Overview of relevant changes:

- According to referees' suggestions the two papers NHESS-2019-164 "Sandbag Replacement Systems – Stability, Functionality and Handling" and NHESS-2019-165 "Sandbagging versus Sandbag Replacement Systems: Costs, Time, Helpers, Logistics" were merged.
- Therefore, a new title was chosen for the manuscript.
- Major changes comprise the revision of abstract, introduction and conclusions.
- Experiences during the Elbe flood 2013 were included (introduction), as well as a sketch of the test set up and typical failure mechanisms of sandbag replacement systems (both section 2). Furthermore, an overview of system dimensions and further properties of the tested sandbag replacement systems was inserted in the appendix.
- Section 2 relates to the paper NHESS-2019-164 and section 3 to NHESS-2019-165
- For minor changes please see authors' replies to referees.

Interactive comment on “Sandbag Replacement Systems – Stability, Functionality and Handling”

by L. Lankenau et al.

Anonymous Referee #1

General comments

The manuscript discusses the advantages and disadvantages of so-called sand-bag replacement systems (SBRS) over regular sandbags. The discussion is based on systematic tests of the SBRS with regard to their functionality, stability and handling, which are described and analyzed in Masolle at al. 2018 (https://doi.org/10.3390/geosciences8120482).

One new aspect of this manuscript is the qualitative evaluation of the different SBRS in accordance with Guidelines for Loss Prevention issued by German Insurers for Mobile Flood Protection Systems and the summary of the important advantages and disadvantages of different SBRS.

This discussion is certainly interesting and might also be needed at the level of municipal administrations.

From a scientific point of view, however, this manuscript adds only little what has not already been investigated and published by Masolle at al. 2018. Thus, this manuscript seems to be a summary of Masolle at al. 2018 as the stability, functionality and handling are already discussed and analyzed in this paper. The conclusions of this manuscript and the one of Masolle at al. 2018 are almost identical aswell.

Reply: Interactive comment “Reply to Referee #1 comment” dated 07 June 2019: Both articles – the published article Massolle et al. 2018 and the present manuscript Lankenau et al. – are based on the same testing series of sandbag and sandbag replacement systems (SBRS). Therefore, some repetitions are unavoidable for an understanding of the executed investigations like the description of the testing facility and the tested constructions (chapter 1. Introduction and chapter 2. Description of tests). Furthermore, both articles conclude that SBRS show clear benefits compared to conventional sandbag systems, but proper testing and certification is needed. Nevertheless, the research focus of the manuscript Lankenau et al. is different from that of Massolle et al. Whereas the latter is focussing on the assessment of testing results related to barrier heights, set-up times, and seepage rates of SBRS, the present manuscript offers a broader view on functionality, handling and overall applicability of the tested SBRS. In Lankenau et al. an evaluation scheme was elaborated based on the following aspects: area of application, stability, procurement and durability, installation, dismantling and maintenance as well as logistics. These aspects are highly relevant in the development of mitigation and adaptation strategies for flood defence. Not only seepage rates are important in the planning of operational flood protection, but also questions like system applicability in a specific application area with e.g. uneven ground or required storage space for SBRS have to be answered. These results are not only highly relevant for disaster control administrations but should also be included in the development of innovative and risk-adaptive civil protection strategies. Therefore, spreading of the research results not only on administration level but also among scientists would be appreciated.

Therefore, I think this manuscript could be beneficial as a summary for administrations. The scientific gain, however, seems too little to justify a publication in NHESS.

Reply: In order to increase the scientific gain the two papers NHESS-2019-164 “Sandbag Replacement Systems – Stability, Functionality and Handling” and NHESS-2019-165 “Sandbagging versus Sandbag Replacement Systems: Costs, Time, Helpers, Logistics” were merged. Furthermore, a revision of the document according to other Referees’ comments has been done. Leading e.g. to a more in detailed introduction of the topic of sandbag and sandbag replacement systems (SBRSs), including further aspects relating the costs of sandbagging and SBRSs, typical failure mechanisms of SBRSs and a revision of the conclusion.

Interactive comment on "Sandbag Replacement Systems – Stability, Functionality and Handling"

by L. Lankenau et al.

Anonymous Referee #2

The paper addresses a highly relevant topic: i.e. the use of alternative systems for temporary flood defence. The manuscript described a series of full scale tests. This work is relevant for a technical community, also for users (e.g. governments, consultants etc.). However, the technical and scientific novelty could be more clearly addressed (see also the comments by reviewer 1). Also, the presentation of the manuscript could be improved. I provide a number of suggestions below.

Approach:

- Chapter 1: It seems that the objectives are not explicitly stated in chapter 1. Page 3 presents a lot of past studies on temporary flood defences, but a clear statement of knowledge gap and objectives seems to be missing

  Reply: Chapter 1 has been restructured and additional information has been included in order to introduce the topic of sandbag and sandbag replacement systems in more detail as well as to include further relevant aspects relating the costs of sandbagging and sandbag replacement systems (SBRSs), which is necessary due to the merging of the two papers (NHESS-2019-164 and NHESS-2019-165). The statements relating knowledge gap/ objectives can especially be found on page 8 line 12 onwards.

- Chapter 2: I think the approach and added value could be more clearly introduced. What are typical failure modes of these systems, and which ones are you going to test? (see for a brief discussion of some failures modes also Lendering K.T., Jonkman S.N., Kok M. (2016) Effectiveness of emergency measures for flood prevention, Journal of Flood risk Management 9 (4) , 320-334.)

  Reply: Typical failure mechanisms of SBRSs have been included (Figure 7 – page 12). An explanation on investigated failure mechanisms has been added (page 12, line 5 onwards).

- I would suggest to include a sketch of the basin and the test layout

  Reply: A sketch of the basin and the test layout has been added (Figure 5 – page 9)

- I would suggest to include a table (perhaps in appendix) with some more information on the type and other properties of the systems shown in fig.2

  Reply: A table has been added (Table A1 – page 34)

- Chapter 3: I propose to clarify which aspects (ion table 1) are based on the tests, and which are based on "manufacturers specification or "authors considerations" (p7, line 9/10)

  Reply: Corresponding aspects have been clarified in the explanations/remarks of table 2 – page 21

- Table 2, formulations can be more clear, e.g. "uneven ground", do you mean whether the system "can be applied on uneven ground?" Also, for the aspect of height of retained water you give a score (+,-,0) based on the retaining height. Why not just mention the retaining height in the table. Some systems may be very reliable, but "just" designed for low heads.

  Reply: Formulations in table 3 have been made clearer. The "height of retained water" refers to available system heights, from which only one system variant could be tested. This has also been made clearer in table 3. In order to give an overview of reached water heads during the test setups a graph (Figure 10 – page 18) has been inserted.

- I would propose to include a discussion section, to outline limitations and next steps of testing, further development of these systems, certification and standardization of testing of SRS'.

  Reply: In general the proposal to include a discussion section is very welcome. However, the document has already reached a considerable length. Furthermore, some aspects as the limitations, next steps of testing and further development of these systems require further comprehensive explanations, which seem to be outside the scope of this paper. Whose intention is – together with the companion paper - to focus on the functionality, stability handling as well as costs of SBRSs and rather not to develop test routines. Nevertheless, a more detailed discussion has been added in the conclusions.

- Presentation: In general the use of English language could be improved, review by a native speaker would be beneficial, see detailed suggestions below.

  Reply: The manuscript has already been initially proofread by a professional translator – a native speaker. Nevertheless, we have tried in the revision to improve possible questionable formulations.

- The abstract can be improved, it could be more specific on the methods & tests, and findings & results and added value of the proposed approach

  Reply: The abstract has been revised.

- Some parts can be shortened e.g. descriptions on p5/6

  Reply: The authors agree that some descriptions in section 2.2 (Test results) are quite detailed. However, from the authors' point of view shortening the descriptions would lead to a loss of relevant information. Since a variety of different systems has been tested, a fairly detailed description is essential from the authors' point of view.

- Fig 3 is not clear in black and white

  Reply: The Figure (Figure 8) has been sharpened.

- Examples of sentences which could be improved: âA˘ c´ First sentence in abstract âA˘ c´ Line 21 / 22 ("their geometry in connection with. . .. . ." is not clear to me) âA˘ c´ Etc.

  Reply: The sentences have been revised.

Please note: All labelling (Figures, tables), pages and lines in the replies refer to the revised manuscript in the track change mode.

Interactive comment on “Sandbagging versus Sandbag Replacement Systems: Costs, Time, Helpers, Logistics” by L. Lankenau and B. Koppe

Anonymous Referee #1

The manuscript compares the use of sandbags with alternative flood protection systems, the so-called Sandbag Replacement Systems (SBRS), in terms of costs, helpers and logistics for installation and dismantling. Three different cases are considered: temporary flood dam, load drain in the case of a saturated dyke over an extensive area and ring dike for reinforcement against heavy punctual exit of seepage on the inner embankment of the dyke. The manuscript is well written and structured and addresses, despite a lot of simplifications, an interesting and rarely explored topic in the literature, that is the assessment of alternative protection systems in case of a inundation event, which can be more efficient and convenient than the traditional sandbags.

- Although this, the paper does not address the topic of the efficiency of these methods and it is limited to cite the other manuscript of the same authors (and, for example, not in the introduction, where it is fundamental in order to understand why the authors write about this topic), in which the topic is discussed. It is not clear, in the current version of the manuscript, why it is so important to focus on the SBRS and the reason why a comparison in terms of costs, helpers and logistic is necessary.

  Reply: The introduction has been restructured and additional information has been included in order to introduce the topic of sandbag and sandbag replacement systems in more detail as well as to include further relevant aspects relating the costs of sandbagging and sandbag replacement systems (SBRSs).

- The authors in this manuscript compared three different type of SBRS, but it is not clear why they take these methods among all the available ones (the reason is maybe that they have better performances, but it can only understood by reading the other manuscript).

  Reply: The SBRS to be chosen should cover a wide range of different SBRS types. Furthermore, the systems were indeed chosen, because they showed a good overall performance in the field test. An explanation was added in the manuscript – page 25, line 12.

- In addition, the SBRS are very shortly described, taking for granted that their characteristics are clear and well known (but it is not always obvious).

  Reply: A more detailed description of the functionality of SBRSs has been included in the Introduction (page 2, lines 5 et seqq.), as well as by including the description of the field tests and the results (Section 2).

- In my opinion, the manuscript needs to be re-structured considering also a part about the "hydraulic" efficiency of the SBRS, because, in the current version, it is not enough interesting to be published in NHESS, but can be important more for municipal administrations. The manuscript would earn a lot in terms of quality with the consideration of the "hydraulic tests" of the other manuscript. I suggest to the authors to consider the idea of unifying the two manuscripts, which seem to be a bit poor if considered singularly.

  Reply: The proposal to merge the two companion papers into one, is very welcome. The papers have been merged.

