HESS-2017-748 Socio-hydrological spaces in the Jamuna River floodplain in Bangladesh

Referees comments, Author's response and Author's changes in manuscript

1 Comments from referees/public

Comments from Anonymous Referee #1

5   This is an interesting work based on a strong empirical and field based work. While I enjoyed reading the work, I was bothered by the concept of "socio-hydrological space" that the authors are pushing for. Why not just call it "social-hydrological system"? By calling it a "socio-hydrological space," what new things become possible that couldn't be achieved when you just simply call it socio-hydrological system? The notion of system has been around for long and it is exactly what the authors are trying to do. A system refers to an "integrated whole" and is composed of several interacting parts or

10   elements. Of course, this assumes the presence of a boundary delineating which parts are inside the system and which are outside of it. And this boundary can be of different forms: spatial boundary, organizational boundary, ecological boundary, you name it. People specify these boundaries in an attempt to analyze and address specific research questions. So, system boundary is arbitrary and a system can be also nested within a higher level system. Let me challenge the authors. Can you define a larger socio-hydrological space that includes those three socio-hydrological spaces you described in the paper? I'm

15   sure you could if you're comparing larger-level spaces between two very different regions. So, why not just use the term system? In social ecology, they use the term "social-ecological system." They don't use "social-ecological space."

I also would like to see more discussion on how flood coping strategies vary by SHS1-SHS3. The authors do describe something, but not detailed enough. More details on how individual level strategies (cropping pattern, migration strategies, home floodproofing) and group-level strategies (activities organized by communities) should be provided.

20   Figure 2 needs some improvement. Hard to see dotted line (levee). Hard to see boundaries of SHS1-3. If printed in B&W, these can't be distinguished.

I am also bothered by expressions like "adaptation space" and "levee effect space" in page 4. Adaptation and levee effect are emergent phenomena generated by system dynamics. I don't know what you mean by these can be rendered in terms of SHS. Quite a few awkward grammars here and there. E.g., "channels more and more move into" (page 8).

25   In page 15, the authors say "the concept provides a methodological and theoretical advance in the socio-hydrology." I am not convinced why this is so.

Comments from Anonymous Referee #2

Ferdous and colleagues developed a new concept called 'socio-hydrological spaces' which they define as a geographical area

30   with distinct hydrological and social features that give rise to distinct patterns and emergent behavior. They then apply this

concept to an analysis of the Jamuna River floodplain in Bangladesh. In case study they identify three distinct socio-hydrological spaces defined by geographical features and support this delineation with primary and secondary data. The example application is well supported by primary data collection. The application of mixed-method approaches is important in socio-hydrology and the topic is of interest to HESS readers. However, I do have a series of concerns that if addressed would strengthen the paper. I believe that with certain revisions it would be suitable for publication.

Comments

1. The definition of 'socio-hydrological spaces' hints at two different types of spaces. The first is space as a geographical area. The second is space as a portion of the parameter space which leads to a distinct set of emergent dynamics. (The examples of the adaptation space and levy effect space on page 4 further raise the question of the second type of space.) In the case presented, geographical features (e.g. embankment) are used to divide the case area into three sub-areas with different dynamics. Because these geographic features define the dynamics of the system all of the unions exhibiting similar dynamics are spatially clustered. However, I can envision cases in which the features defining the socio- hydrological dynamics are social not physical features. In these cases, I am not sure the 'spaces' would be contiguous. How would this approach be applied to a case where geographical features are poorly aligned with system dynamics? Or is this tool suitable for only the cases where geographical features are aligned with system dynamics?

2. In the definition section (pages 3-4), the authors present this concept/tool as an alternative to either narratives or mathematical models. However, in the case that follows the authors present both the 'socio-hydrological space' delineation with a case narrative, which I think was effective. Rather than serving as an effective standalone tool, 'socio-hydrological spaces' compliments these other approaches. I think the author's argument for this tool would be more convincing if they could frame it as part of a broad research plan. For example, the authors note that SHS is descriptive not explanatory. If combined with other approaches could it enhance the explanatory power of a study?

3. While it is important to expand the approaches used to address socio-hydrological questions and to synthesize quantitative and qualitative data, this is not the first study to do so. The authors should acknowledge other efforts in this space such as data-driven narratives (Treuer et al. 2017) and the pairing of statistical analysis and narratives (Hornberger et al. 2015), and articulate what 'socio-hydrological spaces' adds.

4. I think there is potential for this concept to be used comparatively across say multiple flood plain cases. Please speak to this potential.

5. Lastly, there are some typographic errors and awkward phrasing in the manuscript and it would benefit from a thorough review.

References

Hornberger GM, Hess DJ, Gilligan J (2015) Water conservation and hydrological transitions in cities in the United States. Water Resour Res 51(6):4635–4649.

Treuer G, et al. (2017) A narrative method for analyzing transitions in urban water management: The case of the Miami-Dade Water and Sewer Department. Water ResourRes 53(1):891–908.

Comments from Anonymous Referee #3

The authors aim to present a "new way of looking at and analysing socio-hydrological systems", and use a study area in the highly dynamic floodplains of the Jamuna river in Bangladesh.

After reading the introduction, I wanted to know: -how to construct and define a SHS -how the SHS improves or benefits the field of socio-hydrology, -how to apply the SHS to other research areas, or even to other areas within the country.

General comments

I am impressed by the authors' knowledge of the study area. The methods used to construct the survey seem sound, the questionnaires (ESM1) suitable to the research question at hand. The topic is of interest to HESS readers.

Overall, the paper seems to be a further development to the classification performed in Di Baldassarre 2013 and 2015 and rests on the assumption of two patterns of society river interactions. (see also p. 5, line 1-5). While I understand that the concept of SHS is new to the field in terms of vocabulary, I don't see why the classification from Di Baldassarre 2015 which is criticized by the authors cannot simply be performed on a smaller scale. Do we need SHS for that? How could the SHS concept be extended to the entire country? I am also not convinced by the results that this approach and the presented results draw "analytical attention to how flood dynamics co-evolve with societal dynamics".

My initial questions were only answered partly. I am unfortunately not sure how this method is an improvement or benefit to the field of socio-hydrology. I see the study's strong point in the extensive empirical field survey, but feel that this requires more work to show statistical relationships gathered from the individual SHS and then comparing those to hydrological data (flood extent, erosion, etc.).). I also cannot easily detect how the SHS approach is useful in specifying the interaction between sociological and hydrological processes in the sense of the two-way feedbacks key to socio-hydrological approaches.

At present, SHS still seems to be a rather descriptive and classical approach to me, with the statistical methods mainly from the field of basic exploratory data analysis. While there is no harm in that, the authors do stress that they present a "new approach". The extensive surveys should be brought into context with actual observed data (especially Sec 5.1-5.4), in particular if the authors consider using this approach to make predictions (although it is unclear to me what they wish to predict and how, this is only mentioned in the beginning of the paper and should definitely be elaborated on). The authors should also address the uncertainties in their work – there are a lot of biases inherent in conducting surveys, and I'm not sure the time span 1960-2016 is feasible due to the large number of external factors that could also contribute to e.g. migration or farm land area (such as the independence of Bangladesh in 1971).

Minor and major remarks

Section 3.1: Not entirely sure why this specific study area was chosen. How big are the individual SHS? Section 3.2: Why are socio-economic factors not relevant for the construction of the SHS? I would assume this makes a difference in how the livelihoods are affected by flooding in the individual SHS. (Add-on: on p.8, line 16 the occupation is listed as a delineating factor. I don't see this in section 3.2, where the delineation is based on "differences in geophysical characteristics and flood protection measures". Section 3.3: Is "evidence'' the right word to use? Perhaps "data'' is more suitable. Sections 4.1-4.3:

can these be classified as Results? I would consider this to be part of the methodology/study area description. (VERY narrative). Section 4.2 Could benefit from references on chars. Sometimes, chars is in quotes, most of the time not. Please be consistent. Section 5.1 How was this verified? Using the household's answers can be deceptive, as there is a strong bias to the length of time since the last flood event. Also, of course a char in the Jamuna cannot be flooded by another river.

5   Sections 5.4 Using only household surveys to state that e.g. "riverbank erosion is experienced in each zone", and to comment on how high these rates are without presenting physical observations is in my opinion not conclusive. I strongly suggest backing these statements up with observed erosion data. Also, how far away from the river do your respondents live? This can bias the answers, making the statements even more inconclusive. Section 5.7: how is this section relevant?

p. 3, line 24ff You state that the concept's importance lies "in its emphasis on how the interactions between society and

10   water are always place-bound'' Perhaps I use a different interpretation for the word place-bound, but the levee effect you mention afterwards is anything but place-bound. Rather, you describe yourself how this was introduced for the Po floodplain as well as by White in the US. Please clarify. P.5, line 3ff please clarify what you mean in this sentence – unclear to me. p.5, line 17: I am surprised that you do not mention any of the extreme flooding after 2007 – just last year severe flooding in the region occurred. On p.6, line 10 you do mention the flood of 2016, so please check for consistency. Perhaps it would also be

15   good to just name those years in which the study area was extremely flooded, not "general'' extreme flood years in Bangladesh. p.6, line 11: how much percent was flooded? p.8, line 1: when were the focus group discussions with respect to the study years and the flood season? Also, during which season/months were the surveys conducted? p.8, line 10: Frequency analyses for what? The following sentence is unclear. p.8, line 26: how much of the bankline is eroded? p.9, line 29: migration to where? Outside of SHS3? p.10, line 17: is the unexpected flood frequency observed through e.g. data or

20   satellite imagery? p.11, line 6: please include the flood damage information in the description of data and methods. How did you analyse what? How do the individual floods compare with respect to magnitude and flood duration in the individual SHS in each of those years? What about the study years? p.12, line 1: is there a citation for this? How low is the average elevation? It would be good to include this in the general description of the SHS. p.12, line 13: how is the number of farmers with large households determined? If only from the questionnaire, how did you control for other biases such as migration,

25   change of occupation? How certain do you think this number is? I would argue that the changes in SHS1 are not significant, and that they in particular cannot be attributed solely to consecutive flood events. Also, why 1960? Does it not make it more difficult to evaluate the results before/after Bangladesh became independent? When was the embankment in SHS1 built? Could the reduction of large farms not simply be due to other socio-economic developments in the region? Is this also solely based on information from questionnaire? p.12, line 24: this is a major concern I also share in these types of studies (and I

30   am not convinced this can be verified through a focus group discussion- how?). This is also why I stress the need for observed data. p. 13, line 7: increased by how much over what time period? p. 13, line 15: Did the respondents arrive or leave? The last two sentences of this paragraph are unclear to me. p. 14, line 11: which interactions between sociological and hydrological processes did you identify? Which two-way feedback are you referring to? p. 14, line 20: when do you consider the initial selection of the SHS to have "statistical meaning"? How is this transferable? How can you be sure they are

consistent over time? What is the added value of SHS if their boundaries are mobile? p. 15, line 18 ff: I agree. Please expand your methodology to include when your selected SHS need to be updated – for now, this is not quite clear. p. 15, line 22: what advance did you show? Which questions did you now answer that could not be answered before? How can you apply this in a broader sense? p. 16, line 16: To which policies, for example? What is a "rapid rural appraisal"?

5   Literature

Literature cited: the work largely cites and even uses figures from the same two papers (Di Baldassarre 2013a and b). While this is of course expected when developing the work of one research group further, what exactly is the point referencing literature such as the authors did in p.3, line 14 or p.4, line 15? I suggest to simply let the reader know where to look for the information or statement in the sentence before. FICHTER and nhc, 2015 does not look correct.

10   Language

Language is mostly good, but could definitely benefit from a careful read-through by a native speaker or a language editing service. E.g., p 2 Line 30 sees three uses of the word "different'' in one sentence, and there are numerous grammatical or typographic mistakes throughout the paper. Be careful to introduce abbreviations before you use them (e.g. in abstract). p.5, line 27: "To evidence and understand: " sounds a bit awkward p.8, line 21: "inundated" instead of "ponded"? p. 15, line 14:

15   what is "people mobility"?

Figures

Figure 2: cannot decipher the black names when printing out copy, perhaps resolution needs to be better. I had to look really closely to detect the boundaries of the individual SHS. Why is the land colored red? Figure 4: please include the number of respondents for each subset. Figure 5: Perhaps consider labeling all axes outside of plot or all inside plot (consistency). Also,

20   it should say "SHS3". Starting when can a farmer be considered to sustain the own household? Figure 7: why is the land red? Why was the dry season chosen? A different coloring would greatly benefit the readability of the figure.

Comments from Anonymous Referee #4

The authors propose a new concept to study the interactions between humans and floods in a socio-hydrological system.

25   They introduce the concept of Socio- Hydrological Spaces to describe a system that shows specific interactions between social, economic, hydrological, etc. factors that result in a certain behaviour of the system and apply this to a case study in Bangladesh.

Although I can understand the advantages and potential of a comprehensive systematic approach to the study of "Socio-Hydrological Spaces" (which the authors seem to be aiming at) this new approach is quite poorly defined and explained. The

30   authors merely give human-flood systems a different name (i.e. Socio-Hydrological spaces) and proceed to describe a case study as if this is a new approach. Mostert (2017) recently published an article in this same journal, arguing for case-study research as an alternative approach for socio-hydrology and while his example of a case study is perhaps more qualitative than the one presented here, the authors should perhaps try to relate to his paper. Also, a very similar approach to the one

presented in this manuscript for describing a case study of how humans and floods coexist, is presented by Hazarika et al. (2015).

The concept/approach would be new and in my opinion useful, if a general framework would be presented to analyze a case study/SHS in a comprehensive and consistent way, which would allow for the comparison of different Socio-Hydrological Spaces, their specific characteristics, and the feedbacks and phenomena that arise from the characteristics of this particular system. However, after reading the manuscript I did not really see how the method/concept that is presented here adds something new and useful to the already existing approach of a case study description.

Some more specific comments:

1) On page 2 in line 24-26 the authors state that "interactions and feedback mechanism between hydrological and social processes in floodplains remain largely unexplored and poorly understood" citing Di Baldassarre et al. 2013a. However, since this paper in 2013 there have actually been quite some studies that have explored these interactions (just a few examples: Viglione et al. 2014, Chen et al. 2016, Ciullo et al. 2017, etc.) and in fact the authors do acknowledge this later in the manuscript (page 3, line 5-6).

