Response to Reviewers

We would like to thank the reviewers for their constructive and very helpful feedback, which led to a considerable improvement of the paper. In the table below, we refer to the reviewers' comments and how they were addressed.

Referee 1 – as written

The paper describes an inventory of the existing and potential nbS in the wider Cologne area. In general terms the paper is easy to read in terms of language used and accessible figures and tables. The paper reads a bit more like a report than a scientific paper, with a large number of maps/figures and tables. The 'new' contribution to science lies especially in the mapping of the measures for the specific area of Cologne, yet there is limited new insights to the scientific domain beyond that specific mapping, making the paper a bit 'boring'/'small scaled'.

The focus of the paper is on mapping and categorizing potential measures that will help in flood risk reduction, and separates clearly how this is spatially diverse for the different subbasins in the area, depending on topography and land-use. It recognizes various types of flood risk (riverine, pluvial and flashflood) and acknowledges the different risks in urban and rural zones. The paper lacks a good analysis of the impact on other societal challenges in the area (e.g. droughts, biodiversity and social goals).

In general the paper is good for publication with large revisions:

Comment 1: A major issue that needs improvement in the current manuscript is its vagueness of defining and quantifying risks, in relation to the types of events that groups of NbS may still cater for. E.g. : what risks are you assessing for? (loss of lives/damage to infrastructure/damage to agricultural yields etc) and when do these risks occur (which types of events). Also: When does an event become too large to handle, despite the measures implemented (viz. if a hurricane would pass, nothing can be done, you just have to sit it through, ensure proper early warning, evacuation and discuss rebuilding by design taking water and soil systems better into account. NbS might take the sharpness away of a peak, but if the peak is still higher than a tipping point for damage, the damage will still occur. At the same time nbS might be especially helpful in less extreme events that will also occur and cause damages (e.g. 1:50 year event/ 1: 20 year event) that is also more in line with what authorities may want to/can invest in.

Response: We agree that clarifying the types of flood events that different NbS target is essential for understanding their risk mitigation potential. To address this, we have made it clearer in the manuscript that retained floodplains primarily serve to manage minor to moderate floods, typically in the range of HQ10 to HQ50 and up to HQ100 events. In contrast, retention basins such as those in Köln/Niederkassel are generally filled only during larger flood events of the Rhine River at the HQ100 level, with the Worringer Bruch basin designed for even more extreme events between HQ100 and HQ200. Regarding the reference to hurricanes, while such extreme events are understandably beyond the scope of our study focused on the Cologne District and Rhine catchment, we acknowledge the broader point that certain extreme events exceed the design thresholds of both NbS and grey infrastructure. As noted, effective management of such rare events relies on early warning, evacuation, and resilient rebuilding that integrates water and soil system considerations.

Comment 2: Given the title 'under a changing climate' I would have expected more attention to the changes in event types due to climate change and the impact this may have on the contribution and functionality of measures. Are there areas that are OK now, but will be at risk in future scenarios of change? Similarly: the quantification of the contribution of the nbs to reducing the risks can be further clarified: e.g. in the tables there is hectares listed, but how does that relate to peak reduction? how many hectares or m3 do you need to really reduce a certain type of risk significantly, and is that available? Where are the bottle necks in the system? Do the NbS contribute to solving issues at the bottle necks? (e.g. : can you add a map with bottlenecks?)

Response: Regarding the impacts of climate change, we have discussed the expected changes in event types, such as increased frequency and intensity of intense summer rainfall and drought periods, and how these may influence flood risks and the functionality of NbS. While some areas are currently well-protected, others may face increased risk under future climate scenarios due to these changing hazard dynamics. We have clarified these points in the manuscript to reflect the evolving nature of flood risk.

Concerning the quantification of NbS contributions, we agree that translating hectares or cubic meters of retention area into actual flood peak reduction is important. However, detailed hydrological modelling to directly link spatial extents with peak flood reductions was beyond the scope of this qualitative and mapping-focused study. Nevertheless, we provide information on retention capacities and approximate flood event ranges that different NbS cater to, as detailed in the table below, to help contextualize their potential impact.