- In case authors consider to review the manuscript in this direction, I would also suggest to better justify some values, for example the costs of trucks and fuel (it is not clear to me which is the considered distance to cover, the sandbag requirement (Table 1: why Acqua defence and Aquariva need sand?) and the price used for sand (it is written, during the event it rises sharply: which price is considered in the manuscript? during the event? an average value? etc.) I would also better explain what the terms in the tables mean, for example "time materials", "time logistics", etc. (Table 3, e.g.)

  Reply:
  - Costs of trucks and fuel: Explanation added – page 24, line 14 et seqq.
  - Sand requirements: To weight done the upstream skirt. Becomes clear through integrating the part about the hydraulic tests – see section 2.
  - Price for sand: A Price increase during the event is considered
  - Explanation of terms in the tables: Explanation added– page 29, line 27 et seqq.

- In Sec. 3.2, it is not clear to me why SBRS don't require additional helpers in case of poor acces to the site, as it happens for sandbags.

  Reply: SBRSs do not need additional helpers in case of poor accessibility, because due to their relatively low weight they can be put in place with much more easy means in the required amount, e.g. by the use of special vehicles which can access even wet ground but which cannot carry a lot of weight. Explanation added – page 30, lines 15-17.

- In the conclusions, I could not find anything about the higher costs of SBRS, although I think it is a relevant result of the analysis.

  Reply: A corresponding conclusion was added, page 32 – lines 23 et seqq.

- I think some considerations on the long terms is also needed, in order to say that the higher costs of SBRS are amortized because they can be reused.

  Reply: See page 25 lines 28-34 and page 26, lines 12-13.

- I was also curious to know if there are studies on the case in which these protection systems turn out to be undersized and are, for example, overtopped: can they be reused? How is the amortization reduced?

  Reply: When SBRSs are undersized but can be overtopped they should usually be reusable, therefore the amortisation is not influenced. If an undersized SBRS cannot be overtopped, a failure of the system with resulting costs must be expected. Which of the tested SBRSs could be overtopped, can be seen in Figure 10, page 18.

- Finally, I found a couple of other papers which addressed the comparison of the performance of different flood protection systems, and which the authors can consider as additional material: Wibowo & Ward, 2016 "Evaluation of temporary flood-fighting structures" and Rappazzo & Aronica, 2016 "Effectiveness and applicability of flood barriers for risk mitigation in flash-flood prone Mediterranean area".

  Reply: The Authors are grateful for the additional material mentioned by the Referee. The paper by Wibowo & Ward (2016) is based on the tests published by Pinkard et al. (2007), which is cited in the manuscript. Rappazzo & Aronica (2016) focus mainly on pre-installed SBRS, which are outside the scope of the investigations. However a recent publication by Popp et al. (2019) was considered in the revised document.

Please note: All labelling (Figures, tables), pages and lines in the replies refer to the revised manuscript in the track change mode.

Interactive comment on "Sandbagging versus Sandbag Replacement Systems: Costs, Time, Helpers, Logistics" by L. Lankenau and B. Koppe

Anonymous Referee #2:

The article describes Sandbag Replacement Systems (SBRS) in relation to sandbags during emergency management of floods and is interesting to read. It contains research results in terms of costs, helpers and logistics. I recommend a review (major revisions) and a focus on the following aspects:

- The article is very much orientated to the situation in Germany. Existing literature comparing different flood protection systems is not used in a sufficient way. Especially the experience of the emergency management during the recent flood disasters in Europe should be considered. In addition to that, a proper explanation (e. g. figure 1) and a translation of the German terms are necessary.

  Reply:
  - A more detailed description of the experiences during the Elbe flood 2013 (see page 5, lines 9 et seqq.) and the testing scheme at the TuTech Centre for Climate Impact Research – KLIFF – at the TU Hamburg has been included (see page 8, line 4 et seqq.)
  - A more detailed description of SBRSs has been included in the introduction, page 2, line 6 et seqq., page 4, line 11 et seqq.. Furthermore, the description of hydraulic tests of SBRSs was included (section 2), which also introduces the functionality of the SBRSs in more detail.
  - The German terms have been translated (see figure 3, page 4 and figure 5, page 11)

- It is not quite clear which applications of SBRS and sandbags are considered. In chapter 2, "extreme flood events" are mentioned for the technical assistance of THW. But is SBRS really a tool for "extreme events"?

  Reply: Sandbags as well as SBRS are used in emergency flood control – especially in case permanent flood protection systems like dikes are failing or in case no permanent flood protections schemes are available because the currently endangered area was thought not to be at risk. Thus, sandbags as well as SBRS are certainly used in extreme flood events. Explanation added – page 2, line 11 et seqq.

- The authors compare SBRS with the use of sandbags but do not describe the hydraulics. In my opinion, without a substantial description of the hydraulic situation this is difficult to understand. In Figure 1, "temporary flood protection dams" are visualized. But there is no explanation, if all the four SBRS are equal to each other and what their behaviour will be as a response to different hydraulic conditions.

  Reply: A more in detailed description of the hydraulics has been added in the introduction – page 2, lines 5-16. Furthermore a section about the large-scale tests has been inserted, which also introduces a more detailed investigation of the hydraulic conditions– section 2. Furthermore, typical failure mechanisms of SBRSs have been included (Figure 7 – page 12). An explanation on investigated failure mechanisms has been added (page 12, line 5 onwards).

- The overall description of SBRS should take into consideration relevant technical aspects. In chapter 2, some statements are made, e. g. relating “mechanical influences” or “vandalism” without a detailed discussion.

  Reply: A corresponding discussion was inserted in the introduction – page 4, lines 7 – 10, as well as in the conclusion, page 31, line 13 et seqq.

- Chapter 3 mainly focuses on costs. It is somehow confusing to understand the exact definition for example of “helpers”. Some other terms are used in the article: “employee”, “THW-helper” etc. Is this all the same? Is it used as a synonym? Are the costs always the same, no matter if a helper has a special expertise and training (like the “THW helper”)? And is 5 EURO per helper and day (chapter 3.2) really a serious value?

  Reply:
  - Within the authors investigations the terms helpers and THW-helpers are synonyms - the document has been checked for consistency. In the passage about the reviewed literature the term helper is a general term for the person installing and dismantling the systems. The term employee is mentioned in relation to the publication by Ogunyoye et al. 2011, who considered helpers which are employed on a regular basis, this has been made clearer – see page 7, line 17.
  - It is recommended that SBRSs are only set up by trained personnel. During a flood, the German Federal Armed Forces and other relief organisations such as fire brigades and the police can be deployed in addition to THW. Depending on the organisation, the individual costs may vary: this, however, has not been taken into consideration for the present cost estimate (page 24, line 11 et seqq.)
  - The cost estimation of 5 Euro per helper and day is only related to the costs for upper control like disaster control management, technical incident command and platoon, but not for the helper itself. These are realistic overhead costs related to the number of helpers in action. The statement was made clearer – page 29, line 22.

- Some of the mentioned costs (table 1 and 2) need clarification: What does “cost of materials” or “cost of trucks” mean? In the text, it is expressed that there are “comparatively low costs for the use of THW vehicles”. But is this for Germany only?! Then it should be clarified that all the statements are based on figures and numbers of the German disaster relief system.

  Reply:
  - It has been stated that all the statements are based on figures and numbers of the German disaster relief system – page 24, line 4 and 19, as well as page 32, line 24.
  - Costs of Material: sand, sandbags respectively acquisition cost for SBRSs, including component parts – page 23, line 23.
  - Cost of trucks: hiring the truck, fuel, driver, repair – page 23, line 23

- Table 3: For SBRS systems “2,5 helpers including lower command” are needed? What does that mean?

  Reply: In case of SBRSs group leaders can take care of two different areas of application – therefore only half a helper is counted for the lower command per 100 m for the installation of a SBRS. The other two helpers are installing the SBRS, resulting in 2.5 persons per SBRS. Page 25 – lines 7-9.

- The conclusion is not based on the research results. A number of “political statements” are mentioned, e. g. “In particular it is necessary to provide financial support to the municipal authorities responsible for the purchase of the system”. No arguments for this statement are mentioned or discussed throughout the article. Overall, I find the conclusion more relevant for stakeholders or municipalities but with little scientific value.

Reply: The conclusion has been revised and cleared from political statements.

- I recommend to review the English language and strongly emphasise a correct use of technical terms, e. g. emergency or disaster management.

  Reply: The English language has been reviewed.

Please note: All labelling (Figures, tables), pages and lines in the replies refer to the revised manuscript in the track change mode.

~~Sandbag Replacement Systems~~Sandbag Replacement Systems - ~~Stability, Functionality and Handling-~~ a nonsensical and costly alternative to sandbagging?

Kommentiert [ll1]: Abstract as well as sections 1 and 2 originate from the manuscript nhess-2019-164 - Sandbag Replacement Systems - Stability, Functionality and Handling. Track changes relate to changes made in that document.

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Abstract. In addition to the flood defence with sandbags, different sandbag replacement systems (SBRSs) have been available for a number of years for use in operational flood protection. ~~The classic aid in operative flood defence is the sandbag. Over the past few decades, though, so-called sandbag replacement systems (SBRSs) have also been available for flood fighting.~~ The use of sandbags is time-consuming as well as highly intensive in terms of materials and personnel. In contrast, the use of SBRSs entails higher investment costs. However, SBRSs are reusable and require lower costs for helpers and logistics, so that the higher investment costs are offset by repeated use. ~~Although the use of sandbags is time-consuming as well as highly intensive in terms of materials and personnel, s~~So far, SBRSs are rarely used in Germany in operational flood protection. The reasons lie on the one hand in the different financing modalities of investment and operational costs and on the other hand in the low technical confidence in SBRSs. ~~However, owing to their functionality and their labour and time-saving characteristics, they can make an essential contribution to flood protection – and this all the more so in view of the expected consequences of climate change.~~ These problems are addressed by the research program~~In order to foster confidence in such systems,~~ of the Institute of Hydraulic Engineering at the Hochschule Bremen - City University of Applied Sciences (IWA). A ~~carried out a~~ series of systematic large-scale tests of sandbag systems and SBRSs ~~that focused~~with focus on ~~the~~ functionality, stability and handling ~~of the systems~~ was carried out. It showed that the majority of SBRSs are able to provide comparable protection as sandbag systems with a significantly reduced use of materials, logistics and helpers. Nevertheless, it is advisable to develop and perform well-defined certification tests for SBRSs, to define clear instructions for the use and to identify limits to the use of certain SBRSs. For example, not all systems work equally well on different surfaces.

In addition to the practical tests, costs for the procurement and use of various sandbag systems and SBRSs were determined on the basis of realistic scenarios. This will provide a methodology as well as concrete figures for the holistic costing for provision and use of different protection systems. It turned out that the higher investment costs for SBRSs compared to sandbag systems are already amortized on the second use of the reusable systems.