2) On page 2 the authors state that there are currently two approaches to sociohydrology: qualitative studies and conceptual mathematical modelling studies. As I mention above, there are in fact other approaches (e.g. Mostert et al. 2017 and Hazarika et al. 2016) very similar to the approach that is presented here as a new approach.

3) The authors repeatedly state that running a conceptual mathematical model based on differential equations is much more data-demanding than the approach taken here. However, running a conceptual model like that does not require any data at all! Unless one wants to compare the model with real data, which would indeed make it more data-demanding, but I would argue that it would be just as data-demanding as the approach taken here. In fact, in my opinion, using surveys and interview data is a very data-demanding approach (although a very valuable and useful approach).

4) In the discussion the authors state that the division into SHS and the testing is an iterative process. From the descriptions it seems that the "low char" and the "high char" are quite different from each other, so I wonder why the authors did not update their SHS based on the analysis?

5) In the discussion the authors state that: "Each SHS shows distinct features when comparing flood-society interactions, proving that the dynamic interactions of floods is dependent on different hydrological and societal characteristics along the Jamuna River." The authors do indeed describe the different hydrological and societal characteristics of the three SHS, however, I miss the translation to the different dynamic interactions that follow from these characteristics. The description stops at describing the characteristics and does not describe the interactions and feedbacks that we are interested in in socio-hydrology. Are there in fact different ways of coping with floods in these three SHS? And if so, why do they behave differently? Which societal and hydrological combinations of characteristics lead to which kind of interactions?

In the conclusion, the authors conclude that the concept draws attention to how historical patterns of coevolution of social behavior, natural processes and technological adoptions give rise to different landscapes, different styles of living, and different ways of organizing livelihoods, while in fact the concept as it is presented here and applied to the case study, does

not do this at all. It leaves me wondering what the different patterns, different styles of living, etc. are that emerged in these three SHS.

6) A large part of the discussion is about the spatial boundaries. The authors stress the point that the boundaries of the SHS move in time and that the physical boundaries between the three SHS are not fixed in time. While this is true, I do not really see why this is of importance. The SHS you define are defined by the characteristics of the system, not by the exact coordinates. For example, the authors define SHS 2 as a char within the river, if the river moves a kilometer and the char moves with it (or a different char forms), this does not change the definition of SHS 2 as a char within the river. The same holds for the social boundaries, if one person moves to another SHS and adopts the strategies of that SHS, then the SHS does not change, does it? I think the authors could spend less attention on this in the discussion.

7) Figure 4 is not really consistent. The legend is placed in different locations, some graphs do show the total percentage on top of the bars and others don't (and some do but miss the %). Also, when printed in black and white, the difference between the color of SHS 1 and SHS 3 is not clear.

8) The format of figure 5 does not really allow for an easy comparison between the three SHS, I would suggest choosing another type of figure.

2 Author's final response to referees

Dear Professor Sivapalan,

We have submitted a revised version of our paper "Socio-hydrological spaces in the Jamuna River floodplain in Bangladesh". Following the reviews, we have improved and expanded our sections on the reasons for and definition of socio-hydrological spaces. We have also fixed the more minor issues raised by reviewers. Below, we respond to the main reviewers' comments.

We propose the concept of socio-hydrological spaces (SHS) as a useful 'tool' in the research on socio-hydrology of floodplains (and probably elsewhere). The critique by the reviewers on this proposition can be summarised as three questions:

1. What is a SHS?

2. How do you apply SHS to a case?

3. Why should we have SHS in addition to existing concepts = what use is SHS for socio-hydrology?

The second question has answered by adding more detail to the paper. The first and last questions are more difficult because they relate to the paradigm(s) in use in socio-hydrology. In summary, what we do try to do is to bridge the gap between modelling and rich case descriptions of reality. We have now expanded the paragraphs in the Introduction that explaining this, and added a separate section 'Patterns in hydrology' to provide a better underpinning of our proposal. With the proposal of SHS we are in essence saying that we are looking for a middle ground where we preserve the variability of reality and the

unpredictability of human behaviour and decisions, not fit these into a model (which could be "there is either fight or adapt"), while at the same time recognising patterns (combinations of the same fight and/or adapt responses).

This middle ground is reflected in the expanded definition of SHS in Section 3, and below:

5   *Definition of SHS: bottom up (data driven) vs top down (hypothesis/model driven)*

In the paper we define a SHS as "a geographic area with distinct hydrological and social features that gives rise to the emergence of distinct interactions and dynamics between society and water, which also vary with time a space". This can be considered a data driven definition. We currently label these distinct interactions and dynamics as 'levee effect' and adaptation effect'. I believe we should re-label these 'fight' vs 'adapt' since the levee effect is a result of fighting, not action

10   itself.

SHS can also be defined from the general patterns found in human-flood interactions (as in Di Baldassarre et al.) as "a geographical area where the empirical/concrete manifestation/expression of a specific combination of generic socio-hydrological patterns (here: fighting and adaptation dynamics) is distinct from neighbouring areas". This can be considered a model driven definition. This top down definition has been added to the paper.

15   Both definitions apply simultaneously, and are used in iterative mode to study the socio-hydrology of an area. The top down definition guides the researcher to look for these generic patterns in the area of study, resulting in preliminary delineation of SHS and their qualitative descriptions (or narratives); these results have the function of being hypotheses in the next step. In this next step, spatial data analysis to confirm/reject these initial hypotheses, that is, they provide the data driven (bottom up) delineation of SHS.

20   SHS is thereby a missing link between a specific (concrete) case (e.g. Jamuna or Po floodplain) and generic (abstract) patterns = a link between observations and theory/model. The concept of SHS is needed because it turns out that the generic patterns that seem to map 1-to-1 onto reality in certain cases (a whole floodplain (in time or space) or when applied at river basin scale) do not map 1-to-1 onto reality in Bangladesh, or when floodplains are examined in detail. Hence: SHS are needed to refine the analysis of human-flood interactions from the generic (either fight or adapt) to the concrete and local

25   (where both may co-exist in time). SHS allow better representation of the reality of these interactions, while at the same time enabling comparison between cases by referring to generic patterns.

This is what we put in our earlier reply to reviewers, which summarises the above: "We propose "socio-hydrological space" as a tool that helps to make the necessary intermediary step between the messy reality of the specific location (space) and the abstract system of conceptual and mathematical models. The primary function of SHS is as a lens through which to view the

30   complex reality of specific cases in order to find patterns in human-river interactions, which can then be compared to patterns in other locations to see if further generalisation towards universal models is possible. Its use invites the researcher to have an open mind to the existence of expected or unexpected patterns in location-specific data using a thorough understanding of the location: society, economics, natural system, technical interventions, etc. Subsequently, other cases may be analysed in order to explore whether the same or different patterns occur. These patterns can then be generalised

through the more formal conceptualisation of socio-hydrological systems. On the one hand SHS thereby relates to a specific space, on the other hand it helps to find general patterns of human-river interactions."

Reflection on other comments by the referees

5   **Referee #1** asked why we do not use 'socio-hydrological system' instead of SH space, since system is an accepted and widely used concept (this implies: we should apply the principle of parsimony). (S)he also points out that a system can be delineated by other types of boundary than a spatial one (this implies: system is more widely useful as a concept). Our reasons are that:

- A system may be conceptual/abstract or concrete/real, which may lead to confusion between the two when used in a text;
10   we want to focus on the concrete and not leave any doubt about that. Worse, from this confusion, using 'system' may lead to the conflation of one with the other as if the conceptual system represents the reality (near) perfectly – which is the proposition made by many socio-hydrologists (see above).

- Because we want to start with a concrete situation to delineate SHS, we need concrete, visible and tangible boundaries = spatial ones.

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Referee #2 raises similar issues. (S)he points out that there is an ambivalence in the paper between SHS as a spatial entity and SHS as a portion of the parameter space that has distinct emergent properties. With the revised definition of SHS above, we make explicit that SHS has both characteristics. On the other hand, reality cannot be fitted completely into the parameter space of a model, and we do not want to limit our understanding of the SHS that we find in BD to this parameter space. Like
20   reviewer #1 (s)he suggests that the SHS could equally be delineated by social boundaries (instead of spatial ones), because the system's dynamics are not necessarily aligned with geographical features. While this is true in theory, in the practice of the study of human-flood interactions it is found that space constitutes the boundaries within which humans operate and organise themselves to deal with floods.

25   **Referee #3** asks why we do not scale up and lump a larger area (such as the whole study area, or larger) into one SHS. Reference to our definition should answer this: in a larger area the characteristics are no longer the same and different from other areas. Reviewer #3 is not happy that we have provided statistical proof that the SHS are distinct. We should stress that we have used the ANOVA test to prove the classes are distinct for all graphs, and also that we can only illustrate the concept here and not provide all details. Related to this, (s)he finds the shifting spatial & societal boundaries (as discussed in our
30   Discussion) problematic. Interestingly reviewer #4 has no problem with this: "The SHS you define are defined by the characteristics of the system, not by the exact coordinates. For example, the authors define SHS 2 as a char within the river, if the river moves a kilometre and the char moves with it (or a different char forms), this does not change the definition of SHS 2 as a char within the river. The same holds for the social boundaries, if one person moves to another SHS and adopts the strategies of that SHS, then the SHS does not change." We have thanked reviewer #4 for this insight in a footnote.

To respond further to these three comments, we would like to add that the resulting ambivalence between SHS as a spatial entity and SHS as a portion of the parameter space that has distinct emergent properties is intentional: SHS has both characteristics. Reality cannot be fitted completely into the parameter space of a model, and we do not want to limit the understanding of the SHS that we find in reality to this parameter space. This is also one of the reasons why we use 'space'

5   instead of 'system'. A system in socio-hydrology may be conceptual/abstract or concrete/real, which may lead to confusion between the two when used in a text; we want to focus on the concrete and not leave any doubt about this, which the use of 'system' may do. Worse, from this confusion, using 'system' may lead to the conflation of one with the other, as if the conceptual system represents the reality (near) perfectly, which we do not believe is possible. Because we want to start with a concrete situation to delineate SHS, we need concrete, visible and tangible boundaries, which are spatial ones. The spatial

10   boundaries of SHS may be physical, such as a river bank, but also due to social characteristics, such as a distinction between rural and urban land use which will give rise to other socio-hydrological dynamics. The other reason why we introduce the concept of SHS alongside 'socio-hydrological system' is related to complexity. 'System' is the appropriate term for an entire delta, which can be divided into subsystems depending on research goals. The smallest of these subdivisions would be a SHS, where socio-hydrological dynamics are unique. A similar distinction can be found in ecological systems research,

15   where one ecosystem contains many habitats as smallest unit of study. We considered adding this paragraph to the paper, but decided it may detract readers by raising another issue, so omitted it in the revised submission.

Referee #4 posits that the concept of SHS would be useful if it was a generic framework for analysing a case study. It could then be applied in a consistent and comprehensive way to enable comparison across cases. (Ss)he finds that the use(fulness)

20   of the SHS concept currently does not raise above the Jamuna case. Hopefully the new definition and better explanation will convince reviewer #4. (S)he also thinks that the current description of the three SHS only lists human and flood characteristics separately and omits the interactions. If we agree that the two responses 'fight' and adapt' present the two principal types of interaction, we can use these to label the three SHS more explicitly with 'fight' and/or 'adapt' to include the respective interactions are requested.

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We hope you consider this manuscript to be ready for publication in HESS.

Kind regards,
Ruknul Ferdous and co-authors.

Socio-hydrological spaces in the Jamuna River floodplain in Bangladesh

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Abstract. In this paper, we propose a concept that captures the different socio-hydrological patterns that result from different societal choices on how to deal with rivers, floods and erosion: 'socio-hydrological spaces'. Socio-hydrology aims to understand the dynamics and co-evolution of coupled human-water systems. Our proposed concept will help to understand the detailed human-water interactions in a specific location. This paper uses a, with research consisting of generic models as well as specific case studies. In this paper, we propose a concept to help bridge the gap between these two types of socio-hydrological studies: socio-hydrological spaces (SHS). A socio-hydrological approachspace is a geographical area in a landscape. Its particular combination of hydrological and social features gives rise to the emergence of distinct interactions and dynamics (patterns) between society and water. Distilling these patterns through comparing case studies provides a promising way to describe relate contextual specificities to the generic patterns described by conceptual models. Socio-hydrological research on human-flood interactions in has found two generic patterns, i.e. 'fight' or 'adapt'. Through the use of SHS, these generic patterns can be used to begin comparing different cases globally. We illustrate the use of SHS for the Jamuna floodplain, Bangladesh. In this vast space (a braided river bed of 6-16 km) the differences between land and water are temporary and shifting. To illustrate how the concept can be used, we first classified and identified socio-hydrological spaces and then validated through theWe use narratives and experiences of local experts and inhabitants to empirically describe and delimit SHS. We corroborated the resulting classification through the statistical analysis of primary data collected for the purpose (household surveys and focus group discussions) and secondary data (statistics, maps etc.) that were collected in 2015 and 2016. The principal set of primary data consists of approx. 900 questionnaires on several themes: flooding, riverbank erosion, social processes of the study area. The concept of SHS.). Our example of the use of SHS shows that the concept draws attention to how historical patterns in the co-evolution of social behaviour, natural processes and

technological ~~adoptions~~interventions give rise to different landscapes, different ~~style~~styles of living, and different ways of organizing livelihoods. ~~However, we contend that this concept could be used~~ This provides a texture to the more generic patterns generated by socio-hydrological model, promising to make the resulting analysis more directly useful for decision makers. We propose that the usefulness of this concept in other ~~places~~floodplains, and for other socio-hydrological systems

5   than floodplains, should be explored.