Regarding bottlenecks in the system, we recognize their critical role in flood dynamics. Key bottlenecks such as narrow valleys and urban constrictions are described and illustrated in the current figures. While we do not include a dedicated bottleneck map, these features are discussed in relation to NbS placement and effectiveness. This is also detailed further in the table below.

More detailed responses to other comments are provided in the table below.

Referee 2 – as written

General comments

The authors focus on categorizing and mapping NbS along the Rhine River in two subcatchments that were affected by flooding in 2021 (Wupper and Erft basins) and in the city of Cologne. The authors then identify potential areas where NbS could be implemented in the future, and discuss potential benefits, challenges, and constraints to widespread implementation of NbS. NbS is framed as a climate adaptation strategy for the region.

The authors apply a landscape perspective, using geomorphological and hydrological dynamics of the region and GIS techniques to identify potential NbS types and locations. Without the use of flood modeling software or a formal modeling framework, these findings serve primarily as a screening-level assessment that may inform local modeling or monitoring work in the future.

Overall, this paper has the potential to make a useful contribution to the literature. However, there are a few areas that should be addressed in future revisions. Specific comments and recommendations are provided below.

We have responded to the specific comments in the table below.

Reviewer 1	**Response**
The paper lacks a good analysis of the impact on other societal challenges in the area (e.g. droughts, biodiversity and social goals)	We briefly discuss the societal challenges related to the topic, including climate change impacts, adaptation strategies, and the associated risks from climatic extreme events and natural hazards such as heat, drought, wildfire and storm. We also consider related concerns, including biodiversity, but can only address these aspects to a limited extend, as they fall beyond the scope of our paper. To provide more focused context, we have added a "Study Area" section where these issues are introduced, and we revisit them again in the discussion.
A major issue that needs improvement in the current manuscript is its vagueness of defining and quantifying risks, in relation to the types of events that groups of NbS may still cater for. E.g. : what risks are you assessing for? (loss of lives/damage to infrastructure/damage to agricultural yields etc) and when do these risks occur (which types of events).	We thank the reviewer for highlighting the importance of clearly defining and quantifying the risks associated with different types of flood events and the corresponding NbS. Our study focuses primarily on the spatial mapping, categorisation and assessment of existing and planned NbS measures for flood risk reduction in the Cologne district, rather than on a comprehensive risk assessment. Therefore, a detailed quantification of specific risks such as fatalities, infrastructure damage or impacts on agriculture in relation to different flood scenarios would go beyond the scope of this manuscript. Nevertheless, to provide clarity, we have revised the manuscript to better specify the types of flood hazards considered (e.g., river floods, flash floods, rain floods) and the general risk contexts that these NbS target. We believe that this contextualisation improves the focus of our study while respecting its defined scope.
Also: When does an event become too large to handle…. At the same time NbS might be especially helpful in less extreme events that will also occur and cause damages (e.g. 1:50 year event/ 1: 20 year event) that is also more in line with what authorities may want to/can invest in.	We agree with the reviewer's point and have added clarifying text to the manuscript to specify that retained floodplains primarily serve to manage minor to moderate flood events, typically ranging from HQ10 to HQ50 and up to HQ100. Retention basins, such as those in Köln/Niederkassel, are generally activated at HQ100 levels, while the Worringer Bruch basin is designed to operate between HQ100 and HQ200 events. We acknowledge that there will always be extreme flood events that exceed the capacity of both NbS and engineered (grey) infrastructure. Cities must carefully balance considerations of cost, land availability, and the statistical probability of such infrequent but severe events when planning flood protection measures. We have incorporated this perspective into the revised manuscript to reflect the practical realities of flood risk management.