~~**The experience gained shows that SBRSs have the potential to make flood defence more efficient than the use of sandbags alone. Since SBRSs are technical systems whose functional capability must be proven before they can be used, it is recommended to introduce a official test and certification procedure.**~~

1 Introduction

The classic aid in operative flood defence is the sandbag. So-called sandbag replacement systems (SBRSs) have also been available for some time now, although their use is still very limited. Figure 1 shows such mobile, location-independent flood defence systems: they can be subdivided into tube, basin, flap, trestle, dam or panel systems and bulk elements. The systems protect againstcounteract -flooding either by their bulk weight, which is induced by- (water, sand, respectively, concrete) (container and bulk systems) or their geometry in connection with the vertical hydrostatic water pressure (flap, trestle, dam and air-filled tube systems – not shown in Figure 1), which either way results in frictional forces on the ground. Though, panel systems consist of panels which are hold in place by sticks driven in the ground on alternate sides. But commonly, location-independent mobile flood protection systems do not need additional anchoring to the ground. However, some producers offer such a possibility, which introduces a safety surplus or can be necessary when high flow velocities or wind stress on the not jet impounded system are expected. -Sandbags as well as SBRSs are used in flood disaster management – especially in case permanent flood protection systems like dykes are failing or in case no permanent flood protection schemes are available because the currently endangered area was thought not to be at risk. Thus, sandbags as well as SBRS are used in extreme flood events. There is no obligation to demonstrate the functionality of an SBRS so far. In general, however, SBRSs are suitable for flood protection and can be equated with sandbagging in terms of functionality. Although, depending on construction, geometry and filling of the individual system their safety against failure might differ.

Typical failure mechanisms of SBRSs are shown in Figure 7.Sandbagging is time-consuming as well as highly intensive in respect of materials and personnel. However, the advantage of using sandbags lies in the possibilities for flexible deployment and many years of practical experience. So far, SBRS are rarely used in Germany. During the Elbe flood in 2013, for example, mobile SBRS were only used sporadically (cf. AQUARIWA, 2019; Mobildeich, 2019), and this despite the fact that they hold the potential for a much more efficient flood defence, as their use entails significantly lower material, personnel and time requirements than conventional sandbagging. The main disadvantage of SBRS is the higher cost of acquisition. However, in contrast to sandbags, SBRS are reusable, do not have to be disposed of at high cost after a flood event and can be set up and dismantled with considerably less manpower, and the higher acquisition costs can be amortized over subsequent operations.

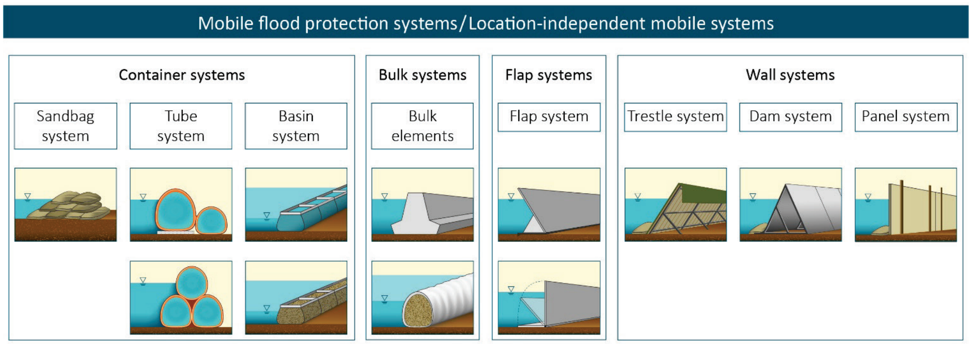

Figure 1: Classification of mobile, non-location dependent flood protection systems (Massolle et al., 2018).

Sandbagging is time-consuming as well as highly intensive in respect of materials and personnel. SBRSs in contrary, hold the potential for a much more efficient flood defence, as their use entails significantly lower material, personnel and time requirements than conventional sandbagging. For example, 16 500 sandbags and 250 t of sand are required to build up a 100 m long and 1.0 m high sandbag dam (cf. THW, 2017). 60 helpers would need about 10 hours (cf. THW, 2017) only to fill the sandbags and set up the dam and yet the efforts for e.g. logistics of materials and supply of helpers are not considered. However, the advantage of using sandbags lies in the possibilities for flexible deployment and many years of practical experience. Figure 2 shows firemen raising a dyke by setting up a temporary sandbag dam.

Figure 2: Firemen during the Elbe flood in 2013. Setting up a sandbag dam to raise a dyke.

SBRSs either do not need a filling at all or the filling respectively the systems are put in place with technical assistance such as pumps (water filling), wheel loaders (sand filling) or cranes (bulk elements made of concrete). Thus, the systems can be set up and dismantled with considerably less time and manpower (cf. Massolle et al. 2018). Logistical efforts are minimized if no filling is needed or water, which can usually be obtained locally, is used. In contrast to sandbags, SBRSs are reusable and do not have to be disposed of at high cost after a flood event. Therefore, SBRSs can also be suitable for scheduled flood protection measures in areas where no permanent flood protection schemes can be applied. The main disadvantage of SBRSs is the higher cost of acquisition. However, the lower expenditure on helpers, logistics and disposal of material means that these higher investment costs can be offset through a reuse. Furthermore, there is limited confidence and a lack of knowledge in the functionality of SBRSs. Besides the confidence in the general functionality of a SBRS, fear of vandalism or mechanical influences e.g. impacts of flotsam or vehicles as well as the collective failure (domino effect) of a SBRS are of great concerns. According to own estimates, the functionality of sandbag dams can also be endangered by vandalism or mechanical influences but rather less by a collective failure, unless the sandbag dam is heavily overflowed over long distances.

Temporary flood dams made out of sandbags or linear SBRSs are set up in order to protect the hinterland from inundation. Beyond that sandbags are also used at the inner embankment securing saturated dykes either on selective points where there is considerable seepage (temporary ring dam) or over a larger area (load drain). Flutschutz offers corresponding SBRSs (Figure 3). For an explanation of the hydraulic situation at saturated dykes during a flood event see e.g. Simm et al. (2013). Sandbag dams and linear SBRSs are directly exposed to flooding. In contrary temporary ring dams and load drains are generally exposed to lower loads as they are not subjected to the direct influence of high hydrostatic pressures or the dynamic impact caused by waves and flotsam. They are therefore less endangered in their functionality.

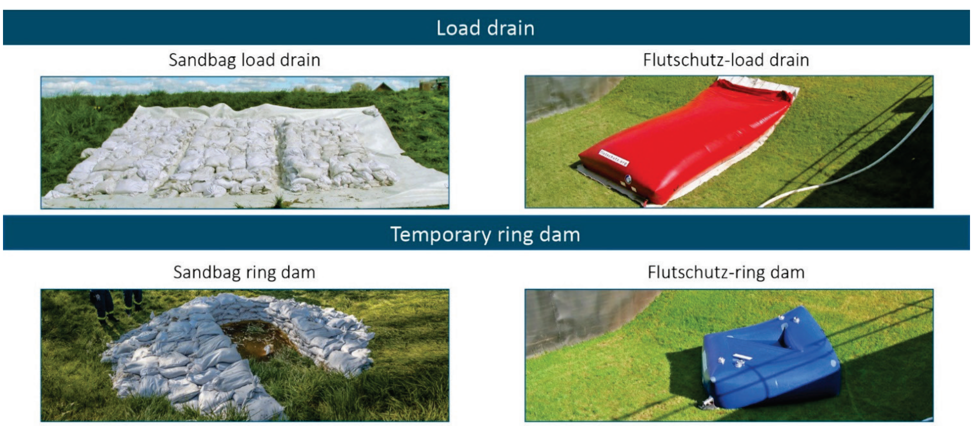

Figure 3: Dyke defence measures for a saturated dyke over an extensive are (load drain) and for heavy punctual exit of seepage (temporary ring dam). Sandbagging (left) and corresponding SBRSs (right).

In Germany, operational flood defence is regulated as part of hazard prevention or disaster control at the federal state level. Direct responsibility lies at the municipal level and thus with the local districts and cities. This includes the responsibility to provide the necessary material for the protection of the general public, whereby as a rule sandbags — which are the significantly cheaper option — are favoured vis-à-vispreferred over SBRSs with their higher investment costs. In case of a disaster event, assistance can be requested from the federal state or the federal government, whereby the financing of such assistance will still remain initially with the affected administrative districts or cities. Ultimately, the costs of major damage events, such as caused by the Elbe floods of 2002, 2006 and 2013, will be borne predominantly by the federal state and the federal government. Once such an event occurs, however, no time can be lost in procuring SBRSs, if they are not already standing by. Thus, the cost of procuring and stocking SBRSs—in addition to a lack of confidence or knowledge about their functionality—presents a major hurdle to their use.

Therefore, in Germany during the Elbe flood in 2013, SBRSs were only used in isolated cases (cf. AQUARIWA, 2019; Mobildeich, 2019), despite the fact that the use of sandbagging for operational flood defence is very time, materials and labour intensive. Figure 4 shows two SBRSs after the Elbe flood in 2013. The two systems were successfully used to prevent the hinterland from flooding (Niedersaechsischer Landtag, 2014). However, some challenges due to vehicle impact and falling-prone trees did occur.

(a) (b)

Figure 4: SBRSs near Gartow (Lower Saxony, Germany) after the Elbe flood in 2013. (a) AQUARIWA, (b) Quick Damm type E.

In order to increase the confidence of decision-makers in SBRSs and to promote the availability of only well-functioning SBRSs, ~~and to promote their use in operational flood defence,~~ it is desirable to carry out systematic tests on functioning, stability and handling and to develop relevant certification procedures~~regarding their suitability for practical use and to develop a procedure for certifying such systems~~. In addition to the functionality of SBRSs their costs and efficiency compared to sandbagging should be investigated to likewise support decision-makers.

At the international level, corresponding certification already exists. It can be awarded by the globally active testing and certification service FM Approvals (FM Approvals 2019), based on the American National Standard for Flood Abatement Equipment (ANSI and FM Approvals, 2014), and the British Standard Institution (BSI, 2019a), which is based on the Publicly Available Specification (PAS) for flood protection products—Specifications Part 2: Temporary Products (BSI, 2014). Specific SBRSs ~~Individual systems~~ certified by FM Approvals can be found under NFBTCP (2019) and SBRSs certified by BSI Kitemark can be found under BSI (2019b) ~~and systems certified by FM Approvals under NFBTCP (2019).~~ In Germany, no corresponding certification or testing system for SBRSs is currently available. However, there is some information can be foundavailable on the design and the scheduled as well as unscheduled use of SBRSs in German-speaking countries, especially: this is currently contained in the recommendations of the leaflet 'Mobile Flood DDefence Systems' issued by the German Association of Engineers for Water Management, Waste Management and Cultural Construction. (BWK, 2005), in the handbook 'Mobile Flood Protection' of the Austrian Water and Waste Management Association (ÖWAV, 2013) and in the decision-making aid 'Mobile Flood Protection' of the Swiss Association of Cantonal Fire Insurers (VKF) as well as the Swiss Federal Office for Water and Geology (BWG) (Egli, 2004).

