EDITOR

Decision: reconsider after major revisions

Dear Jan De Niel and Patrick Willems,

Thank you for revising the manuscript and responding to the referees' reports. Although I find this version of the paper much improved in comparison to the initial submission, I believe the manuscript can, and need to, be improved before I can consider it for publication. Please note that most of my comments below and the comments from the two referees mainly refer to the presentation quality.

Thanks for the reconsideration of our manuscript, and your suggestions for improvement (in addition to those of the referees).

Text editing are needed. There are typos and grammatical errors that should be corrected (some mentioned by the reviewers).

We went through the manuscript again, and hope most of the typos and grammatical errors are now corrected.

Introduction section. I agree with the comments made by Reviewer #1 - instead of giving a long list of references please elaborate and explicitly refer to the contribution of the papers mention to this study. In general, the introduction section needs to explain more in depth the climate and land cover drivers.

We expanded on the literature review in paragraph 3 and 4 in the Introduction.

There is a disproportion between the length of the text (8 pages) and the number of figures (13) and tables (3). I think 4-6 figures and 1-2 tables should be sufficient to present your study properly. Please consider merging some of the figures (for example, 12 and 13) and presenting some as Supplementary Information (e.g. figure 3 and table 1).

We combined Figures 12 and 13; and moved some of the figures and tables to Supplementary Material. (see also last comment of 2nd reviewer)

Figure 4. Please added in the figure caption text to explain subplots (a) to (e).

OK. We added more explanation in the caption.

Please consider having separate sections to present the results and for the discussion.

We prefer to keep the results and discussion in one section, as we feel this is more appropriate for this manuscript.

Catchments. Sometimes you are using numbers and sometimes names when referring to the catchments. Please be consist. In addition, I suggest simplifying the labels of the catchments, e.g. use simple IDs from 1 to 29.

OK. We changed the IDs as suggested (1 to 29). However, for reference purposes, we suggest to keep the original labels in Table 1.

I invite you to upload a revised manuscript, incorporating the proposed changes and additions, and making any other modifications where you see fit ('major revision'). The revised manuscript will be sent for the referees for a third round of revision.

I look forward to receiving the revised manuscript.

Sincerely,

Nadav Peleg

REVIEWER 1

Decision: reconsidered after major revisions.

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" for the second time. I still think the topic of the manuscript is suitable for the journal, and o great interest. The authors tried to address most of the comments of this reviewer (however, some comments were not considered or worked enough), nevertheless, in my opinion the text should be edited by a native English Editor for improving readability an understandability, before being published, as sometimes is difficult to follow the text.

Addittionally I still have some concern on the text that I list below:

1. Introduction

I still think there are a lot of references in the introduction and little content on them. The authors say they prefer to leave it as is, however, for me it does not make sense to refer to many other paper and not mention some ideas or conclusions of those researchers (paragraphs 3 and 4 of the introduction). In fact, the authors do comment on other authors findings on the next paragraph (number 5). In my opinion, this should be revised before publication.

Expanded on the literature review in paragraphs 3 and 4 in the introduction.

P2 L10-13: Do the references follow any order?

This is be alphabetical, based on the last name of the first author.

P1 L8: the objectives should go at the end of the introduction section, so that they can be deleted from this paragraph.

If this is referring to the sentence "The relative importance of both drivers, however, is still uncertain and interaction effects between both drivers are not yet well understood" from the abstract, we prefer to leave this sentence in the abstract. In our opinion, the objective should be mentioned (briefly) in the abstract.

P2 L14: "do not aim to attribute the changes to the specific type of changes that occur". Please clarify this sentence.

The clarification of this sentence comes after the colon. Changed this from: "e.g. an increase in settlement at the expense of agricultural land" to "for example, the isolated effect of an increase in settlement area at the expense of agricultural land would not be quantified".

P2 L15: "mainly because of the heterogeneity of hydrological responses. What do you refer to?" examples?

Included the example of Zhang et al. (2017): "for example, Zhang et al. (2017) found that small mixed forest-dominated watersheds and large snow-dominated watershed are more hydrologically resilient to forest cover change with respect to annual flows."

2. Study area and data

P2 L37-38. "The Southern part with silty soils has low hills op to 150 mTAW. The maximum height is 288 mTAW in the South East." If hills are up to 150 m how can maximum height be 288 m?, please clarify this sentence. Change op by up . I do not think it is necessary to repeat all the time TAW, it makes reading more difficult.

150mTAW vs. 288mTAW: 150 m is in the central Southern part; 288m is in the South East. Rephrased: "The central Southern part with silty soils has low hills up to 150 m. In the South East, the maximum height is 288 m."

Changed “op” to “up”.

Removed TAW, except for the first time (“0 and 10 mTAW, with mTAW […]”).

P3 L3-8. In this text the authors give general average data for the study area. However, they give specific data of ETR for years 1980 and 2010, a general average data, would be more appropriate to be compared with the rest of data given here.

This rise between 540 mm/year to 625 mm/year was an (almost) linear increase. Added this in the manuscript: “Average evapotranspiration was 540 mm/year in 1980 and <u>increased almost linearly</u> to 625 mm/year in 2010”

P3 L9: “Twinty” should be twenty.

Corrected this in the revised manuscript.

3. Methods

About table 1 and periods used to estimate peak-flow anomalies. How can influence the use of different periods in the estimation of those anomalies?. Shouldn’t the same period for all catchments be used? Natural climate variability can be high from one year to other and it can strongly influence hydrological response. The authors should address this question and justify the use of different periods.

Indeed, different periods were used for estimation of the peak-flow anomalies: the longest period is 1971-2018 (47 years); the shortest period is 1987-2018 (31 years). There is a trade-off between (a) using the same period for all catchments, and thus limiting the data for all catchments to 1987-2018; and (b) making use of all available data, working with different periods for the various catchments, and keeping all available data. Both would be valid options to apply our methodology; we chose for the second option. We want to use the available data to the maximum extent possible to obtain the most reliable signal of peak-flow anomalies over time per catchment. Note that the ‘reference peak-flow’ per catchments (i.e. peak-flow anomaly equal to 1) is obtained through averaging over the whole period. Because of this averaging process, the anomalies would only undergo a small (positive or negative) shift when working with a slightly shorter period. This, in the end, would be captured by the estimation of the regression model. Therefore, we chose to use all available data.

Figure 4 was added in order to better explain methodology. However, some more explanation on the figure is needed in the footnote in order to understand it. What are figures a) b) c)….? This could be a general comment for figures and tables, as their foots are sometimes scarce on content and hardly explain what the figure or table means.

Changed the caption of Figure 4. See also the comment of the Editor.

On a previous comment: “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...” The authors response is: “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.” I agree with the answer, however, I don’t see any of it in the new text of the manuscript.

The above answer to the previous comment is indirectly captured in the manuscript. In section 2 we state that some parts are clayey, loamic or sandy; average heights and presence of low hills are also mentioned. This indicates the variability of the selected drivers which are more explicitly introduced in Section 3.3.

As the variability is mentioned in Section 2, and in order to keep the manuscript concise, we prefer not to expand too much on this in Section 3.3.

P5 L3: "However, we assume the area of Flanders to be homogeneous with respect to the considered climate data" What do you mean? only one climatic series is considered for the whole area? Or, are you referring to weather types? Please clarify in the text, How can this affect results? I mean, considering it as homogenous?

Changed in the manuscript to: "However, in this study, climate variability is described through weather types and we assume the area of Flanders to be homogeneous with respect to these weather types".

P6 L34-37: "Further, for the Zuunbeek catchment at SintPieters-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." This makes me think about two previous questions. Is the period important?, can, in this case, different periods be used for anomaly estimation? Can the climate really be considered homogeneous in the study area?

With respect to the period: for the particular case of the Zuunbeek catchment, the step change would always be visible as long as the winter of 2001-2002 is in the period. This winter of 2001-2002 for the Zuunbeek is an very exceptional season (7 events with empirical return period > 1 year), and it is not within the scope of the regression model to explain this kind of extreme events/seasons. Further, as mentioned as a response to a previous question, if this winter would be left out for the estimation of peak-flow anomalies, the reference peak-flow (anomaly equal to 1) would only slightly shift downwards; the difference will be captured by the estimation of the coefficients of the regression model.

With respect to the climate: as mentioned as a response to a previous question: we consider the weather types as homogeneous in the study area and use these weather types in our regression model.