1 Introduction

~~Socio-hydrology has recently been launched by the~~The hydrological sciences community has recently launched socio-hydrology as one of the research ~~theme for~~themes of the current scientific decade of the International Association of Hydrological Sciences (IAHS) "Panta Rhei – Everything Flows" (2013-2022~~)~~), which aspires to 'advance the science of

10   hydrology for the benefit of society' (Montanari et al., 2013 p.1257). Socio-hydrology aims to understand the dynamics and co-evolution of coupled human-water systems~~.~~ (Sivapalan et al., 2012). In traditional hydrology, humans are either conceptualised as an external force to the system under study, or taken into account as boundary conditions (Milly et al., 2008; Peel and Bloschl, 2011). In socio-hydrology, human factors are considered an integral part of the system. Understanding such coupled system dynamics is expected to be of high interest to governments who are dealing with

15   strategic and long term water management and governance decisions (Sivapalan et al., 2012).

As in any newly defined research area, socio-hydrology researchers are looking to determine how to implement their shared goal. This has resulted in a number of overview or position papers (e.g. Blair & Buytaert, 2016; Sivapalan, 2015; Pande & Sivapalan, 2017; Sivapalan & Bloschl, 2015; Troy et al. 2015) as well as several case studies (e.g. Gober & Wheater, 2014; Kandasamy et al., 2014; Liu et al., 2014; Mehta et al., 2014; Srinivasan, 2015; Mostert, 2018). In the discussions, the use of

20   conceptual and deterministic models to analyse concrete situations is an important issue. As in any attempt to produce insights that transcend specific cases, methods of abstraction from reality to find generic patterns and stylised equations (generalisation) are sometimes difficult to reconcile with more detailed representations of what is happening in a specific location (Blair & Buytaert, 2016). While enabling global comparison by using data sets from different locations, generic models unavoidably foreground some elements or dimensions of flood-society dynamics to the neglect of others (Magliocca

25   et al., 2018). On the other hand, attempts to generalize from case-specific detailed models need to be looked at critically in terms of the comparability and commensurability of the phenomena and patterns observed with what happens elsewhere (e.g. Elshafei et al. 2014). In this paper, we propose a middle way between these two methods of generalisation by focussing on tracing patterns in socio-hydrological dynamics. Such patterns appear both in the stylised representations of generic models, but can also be observed in the messy reality of specific cases. Rather than assuming that one form of broad-based set of

30   abstractions or generalizations 'fits' all situations, this mid-level theorizing on the basis of empirically observable patterns was identified by Castree et al. (2014 p.766) as a desirable way forward in environmental research, as it makes it easier to link and translate model-deduced patterns with experienced realities.

We operationalise the search for patterns by proposing a new socio-hydrological concept: socio-hydrological spaces (SHS). The concept will be defined and its implementation explained in Section 3. To illustrate how the concept can be used, we analyse human-flood interactions in the Jamuna floodplain, Bangladesh, making use of the two generic patterns, 'fight' or 'adapt', that were found in earlier research on human-flood interactions. We present this research in Section 2. In the Jamuna floodplain the differences between land and water are temporary and shifting, as is the size of the human population. The application of SHS allows capturing the different socio-hydrological patterns that result from different societal choices on how to deal with rivers, floods and erosion, which in turn produce different living conditions and watery environments (Sections 4 and 5). By providing locally relevant details and texture to more generically deduced patterns, SHS provides a useful methodological addition to the socio-hydrological understanding of floodplains. Its usefulness to other contexts such as irrigated catchments or urban water systems could also be investigated.

2 Patterns in the socio-hydrology of floodplains: fight or adapt

One type of situation that is relatively well studied by socio-hydrologists is the co-evolution of human and water systems in floodplains. After all, the existence of interdependencies between societies and their natural environment is particularly obvious in floodplains. Since the beginning of human civilization, many societies have developed in floodplains along major rivers (Vis et al., 2003). In spite of periodical inundations, a distinct preference for floodplain areas as places to settle and live in stems from their favourable conditions for agricultural production and transportation, enabling trade and economic growth (Di Baldassarre et al., 2010). Yet, floodplain societies have to learn how to deal and live with periodic floods and the relocation of river channels by erosion and deposition (Sarker et al., 2003). In general terms, floodplain societies do this by evaluating the costs of flooding and erosion against the benefits that rivers bring, and by deciding whether to try to mitigate the risks by defending themselves against floods ('fight'), or to adjust to livinglive with themfloods ('adapt'), or any combination of the two (Di Baldassarre, et al., 2013a,b). Therefore, 'fight' and 'adapt' are the two generic patterns in the socio-hydrological dynamics of human-flood interaction. These combine and manifest differently in different locations.

For flood mitigation, societies have usually relied on engineering measures like embankments or levees to prevent flooding, and bank protection and spurs or guide bunds stretching into the river channel to prevent floods and erosion. These measures can be seasonal (temporary) or permanent, and have more or less effect on flood prevention (Sultana et al., 2008). In order to adapt to flood risks, societies may limit costly investments in property or make them movable, and adjust cropping patterns or choose crops that cope with flooding. The construction of flood control measures or changing land use patterns might in turn alter the frequency and severity of floods, leading to a dynamic interaction between the river and the society living alongside it (Hofer and Messerli, 2006). An alternative response to flooding is adaptation, the second pattern in human-flood interactions. In order to adapt to flood risks, societies may limit costly investments in property or make them movable, adjust cropping patterns or choose crops that can cope with flooding, or move away altogether if alternative locations for settlement are available. Even when flood protection measures are in place, residual risks may necessitate adaptation

measures. This means that in any real situation the two patterns of 'fight' and 'adapt' are usually found together in a site-specific configuration, depending on socio-economic, institutional, and natural conditions. We label the areas where the proportions are analogous due to similar conditions 'socio-hydrological spaces' (SHS) (see Section 3).

In the case of a choice for mitigation, societies are liable to enter in a near-vicious circle of path dependency, which has been
5   described as a lock in (Wesselink et al., 2007). Already in 1945 White described how the construction of embankments to protect property in the USA gave rise to what he called 'the levee effect' (White, 1945) where better protection leads to more investment, in turn increasing vulnerability, leading to better protection, etc. Understanding such dynamics interactions between water and people in floodplain areas have become the focus of attention of an emerging analytical approach, socio-hydrology (Sivapalan et al., 2012; Blair and Buytaert, 2016), resulting in a number of studies. These will be discussed in
10   more detail below (Section 2). However, in spite of this and more recent research, the specific dynamics produced by the interactions and feedback mechanisms between hydrological and social processes in floodplains remain largely unexplored and poorly understood (Di Baldassarre et al., 2013a).

In this paper, we propose a new concept to help fill this gap: 'socio-hydrological spaces'. The concept captures the different socio-hydrological patterns that result from different societal choices on how to deal with rivers, floods and erosion, which is
15   turn produce different living conditions and watery environments. The concept thus helps trace and show how flood society dynamics are differently patterned depending on the different societal and hydrological characteristics of different locations. In this sense it is largely a descriptive concept, rather than an explanatory one. Yet, we contend that the systematic and comparative identification of socio-hydrological spaces over time or over flood plains may reveal patterns or systemic characteristics that allow the concept to become predictive of future events. After a discussion of its definition and its
20   usefulness (Section 2), we show how 'socio-hydrological spaces' can be used to describe the human water dynamics the Jamuna River (local name of Brahmaputra River) floodplain of Bangladesh (Sections 4 to 5). We introduce the concept here as a methodological and theoretical advance in the socio-hydrology of floodplains. However, we suggest that its usefulness to other contexts such as irrigated catchments or urban water systems should also be investigated.

2 Socio-hydrological spaces defined

25   The study of floodplains using a socio-hydrological approach has advanced rapidly in the last few years (Di Baldassarre et al., 2013a,b; 2015; O'Connell and O'Donnell, 2014; Viglione et al., 2014). This approach, Chen et al., 2016; Grames et al., 2016; Ciullo et al., 2017; Barendrecht et al., 2017; Yu et al., 2017). In this research, the two patterns 'fight' and 'adapt' take centre stage. The overall aim of this work is aimed at furthering to further understanding of on 'how different sociotechnical approaches in floodplains are formed, adapted, and reformed through social, political, technical, and economic processes;
30   how they require and/or entail a reordering of social relations leading to shifts in governance and creating new institutions, organizations, and knowledge; and how these societal shifts then impact floodplain hydrology and flooding patterns' (Di Baldassarre et al., 2014a2014, p.137).

Two different methodologies tofor the study of floodplains can be broadly distinguished, in parallel with general trends in socio-hydrology found by Wesselink et al. (2017). First, some publications presentIn the first approach, a narrative representation of the floodplain's socio-hydrological system and its development is generated based on qualitative research. This approach identifies, often informed by experiences and knowledges of local experts and inhabitants about histories of

5   living with floods. The resulting studies describe historical patterns in the co-evolution of river dynamics, settlement patterns and technological choices (Di Baldassarre et al., 2013a, 2014a) (see also similar2014). Not all researchers who engage in this kind of studies identify their work byas belonging to socio-hydrology (e.g. Van Staveren and Tatenhove, 2016, Van Staveren et al., 2017a, 2017b). In this qualitative research, the actual societal choices between 'fight' and 'adapt' are descriptively represented, without formalisation.

10   The second approach to studying socio-hydrological dynamics of floodplains focusses on the development and use of a generic conceptual model of human-nature interactions in a floodplain, which is subsequently expressed in terms of differential equations (e.g. Di Baldassarre et al., 2013b, 2015). This generic model is then used to explore scenarios of floodplain development (Di Baldassarre et al., 2013b; Viglione et al., 2014).; reviewed in Barendrecht et al., 2017). This second approach also starts with a narrative understanding of the situation. These narratives narrow down complex realities

15   to a selection of phenomena and elaborate trends and causal relationships that are subsequently captured in mathematical models (see Elshafei et al. 2014 for a clear example of the role of narratives). Generic models aim to explain the feedback mechanisms that produce certain phenomena (often paradoxes or unintended consequences) that have been observed in many places around the world. For example, the stylised models of human-flood interactions introduced by Di Baldassarre et al. (2013b) use a mathematical formalization of a fundamental hypothesis: the levee effect (White, 1945) is explained by a

20   decrease in risk awareness when flooding becomes less frequent because of the introduction (or reinforcement) of structural protection measures. This generic model has been used to explore and compare alternative scenarios of floodplain development (Di Baldassarre et al., 2015; Viglione et al., 2014). Current research includes further refinement (Grames et al. 2016; Yu et al., 2017) or comparison of this generic model to actual data for specific cases (Ciullo et al., 2017; Di Baldassarre et al., 2017). Yet, as societal responses to hydrological changes (including flood occurrences) are 'very complex

25   and highly unpredictable as it strongly depends on economic interests and cultural values' (Di Baldassarre et al., 2015 p.4780), formalisation is challenging.

We introduce here the concept of 'socio-hydrological space' (SHS) that takes an intermediary (statistical) position between the purely qualitative narratives and the deterministic, data-demanding mathematical conceptual models. We define a socio-hydrological space as a geographic area with distinct hydrological and social features that gives rise to the emergence of

30   distinct interactions and dynamics between society and water, which also vary with time. The concept draws attention to the historical patterns in the co-evolution of settlement patterns and technological choices, showing how these give rise to different landscapes and different ways of organizing livelihoods. The concept's importance lies in its emphasis on how the interactions between society and water are always place bound: these interactions therefore defy straightforward generalizations in either hydrological or social terms. We therefore propose the socio-hydrological space as a useful concept

for advancing socio-hydrology: distinguishing different socio-hydrological spaces helps to understand the spatially distinct dynamics of water society interactions, while also providing a relatively straightforward and easy to use tool to describe and analyse and perhaps predict human water systems in floodplains or elsewhere. The concept provides a way to bring local specificity to the study of socio-hydrology of floodplains, and we contend, socio-hydrology in general, though its usefulness in other situations than floodplains remains to be explored.

To use the concept of SHS, we propose a two step approach. First, a thorough understanding of a specific floodplain system (geography, history, technology, societal occupation etc.) results in a preliminary classification of the study area into distinct SHS. Second, the classification is tested for statistical significance using available or newly collected data. If the classification is not statistically significant, merging or splitting of categories should be considered (repeat step 1).

By proposing this definition, SHS neatly fits socio hydrology's ontology of human water dynamics in terms of interacting social and hydrological systems. As mentioned above, SHS takes an intermediary position between the purely qualitative narratives and the deterministic, data demanding mathematical conceptual models. Its understanding (step 1) is more detailed than a general narrative, but its evidence (step 2) is less data demanding and complicated than running a model based on differential equations. We propose the use of SHS to provide a method to capture actual choices in a more formal and generalisable manner as compared to single case descriptions, thereby making comparisons between cases possible, without being constrained by deterministic models or mathematical equations.

3 Socio-hydrological spaces defined

To reflect the intermediary position of SHS between generic models and specific cases, we define a socio-hydrological space in two ways: from the empirical observations, which may include quantitative data but also general contextual knowledge ('bottom-up'), and from the conceptual models of the general patterns found in human-flood interactions ('top-down').

Starting from the empirical observations captured in quantitative and qualitative data, we define a socio-hydrological space as a geographical area in the landscape with distinct hydrological and social features that give rise to the emergence of distinct interactions and dynamics between society and water. Starting from the generic patterns captured in conceptual modelling, a socio-hydrological space is also the empirical expression of a specific combination of generic patterns (here: fighting and adaptation dynamics) in a geographical area that is distinct from the neighbouring one. Importantly, both definitions apply simultaneously, and are operationalised in an iterative manner to study the socio-hydrology of an area as shown in the example for the Jamuna flood plain (Sections 4 to 6).

Using SHS in the analysis of socio-hydrological dynamics helps to make the necessary intermediary step between the messy and many details used to characterize a specific location (space) and the stylised abstraction of generic models. With the proposal of SHS we are looking for a middle ground where we preserve the variability of reality and the unpredictability of human behaviour and decisions, not force-fitting these into a model, while at the same time recognising patterns (combinations of similar or comparable fight and/or adapt responses).

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We thus propose that SHS can serve the function of a lens through which to view and filter the complex reality of specific cases, in order to find patterns in human-water interactions. Such patterns can then be compared and contrasted to patterns in other locations to see if further generalisation towards generic models is possible. The use of SHS invites the researcher to have an open mind to the existence of expected or unexpected patterns in the location under investigation, using a thorough

5 understanding of the specifics of this location in terms of society, history, economics, natural system, technical interventions, etc. Insights from one location can then be compared to analyses of other cases in order to explore whether the same or different patterns occur, and for the same reasons. These patterns can then be generalised through a more formal conceptualisation of socio-hydrological systems, whereby the existing conceptual models may be taken as a starting point. On the one hand SHS thereby relates to a specific space, on the other hand it helps to find general patterns of human-water

10 interactions, which means that use of SHS to analyse different cases enables global comparison.