SBRS can make an essential contribution to operational flood defence owing to their functionality and time-saving characteristics as well as lower requirements for materials and personnel, and this even more so in view of the expected consequences of climate change. It was therefore decided to carry out systematic testing of SBRS in the test facility of the Institute of Hydraulic Engineering at Bremen University of Applied Sciences (IWA). The focus of the test setups was on functionality and stability as well as handling of the systems. First results of the test setups with regard to installation times, water heads and seepage rates have already been published (Massolle et al., 2018). This article summarises the experience gained from the test setups with regard to functionality, stability and handling of the systems in accordance with the guidelines for loss prevention of the German insurers for mobile flood defence systems (VdS, 2014), which are in turn based on the recommendations of the BWK (BWK, 2005), the VKF and the BWG (Egli, 2004). The system assessments obtained in this way serve to provide a practical assessment of the operational capability of SBRS.

Comparable system assessmentsThere are relatively few publications on comparative studies of sandbagging and SBRSs. Within the scope of test setups in the test basin of the U.S. Army Corps of Engineers (USACE), one sandbag dam as well as two sand-filled container systems and one trestle system were investigated (Pinkard et al., 2007). In addition to the time spent on system installation and dismantling, the operational costs for a system set-up with a length of around 305 m and a height of around 0.91 m were also estimated. However, logistical aspects were not taken into account, and it was assumed that labour on the construction of the sandbag dam would be on a free and voluntary basis. In addition, the sandbag requirement estimated in the study differs from the usual approaches in Germany, as the sandbag dam in the U.S. is constructed on a broader basis.

Investigations of the functionality of SBRSs were also carried out by the UK Environment Agency (EA) on the basis of three sources of information; namely, the literature, user workshops with users of systems and interviews with manufacturers and distributors of products. It was found that most of the systems provided adequate protection, but that in some cases operational processes or inaccurate hydraulic assessments led to system failure. The assessments covered the physical, operational and structural characteristics of temporary flood products available on the UK market in 2009. The systems were subdivided into tubular systems, containers, freestanding barriers and frame barriers. Four of the tested systems (NOAQ Tubewall (Öko-Tec Schlauchwall), Tiger Dam, NOAQ Boxwall, Geodesign (Aqua Barrier)) overlap with the systems shown here. The NOAQ Tubewall is comparable with the Öko-Tec Tubewall and Geodesign as a pallet variant with Aqua Barrier. The report furthermore highlights the relevance of life cycle costs when using SBRSs. In addition to the acquisition costs, these include costs for maintenance and repair of the systems, costs for employees – in the investigation the helpers were permanently employed – and their training as well as for the performance of field exercises and costs for storage and transport of the systems. The benefit of an SBRS, on the other hand, also results from the costs of damage that can be prevented during its service life, whereby a properly functioning system is assumed. An exemplary calculation of the life cycle costs of an SBRS is not carried out in the report. Only the acquisition costs of SBRSs, partly including the training of helpers (employees) by the manufacturers, for a 100 m long system with a protection height of about 1.0 m in the four categories examined — tubes, containers, freestanding barriers and frame barriers — are mentioned. (Ogunyoye et al., 2011)

In the frame of a Canadian study, in which the authors assessed the suitability of innovative systems as an alternative to sandbags primarily on the basis of the literature, commercial brochures, theoretical considerations and stability calculations, four different system types were examined. Among the types studied were water- or air-filled tube systems, gabion-like systems filled with sand or soil, dam beams and motorway crash barrierswater-filled systems, inflatable tubular systems, gabion-like systems filled with sand or earth, dam beams and highway barriers. Three of the water-filled systems or inflatable tubular systems are comparable with systems examined in the present study (Aqua Barrier with Hydrobaffle, Clement with Tiger Dam, NOAQ Tubewall with Öko-Tec Schlauchwall); the other system types were not tested. Besides the assessment of the suitability of the systems, the factors to be considered for the cost calculation of SBRS are named, but no comparative calculations are carried out. The stated costs refer to manufacturer's prices for a system with a protection length of 30 m and a protection height of about 1.0 m. The additional financial resources to be considered include costs for storage, assembly and dismantling of the systems as well as training the helpers. Moreover, the durability of the systems must also be taken into account, as a long service life has a positive effect on the number of times a system can be reused. (Biggar and Masala, 1998)

In a study conducted by the University of Kentucky (Mc Cormack et al., 2018), the possible uses of sand-filled temporary flood defence barriers to protect roads from flooding were analysed on the basis of existing operational experience. However, the systems considered are not comparable with those covered in the present study.

In Germany SBRSs have been tested according to the ANSI/ FM Approval guidelines at the TuTech Centre for Climate Impact Research – KLIFF – at the TU Hamburg on a concrete ground (Gabalda et al. 2013). The tests were mainly done on behalf of the manufactures, who have published the information only sporadically (cf. Massolle et al., 2018). Recently Popp et al. (2019) theoretically investigated the use of SBRSs to temporarily increase the height of a dyke and related costs in comparison to sandbagging. Their investigations do not relate to individual SBRs but rather different system types (tube, basin, trestle). However, it is not clear what was included in the cost calculation. Popp et al. conclude that for temporarily raising the dyke height in case of a flood event, it is expected that SBRSs will be used more frequently due to their time-, material- and personnel saving characteristics.

None of the examples mentioned in the literature examined the functionality or costs of temporary ring dams or load drains.

SBRSs can make an essential contribution to operational flood defence owing to their functionality and time-saving characteristics as well as lower requirements for materials and personnel, and this even more so in view of the expected consequences of climate change. Only little information is available on independent, practical tests of SBRSs, for some SBRSs no practical or independent tests are available at all, and a comparing study of the overall costs of sandbagging and SBRSs is totally missing. Both factors - functionality and economic viability - are relevant to assess the suitability of using SBRSs, which introduce great potential to make operational flood defence measures especially for disaster management much more efficient in terms of time, personnel and material. It was therefore decided to carry out systematic testing of SBRSs in the test facility of the Institute of Hydraulic Engineering at Bremen University of Applied Sciences (IWA), Germany to increase the available information on the functionality of SBRSs. The focus of the test setups was on functionality and stability as well as handling of the systems. First results of the test setups with regard to installation times, water heads and seepage rates have been published in Massolle et al. (2018). The present article summarises the experience gained from the test setups with regard to functionality, stability and handling of the systems in accordance with the guidelines for loss prevention of the German insurers for mobile flood defence systems (VdS, 2014), which are in turn based on the recommendations of the BWK (BWK, 2005), the VKF and the BWG (Egli, 2004). The system assessments obtained in this way serve to provide a practical assessment of the operational capability of SBRSs. Furthermore, the present article compares sandbagging and SBRSs in fictitious realistic scenarios in order to enable a comparison of the costs surrounding system deployment as well as the time involved and the amount of helpers. The comparison serves to further clarify the practical suitability of SBRSs and, in addition to the acquisition costs, takes into account the costs respectively efforts of installing and dismantling the systems as well as logistics. In addition to the temporary flood protection dam, appropriate dyke defence measures for operational flood defence (load drain, ring dam) are also considered. The calculated operational costs always depend on the underlying system model or dimensions of the sandbag system and other factors taken into account in the cost calculation - this necessarily calls for a certain degree of simplification. This aspect results in deviations in the findings of the above-mentioned studies by Pinkard et al. (2007) and Ogunyoye et al. (2011) and the present study.

~~For an overview of the SBRS tests performed, the reader can refer to Massolle et al. (2018). Individual systems certified by BSI Kitemark can be found under BSI (2019b) and systems certified by FM Approvals under NFBTCP (2019).~~

2 Functionality, stability and handling of SBRSs~~Description of tests~~

2.1 Description of the test

The tests were carried out in the IWA test facility, which was set up on the premises of the THW Training Centre Hoya as part of the research and development project DeichSCHUTZ (2014-2017) for the development of systems to reduce buoyancy in dykes at risk of failure, funded by the German Federal Ministry of Education and Research ~~(Massolle et al., 2018)~~. The facility consists of a U-shaped basin, the 15 m wide opening of which is closed by a dam (cf. Massolle et al., 2018). For the SBRS tests, various systems were set up across the entire width of the basin parallel to the dam line and the space between the dam and the system was then filled with water (Figure 5~~Figure 5~~). This allows a realistic simulation of the hydrostatic load on the systems. Other possible load parameters such as current, waves, wind, flotsam and vessel impact cannot be investigated in the IWA test facility.

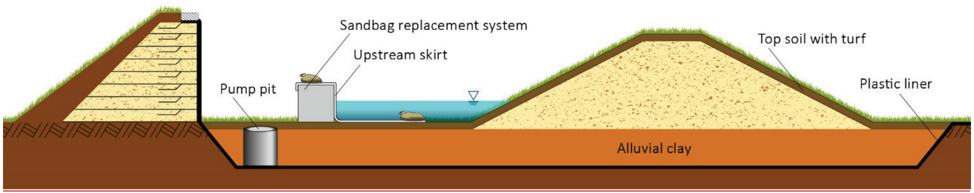

Figure 5: Draft of the test setup in the test facility. Shown is a SBRS with upstream skirt.

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Figure 6 gives an overview of the tested SBRSs. At least one of the container types and wall systems shown in Figure 1 was selected for each of the test setups. Flap systems could not be tested because no manufacturer could be found who was prepared to make a suitable system available. Bulk elements and panel systems were not considered. This is because in operational practice the use of bulk elements requires technical aids being available at short notice to install the elements, which is often impractical for logistical reasons or for reasons of the load-bearing capacity of the foundation soil being impaired during flooding. The use of panel systems is limited to suitable soils and low water levels. Bulk elements and panel systems were therefore not taken into account in the test setups owing to their necessity for framework conditions such as accessibility with heavy equipment and the avoidance of damage to test setups from deep ramming of retaining stakes. Additionally to the linear SBRSs, Flutschutz-load drain and Flutschutz-ring dam have been set up at the embankment of the dyke in the test facility (see Figure 3). The systems were set up on the dry and therefore stable dyke, which does not fully correspond to the reality.