P7 L2: please include "river" before "density".

OK. Changed in the revised manuscript. "With respect to river density, the results show less clarity"

Section 4.2 Effect of single drivers.

P7 L3-11. The authors mention here the use of Wetspa model. However, nothing about it was mentioned before in the methodology section. Further, this reviewer does not understand very well the inclusion of that model. It seems the authors try to justify or explain the results obtained in their research with the results of a model that they do not explain how has been calibrated and applied in the study area. The model was applied by the authors in the study area? In any case, is it really necessary to include this information in the paper? If so, the authors should explain a bit more on its application and justify the need of it. In addition, the manuscript already has lots of figures to add new ones. This part of the section is confusing for this reviewer. "Using runoff coefficient as a proxy for peak flow anomalies", the authors should include some reference for this.

We did not calibrate, nor apply, the Wetspa model for our 29 catchments. We merely use the concept of potential runoff coefficient as used in the Wetspa model structure. This is now stated more clearly in the manuscript by adding the word 'structure' in the following sentence: "These findings correspond to an analysis done on the potential runoff coefficient as used in the hydrological model structure Wetspa (Liu and De Smedt, 2004)".

In this model structure, a potential runoff coefficient is defined as the ratio of runoff volume to rainfall volume; for estimation of these runoff coefficients, reference values are taken from literature (Browne, 1990; Chow et al., 1988 and Fetter, 1980). We compare our results, which are data-based, with the runoff coefficients from a hydrological model structure. As such, we do not feel the need to include Wetspa in the methodology section.

And, yes, according to us it is necessary to include this here, as this comparison confirms our findings.

"Using runoff coefficient as a proxy for peak flow anomalies" => to us, this goes without reference: a higher potential runoff coefficient is equal to higher runoff volume (considering equal rainfall amounts). And it is self-evident that higher runoff volumes will cause higher peak flows and consequently higher peak-flow anomalies.

"From a hydrological point of view and with the above definition of potential runoff coefficient in mind, relative changes in this potential runoff coefficient […]".

Firstly slope and texture are mentioned. However, there I no discussion on them. The authors only try to justify their findings on the use of the Wetspa model.

The link between these catchment characteristics and runoff coefficient/peak-flow anomalies has been investigated before, in qualitative studies and has been quantified by model-based approaches such as the development of the hydrological model structure Wetspa. In those studies (see the various references on the Wetspa development), extensive literature review was done on their conceptualization of the runoff coefficient and tabulated this as a function of land use, soil texture and slope. Our study confirms these previous studies in a data-based way and we choose not to repeat the hydrological interpretation of these results.

Second, the climate system. Little is also said about this. The existence of a negative correlation between some weather types, could be related with the fact that, when one increases the other inevitably decreases? I might be wrong, however, this paragraph on climate system does not give many information and results confusing.

Yes and no. When one increases, only one of the remaining other weather types has to decrease – sometimes there is a positive correlation: NW and N have a positive correlation of 0.36. Added this second example of correlation in the manuscript: "for example frequencies of anticyclonic and cyclonic weather show a negative correlation of -0.79, and frequencies of NW and N have a positive correlation of 0.36."

Finally, when considering land use, the authors only consider urbanization. If this is their main goal in the paper, it should be clear from the title and the introduction.

Urbanization is not the main goal of this paper, but only a part of it. We still investigate the other LULC changes, mainly when looking at the interaction effects.

4.3 Interaction effects.

This reviewer really appreciates the effort made including this new sub-section.

In figure 12 c) only one slope rage is considered, so it is difficult making the same comparison as in the other figures.

Note this is now subfigure (d) instead (c). This needs to be seen as follows: in catchments with a low loamic content, the effect of the slope on peak flow anomalies is lower, compared to catchments high in loamic content.

Here, I have the same questions on Wetspa model that I had in section 4.2.

See answer on this comment before.

Others:

P2 L26 and P3 L21. As suggested by one of the other reviewers before, brackets should be deleted and the authors should decide if they want to maintain or delete the words "relatively" and "main".

OK. Deleted the brackets of relatively and main in the revised manuscript. Probably the reviewer is referring to P3 L26 and P2 L21 of the track changes version of the latest revision – note that the brackets on P3, L21 were already removed in the previous revision.

P3 L21-24: As suggested for the introduction section by one of the other reviewers before, “Sect.” should be replaced by section. Please revise all the text in this sense.

OK. Replaced Sect. by Section throughout the manuscript

There is no need for writing “+” signal before increasing percentages, specially, when it is clearly said in the text that the trends are increasing. So please delete those signals all over the text and abstract: For example. P1 L22: “precipitation might increase with +50 % in winter…” should be “precipitation might increase a 50 % in winter”. Please check also for English correctness.

OK. Deleted the “+” signs, and replaced “might increase with” by “might increase by” for English correctness.

13 figures can be too many for a manuscript. The authors should try to summarize the information or select the really important ones and publish the rest as supplementary material.

Also see our reply on similar comment by the editor. We combined two figures, and moved some figures and tables to supplementary material, as suggested.

REVIEWER 2

Decision: accepted to minor revisions.

It appears that the author undertook a substantial revision. The authors emphasize that both individual drivers and interaction terms are important in explaining the observed changes in river peak flows.

The main problem I had with the first submission was a lack of details and general conclusions. The problem was largely addressed in the revision, but I am not quite satisfied yet.

First, the abstract ends with a sentence saying interaction terms explain up to 32%. It appears to end again without a general conclusion. What is the implication of the interaction terms explaining 32%? Did the authors want to say interaction terms must be considered in such studies or something else? Then please say explicitly. After reading the abstract, my eyebrows went up and I thought "is this the end?"

We now end the abstract stating "This shows the importance to include such interaction terms in data-based attribution studies."

Second, there are still numerous areas that need minor changes. Hereby I list them from the beginning:

The authors use 'e.g.' too often. Most of them are quite annoying and 'for example' should be used instead.

Changed most of the 'e.g.' to 'for example'.

P1: Words 'our' appear a couple of times. I recommend removing/replacing them because the meaning is vague.

Changed "our study" to "this study", and "our findings" to "the findings of this study" in the manuscript.

Changed "our rivers" to "rivers worldwide" in the abstract.

P1L33: I am not sure why the colon is used

Rephrased to: "With respect to the attribution issue in the second step, it is noted that different drivers act in parallel in a complex hydrological system, with interactions between those drivers."

P2L7: "most studies hypothesized that deforestation…" I wonder whether the studies 'hypothesized' or actually 'found' that deforestation cause increased surface runoff. If they merely hypothesized, then what happened to the hypotheses?

Changed the "hypothesized" to "conclude". And, expanded on the literature review.

P2L26: "Section" and "Sect." are used mixed in the document

See also comment of reviewer 1. Changed throughout the manuscript.

Section 2: the authors added a section about data availability at the end. Therefore, all the URLs in this section seem unnecessary (and are annoying)

OK. Deleted the URLs in section 2.

P3L1: "Koppen" has an Umlaut

OK. Changed in the revised manuscript.

P3L4: "1 – 1.5" means one minus one point five. Should be "1-1.5"

Changed to "has increased over the past 30 years by 1 to 1.5 °C".

P3L24: "proposed by (Willems, 2009)" Please correct the citation format. There are other such cases in the document

OK. Corrected the citation format on this location, and other locations.

P4L15: the authors mix commas and semicolons in parentheses

Indeed, this is a typo. Has been corrected in the revised manuscript: "W; (NW, N); (NE, E, SE); (S, SW); U; C; A"

P5L20: "on (100 times) 20 random" I don't understand what the authors meant to say

We tested 100 linear models, each time based on 20 different random calibration catchments. We deleted "(100 times)" in the revised manuscript for clarity.

P6L2: "17.85*Sediment" I wonder why sediment is here. In addition, in this sentence, what did you mean by "the coefficient becomes –3.04 – 0.85*Slope…"? Did you put 1 for Sediment? Then again why Sediment is left in the last term?

Note these examples talk about Settlement and not Sediment.

Sediment should not have been in the last term, this is a typo and should have been A for Anticyclonic. This is now corrected in the revised manuscript.

We do not put 1 for Settlement; we are talking about the overall coefficient for Settlement in the final regression model and thus the exact percentage of Settlement is of no importance here.