It is interesting to note that some of the earlier socio-hydrological research on floodplains can be said to implicitly employ something resembling the SHS concept (Fig. 1). In their study, which is partly based on the Po floodplain, Di Baldassarre et al. (2013a, ~~2014a~~2014) identify two patterns of society-river interactions. In the 'adaptation effect' pattern the use of flood defence technology is limited, resulting in frequent flooding which is in turn associated with decreasing vulnerability (see

15 also Kreibich et al., 2017). The 'levee effect' pattern results when flood protection structures lead to less frequent but more severe flooding, which is in turn associated with increasing vulnerability (Di Baldassarre et al., 2015) (already identified by White, 1945; see also Kates et al., 2006). These two patterns can be rendered in terms of SHS, yielding a classification of:

a) the ~~SHS 'adaptation space'~~'adaptation space' where ~~the use of flood defense technology is limited, resulting in~~ frequent flooding~~,~~ results in less economic development and lower population density and other human adjustments;

20 b) the ~~SHS 'levee effect space'~~'fighting space' where flood protection structures lead to less frequent but more severe flooding, more economic development and higher population density and other human adjustments.
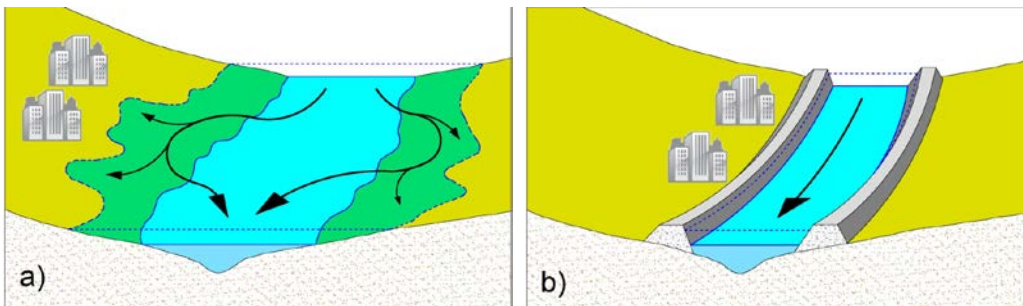

Figure ~~1:~~1: Schematic of human adjustments to flooding: (a) adaptation: settling away from the river, and (b) ~~levee effect~~fighting: raising levees or dikes (after Di Baldassarre et al., 2013b).

25 In these first conceptualizations, one floodplain is assumed to show one or the other pattern at one point in time, while allowing shifts over time from adaptation to levee effect (Di Baldassarre et al., 2013a). ~~(while allowing shifts over time from adaptation to levee effect; Di Baldassarre et al., 2013a). While it does not allow for spatial differentiation within the floodplain, this classification nevertheless results in a distinction of socio-hydrological spaces but this time between different~~

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floodplains, since it connects the specific floodplain space with a specific socio-hydrological interaction. Because the study classifies each floodplain in terms of one type of SHS only, it is able to use these two patterns to classify socio-hydrological interactions in floodplains worldwide (Di Baldassarre et al., 2015). For example, the study classifies Bangladesh as a whole into the 'adaptation' type. This classification categorises a floodplain as having one single socio-hydrological pattern ('fight'

5 or 'adapt'). Di Baldassarre et al. (2015) then classify several floodplains worldwide in one of the two patterns. For example, they classify Bangladesh as a whole into the 'adapt' type. However, it turns out that several sections of the floodplain in Bangladesh are protected by an embankment (see Section 5), with residual flood risks giving rise to adaptation behaviour. Similarly, their classification of the Rhine floodplain in The Netherlands as 'fighting floods' holds in general, though in several places adaptation is being experimented with (Wesselink et al. 2007, Van Staveren and Van Tatenhove, 2016). In the

10 same country, the Meuse valley was classified as 'adaptation' although embankments have been added to protect built-up areas (Reuber et al., 2005; Wesselink et al., 2013). As the goal of generic models is to describe decadal dynamics at large scale (Di Baldassarre et al., 2013b), they can only capture the main phenomena in large areas, such as a whole floodplain (in time or space) or a river basin. Instead, SHS induce the researcher to further refine the analysis of human-flood interactions from the generic to the more local where, for example, both response may co-exist at one time in specific proportions. In this

15 way, SHS allow more specific and detailed representation of the reality of these interactions, while still enabling comparison between cases by referring to generic patterns. In what follows, we illustrate how the concept can be used in a more detailed and refined analysis of the Jamuna floodplain in Bangladesh. We show how its use can provide nuances to the broad-sweep overall classification by showing that within this overall characterisation some areas to some extent exhibit a 'levee effect', while other areas do not fit the two-way classification.

20 3To use the concept of SHS, we propose a two-step approach. First, the top down definition of SHS guides the researcher to look for the generic patterns in the information collected about the study area. As notes this information is based on a thorough understanding of a specific floodplain (geography, history, technology, societal occupation etc.). This results in a preliminary geographical delineation of distinct SHS and their qualitative descriptions by means of narratives, schematised drawings, maps etc.; these results have the function of being hypotheses in the next step. In the second step, quantitative data

25 analysis is employed to confirm, reject or correct these initial hypotheses, that is, this analysis provides the data driven (bottom up) delineation of SHS. If the classification is not statistically significant, merging or splitting of categories should be considered as well as re-drawing the boundaries (repeat step 1). However, this adjustment should always be based on arguments based on a good understanding of the floodplain, since statistical significance by itself does not explain socio-hydrological dynamics.

30 Similar research methods were used before in socio-hydrology, e.g. geo-statistics to study the interaction between river bank erosion and land use (Hazarika et al., 2015), or so-called data-driven narratives (Treuer et al. 2017) and the pairing of statistical analysis and narratives (Hornberger et al., 2015). While the combination of narrative and statistical methods that we use is therefore not new, their application to SHS enables transcending single case studies in the search for more

generalizable patterns. We could therefore envisage that the methods used in Step 2 could be different, as long as they contribute to the goal of identifying and validating SHS.

The following case study demonstrates how the SHS approach can be used. Our goal is not to include all available data to provide an exhaustive analysis, but to show how SHS help to detect and understand socio-hydrological dynamics. The socio-hydrological characteristics and data availability guide the choice of methods in our socio-hydrological analysis of a part of the Jamuna floodplain in Bangladesh. In other circumstances the application of SHS will likely entail different variables and methods.

4 Research approach

~~3~~4.1 Case study area

The delta where the Ganges~~,~~, Brahmaputra~~,~~ and Meghna ~~delta~~ rivers meet the sea in the Bay of Bengal encompasses 230 ~~rivers~~river channels and covers most of Bangladesh (Mirza et al., 2003). It is the largest delta in the world draining almost all of the Himalayas ~~which are~~, the most sediment-producing mountains in the world (Goodbred et al., 2003). The ~~combined~~ flows of the ~~Ganges, Brahmaputra and Meghna Rivers are delivered~~three rivers add up to ~~the Bay of Bengal through the Lower Meghna River, a total~~an average of 1 trillion cubic meter per year of water and 1 billion tonnes per year of sediment. The sediment load is very high, resulting in very dynamic river channels (Allison, 1998). In the early 18th century, the main course of the current Jamuna was flowing through what is now the Old Brahmaputra, to the east of the Jamuna. Sometime between 1776 and 1830 the course of the Brahmaputra shifted from east to west, and the 'new' river was given the name Jamuna. Since then, the Jamuna has shown progressive westward migration and widening, meanwhile transforming from a meandering river to a braided one (CEGIS, 2007). ~~It is also~~The Brahmaputra Right Embankment (BRE) was constructed on the west bank of the Jamuna in the 1960s to limit flooding and increase agricultural production, and also to try to stabilize the position of the river, the latter with limited success despite the addition of groynes and spurs.

Bangladesh is a very densely populated country with more than 140 million of people (964 persons per square km~~); around~~). Around 80% of the population lives in floodplain areas (Tingsanchali and Karim, 2005) and depends on agriculture and fisheries (BBS, 2011). ~~Normally~~In the monsoon season, 25-30% of the floodplain area is inundated ~~by the seasonal monsoon~~ every year (Brammer, 2004). These 'normal' floods are valued by rural ~~people,~~inhabitants because they are beneficial to ~~land~~the fertility of the land, provide ecosystem services (fish stock), and transportation (Huq, 2014). ~~Extreme flood~~According to the classification by the Flood Forecasting and Warning Centre which categorises flooding events ~~(defined by~~as normal, moderate and severe based on flood duration, exposure, ~~depths etc.)~~depth and damage, extreme flood events were observed in 1954, 1955, 1974, 1987, 1988, 1998, 2004 and 2007~~. Subsequently~~ (FFWC/BWDB, 2017); the flood events since then were not judged extreme in the whole country, but in NW Bangladesh, which includes our study area, 2016 and 2017 were also extreme (FFWC/BWDB, 2017). Throughout the years, successive governments have

~~developed and~~ implemented several flood control measures to protect agriculture and populations from floods (Sultana et al., 2008).

Riverbank erosion is associated with flooding in many areas of the country. The extremely poor people who live on the chars (islands in the big rivers) are most exposed to and affected by flood hazards and riverbank erosion. During the period 1973 to 2015, the net erosion was 90,413 ha and the net accretion 16,497 ha along the 220 km long ~~Brahamaputra was about 90,413 ha and 16,497 ha respectively~~Jamuna (CEGIS, 2016). ~~During 1981-1993, about 0.7 million char land dwellers were displaced in Bangladesh. Among half of them were from chars in the Brahamaputra (FAP 16/19 1993).~~ Every year about 50,000 to 200,000 people are displaced by riverbank erosion ~~(IOM,~~ although they usually find another place to settle nearby in the area (Walsham, 2010). Hence, it is clear that hydrological processes (flooding and riverbank erosion) play a vital role in the way people in Bangladesh organize their lives, as manifested among others in patterns of migration, livelihoods and land use.

To ~~evidence and~~ understand ~~how this happens~~these relationships between river and people better, this study focusses on a small area along approx. 30 km of the Jamuna River in the north of Bangladesh (Fig. 2). The total area is about 500 square km and the total population is ~~approximately 0.36 million (BBS, 2011). In the early 18th century, the main course of the current Jamuna was flowing through what is now the Old Brahmaputra, but sometime between 1776 and 1830 the course of the Brahmaputra shifted from east to west, and the river took the name Jamuna.~~approx. 0.36 million (BBS, 2011). ~~Since then, the Jamuna has shown progressive westward migration and widening, meanwhile transforming from a meandering river to a braided one (CEGIS, 2007). Taking this westward migration into account, the government built groynes and spurs on the west side of the river in order to try to stabilize the position of the river, with limited success.~~

The case study area includes parts of Gaibandha district and parts of Jamalpur district (Fig. 2). The total width of the case study area is around 24 km, of which the braided river bed takes approx. ~~12-16 km. The braided river bed measures approx. 4-8~~12-16 km; this includes many inhabited river islands (chars) that flood with varying frequency (every year to only with severe floods). ~~The area to the west is protected by an embankment (the Brahmaputra Right Embankment, BRE) constructed in the 1960s to limit flooding and increase the agricultural production of that area. Its maintenance~~The maintenance of the BRE in the study area has been sporadic. When constructed, the average height was 4.5m, width 6m and slope 1:3 on both sides (CEGIS, 2007). Though extreme discharges could not overtop this embankment, breaches have occurred which caused catastrophic floods and damages (~~FICHTNER and nhe~~RBIP, 2015). In the 2016 flood (observed during the field survey), the BRE was breached in Gaibandha district, resulting in a large ~~portion of the~~ area being flooded. On the left bank there is no human-made protection, but there is a natural levee that has been deposited by the river.
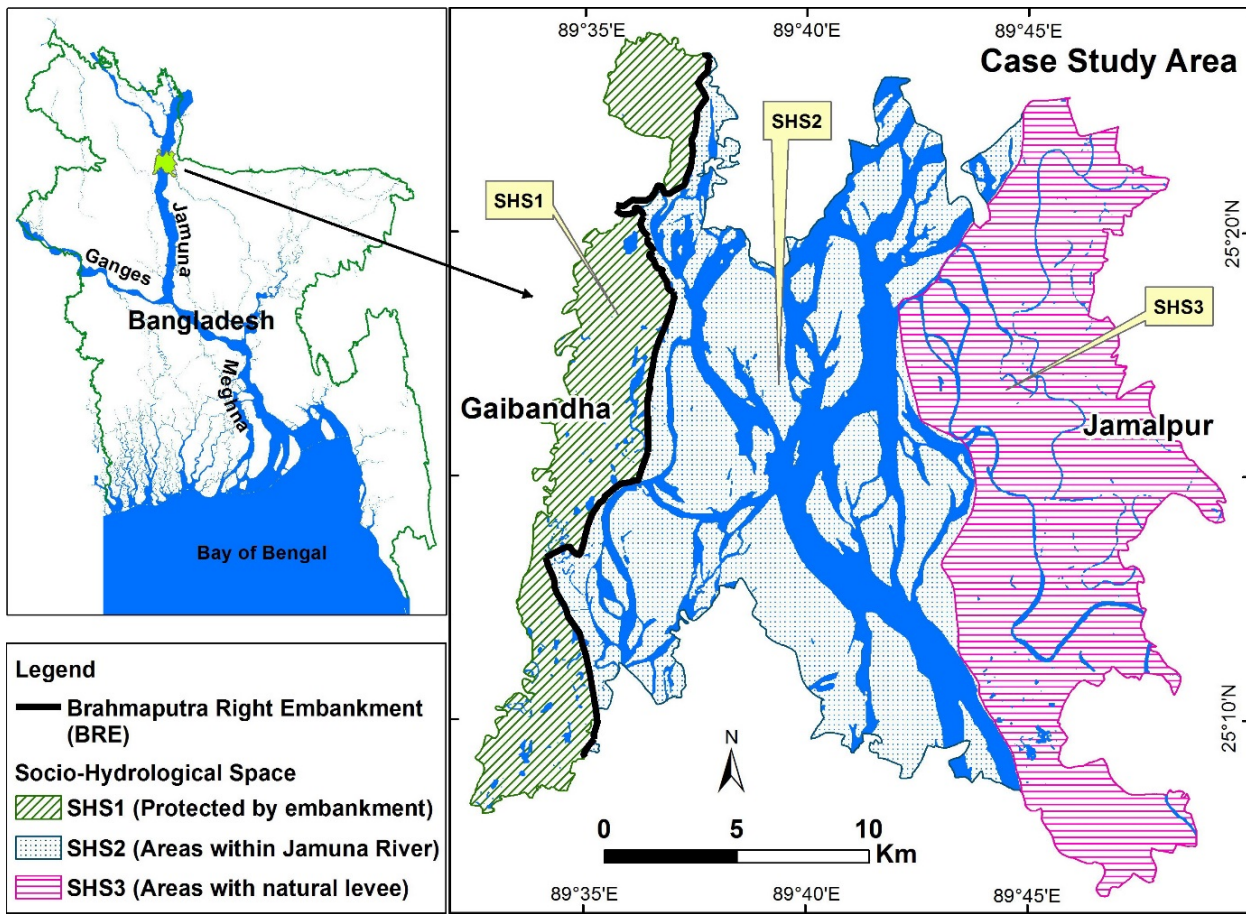
Legend