In cases where the suppliers offered more than one system size, a variant suitable for a water head of 0.6 m was selected for our test setups. This height corresponds to the recommendations contained in the leaflet 'Mobile Flood Protection Systems' (BWK, 2005) for the unscheduled use of SBRS in operational flood fighting. The recommendation results~~, on the one hand,~~ from the increasing danger of foundation-surface failure with increasing water levels~~ as well as from not being able to dimension the systems in advance to cope with the loads occurring at an unknown location~~. Not exceeding the specified maximum water level minimises the risk of damage. If larger system heights are required, the risk must be weighed on a case-by-case basis. Even if the conditions to be expected could be examined on site by a competent person, if possible prior to the use of an SBRS, the time and information required for this is usually not available. Since some systems are not specifically designed for water heads of 0.6 m, over dimensioned systems such as AQUARIWA, aqua defence, Hydrobaffle and Tiger Dam were used.

Figure 6: The various SBRSs tested, (T) Tube system, (B) Basin system, (D) Dam system, (TR) Trestle system.

The SBRSs tested are only a selection of the systems available on the market. In addition, one of the systems investigated, the Quick Damm Type M, is no longer produced, but still in use. Market analysis showed that some system types, such as basin systems and tube systems, are more frequently present on the market than others. However, the number of products of a system type does not allow conclusions to be drawn about its functionality.

Tube systems and basin systems are usually filled with water to ensure their stability. Not many tube systems or basin systems can be filled with sand. Sand fillings were not considered during the test setups as the requirements for filling and dismantling could not be met in the test facility. Therefore only tube and basin systems filled with water were tested. The Öko-Tec Tubewall is an exception. With this system, the tube is inflated with air. The system is stabilised by a plastic sheet called 'skirt' spread out on the water side of the system, which is friction-locked to the tube. The tube is stabilised solely by the vertical hydrostatic pressure acting on the horizontally laid skirt. No other of the tested systems using an upstream skirt are connected to the system in such a friction-locking manner. A not friction-locked skirt is mostly used to improve the leak-tightness of an SBRS, which on the other hand also reduces buoyance forces under the SBRS. An upstream skirt must always be weighted down at the water-side edge, often with sandbags. The trestle and dam systems do not require filling. Typical failure mechanisms of SBRSs are shown in Figure 7. During the test setups the systems were impounded with water. Water heights were increased successive until the system failure occurred due to sliding/ rolling or tipping - stability failure did not occur in any of the systems tested. If no system failure occurred, the systems were not only completely impounded but overflowed. Occurred seepage rates - the sum of seepage through the subsoil and leakage through the system - were measured and the results have been published in Massolle et al. (2018). A SBRS should not only be functional but should also be practical in terms of handling during setup and dismantling as well as necessary space during operation and for storage, reusability and protection against vandalism just to name a few. Altogether, statements about the reliability as well as the practicability and handling of the tested systems could be derived from the test setups and related investigations.

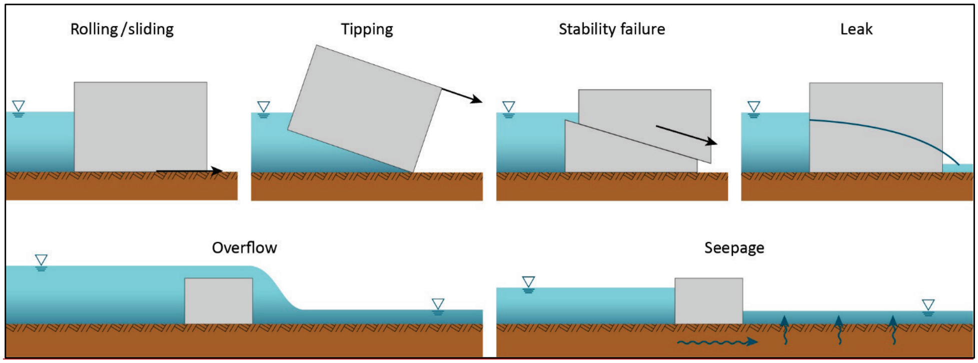

Figure 7: Typical failure mechanisms of SBRSs (BWK, 2005, modified).

The systems were initially dammed up to a water height of 0.6 m, in accordance with the recommendations of the BWK leaflet 'Mobile flood protection systems' (BWK, 2005). After setting a constant seepage rate at a dam height of 0.6 m (cf. Massolle et al. 2018), the water head was further increased in stages until a system failure occurred due to the water ~~volume~~ height exceeding the load limits of the system or a partial overflow of the system occurred. For an overview of the system heights and the impounded water levels achieved see Massolle et al. (2018). The Quick Damm Type M and Aqua Barrier systems were not available in sufficient length and were therefore installed in combination with the AQUARIWA system. The test basin was only briefly filled with water up to a height of 0.6 m. The NOAQ Boxwall system only has a feasible protection height of 0.5 m, but was nevertheless tested because of its simplicity and speed of installation. In principle, the manufacturer recommends the use of the NOAQ Boxwall System on paved surfaces, as this results in a better sealing effect on the underlying surface. According to the manufacturer's training ~~video~~material, the Tiger Dam system can be used with and without anchoring to the ground or additional plastic skirts on the water side, but is only FM-approvals certified if the skirt and the anchoring system are in place (NFBTCP, 2019). Both variants were investigated. The tightening belts pulled around the tubes were fastened in the area of every second wedge with a rope affixed by stakes on the land side and water side. Finally, a plastic skirt was spread in front of the system on the water side, which reached up to the apex of the upper tube.

Full impoundment of the tested systems and water overflow cannot be realized over the entire length of the SBRS due to unevenness of the basin floor and limited pumping capacity in the IWA test facility. This restriction is particularly relevant in case of occurrence of an overflow load, as the unevenness meant that only a slight overflow height could be achieved in the right-hand area of the test facility (Figure 8).

Figure 8: Overflowing SBRS (aqua defence)

If overflow occurs when using SBRSs, it must be prevented from washing away the soil on the landside, otherwise system failure can occur. The overflowing water must ~~therefore~~ be discharged or distributed over a sufficiently large area. Theoretically, an SBRS can overflow if the system is sealed via vertical water pressure, since with increasing water levels the system is increasingly held stable via the vertical pressure. A protruding skirt on the water-side will afford more protection, as the buoyancy forces under the system are thereby minimised. Whether the system will overflow depends on its geometry and/or bulk. With increasing water levels, the probability of failure due to tilting, slipping or rolling increases. Systems that do not benefit from the effect of vertical water pressure for stabilisation are not stabilised further with an increasing water level. In terms of stability, a high bulk and/or a low centre of gravity are fundamentally advantageous here. The tests do not take into account the possibility of the foundation soil giving way with increasing water levels, since damming within the test setups only took place on a defined and stable floor. However, especially at high water levels, underground failure can be an important source of failure.

~~3~~2.2 Test results

~~The Guidelines for Loss Prevention issued by German Insurers for Mobile Flood Protection Systems contain a specimen evaluation form for SBRSs, which is intended to serve as a decision-making aid for system evaluation for persons responsible~~

for flood defence (VdS, 2014). The systems tested were evaluated in accordance with these guidelines (Table 1). The evaluation criteria relate to the area of application, stability, procurement and durability, installation, dismantling and maintenance as well as the logistics surrounding the systems. If a specification could not be determined or derived from the results of the test setups, manufacturers' specifications were used, or the evaluation was carried out on the basis of authors' considerations. The failure mechanisms affecting the surface an SBRS is installed on, such as caused by hydraulic heave or erosion, were not considered due to their dependence on the variable site conditions encountered in operational practice. Also not taken into consideration were the system connections to walls or the like, the possibility of laying the system in curves or with angles or the system behaviour on different substrates (soft, solid, rough, smooth, even, uneven, permeable, impermeable etc.). The evaluation criteria on which the system evaluations are based are described in Table 2.

Table 1. System Evaluation; DKS: Doppelkammerschlauch (double – chamber tube) TD: Tiger Dam, A: Skirt and Anchoring

	AQUARIWA	INDUTAINER	Quick Dammm	Aqua Barrier	aqua defence	NOAQ Boxwall	Flutschutz DKS	Hydrobaffle	Mobildeich	Öko-Tec	TD with A:	TD without A:			Explanation / Remarks
Application area															
Uneven ground	-	-	o	o	o	o	o	+	+	o	+	+			-
Unsurfaced ground	-	-	+	-	-	o	+	+	+	+	o	o			-
Height of retained water (h)	o*	o	o	o	o	-	o	+*	+*	o*	-	+*			* Manufacturer's data – Not all h tested
Height adjustable	-	-	-	-	-	-	-	-	o	-	o	o			-
Overflowable	o*	-	n/s	o	o	+	-	-	+	+	-	+			* Perchance with sand filling
Installation in water	o	-	-	o	o	o	-	+*	+*	-	-	-			* Manufacturer's data
Space requirement in use	-	-	o	-	-	+	-	o	-	-	+	-			-
Stability															
Tipping stability	-	-	o	o	o	o	+	+	+	+	o	+			-
Roll / slide stability	+	o	o	+	+	o	o	-	+	o	-	+			-
Buoyancy stability	+	+	o	+	+	o	o	-	+	o	-	+			-
Anchoring	-	-	-	o	o	-	-	-	-	+	+	n/s			-
Resistance against mechanical effects	o	-	o	o	o	-	o	-	+	-	-	o			-
Resistance against vandalism	-	+	-	-	-	-	-	-	-	-	-	-			-
Domino effect	+	-	+	o	o	-	-	o	-	-	-	-			-
Procurement and durability															
Costs	o	+	n/s	o	-	o	o	o	o	-	+	+			-
Service life	o/+ ***	-*	n/s	n/s	n/s	o**	+	+	o**	o**	+	+			* During continuous operation ** Legal warranty ***o: Water sack +: GRP panel
Reusability	o	o	+	+	+	+	+	+	+	+	+	+			-
Installation															
Installation time	o*	o*	n/s	+	+	+	o*	o*	o*	+	-*	-*			* According to pumping capacity
Equipment requirement	-	-	o	o	o	+	o	o	o	o	o	-			-
Persons	+	+	+	+	+	+	+	+	+	+	+	+			-
Requirement of filling material	o*	o	o*	+	+	+	-	o	o	+	o	o			* Sand filling
Number of individual elements	-	o	+	+	o	+	+	+	o	o	-	-			-

	AQUARIWA	INDUTAINER	Quick Dammm	Aqua Barrier	aqua defence	NOAQ Boxwall	Flutschutz DKS	Hydrobaffle	Mobildeich	Öko-Tec	TD with A.	TD without A.			Explanation / Remarks
Simplicity of installation	+	+	+	+	o	+	+	+	+	o	-	-			-
Weight of individual elements	+	+	o	+	+	+	o-*	o-*	o**	o	o	o			* According to system length **With reel
Dismantling and maintenance															
Simplicity of dismantling	o*	+	o*	+	+	+	o	+	+	+	+	+			* Sand filling
Disposal costs	o*	o	o*	-	o	+	+	+	+	+	+	o			* Sand filling
Cleaning costs	o	-	o	o	o	o	o	o	o	o	o	o			-
Repairs and spares	+	-	+	+	+	-	+	+	+	+	+	+			-
Logistics															
Space for storage/ transport	+	+	o	+	+	+	o	o	o	o	+	+			-
Legend	+ = good o = medium - = bad n/s = not specified														

Table 2. Evaluation criteria.