P6L5: I don't see how Figure 7 shows that the model explains 60% of the changes. Seeing the figure again, I still don't get it.

Changed the reference to the figures: "The model as shown in **Error! Reference source not found.** is able to explain 60% of the changes in river peak flows over time (**Error! Reference source not found.**)."

P7L2: I don't understand "we do make any statements…"

This should be: "we do not make any statements …" Corrected this in the revised manuscript.

P7L12-13: 10%+6%+6% = 22%. Does it mean that there is additional 10% you did not further explain?

Yes, correct. That is why we state "[…] is largely carried by three terms only". (1st paragraph of section 4.3)

LULC and climatic conditions (this is a 4th term) explain another 2% (3rd paragraph of section 4.3).

The remaining 8% is explained by other factors from Table 3, but is not further discussed (4th paragraph of section 4.3).

P7L18-19: authors say "with increasing slope,…" but Figure 12(a) shows decreasing slope from left to right. I recommend plotting the graph with increasing slope from left to right, consistent with (b) and (c).

Increasing slope goes from top to bottom, which is consistent with the loamic content in subplot (b) and in the other interaction plots. Hence, we prefer to leave this as is currently stands.

P8L28-29: "The model also showed that, for most of the considered case studies,…" What did you mean by the considered case studies? Are they previous studies? If so, how are they relevant here?

The considered case studies = the considered catchments in this study. Changed this in the revised manuscript: "The model also showed that, for most of the considered catchments in this study, a decrease in forested area to increase settlement area indeed leads to increased peak flows."

P8L14-16: I don't think these sentences are appropriate for the conclusion

OK. Moved this paragraph to the final paragraph of section 4.1.

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 worldwide. The intensification of the hydrological cycle caused by climate change is projected to cause more flooding in winters and land use/land cover changes could amplify these effects by ~~e.g.~~for example 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.

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 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%. Interaction terms explain up to 32% of the ~~peak flow~~peak-flow changes, where flat catchments with a low loamic soil content are more sensitive to land cover changes with respect to ~~peak flow~~peak-flow anomalies. This shows the importance to include such interaction terms in data-based attribution studies.

1 Introduction

Our environment has undergone unprecedented changes over the past decades, and it is very likely that further changes will 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~~ by ~~+~~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 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. 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~~:~~, it is noted that ~~in a complex hydrological system,~~ different drivers act in parallel in a complex hydrological system, with interactions between ~~them~~those drivers. 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. For the United States, it was found that (extra-)tropical cyclones and convective thunderstorms are the main weather systems~~causes~~ for flood-causing precipitation (Hirschboek, 1991; Smith et al., 2011). In Europe, a strong link between specific circulation types (weather types) and flood frequencies was found, both at continental scale and at river basin scale (Prudhomme and Genevier, 2011). Further, for the Atlantic region, westerly atmospheric circulation patterns are one of the main drivers for high ~~flood-causing~~ precipitation events (Mediero et al., 2015) and increased river peak flows. ~~(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).~~ This is also the case ~~F~~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~~ conclude that ~~deforestation and~~ increased urbanization causes increased surface runoff. A study on the urban developmenet in a watershed in Taiwan reveiled that three decades of urbanization has increased peak flows by 27%. For 95 catchments in the Rhine basin, it was found that increased urbanization would lead to an increase in lower peaks for summer periods and a small increase in the higher peaks in winter periods (Hundecha and Bárdossy, 2004). They also found a considerable reduction of peak runoff and cumulative runoff caused by intensified afforestation. For a case study in Germany, an assumed 50% increase in settlement area would result in increased peak discharges by~~with~~ up to 30% (Bronstert et al., 2002). For the Brussels Capital Region in Belgium, it was found that high flows increased by 32% and annual cumulative flows increased by 40% for a 10% increase in impervious surface for historical conditions (Hamdi et al., 2011). Further, for a small catchment in central Belgium, an increase of built-up land of 70 to 200% would cause an increase of river peak flows of 6 to 16% (Poelmans et al., 2011). ~~(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.~~For example, the isolated effect of an increase in settlement area at the expense of agricultural land is typically not quantified. Also, a lot of uncertainty remains, mainly because of the heterogeneity of hydrological responses ~~-~~and the scale of the river basin/catchment considered;~~:~~ ~~(see e.g.~~ for example, Zhang et al. (2017) found that small mixed forest-dominated watersheds and large snow-dominated watersheds are more hydrologically resilient to forest cover change with respect to annual flows.

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 2), a data-based approach is followed where ~~peak flow~~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 3). Results are presented in Section 4 and overall conclusions are given in Section 5.

2 Study 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 m~~TAW~~. The central Southern part with silty soils has low hills ~~o~~up to 150 m~~TAW~~. In the South East, ~~T~~the maximum height is 288 m~~TAW in the South East~~. The DTM in Figure 1 was taken Model Flanders (“Digitaal Hoogtemodel Vlaanderen”) ~~(https://overheid.vlaanderen.be/producten-diensten/digitaal-~~

Flanders has a maritime climate (*Cfb*, according to the Kö~~o~~ppen 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 the period 1981 to ~~-~~2010); the average temperatures in Flanders, further, has ~~been rising~~increased over the past 30 years ~~with~~ by 1 to~~–~~ 1.5 °C. Average evapotranspiration was 540 mm/year in 1980 and ~~rose~~increased almost linearly 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).

Twe~~i~~nty-nine 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 Supplementary ~~Table 1~~ Table 1. Further, Supplementary Figure 1 and 2~~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. Soil texture is obtained from ~~www.dov.vlaanderen.be~~the Flanders underground database; 3 dominant soil textures (Arenic, Loamic and Siltic) cover 99.3% of the total area of the selected catchments. Therefore, further in this study, only these 3 dominant soil textures were taken into account.

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 hourly discharge series of each catchment is first transformed to ~~peak flow~~peak-flow anomalies (~~Sect.~~Section 3.2). Then, possible drivers are derived from the data introduced in ~~Sect.~~Section 2 and further split into separate categories, see ~~Sect.~~Section 3.3. Finally, a regression model is fitted to the data (~~Sect.~~Section 3.4).

3.2 ~~Peak flow~~Peak-flow anomalies

The methodology to estimate ~~peak flow~~peak-flow anomalies is schematized in Figure 2. The hourly discharge data (Figure 2a) is first split into independent events and extremes are extracted (see Figure 2b), 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 2c). The quantiles in a particular subperiod/block are then compared with the corresponding quantiles based on the reference period and the ratio of these two empirical quantiles defines an anomaly factor (Figure 2d). 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 2d). As such, one can plot and/or investigate ~~peak flow~~peak-flow anomalies catchment over time (Figure 2e). 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.~~ for example, 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.~~Section 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~~,~~ and the river map, ~~and~~ locations of the outlet stations~~,~~ and catchment delineations are defined. Further, based on the DTM, the slope in the catchment 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 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 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 aims to limit the degree of freedom in the final model. In the further analysis, relative frequencies of these daily weather types are considered, based on a rolling window of 5 years (Supplementary~~Figure 5~~ Figure 3), 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) are taken into consideration as possible drivers for this study. It 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, these *LULC*-classes will further not be taken into account. In addition, the *LULC* class Grassland is considered as the complement of (Forest + Agriculture + Settlement). Because the *LULC* database does not show any significant changes after 2005 (Supplementary~~Figure 2~~ Figure 1), the analysis is limited to 1992-2005.

Table 1 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, in this study, climate variability is described through weather types and we assume the area of Flanders to be homogeneous with respect to ~~the considered climate data~~these weather types.

The typical panel data regression model can be described as follows:

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

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~~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 1. As such, $\boldsymbol{X}_{it}$ from Eq. (1) becomes:

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

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:

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

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~~ this study, we added the restriction that there cannot be any interaction between explanatory variables from within the same category: ~~e.g.~~for example $\rho_{area,slope} = 0$.

3.4.2. Model building

Model building happens based on a top down approach. Starting from a simple constant model, with $\boldsymbol{\beta} = \boldsymbol{0}$ and $\boldsymbol{\rho} = \boldsymbol{0}$, 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. Suppose~~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

The final model has 26 terms in 9 predictors (see Supplementary ~~Table 3~~ Table 2). During model building, it was decided to not further consider following variables (Supplementary Figure 4):

- Catchment characteristics: Area;
- Climate variability: W; (NW, N); (NE,E,SE) ~~; A~~ and U.