Brahmaputra Right Embankment (BRE)

Socio-Hydrological Space

SHS1 (Protected by flood embankment)

SHS2 (Areas within Jamuna River)

SHS3 (Areas with natural levee)

Union boundary
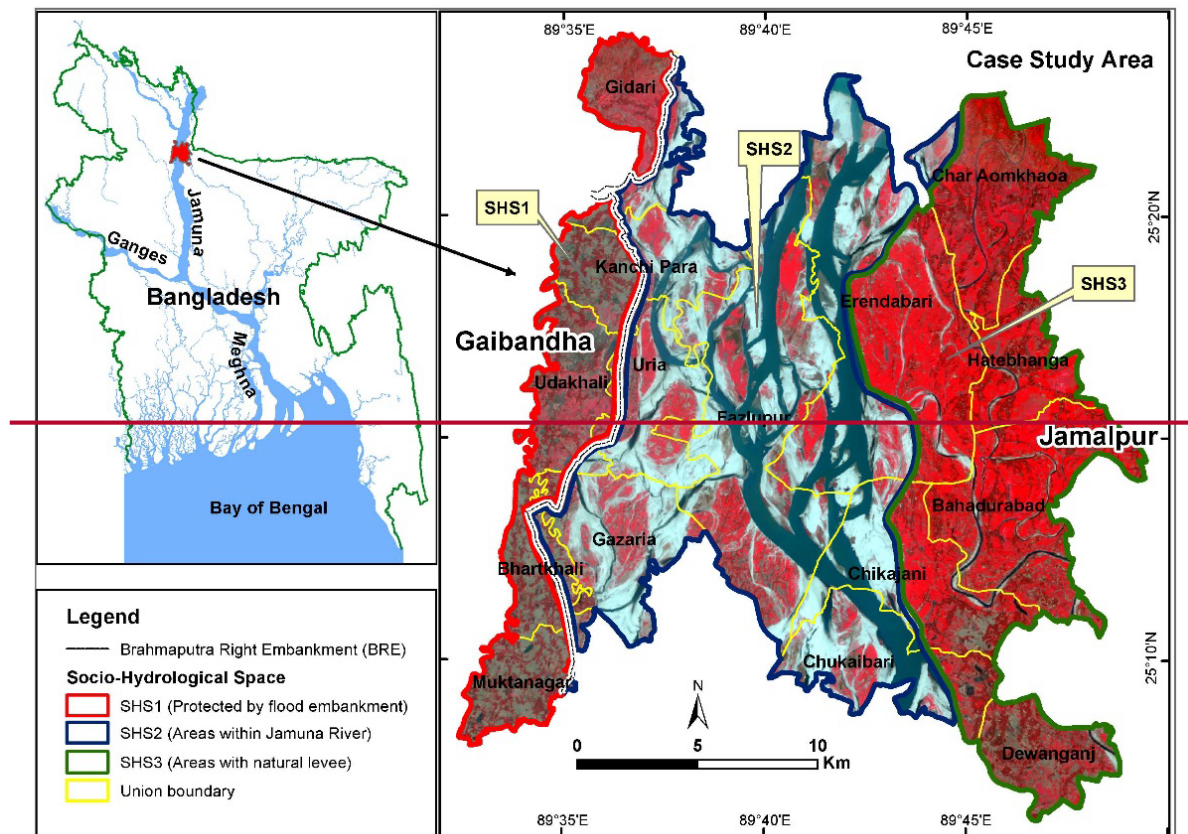
Figure 2: Bangladesh map with case study area and SHS.

~~34~~.2 Step 1: preliminary **identification of SHS and** classification ~~and identification~~**of areas**

~~As~~Throughout the fieldwork period needed to collect the primary data described in Section 4.3 below, a detailed knowledge

5 of physical, technical and social conditions of the area was accumulated by the first author. In collecting this information, he built upon and was guided by his personal knowledge as a resident in a nearby area, as well as by 10 years of professional experience throughout Bangladesh as a water engineer charged with flood forecasting and training residents on using flood and erosion forecasts. Since flood control measures were only developed along some rivers ~~or river banks,~~(see Section 4.1 above), the study area is characterized by different degrees of protection~~, giving rise to the development of~~. In addition to

10 these human-made structures, different ~~socio-hydrological relationships in the same floodplain. This forms~~geomorphological conditions influence local flood frequency and extent as well as the extent of river bank erosion. Inhabitants adapt to these physical conditions, which is apparent e.g. in private investment levels and cropping patterns, but also in public investment e.g. in schools and roads. These qualitative observations formed the basis for distinguishing ~~different~~three SHS in the landscape. ~~We thus started out identification of SHS based on differences in geophysical characteristics and flood protection~~

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measures, yielding a distinction in three SHS: SHS1, which are ~~areas protected by the BRE (west bank); SHS2 refers to the char areas (in the river bed); and SHS3,~~ described in a narrative fashion in Section 5. To demarcate the ~~areas with a natural levee (east bank). We categorized all~~SHS we used administrative ~~areas at the lowest level~~boundaries (unions~~)~~ and mauza) since this enabled the use of Government data in Step 2; 15 unions are included in the ~~case~~ study area ~~into one of these three~~

5 ~~SHS~~.

~~3~~4.3 Step 2: evidence

The ~~categorization of unions into~~demarcation of SHS was validated through the analysis of primary data (household surveys and focus group discussions) and secondary data (statistics, maps etc.) ~~that were~~ collected ~~in~~during the dry seasons of 2015 and 2016. The principal set of primary data consists of approx. 900 questionnaires dealing with several themes: general

10 information (location of settlement and agricultural land, main occupation, age, income and expenditures, wealth and origin of the households), information on different flood experiences (depth of floods, frequency, duration, flood damages, effects on agricultural income and expenditures, adaptation options, migration etc.) and experiences with river erosion (frequency, damages, migration, adaptation options etc.). We also ~~did~~set up focus group discussions in ~~different~~most unions ~~of~~in the case study area to validate and contextualize ~~our~~the survey data. Details of these methods are given below.

15 A cross-sectional method was used to gather the primary data of the case study area. Cross-sectional research involves using different groups of people, both male and female (farmer, fisherman, day-~~labor~~labour, service holder etc.) who differ in the variables of interest but share other characteristics, such as socio-economic status and ethnicity. We aimed to collect approximately the same number of surveys in each of the three SHS. Due to the rural character, most of the respondents were farmers. We introduced an age bias because we wanted to collect historical information on flooding, riverbank erosion,

20 livelihood etc. The household surveys were implemented with a combination of purposive sampling and quota sampling. Purposive sampling is a method where individuals are selected because they meet specific criteria (e.g., farmer, fisherman, day labour etc.). The quota sampling method selects a specific number of respondents with particular qualities (like farmer's age should be 40 or above). We ~~use~~used the Raosoft sample size calculator to determine the required sample size for the surveys by union ~~(the lowest administrative unit of Bangladesh government)~~. This calculator allowed to enter values

25 including acceptable margin of error, response distribution, confidence level and size of the population that is to be surveyed. We accepted a 5% margin of error with 95% confidence level to determine the sample size, which is 1% households (863 household surveys) of the case study area. ~~In total 15 Unions were surveyed along the study area.~~ The questionnaire ~~of~~for the ~~surveys~~survey is provided in supplementary materials (ESM1).

In addition, we performed 12 focus group discussions in the case study area, four meetings in ~~each SHS in~~ different unions

30 in each SHS. About 20 participants were present in each of the meetings. Participants were selected based on occupation and location of the households ~~(i.e.,~~ guaranteeing a uniform spread over the union area~~)~~. The topics of the discussions were: how ~~flood~~ is flooding affecting ~~the livelihood group and~~livelihoods; what ~~are the~~household coping strategies~~; the~~ are used in relation ~~of the household members'~~to flooding, for example changing occupation ~~to the floods~~or raising homesteads;

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migration ~~pattern; human activities~~patterns; community interventions against ~~the~~ flooding; river bank erosion and household coping strategies; ~~human influences on~~community interventions against riverbank erosion; governmental initiatives against flooding and riverbank erosion etc. The agenda of the focus group ~~discussion~~discussions is provided in the supplementary materials (ESM2).

5   ~~In addition, we~~We also collected secondary data like time series satellite images to analyse the morphological dynamics of the Jamuna, census population data to analyse population density from different governmental and non-governmental organisations of Bangladesh. ~~We also present frequency analyses for the three spaces SHS1, SHS2, and SHS3. The significance of frequency differences between spaces was tested by an analysis of variance~~Results of Step 2 are discussed in Section 6.

10   **~~4~~5 Results step 1: Identification of socio-hydrological spaces along the Jamuna River**

As noted, in our study area along the Jamuna~~,~~ three distinct socio-hydrological spaces ~~can be~~were identified~~:~~. SHS1~~:~~ covers the areas protected by the BRE (on the west bank), SHS2~~:~~ covers the char areas (in the river bed) and SHS3~~:~~ includes areas with a natural levee (on the east bank). These are depicted in a schematized fashion in Fig. 3~~.~~

~~The SHS are delineated based on physical conditions~~ and ~~related occupation patterns. Different local geomorphology and~~
15   ~~flood management measures influence the level~~described by means of ~~flood frequency and extent, as well as the level of river bank erosion. Inhabitants of the areas adapt to these physical conditions, which is apparent e.g. in investment levels and cropping patterns~~narratives below.

~~4~~5.1 Areas protected with flood embankment (west bank) (SHS1)

This socio-hydrological space is protected from regular annual flooding, the so-called 'normal floods'~~,~~ by ~~flood~~
20   ~~embankments~~the embankment along the main river Jamuna (BRE) and along some smaller Jamuna tributaries. However, different parts of the area are still frequently ~~ponded~~inundated with excess rainwater, due to their low elevation and limited drainage capacity. Further, ~~smaller~~a few small rivers (Ghagot and Alai) inundate unprotected areas yearly in the western part of the area. ~~The~~Because the BRE effectively protects the area against ~~frequent largescale~~all but the largest riverine flooding from the Jamuna~~ and as a result~~, inhabitants feel ~~relatively~~ confident enough to invest in businesses and homesteads. ~~Yet~~In
25   the study area, Gaibandha district, the BRE is not very well maintained, so the BRE sometimes breaches. Inhabitants build their houses on artificially raised ~~platform~~platforms – often several metres above ground level – to reduce their vulnerability to ~~such~~the resulting floods. River bank erosion in this area is not widespread, but does occur in several locations. SHS1 therefore shows a combination of the 'fight' and 'adapt' patterns.

45.2 Floodplain outside the embankment (west bank) and chars (SHS2)

This is a very dynamic environment. The Jamuna is a braided river, where multiple channels crisscross within the outer boundary of the river. When considered over decades, ~~channels more and more move into~~the outer boundary is moving in a westward direction (CEGIS, 2007). The 'chars' – or river islands – are also moving, progressing or disappearing, due to

5   local erosion ~~and flooding~~ processes. Chars have different ages, which have a direct relation to the height level. As the river still deposits sediment on chars, some older chars have higher elevations than the areas in SHS1, and have shown to remain dry in extreme flood conditions.

If a newly developed char does not erode ~~very quickly~~immediately, it is first colonized by grass, which accelerates deposition of silt during the next flooding. ~~Consequently~~Subsequently, people start to occupy the char, planting fast growing

10   trees and laying out agricultural fields. In the course of time, all kind of facilities like schools, mosques, small shops, bazars etc. are established. Since the chars are not stable, most of the houses built in the chars are semi-permanent and easy to take apart and move~~.~~. House types are kutcha (wood, straw and bamboo mats) or jhupri (straw). Many people raise the plinth levels of their houses to avoid flood damages, but this is not very effective.

~~At~~On the ~~'chars',~~chars inhabitants regularly face ~~agricultural as well as homestead~~ damages from flooding and river bank

15   erosion to agricultural land and crops and their homestead, often leading to complete destruction. Temporary migration during the flood season to safer places, for example the embankment or on railway lines, is therefore very common. Permanent ~~migration~~resettlement occurs only when the land that people live and farm on simply disappears~~. With migration, and the fluctuations provoked by floods, people~~, although they usually find another place to settle on a nearby char when flood water have receded. People also ~~often~~sometimes change their occupation temporarily or permanently. As char

20   dwellers' life styles are defined by flood and erosion, they appear to be able to cope with the harsh conditions. Yet, most of them become poorer through time, because of landlessness, unreliable and changing sources of employment~~and income~~, and frequent temporary ~~or permanent~~ migration or resettlement. SHS2 therefore shows only the 'adapt' pattern.

45.3 Eastbank (areas with natural levee) (SHS3)

The natural levee on the east bank of the Jamuna protects this area from ~~normal~~about half of the annual riverine flooding~~,~~

25   ~~although~~; flooding occurs more frequently than in SHS1. A few areas are flooded by smaller rivers like the Old Brahmaputra and Jinjira. High water levels in these rivers sometimes occur ~~independent~~independently of high water levels of the Jamuna, as these are not part of the same drainage basin.