Given the title 'under a changing climate' I would have expected more attention to the changes in event types due to climate change and the impact this may have on the contribution and functionality of measures. Are there areas that are OK now, but will be at risk in future scenarios of change?	We discuss how climate change is expected to increase the frequency and intensity of intense summer rainfall as well as prolonged droughts, which in turn can lead to increased surface runoff due to dried and hardened soils. This exacerbates the risk of flash floods and pluvial flooding, particularly in urban areas such as Cologne. We further highlight how NbS can help mitigate these climate-driven changes by enhancing infiltration, delaying runoff, and increasing landscape resilience. While a comprehensive analysis of future risk areas under different climate scenarios goes beyond the scope of this study, we do identify potential sites for targeted NbS interventions, especially on slopes and in urban infiltration areas, that are likely to gain importance under changing climatic conditions. We appreciate the reviewer's suggestion and have clarified and expanded this discussion in the revised manuscript.
Similarly: The quantification of the contribution of the NbS to reducing the risks can be further clarified: e.g. in the tables there is hectares listed, but how does that relate to peak reduction? How many hectares or m3 do you need to really reduce a certain type of risk significantly, and is that available?	We have clarified in the revised manuscript that Cologne's flood protection currently relies on a combination of grey, NbS and hybrid measures designed to manage flood events up to HQ200. Furthermore, we have included quantitative information on the floodwater retention capacity of retained floodplains during HQ10-50 flood events, expressed in cubic meters, to better illustrate their functional contribution. Regarding peak flood reduction, we acknowledge that precise quantification requires hydrological and hydraulic modelling, which was beyond the scope of this study. Our aim was primarily to map and categorize existing and planned NbS and provide an initial assessment of their spatial extent and retention potential. We agree that modelling the direct impact of NbS on peak flow reduction is an important next step and suggest it as a direction for future research.
Where are the bottle necks in the system? Do the NbS contribute to solving issues at the bottle necks? (e.g. : can you add a map with bottlenecks?)	Key bottlenecks include the narrow valleys and steep slopes found in parts of the Wupper Basin, as illustrated in Figure 2. The city of Cologne itself acts as a major constriction point along the Rhine, shown in Figure 4, where urban density and infrastructure limit floodwater passage. Additionally, the naturally narrow stream beds and confined valleys in the Erft and Wupper catchments represent bottlenecks that are particularly vulnerable to being overwhelmed during intense rainfall events, such as those in July 2021. While we do not explicitly label these features as "bottlenecks" in the manuscript, we discuss their significance in relation to the capacity and

	limitations of NbS to reduce flood risk in these constrained areas. Regarding the suggestion to include a dedicated map of bottlenecks, we currently rely on the existing spatial analyses and figures to illustrate these features. A detailed, standalone bottleneck mapping would require more extensive hydraulic modelling and local data integration, which is beyond the scope of this study.
In the abstract and introduction you do speak about hydrophobic soils, and its potential effect on flood risks, but in the assessments you don't really tackle this issue anymore. Please add more information on the linkage between drought risks and flood risks, and make it quantified if possible: how bad is the hydrophobicity of the soils for a given event? Does the run-off become 10x high or 100x high? Note of course also that many soil related NbS will take decades to give significant impact, which should be discussed: what are the quick-wins and what are the long-term developments. Can the proposed NbS be 'ready on time'?	We recognize the importance of the linkage between drought risks, soil conditions, and flood risks, including the concept of soil hydrophobicity. In our manuscript, we discuss the effects of dried-out and hardened soils resulting from drought periods, which can increase surface runoff and flash flood risks. However, we do not specifically address soil hydrophobicity as a distinct phenomenon, as comprehensive data on this property was not available for our study area and scope. We appreciate the reviewer's suggestion to quantify the impact of soil conditions on runoff. Unfortunately, precise quantification, such as runoff being 10 or 100 times higher due to hydrophobic soils, requires detailed hydrological and soil process modelling, which was beyond the scope of the present work. We agree that soil-related NbS typically require longer time frames to yield significant hydrological benefits due to the gradual restoration of soil structure and ecosystem functions. We have therefore added discussion on the distinction between "quick-win" NbS interventions, such as urban infiltration measures and retention basins, versus long-term landscape and soil restoration approaches that aim to improve soil permeability and ecosystem resilience over decades. This includes reflection on the feasibility of implementing these NbS within relevant climate adaptation time horizons.
Are there NbS that might also suffer during an event/what is the recovery time after damage and how does that affect follow-up risks?	Thank you for this thoughtful suggestion. The resilience and recovery time of NbS following flood or extreme events is an important topic, as damage to these interventions could influence subsequent risk levels and their effectiveness. However, detailed assessment of NbS vulnerability, recovery dynamics, and implications for follow-up risks is beyond the scope of the current study. Nevertheless, we do touch upon this issue briefly in the discussion to acknowledge its relevance and highlight the need for further investigation. We recognize this as a valuable area for future research to better understand the long-term sustainability and