The catchment area does not have a significant contribution in explaining observed ~~peak flow~~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 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 Supplementary~~Table 3~~ Table 2. ~~E.g.~~For example, 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~~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~~A);
- 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 as shown in Figure 3 is able to explain 60% of the changes in river peak flows over time (Figure 4) ~~(Figure 7)~~. This performance is further broken down into linear effects of the three separate groups and their interactions: ~~(Figure 8). L~~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~~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 cover, soil texture and catchment slope.

Observed ~~peak flow~~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 3). 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~~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~~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 period larger than 1 year, based on data between 1978 and 2016.

~~With respect to the estimation of the regression model, i~~Ideally, one would carry out a split-sample test (in space and in time) for the estimation of the regression model; 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 3 that this approach results in consistent estimations for the ~~peak flow~~peak-flow anomalies – only for catchment L11_518 this consistency was not always found.

4.2 Effect of single drivers

Firstly, the dependency of ~~peak flow~~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 5, that ~~peak flow~~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 river density, the results show less clarity.

These findings correspond to an analysis done on the potential runoff coefficient as used in the hydrological model structure 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.~~for example Figure 6 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 and with the above definition of potential runoff coefficient in mind, relative changes in this potential runoff coefficient can serve as a proxy for ~~peak flow~~peak-flow anomalies. As such, findings with respect to the potential runoff coefficient from Wetspa can be related with the conclusions based on Figure 5:

- Figure 6a shows that potential runoff coefficients increase, with increasing slope. Moreover, the rate of this increase is lower for higher slopes. This corresponds with ~~our~~ the findings of this study on catchment slope.
- Figure 6b 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~~ the findings of this study 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~~peak-flow anomalies (Supplementary Figure 4~~Table 3 and~~ and Supplementary Table 2). 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, and frequencies of NW and N have a positive correlation of 0.36. Because of these correlations, we do not make any statements on the effect of increasing/decreasing frequencies of S+SW or A on ~~peak flow~~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 7), 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~~ of 7 to~~–~~ 10% in river peak 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 8):

- Figure 8a shows effects of LULC changes on ~~peak flow~~peak-flow anomalies as a function of the slope (three particular 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 8 should be interpreted in a relative way. It is seen that, with increasing slope, the effect of LULC changes on ~~peak flow~~peak-flow anomaly goes down. A steeper slope typically results in increased peak flows but the LULC changes influence these ~~peak flow~~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~~peak-flow anomalies, compared to catchments with a high proportion of loamic soils (Figure 8b). Again, trends are consistent for each LULC class.
- And finally, the catchment slope has a larger effect with respect to ~~peak flow~~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 8~~c~~d).

Comparison with the analysis on the potential runoff coefficient from Wetspa (Figure 6) learns the following on the three main interaction effects:

- Slope and LULC: One can see in Figure 6a 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%. In 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~~ by 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 6b). In 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~~ by 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 6c). In 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 8c~~Figure~~ these minor interactions. Periods 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, 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 8c~~Figure 13~~, these interactions might not be significant.

The remaining interaction terms ~~from~~ (Supplementary ~~Table 3~~ Table 2) further explain an additional 8% of the variation in ~~peak flow~~peak-flow anomalies. 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.

5 Conclusion

The regression model is able to explain 60% of the changes in ~~peak flow~~peak-flow extremes. For -catchments L07_289 (Mark at Viaene) and L08_233 (Zuunbeek at Sint-Pieters-Leeuw)~~some individual catchments~~, however, the model is not able to mimic observed step changes~~, e.g. for catchments L07_289 (Mark at Viaene) and L08_233 (Zuunbeek at Sint-Pieters-Leeuw)~~. For the other 27 considered catchments, the direction and the overall trends simulated by the model are found to be accurate.

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 proportion 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~~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~~catchments in this study, a decrease in forested area to increase settlement area indeed leads to increased peak flows. Moreover, 1% increase in 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

Author contribution

JD and PW worked on the concptualization of the research and jointly developed the methodology. JD curated the data, performed the formal analysis and investigation, under the supervision of PW. JD prepared the visualisation and the initial draft, which was critically reviewed and revised by PW.

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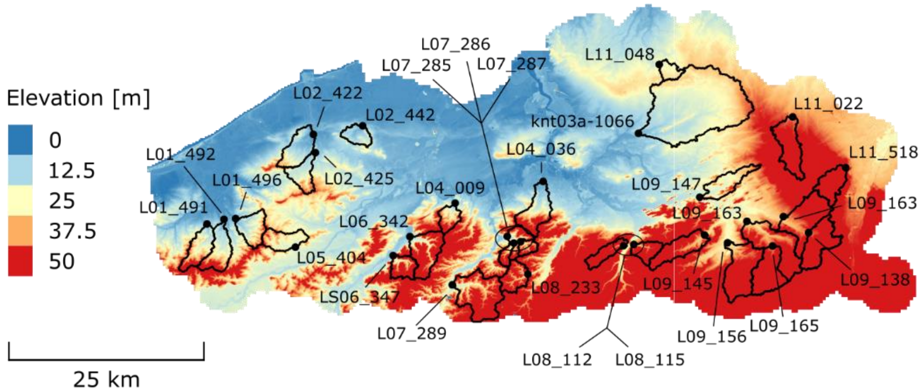
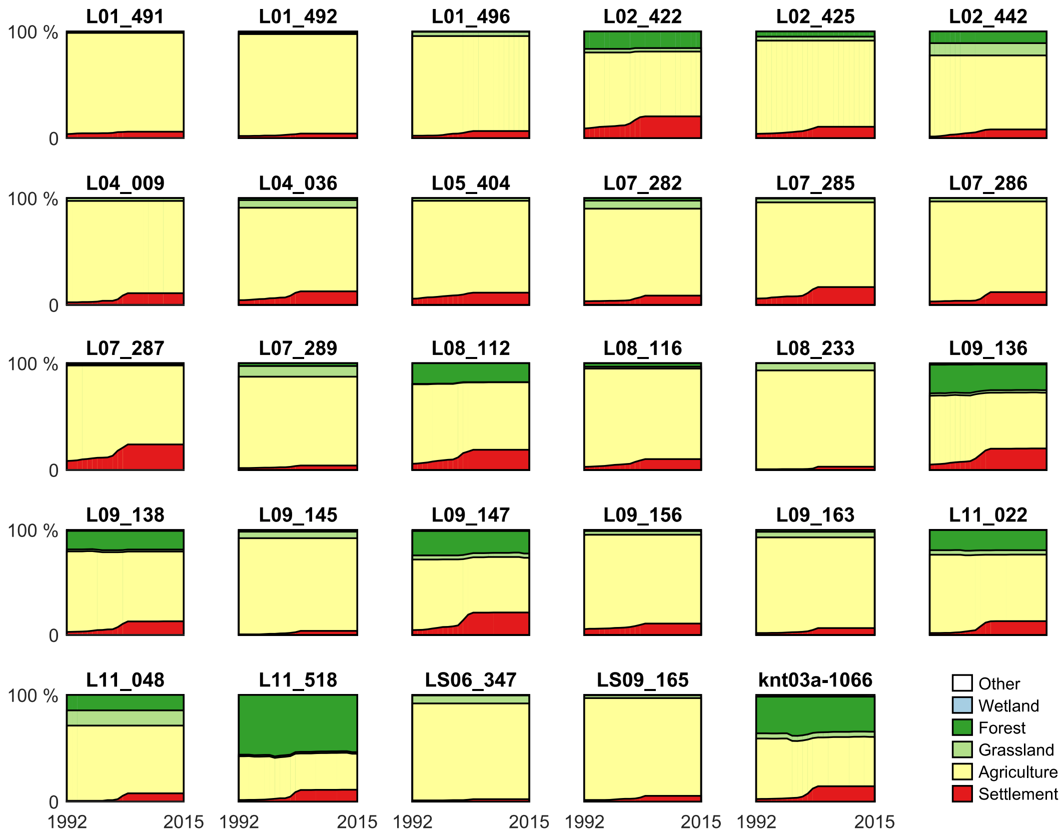


Figure 1. Selected catchments in the Flanders area of Belgium.