River bank erosion is ~~prominent~~conspicuous in this area. Even though the river ~~overall shifts westwards~~as a whole shows a gradual westward shift, due to the presence of highly erodible bank materials on the left bank~~,~~ erosion is still severe in SHS3.

30   For example, 75 ha of land eroded in 2015 in this area, of which 4 ha with housing (CEGIS, 2016). ~~People~~Inhabitants take the initiative to build ~~cross structures (like~~small spurs~~)~~, and bank protection, made from bamboo and wood, to try to stop erosion. However, while these encourage sedimentation at a local scale, they are not sufficient to stop ~~largescale~~large scale

erosion. ~~Like behind the BREA~~s in SHS1, most houses are built on artificially raised mounds, substantially reducing potential for flood impacts. Flooding and riverbank erosion ~~causes~~cause damage to agriculture, homesteads and businesses, in turn impoverishing people. ~~Migration~~As in SHS1 and SHS2, migration is one of ~~their~~the coping strategies, while ~~several farm~~ households also adapt their cropping pattern to accommodate flooding and cultivate fast growing crops after the flood
5 season. SHS3 therefore shows a combination of the 'fight' and 'adapt' patterns, with more 'adapt' and less 'fight' than SHS1.
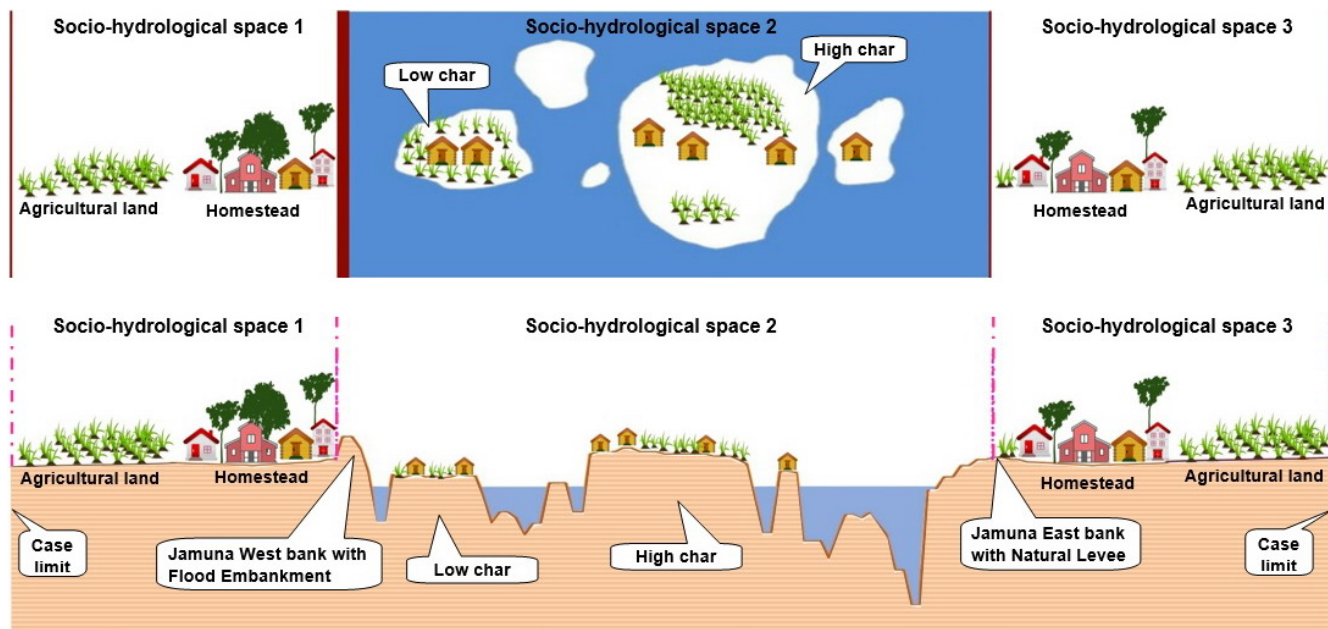
Figure 3: A typical planform and cross-section with distinct SHS along the Jamuna.

~~5~~6 Results step 2: Evidence of socio-hydrological spaces along the Jamuna River

10 ~~In this section we further verify the usefulness of the concept of socio-hydrological spaces by using the collected data. Hence, we assessed whether (or to what extent) it makes sense to categorize~~Using the data described in Section 4.3, in this section we show that the three SHS described above are significantly different. We only show the results for a limited number of variables: perceptions of the sources of flooding; flood frequency; flood damages; average household income and wealth; river bank erosion; migration; homestead types in the three identified SHS. We performed statistical analysis
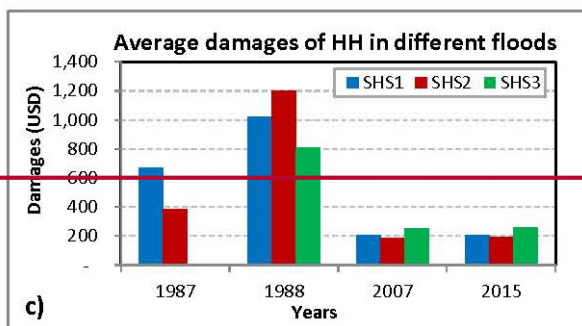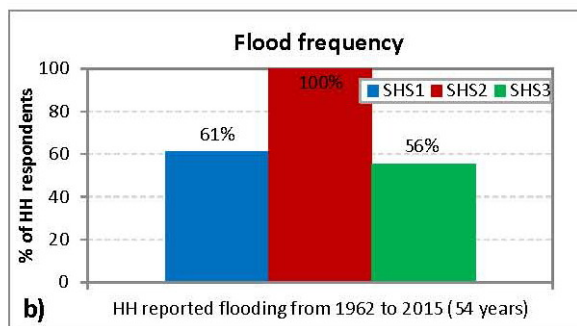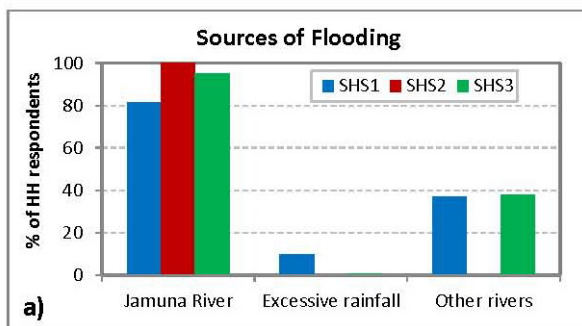15 ANOVA test ($p<0.05$) with these data for all analyses below. In each case the data for the three socio-hydrological spaces ~~to find that all of them are~~were significantly different.

26

56.1 Perception of the sources of flooding

All respondents have experienced flooding in their lifetime, but their perceptions about the sources of flooding are different (Fig. 4a). The main sources of flooding in space SHS1 are excessive rainfall, neighbouring small rivers and the Jamuna (through breaching of the BRE), whereas the sources of flooding mentioned in SHS2 is only Jamuna, and for SHS3 they are the Jamuna, the Old Brahmaputra River and other smaller rivers. A good number of SHS3 people in SHS3 mentioned that the lack of embankment is one of the reasons for flooding, although they also mention excess discharges and river sedimentation.

56.2 Flood frequency

When asked about their recollection of historical flood events (Fig. 4b), in SHS2, people indicated experiencing flooding every year. In both other spaces, this is roughly only once every 2 years. The unexpected relatively high flood frequency for the protected SHS1 may be attributed to the frequent failure of the embankment, or and to the fact that the area is flooded from the regionalwest by the Ghagot River, a tributary of the Jamuna.
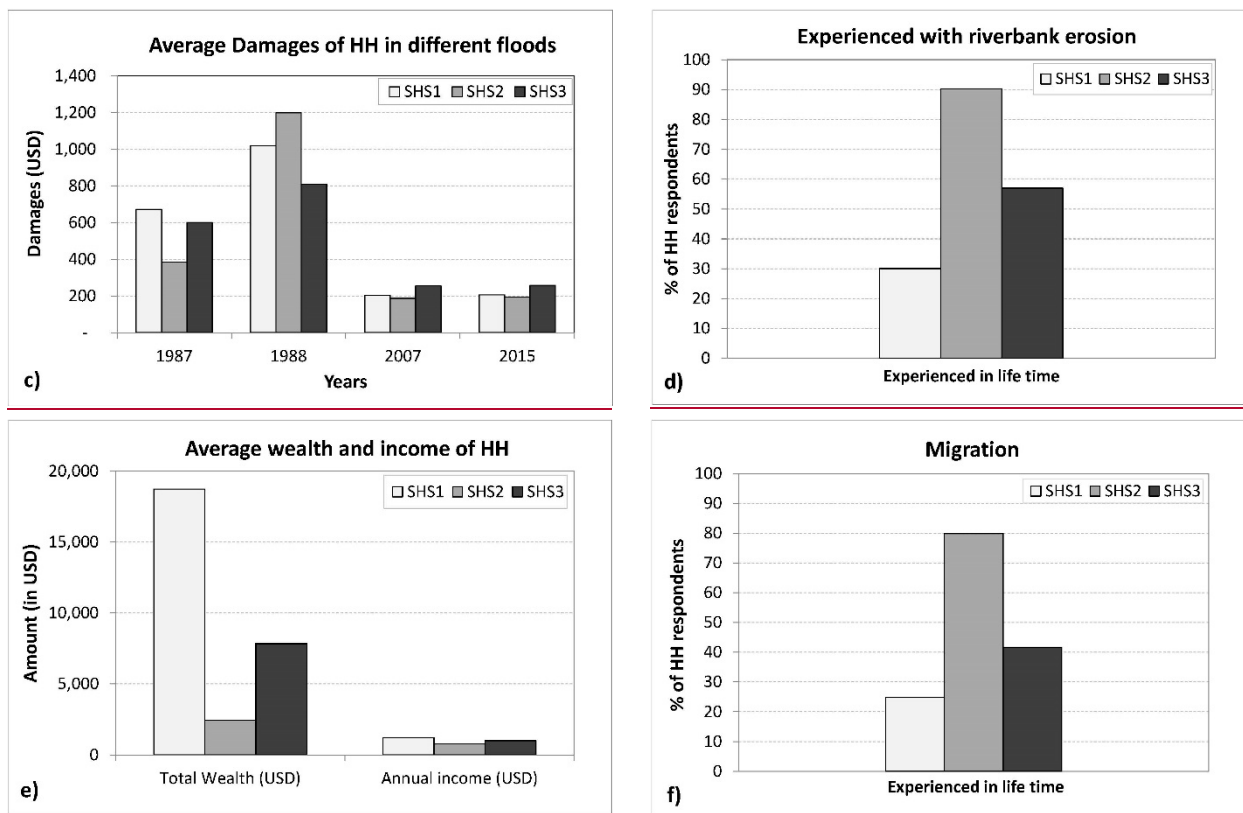
a) Sources of Flooding

b) Flood frequency

c) Average damages of HH in different floods

d) Experience with riverbank erosion

e) Average wealth and income of HH

f) Migration

a) Sources of Flooding

b) Flood Frequency
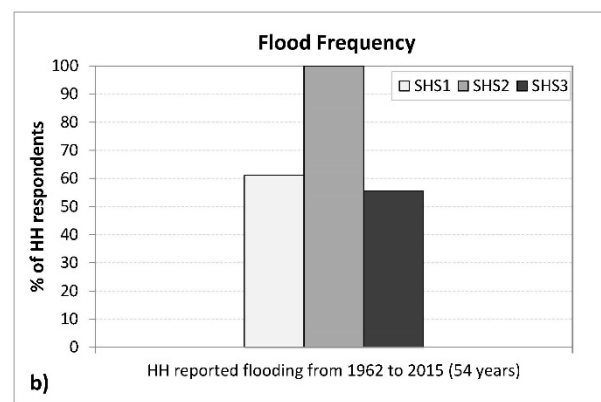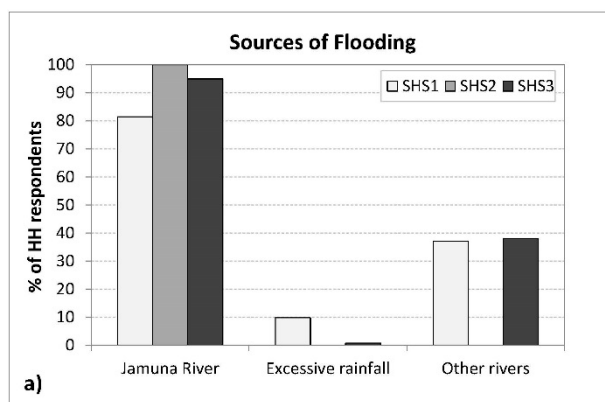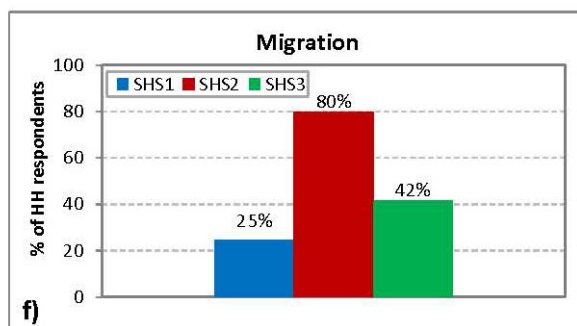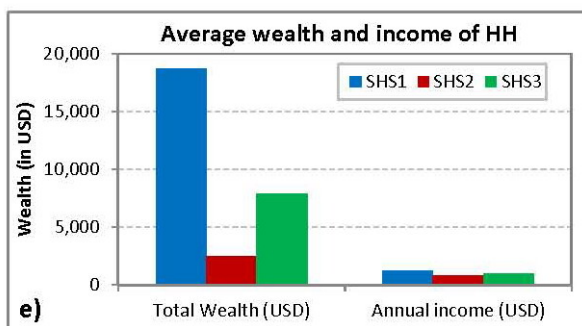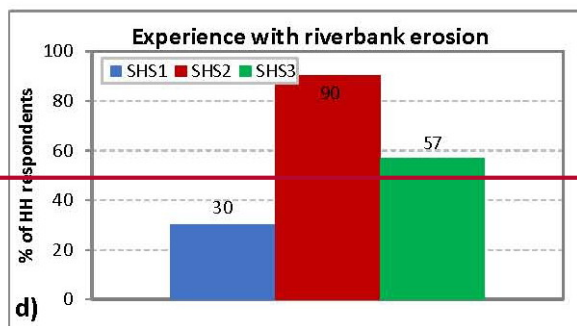
Figure 4: Comparison in between different socio-hydrological spaces (HH = household).