	Evaluation criteria
Area of application	
Uneven ground	Unevenness, curbstones, etc.
Unsurfaced ground	Special requirements for the condition of the foundation surface
Height of retained water	Height of retained water h up to 0.6 m = -; up to 1.5 m = o; up to 3.0 m = + Observe recommendations for unscheduled use of SBRS according to BWK (2005)
Height adjustable	Subsequent increase possible
Overflowable	Overflow capability according to manufacturer (M) or determination in authors' tests (AT) No = -; Yes (AT or M) = o; Yes (AT and M) = +
Installation in water	Manufacturer's specification or own estimate based on system characteristics
Space requirement in use	Depth incl. any upstream skirt ≤1,0 m = +; ≤2,0 m = o; >2,0 m = - (refers to the system variants tested)
Stability	
Tipping stability	Tube systems are less prone to tipping than dam or trestle systems. The heavier the installed systems, the less prone they are to tipping. (Selective) Sinking into the ground increases the risk of tipping. Anchoring or securing against buoyancy counteracts tipping.
Roll / slide stability	Tube systems are generally more susceptible to rolling away. The lower the weight and the smoother the foundation surface of the system, the easier it is for the system to slip. Anchoring or securing against buoyancy counteracts sliding or rolling.
Buoyancy stability	The risk of system failure due to buoyancy is greater for filled systems with a lower weight. Depending on the shape, buoyancy forces can also act on the water side (e.g. tube systems). Systems with a large foundation surface which achieve their load bearing effect through the vertical water pressure from the outside also have a greater risk of failure due to buoyancy. An upstream skirt, drainage, seal or anchoring counteracts failure caused by buoyancy.
Anchoring	System can be anchored against wind, current, slipping or rolling
Resistance to mechanical effects	Susceptibility to damage e.g. by flotsam impact
Resistance against vandalism.	Susceptibility to deliberate damage
Domino effect	Threat to the entire dam due to failure of individual elements
Procurement and durability	
Costs	≤100 €/m = +; ≤300 €/m = o; >300 €/m = - (refers to the system variants tested)
Service life	Service life according to manufacturer ≤1 year = -; ≤5 years = o; >5 years = +

	Evaluation criteria
Reusability	Manufacturer's data
Installation	
Installation time	Installation time according to manufacturer or from own test. For all water-filled systems, the installation time depends on the pump used.
Equipment requirement	Tarpaulins, sandbags, hoses, pumps, adapters or blowers Tarpaulin and etc. = -; Tarpaulin or etc. = o; no equipment requirement = +
Persons	≤2 Persons = +
Requirement of filling material	Sand filling = - ; water filling = o; no filling = +
Number of individual elements	Number of individual parts
Simplicity of installation	System installation easy to understand and to perform
Weight of individual elements	≤35 kg = +; ≤100 kg = o; >100 kg = - (refers to the tested system variants)
Dismantling and maintenance	
Simplicity of dismantling	System dismantling easy to understand and easy to perform
Disposal costs	Foils, tarpaulins, sandbags - Disposal after use
Cleaning costs	Effort involved in system cleaning
Repairs and spares	Minor damage can be repaired by the user. Material and spare parts are available.
Logistics	
Space for storage/ transport	Compactness of the dismantled system

The systems were tested on a grass surface and were set up by two people. In some cases, there were major differences between the manufacturer's time specifications and the times measured during the test setups (cf. Massolle et al, 2018). To be set up, the systems had to be transported manually from the edge of the basin to the point of installation and thus over a maximum distance of 15–20 m. It is quite conceivable that faster installation times can be achieved on surfaces suitable for vehicles to travel on and which offer better logistical conditions. On the other hand, significantly longer manual transport distances — and thus longer assembly times compared to the test conditions — may occur in practice. The installation times for the water-filled SBRSs also depend strongly on the available pump capacity and the water supply. In principle, however, it can be said that installation and dismantling of the systems is generally possible with just two persons and is many times faster than the construction of a sandbag dam. In addition, it is also possible to optimise installation times by using more helpers. Systems that have no need of filling also show a clear time advantage during assembly and dismantling.

Setting up the systems is often self-explanatory and instructions are easy to follow. It is still recommended, though, to involve an expert in order to avoid possible assembly errors with their far-reaching consequences. Assembly errors are always possible. With the Öko-Tec Tubewall system, for example, there is a risk that the drainage mat located under the upstream skirt will be inverted, thus endangering the functionality of the system.

Taking precautions against buoyancy can be generally recommended. Systems such as NOAQ Boxwall, Tiger Dam or Öko-Tec are dependent on this safety precaution. Protection can be ensured by an upstream skirt, a drainage system, a seal on the water-side edge or anchoring of the system. Systems such as the Flutschutz DCT - Doppelkammerschlauch (DKS - double-chamber tube) have good protection against failure owing to buoyancy as result of their high bulk weight, and no further measures are called for. However, completely weighting down an upstream skirt with sandbags or other weights is still generally recommended, as this can also considerably minimise the occurrence of seepage (cf. Massolle et al., 2018). Especially systems with a restricted contact surface are prone to the danger of sinking into saturated ground (aqua defence, Aqua Barrier, Tiger Dam). This also applies to the AQUARIWA system, the filled base of which is flat, but whose plastic skin lies somewhat unevenly. Precise data on how long it would take for the system to fail due to sinking at the contact surfaces cannot be derived from the test carried out due to its relatively short duration of just a few hours (cf. Massolle et al, 2018). In principle, there is a correlation between the depth of subsidence, the magnitude of the load exerted, the type and the antecedent wetness of the ground underneath as well as the duration of a flood event, which can last up to several days and even weeks. Some subsidence of the systems lying on a restricted contact surface could be observed during water impoundment, but this did not lead to failure during the test setups, presumably due to the short damming time of just a few hours. Figure 9 shows the aqua defence system during dismantling. The system sank the deepest into the foundation soil in the area of the greatest water depths during damming - at the top of the picture. In this area, however, the system also overflowed while the test basin was being filled with water, so that some of the increased subsidence was probably due to erosion of the foundation soil.

Figure 9: Supporting columns sunk into the saturated foundation soil while damming (aqua defence).

Especially in the case of fine sandy soils, there is a risk of foundation soil failure due to hydraulic heave or erosion caused by water flowing under the system. Especially when additional pumping is used, care must be taken that the soil under the systems is not removed with the flow of water being pumped out. There is also a risk that the friction between soil and system on paved ground will be reduced by the presence of loose grains of sand or gravel. Here, it is recommended to sweep the areas around the contact surfaces prior to installation. Minor unevenness can be levelled out with sandbags or lime that swells in contact with water. When installing the systems, attention must be paid to whether there are gradients in the terrain across or along the planned system line, as this would increase the risk of tipping, sliding or rolling. Some systems shifted or were deformed when the test basin was being filled with water, owing to play in their construction or expansion of the material they are made of, but then stabilised again (Flutschutz-~~DKS~~DCT, Hydrobaffle, Tiger Dam, Aqua Barrier). The pending failure of all the tested systems when overloaded was always indicated by visible shifting, but this was usually so quick that there was no possibility of taking countermeasures over longer lengths.

In terms of seepage rates, the tested systems are either comparable to a sandbag dam or to a sandbag dam with protruding plastic skirt (cf. Massolle et al. 2018).

In summary, it can be stated that all the systems tested remained stable at the water levels specified by their manufacturers (Figure 10). The systems aqua defence, NOAQ Boxwall, Mobildeich, Öko-Tec Tubewall (Öko-Tec TW) as well as Tiger Dam with anchoring and skirt (Tiger Dam with A.) held a full water head with low incidence of overflow. The systems we could not dam up to maximum capacity (AQUARIWA, INDUTAINER, Flutschutz-~~DKS~~DCT, Hydrobaffle) were capable of reaching higher water levels than those specified by the manufacturers. The Tiger Dam tube system was only able to achieve the protection height of 0.6 m specified by the manufacturer by the additional use of an upstream skirt and anchoring to the ground: a test setup without skirt and anchoring threatened an early system failure. The Quick Damm Type M and Aqua Barrier systems were not available in sufficient quantities and could only be tested in combination with the AQUARIWA system. Therefore, water was only dammed up to a height of 0.6 m. Since the tests were carried out without any further loads caused by currents, waves, flotsam, etc., the possibility of increasing the protection heights given by the manufacturers cannot be deduced. Table 1 summarises the advantages and disadvantages of the various system types determined in the frame of our test setups.

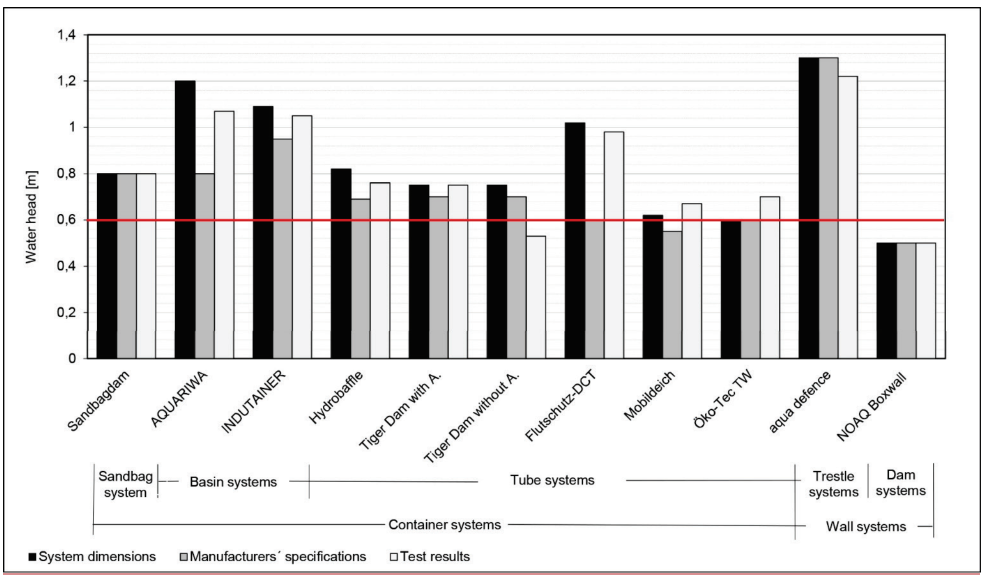

Figure 10: Water levels achieved during the test setups (Massolle et al., 2018).

Table 1: Summary of the most important advantages and disadvantages of different system types.