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~~Figure 2. Land cover and land cover changes over time (1992 – 2015) for the selected catchments.~~

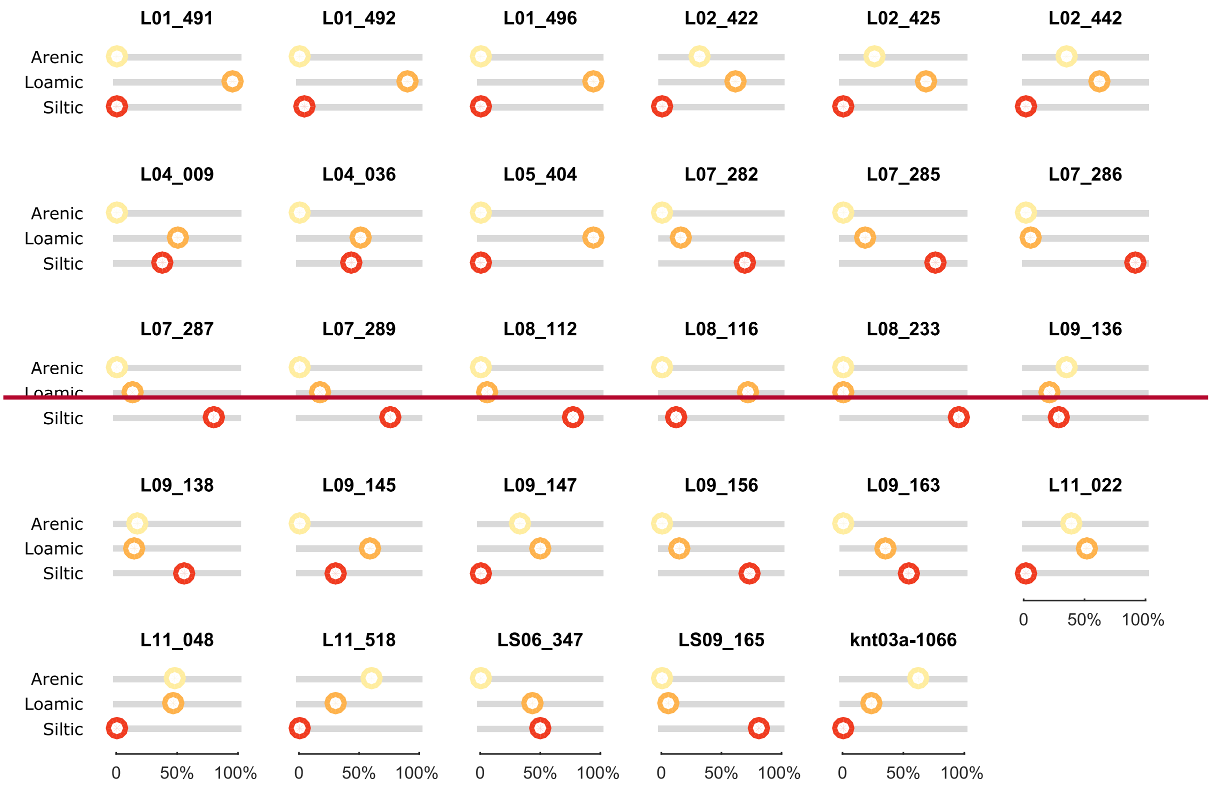

Figure 3. Relative areas of soil texture (arenic, loamic and siltic) for the selected catchments. Data from: www.dov.vlaanderen.be

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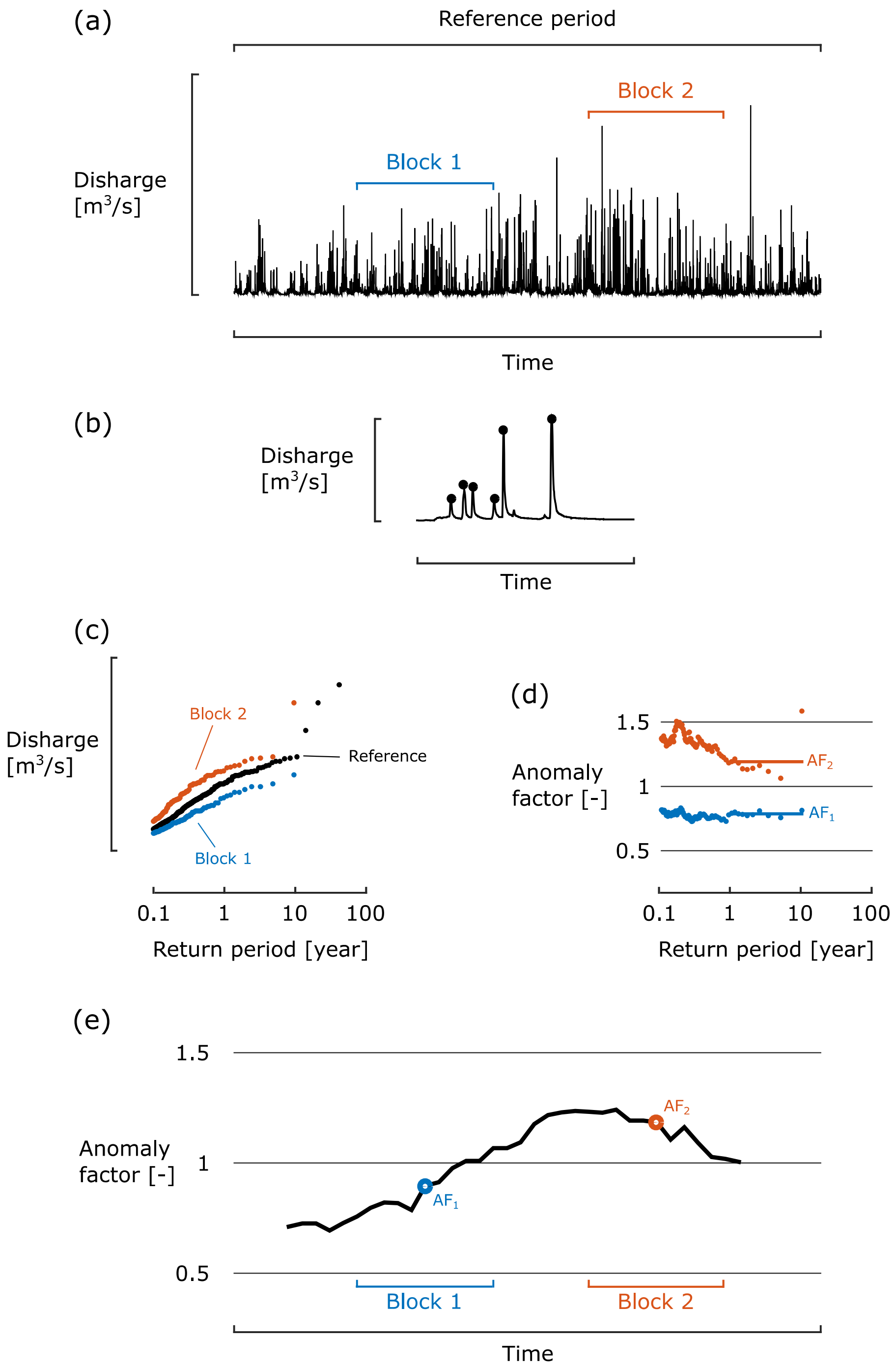
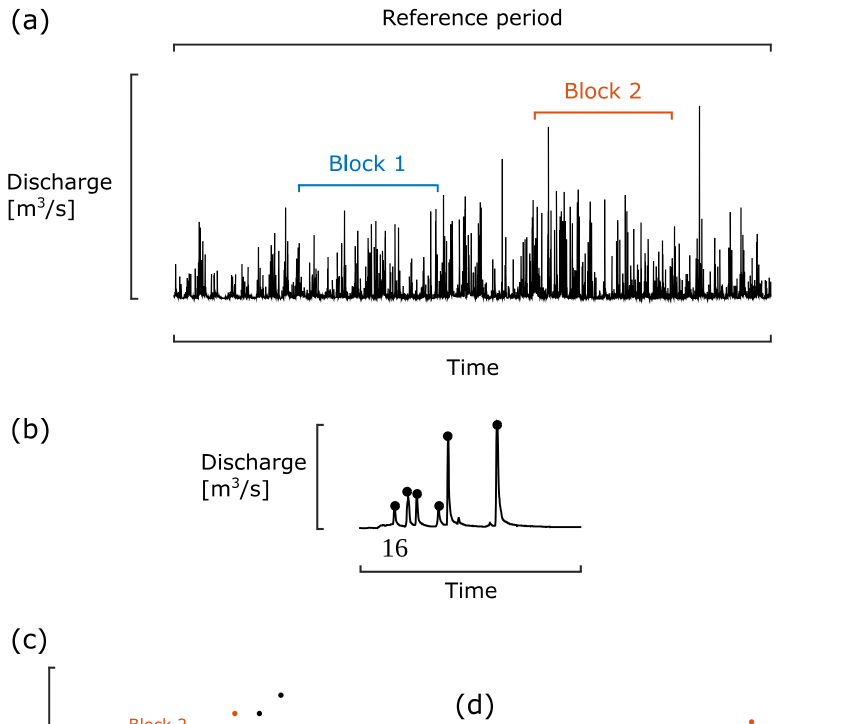
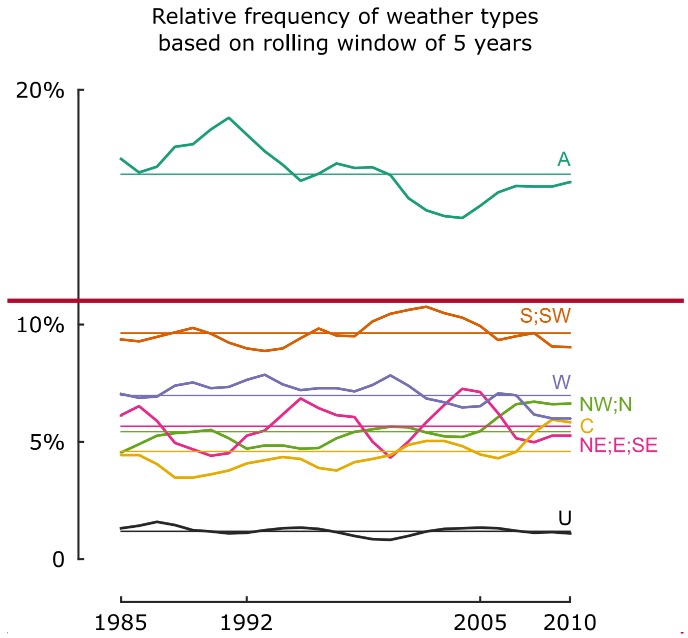