	adaptive management of NbS in changing climate conditions.
The lack of quantified impact of the NbS proposed and lack of the summing of their combined impact is to be further addressed and discussed, also acknowledging aspects of e.g. In the results section there is a lot of information that might be better positioned in a section on 'case study descriptions' e.g. at the start of the methods, and superfluous information that does not contribute to the overall aim of the mapping (e.g. sentences from 283 onwards on the institutional setting) may be better removed throughout the results part (in general: avoid discussion style sentences that have also references to other documents/studies, but stick more to the plain results. Stick site descriptions in the site description and points of discussion in the discussion section).	We acknowledge that a more explicit discussion of the combined quantitative impact of NbS would strengthen the manuscript. While detailed hydrological modelling to sum and quantify the integrated effects of the NbS was beyond the scope of this study, we have enhanced the discussion to better reflect the potential cumulative contributions and limitations of NbS based on available data. Regarding the manuscript structure, we have reviewed the placement of site-specific information and institutional context. As suggested, we have relocated certain descriptive elements, including some case study descriptions, to the new "study area" section to improve clarity and flow, and removed or condensed parts of the results section that contained discussion-style content or extensive referencing. This restructuring ensures that the results section focuses primarily on the presentation of our findings, while interpretative elements and broader contextual information are addressed more appropriately in the discussion.
In the tables with the descriptions of individual NbS the categories co-benefits and risks/challenges are often seemingly incomplete or aspects are mentioned that might be valid for all of the listed NbS, nor is it clear how the selection of the listed items what made. Some of these mentioned risks such as the ones on invasive species and mosquitoes need to be better discussed in the discussion section, as often their presences is either unavoidable (invasives) or manageable (mosquitoes) when dealt with care of e.g. assuring connectivity and avoiding stagnancy.	We would like to clarify that the descriptions of co-benefits and risks/challenges in the NbS tables are drawn directly from the literature sources cited. We included only those aspects specifically mentioned in these secondary sources to ensure accuracy and consistency. While we acknowledge that additional co-benefits and risks may exist, a comprehensive evaluation of all potential aspects was beyond the scope of this study. To improve transparency, we have added footnotes to the tables clarifying that the descriptions are based on existing literature and highlight the co-benefits reported therein. We also appreciate the reviewer's suggestion regarding invasive species and mosquitoes; accordingly, we have expanded the discussion section to address how these challenges can often be managed effectively through design considerations such as maintaining connectivity and preventing water stagnation.
Also, e.g. the measure in table 3 on multifunctional areas only lists recreation as a co-benefit, but surely there is also an increase in habitats and landscape aesthetics? E.g. their impacts on groundwater and potential groundwater-driven floods, co-incidence of peaks from various tributaries and changes therein due	The multifunctional retention areas described in Table 3 primarily involve modifications to existing inner-city parks, such as the pilot site in Eil-Süd, where rainwater retention is facilitated while maintaining recreational function and updating playground infrastructure. We have clarified this in the revised table to better reflect that these NbS utilize existing green spaces and do not include paved areas that are not considered NbS

