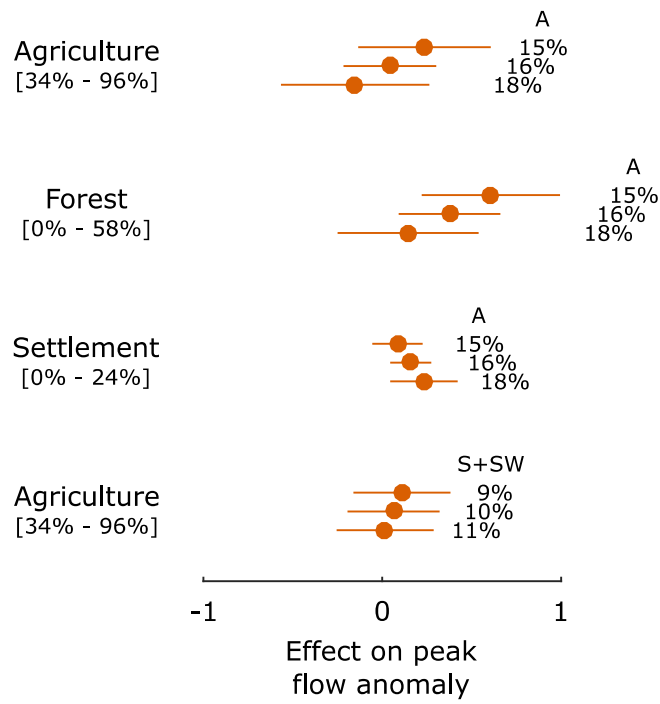9%
10%
11%

-1   0   1

Effect on peak
flow anomaly

Figure 13. Estimated effect on peak flow anomalies from changing LULC (Agriculture, Forest and Settlement) and climatic conditions (relative frequencies of weather types S+SW and A), averaging out the effects of the other predictors. Horizontal bars indicate confidence intervals for the estimated effect.

5

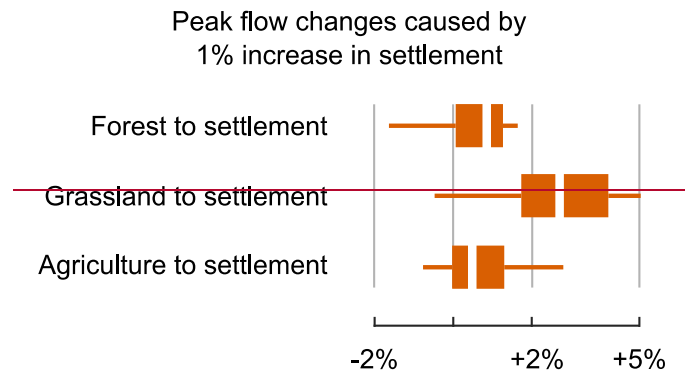22

Peak flow changes caused by
1% increase in settlement

Forest to settlement

Grassland to settlement

Agriculture to settlement

-2%   +2%   +5%

Figure 8. Increasing settlement area will, in most cases, lead to increased peak flows.

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Table 1. Main characteristics of the selected catchments.

Id.	Outlet station	River	Area [km²]	Period		# years
knt03a-1066	Grobbendonk Troon	Kleine Nete	587	1982	2018	36
L01_491	Oostvleteren	Poperingevaart	64	1972	2018	46
L01_492	Reninge	Kemmelbeek	88	1986	2018	32
L01_496	Merkem	Marktjevaart	77	1986	2018	32
L02_422	Sint-Michiels	Kerkebeek	93	1983	2018	35
L02_425	Oostkamp	Rivierbeek	65	1983	2018	35
L02_442	Maldegem	Ede	46	1984	2018	34
L04_009	Massemen	Molenbeek	44	1987	2018	31
L04_036	Liezele	Molenbeek	104	1975	2018	43
L05_404	Moorsele	Heulebeek	73	1985	2018	33
L06_342	Nederzwalm	Zwalmbeek	111	1972	2018	46
L07_285	Essene	Bellebeek	90	1975	2018	43
L07_286	Sint-Katarina-Lombeek	Hunselbeek	22	1983	2018	35
L07_287	Ternat	Steenvoordebeek	26	1983	2018	35
L07_289	Viane	Mark	123	1976	2018	42
L08_112	Heverlee	Voer	49	1986	2018	32
L08_115	Heverlee	Molenbeek	48	1986	2018	32
L08_233	Sint-Pieters-Leeuw	Zuunbeek	65	1978	2016	38
L09_136	Hasselt	Demer	270	1983	2018	35
L09_138	Bilzen	Demer	116	1972	2018	46
L09_145	Ransberg	Velpe	97	1975	2018	43
L09_147	Molenstede	Zwart Water	79	1986	2018	32
L09_156	Rummen	Melsterbeek	153	1983	2018	35
L09_163	Spalbeek	Herk	274	1977	2018	41
L11_022	Overpelt	Dommel	112	1971	2018	47
L11_048	Merksplas	Mark	32	1983	2018	35
L11_518	Opoeteren	Bosbeek	76	1985	2018	33
LS06_347	Etikhove	Molenbeek	51	1972	2018	46
LS09_165	Wellen	Herk	111	1972	2018	46

5

Table 2. Drivers considered for this study

Catchment specific *CAT*

Topographic	Soil texture [% of total area]
Area [km²], Slope [%] and Density [m/km²]	Arenic, Clayic, Loamic, Loamic/Arenic, Loamic/Clayic, Loamic/Siltic, Siltic, Siltic/Clayic, Sitlic/Clayic/Loamic, Sitlic/Loamic

Climate variability *CLIM* – weather types [% of time in a rolling window of 5 years]

W; (NW, N); (NE, E, SE); (S, SW); A; C and U

Land cover *LULC* [% of total area]

Settlement, Agriculture, Grassland, Forest, Wetland and Other area

Table 3. Coefficients of the 26 terms in 9 predictors of the final model.

(Intercept)	-3.16	A	16.06	Loam:Forest	3.92
Slope	0.36	Slope:Loam	1.04	Loam:Agriculture	1.71
Density	0.05	Slope:Silt	0.75	Loam:Settlement	6.47
Loam	-10.45	Slope:Forest	-0.45	Silt:Agriculture	-1.51
Silt	-7.06	Slope:Agriculture	-1.22	Forest:A	-22.60
Forest	3.71	Slope:Settlement	-0.85	Agriculture:S_SW	-8.11
Agriculture	13.08	Density:Loam	66.84	Agriculture:A	-17.77
Settlement	-3.04	Density:Silt	73.81	Settlement:A	17.85
S_SW	11.13	Density:Agriculture	-75.22		

5