(a)
Reference period
Block 2
Block 1
Disharge
[m³/s]
Time
(b)
Disharge
[m³/s]
Time
(c)
Block 2
Reference
Block 1
Disharge
[m³/s]
0.1 1 10 100
Return period [year]
(d)
1.5
1
0.5
AF₂
AF₁
Anomaly
factor [-]
0.1 1 10 100
Return period [year]
(e)
1.5
1
0.5
Anomaly
factor [-]
AF₂
AF₁
Block 1
Block 2
Time

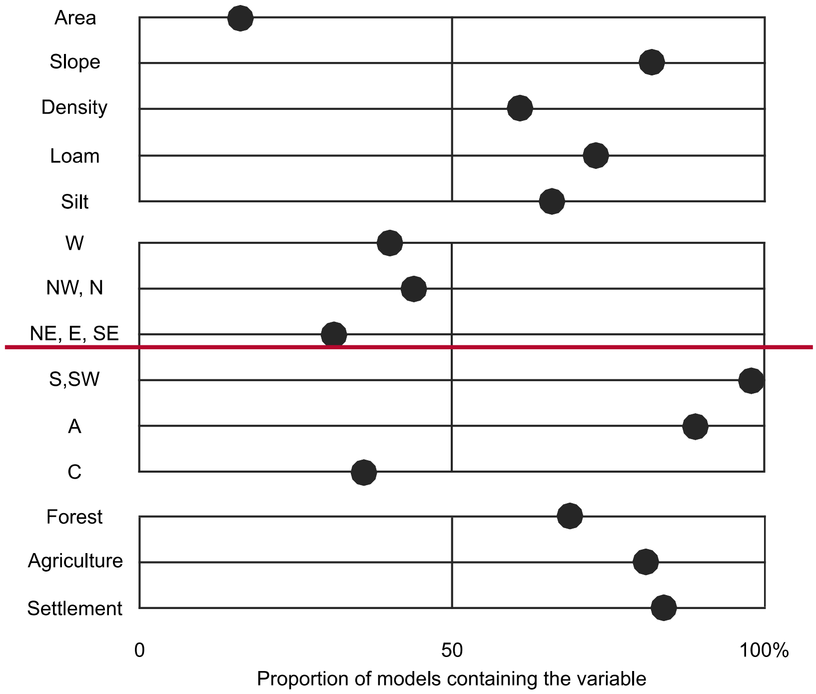

(a)
Reference period
Block 2
Block 1
Discharge
[m³/s]
Time
(b)
Discharge
[m³/s]
Time
(c)
(d)

16

Figure 2. Schematic overview of methodology to estimate ~~peak flow~~peak-flow anomalies for two specific block periods over a period. (a) Hourly discharge data with indication of two block periods and one reference period; (b) Selection of peak flows; (c) Extreme value distribution of peak flows for two block periods and one reference period; (d) Anomaly factors for the two block periods as a function of return period and average anomaly factor for return periods larger than one year for the two block periods; (e) Average anomaly factors over time, with the average anomaly factors of the two block periods highlighted.



~~Figure 5. Relative frequency of Lamb weather types over the years.~~



~~**Figure 6. Variables appearing in >50% of the calibrated models are selected to explain changes in river peak flows.**~~

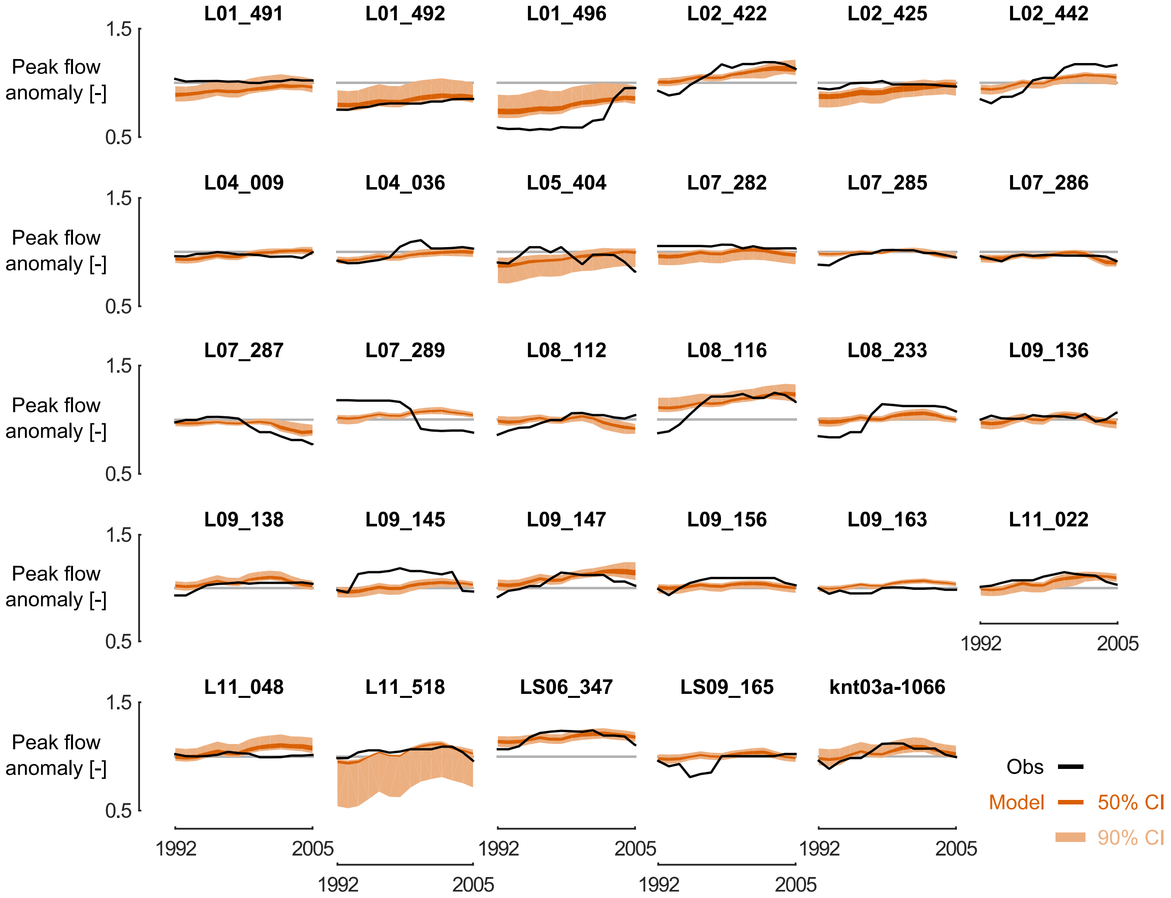


Figure 3. Regression model combining catchment characteristics, climate variability and land cover changes to explain streamflow variability.