to NbS, that might enlarge downstream risks if done incorrectly.	Regarding potential impacts on groundwater and groundwater-driven floods, it is important to note that the retained stormwater in Cologne primarily addresses pluvial flooding caused by intense local rainfall. Due to the hydrological context of Cologne, rainfall events do not directly generate Rhine River floods, and thus these NbS focus on managing urban surface water rather than influencing regional groundwater or river flood dynamics.
NbS for floods may impact droughts response too, and vise-versa (see e.g. Fennell et al 2023). this is to be further discussed and quantified, as is the role of NbS in co-benefits related to other legal requirements such as the WFD and the new nature restoration regulation.	Thank you for highlighting the important interconnections between NbS for flood and drought management, as well as their alignment with broader legal frameworks such as the Water Framework Directive (WFD) and the Nature Restoration Regulation. We acknowledge that NbS often provide multiple co-benefits and can simultaneously contribute to managing both flood and drought risks. While our manuscript touches on these interdependencies, detailed quantification of these interactions and their compliance implications was beyond the scope of the present study. However, to improve clarity, we have added the notation “implemented for WFD” in Tables 4 and 5 to explicitly indicate which NbS are carried out in response to EU regulations. We also reference this aspect earlier in the manuscript (line 86). Furthermore, we have expanded the discussion to better highlight the multifunctional role of NbS in addressing overlapping hazard management goals and meeting legal environmental requirements.
In general the paper would benefit from adding a schematic that visualizes what types of measures are best placed where in the landscape.	We considered what such an illustration might look like, but then came to the conclusion that it would either be too complex or a simplification that would not do justice to reality. In addition, the information would duplicate that on the maps. We therefore decided not to create such an illustration.
In general it would be best if the paper really focusses on the mapping and the catalogue of measures, adding more discussion on the impact for different types of events and do that well, and stay further away from the rather generic discussion aspects of challenges in the implementation of NbS and stakeholder-acceptance aspects. That part of the discussion (from roughly line 490 onwards, and related sentences in the conclusion) is not to the point for the topic of the paper, filled with platitudes and not constructively suggesting ways forward on those topics	We appreciate the suggestion to sharpen the focus of the manuscript on the mapping and cataloguing of NbS measures, and to strengthen the discussion on their potential impacts across different types of events. We agree that some parts of the discussion, particularly those related to general challenges of NbS implementation and stakeholder acceptance, are broader than the core topic of this paper. Accordingly, we have shortened and refined this section to focus more directly on how the applied GIS-based methods contribute to identifying suitable NbS intervention areas. At the same time, we maintain that addressing implementation challenges remains a necessary precondition for

either. It is better to focus more on why the used method was helpful and how you recommend this method to be further used elsewhere/improved upon, e.g. how the TWI was useful and what other mapping tools are out there – how does your approach compare to those?	NbS effectiveness, and we briefly highlight this connection while keeping the focus aligned with the study's objectives.
Structure of the paper Improvements can be made in the structure of the paper, with clearer separation of what goes into introduction, method, results, discussion and conclusion, and reducing some superfluous texts, for instance: In the last part of the introduction the 'aim' of the paper is taking up a lot of space that can be shortend and part of the text be moved to the methods section.	We agree that clearer separation between the introduction, methods, results, discussion, and conclusion sections can improve readability and coherence. In response, we have shortened the latter part of the introduction, particularly the section outlining the aims of the paper, and moved some of the more detailed elements to the methods and study area sections as appropriate. Additionally, we have reviewed the manuscript to reduce superfluous text and ensure that content is placed in the most suitable sections.
In the results section there is a lot of information that might be better positioned in a section on 'case study descriptions' e.g. at the start of the methods, and superfluous information that does not contribute to the overall aim of the mapping (e.g. sentences from 283 onwards on the institutional setting) may be better removed throughout the results part (in general: avoid discussion style sentences that have also references to other documents/studies, but stick more to the plain results. Stick site descriptions in the site description and points of discussion in the discussion section).	We agree that relocating detailed case study descriptions, such as the institutional setting and other contextual information, would improve the clarity and focus of the results section. In response, we have moved relevant descriptive content to the "study area" section and removed superfluous text from the results. We have also revised the results to focus strictly on presenting findings without discussion-style commentary or extensive referencing. This restructuring enhances the manuscript's coherence and aligns the content more closely with the intended purposes of each section.
In the discussion not much is said on the used method, e.g. the usability of the TWI and other data, their reliability and the accuracy. This would be useful to add.	We have amended the manuscript to better highlight the rationale and applicability of the Topographic Wetness Index (TWI) and other spatial data used in our analysis. Specifically, we revised the text in lines 170-172 to clarify the landscape features in the Wupper and Erft basins, providing context for the inclusion of TWI and soil/sinuosity maps. Additionally, we have added relevant references and expanded explanations (lines 373-378 for Wupper, and 388-389 for Erft) to discuss the usability, reliability, and role of these maps as an initial step in identifying potential NbS implementation areas. We believe these additions strengthen the methodological transparency and practical relevance of our study.
In the method section: use past tense when describing what you have done (now its both past and present tense	Thank you for the suggestion. We have made the requested changes accordingly.