~~5~~6.3 Flood damages

From analysing the flood damage information for extreme events in 1987, 1988 and 2007 and normal conditions in 2015, it becomes clear that 1988 was the most severe year for all three spaces ~~(,~~ ranging from 800 USD per household in SHS3 to 1200 USD in SHS2~~)~~ (Fig. 4c). In other years, average damages ~~where significantly~~were much less. In 1987, damages in SHS1 ~~was~~were highest ~~(~600 USD), compared to~~ of the ~~other zones and damages in 2007 and 2015 were of equal size without large variety between the~~ three spaces ~~(around ~200 USD). The relatively high damage in SHS1,~~ (~700 USD/household). This may be attributed to poor drainage capacity in ~~these times~~SHS1, as well as ~~that the~~a lower average land elevation~~ is lower than in the other zones.~~, resulting in deeper and longer water logging. Damages in 2007 and 2015 show little difference between the three SHS (~200 USD/household).

~~5~~6.4 River bank erosion

Riverbank erosion is experienced in each ~~zone~~SHS, but (as expected) mainly by inhabitants in the dynamic SHS2~~.~~ (Fig. 4d). However, erosion ~~rates~~ in SHS3 is also very high ~~(>~~, with over 50% of the interviewed people ~~have~~having experienced it

29

themselves)~~.~~. In SHS1 expected rates are lowest, but still considerable, as 30% ~~has~~have experienced it. ~~Almost an identical distribution is found (Fig. 4d) in that households had to move~~ due to breaching of the ~~riverbank erosion~~BRE.

~~56~~.5 Average household income and wealth

The average wealth distribution (Fig. 4e) shows clearly the economic differences between the households in the three ~~spaces~~SHS. In the protected areas, people have much more wealth ~~(,~~ on ~~an~~ average about 19,000 USD~~).~~/household, against approx. 2,500 USD in SHS2 and 8,000 USD in SHS3. Household wealth includes land (homestead, agricultural, other land), ponds, houses and housing materials, livestock and portable wealth like savings, gold and silver. About 80% of the people in the case study area are farmers, ~~thus~~so their income ~~and wealth~~ mostly depends on their agricultural production~~.~~, complemented by remittances from migrant labour by family members for some families and from occasional day labour in agriculture, construction or fishing, or as rickshaw driver or van puller. Their starting position and subsequent losses depend to a large extent on where they live.

The current situation is (much) worse for most households than in the past. As per our ~~surveys~~survey, in SHS1 there were 7% large farmer households (~~lands~~with land> 3 ~~hectares~~hectare) in 1960 ~~in SHS1~~ but after consecutive flooding events, this was reduced to only 2% in 2015 (Fig. 5). Those who owned ~~more~~most land in the past (> 3 ~~hectares~~hectare) gradually saw a decline in their farm land to ~~become~~ medium (~~from~~ 1 ~~to~~-2.99 ~~hectares~~hectare) or small ~~farmers (lands from~~ (0.2 ~~to~~-0.99 hectare), with some even becoming landless. There were only 16% landless households in 1960, but this increased to 28% in 2015.

In SHS2 and SHS3~~,~~ a comparable pattern can be observed. The number of large farm households reduced from 18% to 1~~%~~ and landless farmer households increased from 7% to 48% in SHS2. ~~On the other hand, the land owned and farmed by~~ In SHS3 the proportion of large ~~farmers~~landowners reduced from 10% to 2~~%~~ and ~~the proportion~~that of landless farmers increased from 18% to 41~~% in SHS3.~~%. More than 80% of the respondents from SHS2 ~~told~~reported that they could not recover from the losses due to flooding and riverbank erosion. Many of them ~~had~~have to change their occupation temporarily, ~~with~~and 3% of the respondents in SHS2 ~~changing~~changed their occupation permanently from farmer to day labourer. This is less than the reduction in land ownership would suggest because landless farmers will try to rent land to be able to cultivate their own crops. If this is the case, they share crops with the land owners or pay a fixed amount per year.

There is a possibility that some respondents exaggerated reported losses in the hope that the research would help to mobilize funds. ~~This is why we arranged~~The focus group discussions ~~to verify the outcomes from the household surveys. These~~clarified this issue. They revealed that ~~the~~ cropping patterns ~~of the protected areas~~ in SHS1 ~~and the unprotected areas,~~ SHS2 and SHS3 are different. Respondents in SHS1 are cultivating three crops per year. In ~~the~~ SHS3 ~~areas~~ people used to cultivate three crops ~~earlier~~in the past, but due to flooding~~,~~ they now cultivate either two crops or only one crop per year ~~because they cultivate,~~ only in the dry season after floods have subsided. From the survey data it appears that in SHS1 only 15% of the respondents changed cropping patterns between the 1960s and the 2010s, against 53% in SHS3 and 40% in

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SHS2. A very small number of people have changed land use completely, for example from agriculture to homestead, from low elevation land to high elevation land by filling silts, or from agriculture to fallow etc.
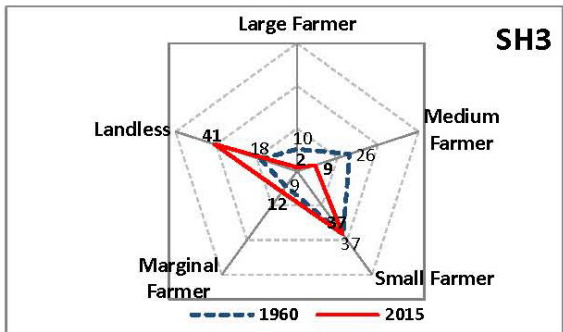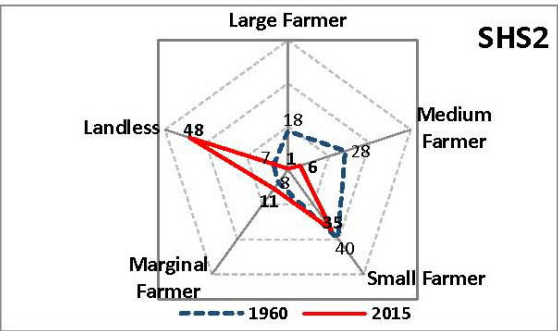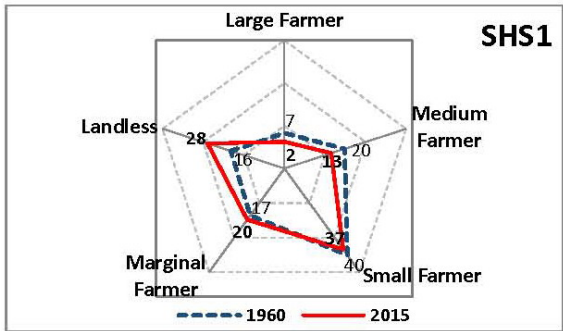
Farmer categories by Bangladesh government:
  [1 acre = 0.405 hectare]
- Large Farmer (land > 7.5 acre)
- Medium Farmer (land, 2.5 – 7.5 acre)
- Small Farmer (land, 0.5 – 2.5 acre)
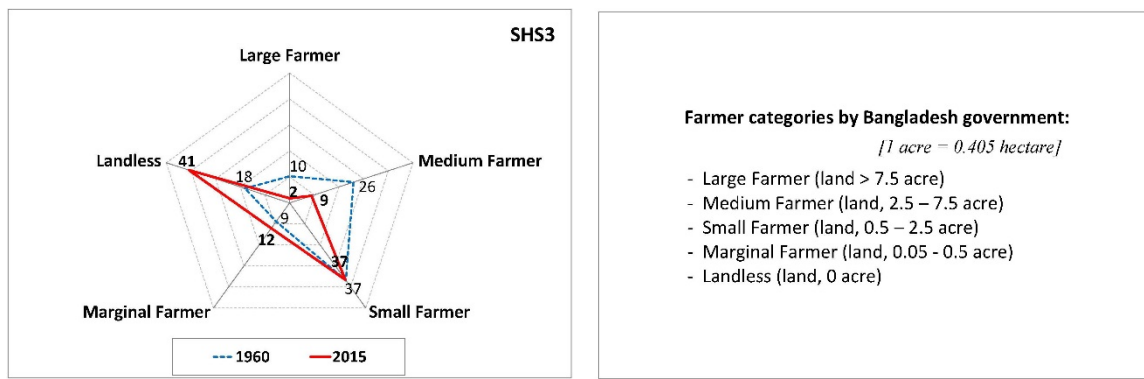- Marginal Farmer (land, 0.05 - 0.5 acre)
- Landless (land, 0 acre)
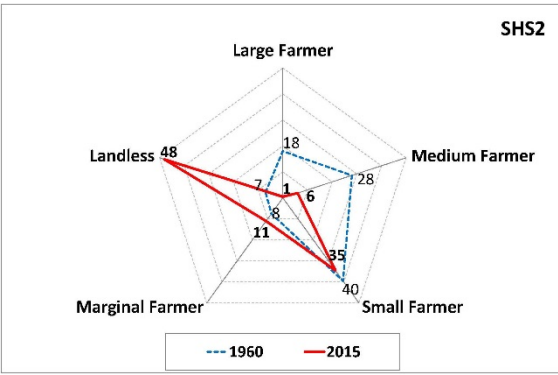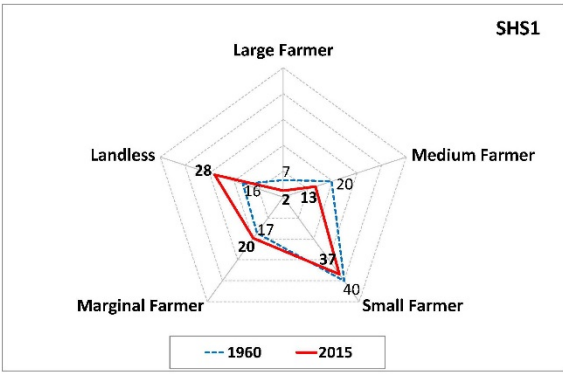
Figure 5. Agricultural land changes with time of the different types of farmer (% of HH respondents).

5.6 Migration

The population density in the three spaces from census data show much higher densities in SHS1 than in SHS2 and SHS3. In SHS1 it is 1,500 person~~/km2~~ per square km (varying between 1,000 to 3,000 person~~/km2~~ per square km in the different villages in SHS1), while population density in SHS3 is 800 person~~/km2~~ per square km (between 100 to 2,000 person~~/km2).~~ per square km, the lowest figure being for very few villages adjacent to the east bank). It is lowest in SHS2 at 400 person~~/km2.~~ per square km (varying between 30 to 1,000 person per square km) (BBS, 2011). The historical population data from ~~BBS~~1961 to 2011 show that population density has increased in most of the unions ~~in the spaces~~, except in SHS2~~.~~ (CPP, 1961; BBS 1974, 1981, 1991, 2001 and 2011). Unfortunately, there are no official records of the exact number of people who migrate ~~long~~out of the area on a temporary or ~~a short distances.~~permanent basis. From our survey, we found that ~~the people are mostly migrating from SHS2. Most of the~~ temporary or permanent migration ~~occurs from~~is most frequent in SHS2, mostly to SHS1 and SHS3. From 1988 to 2015, 17% of respondents had migrated to SHS1 and 8% to SHS3.

Riverbank erosion is one of the main reasons for ~~moving~~relocation from their place of origin (Fig. 4f). We found that 80% of the households in SHS2 had moved at least once. Most of them moved within 5 km, but in focus groups it was said that about 25% of people of that area had migrated away to other districts. About 68% of respondents were born in SHS1 and still live there, while 25% migrated to SHS1 from other places due to riverbank erosion. In SHS3, about 58% were born locally and the rest ~~immigrated~~moved into the area, again mostly due to riverbank erosion. The respondents who ~~immigrated to new places mostly~~relocated within the study area knew that their ~~new places are~~destination was flood prone and ~~also experience~~at risk from riverbank erosion. However, the lack of available land is a major problem ~~and the reason why~~so they ~~move to a risk prone area~~contend with sub-optimal conditions.