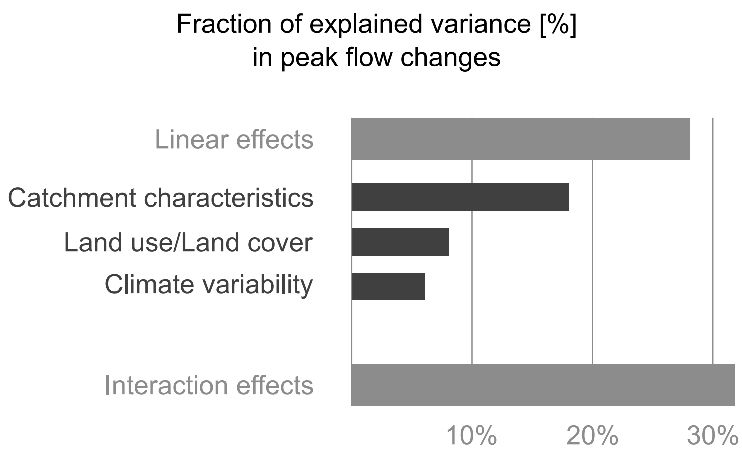


Figure 4. Linear effects and interaction effects between catchment characteristics, climate variability and land cover changes play an equal role in explaining streamflow variability.

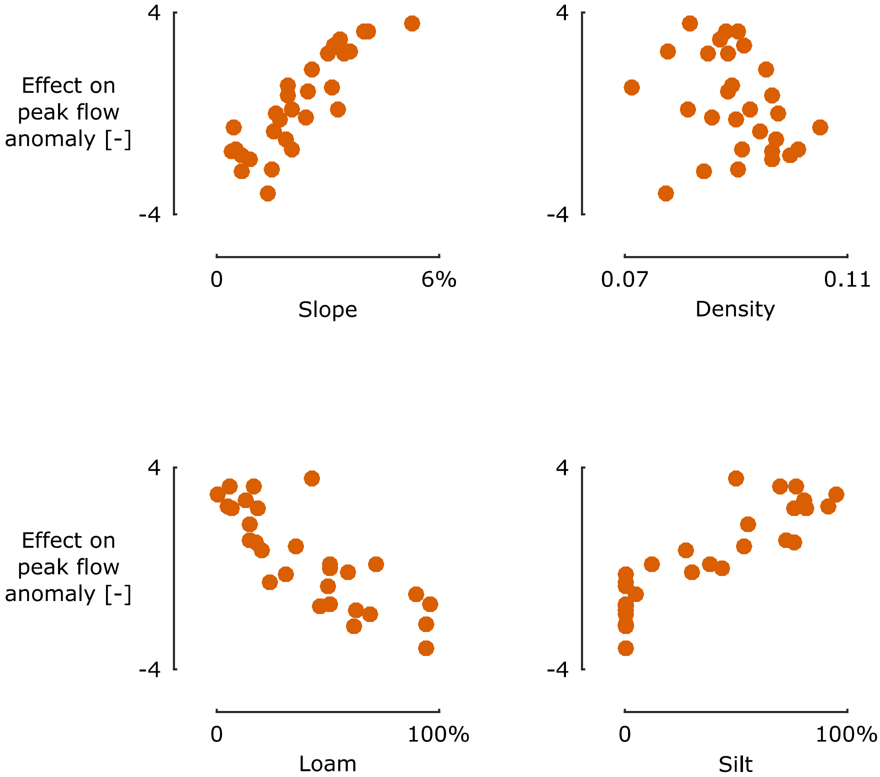


Figure 5. Effect of catchment characteristics on ~~peak flow~~peak-flow anomalies for the 29 selected catchments.

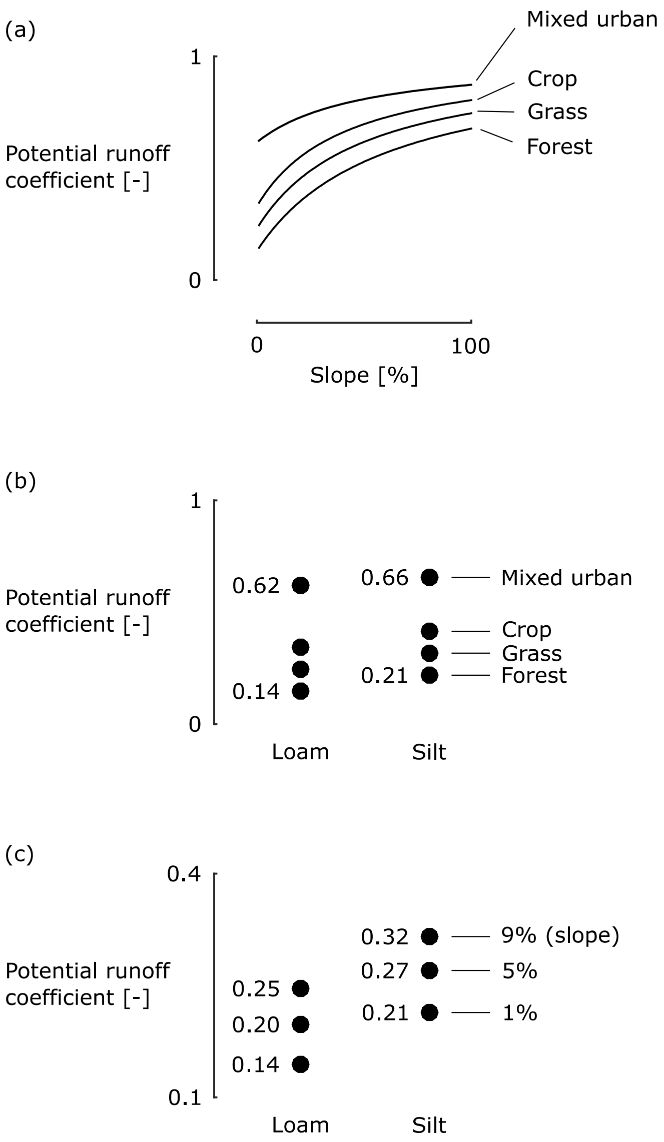


Figure 6. Potential runoff coefficient from the Wetspa hydrological model (Liu and De Smedt, 2004)**, (a) as a function of slope, for different LULC categories (loamic soil texture), (b) as a function of soil texture class for different LULC categories (near-zero slope) and (c) as a function of soil texture class for different slopes (forested area).**