fluctuating). The methods section does not need further 'aim'sentences as those are part of the introduction.	
Some details: What is the Saga? (line 152), some more analysis on the TWI might be beneficial: is there a general trend for specific land uses at specific TWI? – SAGA is the gis tool, made note of what to change.	We have clarified that SAGA refers to the GIS tool used for the spatial analyses and have amended the wording accordingly. Regarding the suggestion for additional analysis of the TWI in relation to specific land uses, while it is an interesting avenue, it is beyond the scope of the current study but could be considered for future research.
Line 160 'class' , not 'cass' - yes Line 293: 'when water is low water' => edit for clarity - yes Line 312 – full paragraph is not needed (or should go to a case description)	We have corrected the typo from "cass" to "class" at line 160 and revised the sentence at line 293 for improved clarity ("when water is low water"). Regarding the paragraph at line 312, we have removed it from the results section and, where appropriate, relocated relevant information to the case description to enhance the manuscript's focus and structure.
Line 319: interesting remark on the lowering of the water level (not the flow), but I would like to know these types of things for all measures at given locations if possible. Removing 300 trees is limited damage if it significantly reduces damages – viz. how many trees are there in the basin in total?	We clarified that this is during a HQ100 flood. We agree that understanding the scale of trade-offs, such as tree removal relative to overall benefits and basin-wide context, is important for evaluating NbS interventions. While specific data on the total number of trees within the entire basin was not available for this study, we have clarified in the manuscript that the removal of approximately 300 trees at the Wiembach Allee in Leverkusen represents a localized impact weighed against potential significant flood risk reduction. Comprehensive quantification of such ecological trade-offs across all measures would require detailed ecological and spatial analyses beyond the scope of the current work.
Line 324: full paragraph can go to the case description.	Thanks for the suggestion; done.
Line 359: table 6 is now positioned very far away from this point of text – I assume it will be better when lay-out is done, but check	The final layout and positioning of tables are determined by the journal editors and typesetters, so the placement may differ in the published version. We will review the proof version carefully to ensure the readability and coherence of the manuscript at that stage.
Line 368: 'an analysis of…' => method section	Rephrased because it's a discussion of the analysis.
Line 371: soil water retention increase: yes in the hedges, but not on the land around the hedges, please discuss the need to combine with e.g. different agricultural practises on the plot to really make an impact.	We agree that while hedgerows can improve soil water retention locally, enhancing the broader landscape benefits requires complementary agricultural practices. Accordingly, we have added references to practices such as reduced tillage, no-till and strip tillage, as well as reduced stocking

	rates, to emphasize the need for integrated land management approaches to achieve meaningful improvements in soil water retention.
Line 372: 'plantings can…' I disagree – this is a can of worms and not valid in many situations depending on land use practises. Suggest to remove the sentence.	We have removed the sentence.
Line 373: 'locations of high TWI' => interesting, but poorly analysed: please improve your analysis of the TWI results.	We have added references and a better explanation that these maps are the first step in an analysis for potential NbS implementation.
Figure 9: the title of the legend is misleading, as the figure is not about flood and erosion reduction, but only maps the current riparian vegetation status. Remove the first part of the title. In general, this figure is not very informative or helpful, consider removing it completely?	We have amended the map heading but will retain the map as is, since it serves as an illustration of the types of NbS that can be implemented in the tributaries, considering their varying landscape, land use, and flood hazard characteristics.
Line 381: rest of the paragraph to go to site description or not needed information.	We think this detailed information is not needed, so we have deleted it.
Line 435: check grammar	We have rephrased the sentence.