5.7 Homestead types

The construction type of ~~the~~ houses is different between the spaces (Fig. 6). Most of the pucca houses (well-constructed buildings using modern masonry materials) and semi-pucca or half pucca houses (made of brick and tin) are within ~~the~~ SHS1

and SHS3, where people feel comparatively safe against flooding and erosion. As a result, they invest more in their ~~accommodation.~~home. In SHS2 a high proportion of kutcha (wood, straw and bamboo mats) and jhupri (straw) houses is observed, since these are easy to take apart and move in case of flooding or erosion, and less costly to construct.
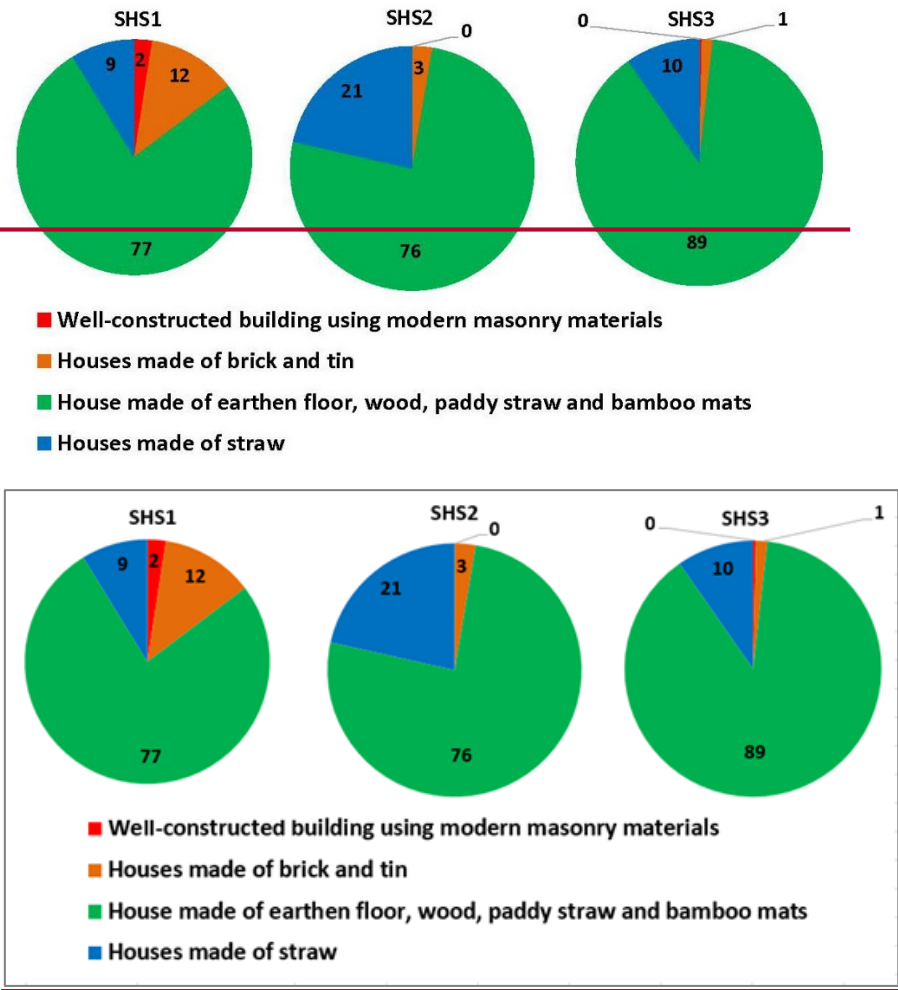

Figure 6: Homestead type of households.

~~6~~7 Discussion

~~We introduced the concept of socio-hydrological spaces (SHS) and applied it to a test area along the Jamuna River in Bangladesh. We found it convenient and useful for categorizing and specifying the interaction between sociological and hydrological processes in the three identified SHS we distinguished in this location. The concept draws attention to the historical patterns of the hydrological processes of the Jamuna River and as well as different social processes along the three~~

33

~~spaces. Each SHS shows distinct features when comparing flood-society interactions, proving that the dynamic interaction of floods and society is depending on different hydrological and societal characteristics along the Jamuna River.~~

~~A key point in the application of the proposed methodology is the initial identification of potential SHS. This step has to do with the difficulty -and somehow subjectivity- to initially determine the boundaries of the identified spaces. In our example,~~

5 ~~we started by fixing the boundaries of three spaces~~Based on thorough in-depth knowledge of the natural, technical and social conditions of the study area in the floodplain of the Jamuna River in Bangladesh, we proposed distinguishing between three SHS as the basic spatial units each with distinct socio-hydrological characteristics. Human-flood dynamics are different in each space, ranking from 'adapt to floods' (SHS3), to more (SHS1) or less (SHS2) 'fighting floods' in combination with 'adapt to floods' to the extent necessary. We then proceeded to demonstrate, through statistical analysis of primary and

10 secondary data, that the SHS show significant differences in the following hydrological and social variables: perceptions of the sources of flooding, flood frequency, flood damages, average household income and wealth, river bank erosion, migration, and homestead types. Our goal was not to prove that these boundaries to the SHS are the best, since this would require much more detailed social and hydrological data than currently available. However, we did show that there are good reasons to consider the three SHS as distinct both from a narrative and from a statistical perspective, and that such a

15 distinction provides a good starting point for further socio-hydrological analysis of human-flood dynamics of the area.

The issue of drawing boundaries around the SHS merits some further discussion. We started by outlining the boundaries of three SHS based on the presence of distinct physical features in the landscape: the embankment on the west bank, the natural levee on the east bank, and the ~~area~~riverbed in between. ~~This is of course an arbitrary selection.~~ The ~~second step of the methodology aims at proving whether the selection has a statistical meaning, which means~~ exact boundaries were drawn on

20 pragmatic grounds, using the administrative boundaries that ~~the identified SHS do show distinct and unique dynamics when selected variables are compared. If not, an iteration of the boundary selection needs to be made and verified.~~

~~Furthermore, the initially selected~~best align with the physical features. These boundaries might show ~~the approximate~~ SHS in the present, but ~~if~~ the ~~identified SHS~~ boundaries of the physical and social systems are not fixed ~~over time they need to be redefined. This is for example the case in our test area: an analysis over time of the physical characteristics of the SHS~~

25 ~~boundaries show that they~~in time. The physical boundaries of the SHS are quite dynamic due to continuing bank erosion along both banks of the Jamuna (~~Fig. 7~~CEGIS, 2007). In particular, by analysing satellite images of the case study area from the late 1960s up to now, ~~one can easily check~~it appears that the west bank has been migrating westward and the east bank has been migrating eastward. As a result, the length-averaged width of the river has increased from 8.17 km to 11.68 km (CEGIS, 2007). Since the construction of the BRE in the 1960s, many breaches have occurred due to river bank erosion,

30 forcing relocation of the embankment in many places (~~FICHTNER and nhc~~RBIP, 2015). At the same time due, to erosion of the east bank the natural levee also moved somewhat over time. Thus the physical ~~boundary lines~~boundaries between SHS1-SHS2 and SHS2-SHS3 are not fixed in time, ~~showing mobility of the SHS boundaries.~~
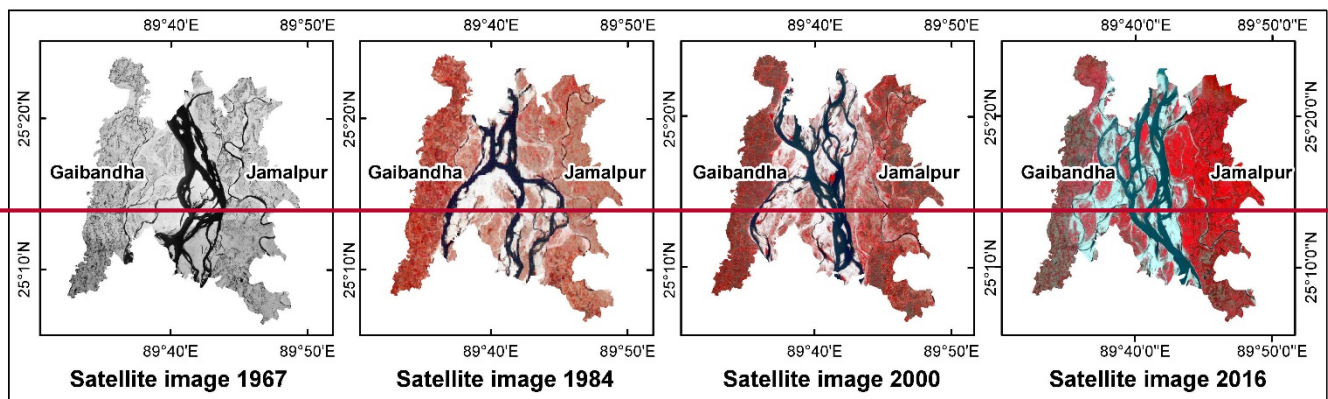
It should also be noted that in this specific application, thethey are since they use the current physical boundaries. The social boundaries of the SHS are not fixed either. In fact, as emerges from the data collection, migration in the Jamuna floodplain is

5   not rare, thus people mobility within the SHS might change the social features of those currently living in each SHS. For our analysis, we have surveyed households accordingare also dynamic. Due to their current locations. However,frequent relocations and migrations, the current inhabitants of the SHS may not have lived there throughout the study period since in every extreme event some migration occurs among the spaces (see Section 5.6). That social and physical boundaries.6). Therefore, the social boundaries between SHS1-SHS2 and SHS2-SHS3 are not fixed in time either, while our statistical

10 analyses assume that they are since they relate to the SHS shift in timecurrent inhabitants. The dynamic nature of the boundaries of the SHS is unavoidable and indeed intrinsic to the highly dynamic socio-hydrology of the floodplain system. Thus, Step 1 in the methodology, identification of SHS, should explicitly and in a transparent way illustrate the criteria for setting up the initial (spatio-temporal) boundaries of SHS and thus highlight under what circumstances SHS boundaries should be revised or update.It is therefore important to remember that the SHS are defined by their unique socio-

15 hydrological characteristics compared with the surrounding area, not by their exact coordinates. For example, SHS2 is defined as a char within the river. If the river moves a kilometre and the char moves with it (or a different char forms), this does not change the definition of SHS2 as a char within the river. The same holds for the social boundaries, if one person moves to another SHS and adopts the strategies of that SHS, then the SHS does not change[1]. Ideally, the data collection and analyses of time series in Step 2 would follow these shifting boundaries, but this will most likely not be possible for due to

20 data scarcity or time constraints.

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[1] We would like to thank one of the anonymous reviewers for helping us to formulate this insight.
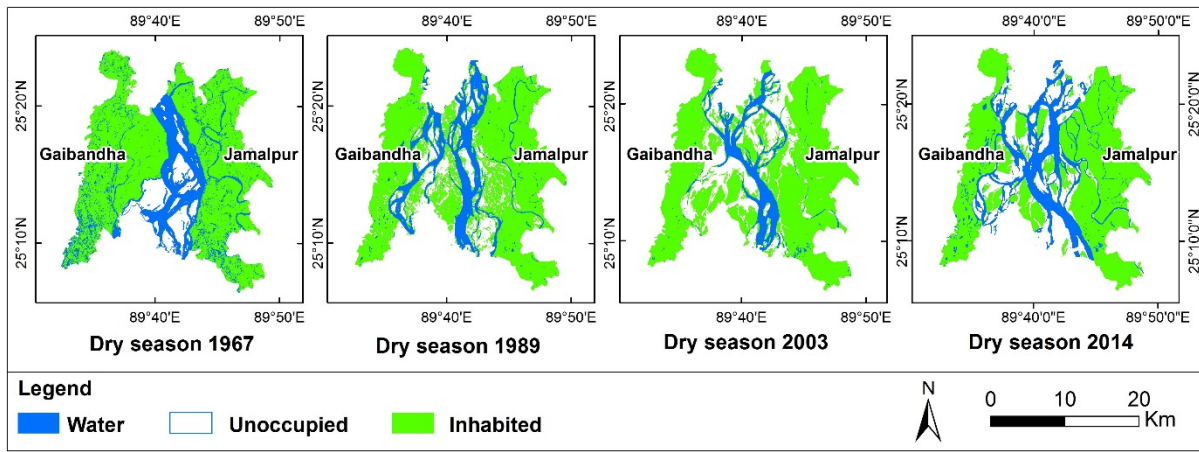
Figure 7: Time series dry season satellite images of the case study area.

We tested the SHS concept in a quick changing socio physical environment, namely a floodplain in Bangladesh, and find that the concept provides a methodological and theoretical advance in the socio hydrology of floodplains as it helps identifying and categorizing human-water dynamics in specific geographical locations. We believe that the concept has a broader validity and can be applied to identify micro socio - hydrological contexts in other floodplains, characterized by different socio physical features.

Finally, a step forward in this research topic is the application of the SHS methodology shown here for the Jamuna floodplain to analyse physical processes other than floods, such as drought, salt intrusion, irrigated catchments or urban systems.

7 Conclusions

Socio-hydrological space (SHS) is a concept that enriches the study of socio-hydrology because it helps understand the detailed human-water 8 Conclusions

We introduced the concept of socio-hydrological spaces (SHS) and applied it to a floodplain area along the Jamuna River in Bangladesh. SHS delineate areas where the interaction between social and hydrological processes show distinct characteristics, which in the case of floodplains can be expressed as different combinations of two basic patterns already identified in the literature: 'fight floods' or 'adapt to floods'. Applying SHS to other floodplains will enable global comparison of the existence and effects of these patterns in human-flood interactions in a specific location. We demonstrated its use in a small area along the Jamuna floodplain in Bangladesh. The elsewhere. For example, similar SHS to the ones found in the Jamuna floodplain are known to exist further down and upstream along the same river (known as Brahmaputra in India), so it would be worthwhile to compare socio-hydrological characteristics and analyse their differences and similarities.

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Applying the SHS concept draws attention to ~~how~~the historical patterns in the co-evolution of social behaviour, natural processes and technological adoptions that give rise to different landscapes, different styles of living, and different ways of organizing livelihoods~~. The~~ in specific geographical locations. The SHS concept suggests that the interactions between society and water are place-~~-~~bound and specific because of differences in social processes ~~and river~~, technological choices

5   and opportunities, and hydrological dynamics. ~~Rather than a generalized model for understanding how such interactions occur, the concept draws analytical attention to how flood dynamics co-evolve with societal dynamics.~~ Such attention is useful anywhere in the world and also for other socio-hydrological systems than floodplains. ~~This~~It will be therefore be worthwhile to see whether SHS can also be used to analyse physical processes other than floods, such as droughts, salt intrusion, irrigated catchments or urban systems. The usefulness of SHS does not only result from what it allows to see, as

10   explained above, but also from the relative ease of application in situations where data are too sparse to use fully deterministic models (~~as~~which is the case nearly anywhere in the world). Compared with existing approaches in socio-hydrology, the concept allows taking an intermediary (statistical) position between ~~purely qualitative narratives and deterministic, data demanding mathematical conceptual models. Its understanding is more detailed than a general narrative, but its substantiation is less data demanding and complicated than running a model based on differential equations.~~ specific

15   cases and generic models. As such, it is argued that specific case studies, SHS, and generic models are complementary approaches with their respective advantages and disadvantages, making them useful for different purposes in different contexts.

Because SHS are place bound, and can only be found (literally) on the ground, the use of SHS forces the researcher to actually go to the field, talk to inhabitants and officials, and obtain a thorough understanding of the specifics of the location.

20   This also means that the use of SHS will make socio-hydrological analyses more policy-relevant. In terms of practical use, it can ~~for instance~~ be added as additional element to rapid rural appraisals, or other social assessments, to draw attention to how material conditions (hydrological and technical/infrastructure) co-shape social situations. This would be useful for developing interventions under disaster management, but also other development goals. In summary, SHS provides a new way of looking at and analysing socio-hydrological systems.

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