Basin system		
Advantage	-	High stability even no or small volumes of retained water (with influence of wind or similar)
	-	Seals well even with low volume of retained water
	-	Offer high safety with sand filling
Disadvantage	-	Installation time
	-	Filling material
Tube system		
Advantage	-	High stability even no or small volumes of retained water (with influence of wind or similar)
	-	Seals well even with low volume of retained water
Disadvantage	-	Installation time
	-	Filling material
Flap, trestle, dam systems		
Advantage	-	Installation time
	-	No filling material
	-	Usually overflowable
Disadvantage	-	Good stability only with increasing height of retained water (problematic with wind influence or similar)
	-	Good seal only with higher levels of retained water

The system dismantling of the tested SBRS was generally uncomplicated. In the case of water-filled systems, it must be ensured that the number, position and size of the openings for emptying the systems significantly influence the emptying time as well as the possibility of simple complete emptying. Even if only a small amount of residual water remains in the system, the resulting weight can exceed a manageable level. All systems must always be cleaned and dried before being stored for reuse. The INDUTAINER system may be considered as a disposable system, as cleaning or drying is difficult owing to its intricate design. However, it has a comparatively low purchase price, so that the use of the system can be economical even if only used once. Some other SBRS also have limited disposal costs after use. This applies in particular to systems in which the upstream skirt is (preferably) to be weighted down with sandbags. The required sandbag requirement, however, is low at approx. four sandbags per metre.

~~Mechanical effects, for example from flotsam or vehicle impact and vandalism, were not investigated within the scope of the test setups, but play a role in the discussion surrounding the usability of SBRSs. Minor damage can be repaired with appropriate repair kits and, in the case of water- or air-filled systems, can be compensated by refilling with pumps, if available. Furthermore, in the case of container systems and damage to individual containers with an upstream skirt, the forces can be absorbed for short times by the skirt (cf. Wagner, 2016) until it is possible to close the gap. In test series at the TU Hamburg, it was shown that SBRSs can also withstand a strongish flotsam impact (cf. Flood protection, 2019; Aquaburg, 2019).~~

These tests, though, were carried out under idealised conditions using a bundle of wooden slats as flotsam. Since the failure of an SBRS threatens the flooding of the hinterland with a correspondingly high damage potential and SBRSs are to be regarded as more susceptible to mechanical impacts and vandalism due to their design, these aspects should be evaluated particularly critically. Mechanical effects and vandalism, though, are also relevant when using sandbag systems. In the opinion of the authors, these aspects should therefore not be an exclusion criterion, despite their particular relevance for SBRSs. However, it is advisable to make higher demands on monitoring of the systems during their use.

The Guidelines for Loss Prevention issued by German Insurers for Mobile Flood Protection Systems (VdS, 2014) contain a specimen evaluation form for SBRSs, which is intended to serve as a decision-making aid for system evaluation for persons responsible for flood defence. The systems tested were evaluated in accordance with these guidelines (Table 2). The evaluation criteria relate to the area of application, stability, procurement and durability, installation, dismantling and maintenance as well as the logistics surrounding the systems. If a specification could not be determined or derived from the results of the test setups, manufacturers' specifications were used, or the evaluation was carried out on the basis of authors' considerations. The failure mechanisms affecting the surface an SBRS is installed on, such as caused by hydraulic heave or erosion, were not considered due to their dependence on the variable site conditions encountered in operational practice. Also not taken into consideration were the system connections to walls or the like, the possibility of laying the system in curves or with angles or the system behaviour on different substrates (soft, solid, rough, smooth, even, uneven, permeable, impermeable etc.). The criteria on which the system evaluations are based are described in Table 3. System dimensions and further properties of the tested SBRSs are shown in Table A1.

Table 2: System Evaluation; DCT~~KS~~: Double-chamber tube~~ppelkammerschlauch (double – chamber tube)~~ TW: Tubewall, TD: Tiger Dam, A: Skirt and Anchoring, RD: Ring dam, LD: Load drain

	AQUARIWA	INDUTAINER	Quick Damm	Aqua Barrier	aqua defence	NOAQ Boxwall	Flutschutz-	Hydrobaffle	Mobildeich	Öko-Tec TW	TD without A.	TD with~~out~~ A.	Flutschutz-RD	Flutschutz-LD	Explanation / Remarks
Application area															
Uneven ground	-	-	o	o	o	o	o	+	+	o	+	+	+	+	Test/ own estimate-
Unsurfaced ground	-	-	+	-	-	o	+	+	+	+	o	o	+	+	Test/ own estimate-
Height of retainable~~ed~~ water (h)	o*	o	o	o	o	-	o	+*	+*	o*	-*	+*	/	/	Test/ * Manufacturer's data, e.g. n ~~–N~~ot all system ~~h tested~~heights tested
Height adjustable	-	-	-	-	-	-	-	-	o	-	o	o	/	o	Manufacturers' data-
Overflowable	o*	-	n/s	o	o	+	-	-	+	+	-	+	+	/	Test/ * Perchance with sand filling
Installation in water	o	-	-	o	o	o	-	+*	+*	-	-	-	/	/	Own estimate/ * Manufacturer's data
Space requirement in use	-	-	o	-	-	+	-	o	-	-	+	-	/	/	Manufacturer's data
Stability															
Tipping stability	-	-	o	o	o	o	+	+	+	+	o	+	/	/	Test & own estimate-
Roll / slide stability	+	o	o	+	+	o	o	-	+	o	-	+	o	o	Test & own estimate-
Buoyancy stability	+	+	o	+	+	o	o	-	+	o	-	+	/	/	-Test & own estimate
Anchoring	-	-	-	o	o	-	-	-	-	+	~~+~~/	~~n/s~~+	/	/	Manufacturer's data
Resistance against mechanical effects	o	o	o	o	o	-	o	-	+	-	-	o	+*	+*	Own estimate/ *if, only from landside-
Resistance against vandalism	-	+	-	-	-	-	-	-	-	-	-	-	-	-	Own estimate-
Domino effect	+	-	+	o	o	-	-	o	-	-	-	-	/	/	Own estimate-
Procurement and durability															
Costs	o	+	n/s	o	-	o	o	o	o	-	+	+	-	-	Manufacturer's data
Service life	o/+ ***	-*	n/s	n/s	n/s	o**	+	+	o**	o**	+	+	+	+	* During continuous operation/ own estimate ** Legal warranty/ Manufacturer's data *** o: Water sack/ Manufacturer's data +: GRP panel/ Manufacturer's data
Reusability	o	o	+	+	+	+	+	+	+	+	+	+	+	+	Manufacturer's data
Installation															
Installation time	o*	o*	n/s	+	+	+	o*	o*	o*	+	-*	-*	+*	+*	Test/ * According to pumping capacity
Equipment requirement	-	-	o	o	o	+	o	o	o	o	o	-	o	o	Manufacturer's data
Persons	+	+	+	+	+	+	+	+	+	+	+	+	+	+	Manufacturer's data or own estimate-
Requirement of filling material	o*	o	o*	+	+	+	-	o	o	+	o	o	o	o	Manufacturer's data/ * with ~~S~~sand filling
Number of individual elements	-	o	+	+	o	+	+	+	o	o	-	-	+	+	Manufacturer's data
Simplicity of installation	+	+	+	+	o	+	+	+	+	o	-	-	+	+	Tests-
Weight of individual elements	+	+	o	+	+	+	o-*	o-*	o**	o	o	o	+	o	Man.'s data/ * a~~A~~ccording to system length **w~~W~~ith reel
Dismantling and maintenance															
Simplicity of dismantling	o*	+	o*	+	+	+	o	+	+	+	+	+	o	+	Test/ * ~~S~~sand filling - own estimate
Disposal effort~~costs~~	o*	o	o*	-	o	+	+	+	+	+	~~+~~o	~~o~~+	+	+	Manufacture's data/ * s~~S~~and filling
Cleaning effort~~costs~~	o	-	o	o	o	o	o	o	o	o	o	o	o	o	Own estimate-
Repairs and spares	+	-	+	+	+	-	+	+	+	+	+	+	+	+	Own estimate-
Logistics															
Space for storage/ transport	+	+	o	+	+	+	o	o	o	o	+	+	o	o	Manufacturer's data-

Legend + = good o = medium - = bad / = not relevant -n/s = not specified

Table 3: Evaluation criteria.

	Evaluation criteria
Area of application	
Uneven ground	Applicable on ~~U~~unevenness, curbstones, etc.
Unsurfaced ground	Special requirements for the condition of the foundation surface
Height of retainable~~ed~~ water	Height of retainable~~ed~~ water h up to 0.6 m = -; up to 1.5 m = o; up to 3.0 m = + Observe recommendations for unscheduled use of SBRS according to BWK (2005)
Height adjustable	Subsequent increase possible
Overflowable	Overflow capability according to manufacturer (M) or determination in authors' tests (AT) No = -; Yes (AT or M) = o; Yes (AT and M) = +
Installation in water	Manufacturer's specification or own estimate based on system characteristics
Space requirement in use	Depth incl. any upstream skirt ≤1,0 m = +; ≤2,0 m = o; >2,0 m = - (refers to the system variants tested)
Stability	
Tipping stability	Tube systems are less prone to tipping than dam or trestle systems. The heavier the installed systems, the less prone they are to tipping. (Selective) Sinking into the ground increases the risk of tipping. Anchoring or securing against buoyancy counteracts tipping.
Roll / slide stability	Tube systems are generally more susceptible to rolling away. The lower the weight and the smoother the foundation surface of the system, the easier it is for the system to slip. Anchoring or securing against buoyancy counteracts sliding or rolling. Flutschutz load drain and ring dyke always have to be positioned partly on the horizontally plane in front of the landside dyke embankment.
Buoyancy stability	The risk of system failure due to buoyancy is greater for filled systems with a lower weight. Depending on the shape, buoyancy forces can also act on the water side (e.g. tube systems). Systems with a large foundation surface which achieve their load bearing effect through the vertical water pressure from the outside also have a greater risk of failure due to buoyancy. An upstream skirt, drainage, seal or anchoring counteracts failure caused by buoyancy.
Anchoring	System can be anchored against wind, current, slipping or rolling
Resistance to mechanical effects	Susceptibility to damage e.g. by flotsam impact
Resistance against vandalism.	Susceptibility to deliberate damage
Domino effect	Threat to the entire dam due to failure of individual elements
Procurement and durability	
Costs	≤100 €/m = +; ≤300 €/m = o; >300 €/m = - (refers to the system variants tested)
Service life	Service life according to manufacturer ≤1 year = -; ≤5 years = o; >5 years = +
Reusability	Manufacturer's data
Installation	
Installation time	Installation time according to manufacturer or from own test. For all water-filled systems, the installation time depends on the pump used.
Equipment requirement	Tarpaulins, sandbags, hoses, pumps, adapters or blowers Tarpaulin and etc. = -; Tarpaulin or etc. = o; no equipment requirement = +
Persons	≤2 Persons = +
Requirement of filling material	Sand filling = - ; water filling = o; no filling = +
Number of individual elements	Number of individual parts
Simplicity of installation	System installation easy to understand and to perform
Weight of individual elements	≤35 kg = +; ≤100 kg = o; >100 kg = - (refers to the tested system variants)
Dismantling and maintenance	
Simplicity of dismantling	System dismantling easy to understand and easy to perform
Disposal costs	Foils, tarpaulins, sandbags - Disposal after use
Cleaning costs	Effort involved in system cleaning
Repairs and spares	Minor damage can be repaired by the user. Material and spare parts are available.
Logistics	
Space for storage/ transport	Compactness of the dismantled system