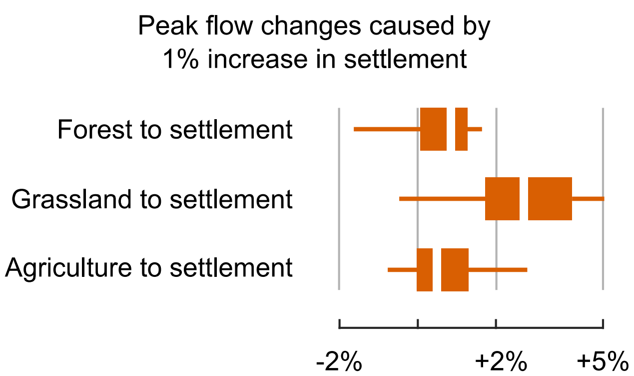
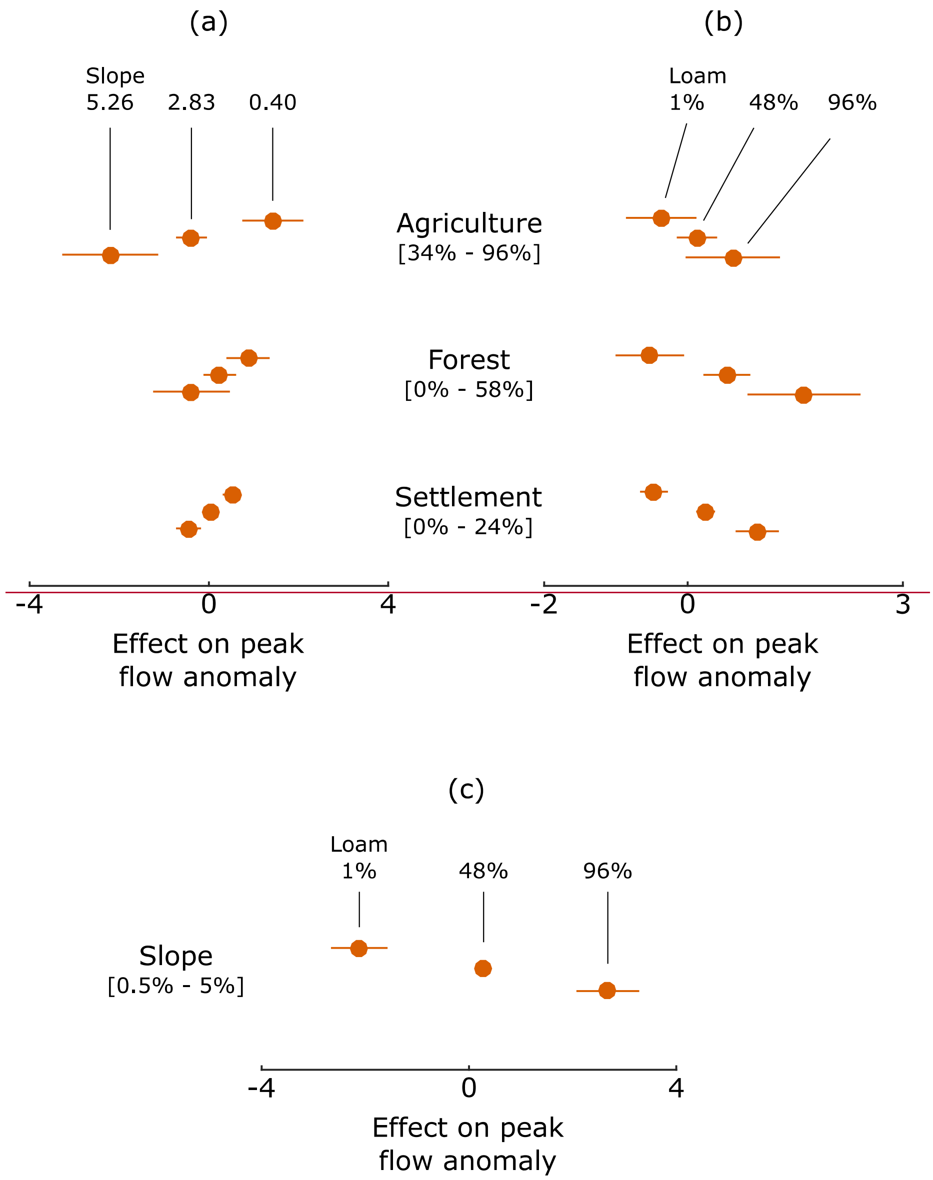


Figure 7. ~~Peak flow~~Peak-flow changes by increasing settlement area through decreasing forest, grassland or agriculture.


(a)
Slope
5.26
2.83
0.40
(b)
Loam
1%
48%
96%
Agriculture
[34% - 96%]
Forest
[0% - 58%]
Settlement
[0% - 24%]
-4
0
4
-2
0
3
Effect on peak flow anomaly
Effect on peak flow anomaly
(c)
Loam
1%
48%
96%
Slope
[0.5% - 5%]
-4
0
4
Effect on peak flow anomaly

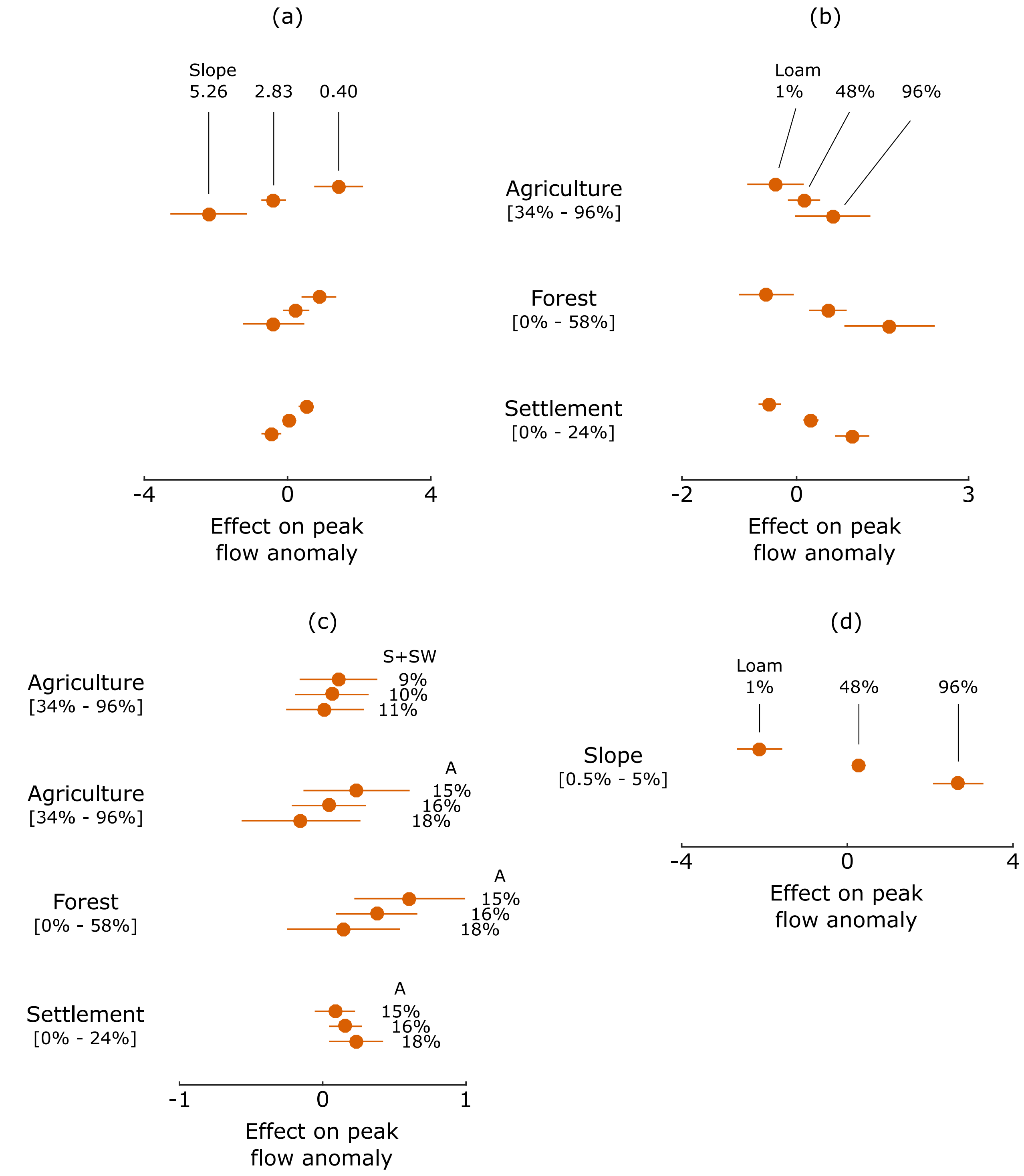


Figure 8. Estimated effect on ~~peak flow~~peak-flow anomalies from changing (a) slopes and LULC, (b) soil texture (loamic content) (c) climatic conditions (relative frequencies of weather types S+SW and A) and LULC, and (~~c~~d) slopes and soil texture (loamic content), averaging out the effects of the other predictors. Horizontal bars indicate confidence intervals for the estimated effect.

~~**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.**~~

~~**Table 1. Main characteristics of the selected catchments.**~~

~~Id.~~	~~Outlet station~~	~~River~~	~~Area [km^2]~~	~~Period~~		~~# years~~
~~knt 03a – 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~~

Table 1. Drivers considered for this study

Catchment specific *CAT*

Topographic	Soil texture [% of total area]

Area [km^2], Slope [%] and Density [m/km^2]	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		