3 Costs of deployment, time involved, helpers and logistics

3.1 Description of scenarios

The costs as well as time, helper and logisticss requirements for the installation and dismantling of sandbag systems and SBRSs were determined for three different cases:

1. Temporary flood dam
2. Load drain in the case of a saturated dyke over an extensive area
3. Ring dam for reinforcement against heavy punctual exit of seepage on the inner embankment of thea dyke

In case 1, systems directly exposed to flooding are considered, while cases 2 and 3 refer to systems used to stabilise the landside embankment of a break-prone dyke. The latter systems are generally exposed to lower loads as they are not subjected to the direct influence of high hydrostatic pressures or the dynamic impact caused by waves and flotsam. They are therefore less endangered in their functionality. In case 1, in addition to the sandbag dam, three different SBRS types (basin, tube and trestle) were considered. Regarding the temporary flood dam, based on the experiences of the test performances described in section 2, Oone manufacturer of each system type was selected. However, there was more than one suitable system of each system type but the scope of the investigations had to be limited due to financial and temporal reasons. Regarding their function, protection against flooding, based on the experience of the test setups the chosen systems can be seen as equivalent to sandbagging. Although the systems show different safety margins, but the degree of safety can only be defined in detail knowing relevant parameters such as the coefficient of friction, which have been outside the scope of the analysis carried out. In cases 2 and 3, the only suitable SBRSs on the market are provided by Flutschutz. The system performances on the dry dyke were in accordance with the manufacturer's statements. Furthermore, the mode of action of the corresponding SBRSs is the same as for sandbagging. The authors therefore assume the SBRS Flutschutz-load drain and Flutschutz-ring dam equivalent to sandbagging, not taking into account possible differences in safety margins. -When determining the costs for the installation and dismantling of the systems, in addition to the acquisition costs, the costs for logistics (hiring the truck, fuel, driver, repair) and helpers were taken into account as well as the costs of materials (sand, sandbags respectively acquisition cost for SBRSs, including component parts) and the disposal of sand and sandbags.

In the case of the temporary flood dam, a protection length of 100 m and a protection height of 1.0 m were assumed. The height of the sandbag dam was assumed to be 1.0 m, as the dam can theoretically protect against water levels up to its full height. The SBRS AQUARIWA (basin system) with a protection height of 1.0 m and a freeboard of 0.5 m, the Flutschutz-DKS DCT with a protection height of 0.6 m and a freeboard of 0.3 m as well as aqua defence (trestle system) with a maximum protection height of 1.3 m (identical to system height) were compared. The differences in the protection heights are system specific and cannot therefore be avoided. The Ppractical tests (cf. Massolle et al., 2018) have shown that the Flutschutz-DKS DCT can dam a water head up to a height of 1.0 m, whereby, due to the lateral pressure exerted when filling the test basin, performance can be increased above the system height of 0.9 m specified by the manufacturer. In case 2, the sandbag load drain was compared with a one Flutschutz- Auflast (load drain) was compared with the equivalent length of a sandbag load

Kommentiert [II2]: The paragraphs in section 3 originate from the manuscript nhess-2019-165 - Sandbagging versus Sandbag Replacement Systems: Costs, Time, Helpers, Logistics. Track changes relate to changes made in that document.

drain, and in case 3, one Flutschutz- ring dam was compared with one ~~the~~ sandbag ring dam ~~was compared with a Flutschutz-Quellkade (ring dam)~~(see Figure 3). ~~The systems evaluated in cases 1 (temporary flood dam), 2 (load drain) and 3 (ring dam) are shown in Figure 1.~~

~~The~~ All cost calculation assumed technical assistance provided by the ~~emergency~~ disaster services of the German Federal Agency for Technical Relief (THW). Such federal assistance takes place within the framework of inter-agency cooperation and is generally requested by the responsible state authorities during extreme flood events in Germany. For the resources made available — primarily vehicles, pumps and hoses — as well as THW helpers, the costs were calculated on the basis of the ~~*Verordnung über die Durchführung und Abrechnung von Hilfeleistungen des Technischen Hilfswerks* (~~Ordinance on the Implementation and Invoicing of Assistance ~~P~~provided by the T~~echnical Relief Agency~~HW (*Verordnung ueber die Durchfuehrung und Abrechnung von Hilfeleistungen des Technischen Hilfswerks*~~)~~, in accordance with the Annex to Section 4 (3) of the THW Invoicing Ordinance (THW-V, 2019). During a flood, the German Federal Armed Forces and other relief organisations such as fire brigades and the police can be deployed in addition to THW ~~and emergency services~~. Depending on the organisation, the individual costs may vary: this, however, has not been taken into consideration for the present cost estimate.

The distance between the filling station for sandbagging respectively the place of storage of SBRSs and the site of operation is 5 km, i.e. 10 km for one round trip. Optimum access to the site of operation allows the use of trucks. Due to the heavily soaked subsoil in case 2 and 3, the access from the dyke defence road to the dyke toe is limited, therefore additional helpers to form a sandbag chain and pass on the sandbags to the dyke are needed. The comparable SBRSs in case 2 and 3 can be carried to the dyke by two persons. The operation is carried out with THW personnel and means, i.e. trucks, as well as pumps and hoses for the water filled SBRSs are provided by the THW. Furthermore, it is assumed that the travel distances for installation and dismantling of the systems are the same length. That is why the logistics of installation and dismantling show no differences.

The requirement for sandbags and sand as well as the labour needed for filling and laying the sandbags are based on empirical values supplied by THW (THW, 2017). The labour time needed for the installation of the SBRS was estimated on the basis of the authors' empirical values (cf. Massolle et al, 2018). In the case of water-filled systems in particular, the time required to dismantle an SBRS is less than that required for the installation, as the systems can be allowed to drain empty at the same time without the need for pumps. For the water-filled systems, 20% of the time required for installation was therefore estimated for dismantling. In practice, it should be noted that these estimates depend on the conditions and accessibility on site and, moreover, at least in Germany that dismantling is generally not financed by the federal authorities and therefore also not by THW. With the end of the flood hazard — and thus the disaster event — assistance on the part of the federal authorities is terminated: the municipalities and administrative districts become responsible for the measures taken. Owing to a lack of helpers, this can often lead to considerable problems following major flood events.

The following times were assumed for cleaning the systems:

- Flutschutz-~~DKS~~DCT, length 10 m: 1.5 h

- aqua defence, length 1.22 m: 5 min
- AQUARIWA, length 1.5 m: 5 min
- Flutschutz-load drain: 1 h
- Flutschutz-ring dam: 1 h

The sandbag requirement for SBRSs with upstream skirt (AQUARIWA, aqua defence) is 4 sandbags per linear metre. The basic helper requirement is 10 persons ~~per sandbag dam~~for sandbagging and 2.5 persons per SBRS, whereby foremen (group leaders, i.e. lower command) are taken into account. In case of SBRSs group leaders can take care of two different areas of application – therefore only half a helper is counted for the lower command per 100 m for the installation of a SBRS. The other two helpers are installing the SBRS, resulting in 2.5 persons per SBRS. In practice, the systems should be set up by a larger team of helpers, but fictitious helper teams with a minimum number of helpers were assumed for the calculation. Per helper hour, 22.00 € is estimated as the average loss of remuneration to be reimbursed (THW-V, 2019). The average weight of a sandbag is 12 kg (THW, 2017). A requirement of 15 kg sand per sandbag was assumed in order to take overfilling and sand losses into account. On the other hand, no reserve margin for defective sandbags etc. is taken into account, but is considered to be included in the excess demand for sand. A sandbag purchase price of 0.20 € takes into account the slight price increase to be expected during a flood event, sand is calculated with a price of 10,5 €/t. Travel costs were assumed to be 1.52 €/L diesel and 25 L/100 km. No voluntary or private-sector assistance is taken into account. However, the participation of other volunteers, for example local people, can significantly reduce the costs for the construction of a sandbag dam, as the helper costs make up the largest cost factor. It should be taken into account, though, that in case of volunteers from the local population, the resulting costs are usually borne by the volunteers themselves — the costs are therefore only transferred. The calculation also does not include costs for travel/ food/accommodation/ sanitary needs of the ~~volunteers~~helpers, upper command, long transport routes/ alternative means of transport in case of poor access, other material requirements (shovels etc. for filling the sandbags), the transport of sand/ supplementary materials as well as storage of SBRSs/ sandbags/ shovels etc. and necessary repairs to ~~the~~ SBRSs.

In principle, the selected SBRSs are reusable. Only the AQUARIWA system needs to have the inner bags replaced after using the system; the price per bag is low and was therefore neglected in the calculation. However, to replace worn off elements 5% of the investment costs are estimated. It is assumed that with smaller quantities of SBRSs, storage on site, e.g. by local dyke management units (*Deichverbaende*), is possible without difficulty. Only in the case of larger stocks ~~will~~ higher demands are~~be~~ placed on storage ~~requirements~~capacities.

Just like SBRSs, sandbags must ~~also~~ be stored. They have a significantly lower shelf life than SBRSs. If stored properly, filled sandbags have a maximum shelf life of 5 years. If unfilled, they can be stored for up to 10 years. However, it should be noted that the shelf life of filled sandbags may be severely limited if they are stored under poor conditions. When stored outdoors, after only a few months sandbags can be so decomposed that they are no longer fit for use. In the case of SBRSs, the guarantee period specified by the manufacturer must be compared to the actual shelf life. Inquiries to manufacturers have shown that not all producers give a guarantee or that the guarantee often only amounts to a few years. When interviewed, however, some manufacturers stated that the service life of demonstration models reached 10 years and more. Considering the materials used in the production of the SBRSs, such as tarpaulin fabric, galvanised steel or fibreglass-reinforced plastic, it can certainly be assumed that an SBRS can have a service life of 10 years and more. In view of this, the calculation equates the repair requirements of SBRSs with the inspection and renewal requirements of stored sandbags.

The need to regularly test the construction of SBRSs is likewise equated with the requirement to carry out flood protection exercises when relying on the use of sandbag systems. It was also assumed that the sandbag systems, like the SBRSs, should be continuously monitored during a flood event in order to monitor their functionality and to check the systems for damage caused by mechanical influences or vandalism. If deemed appropriate, the SBRSs should be inspected at shorter intervals than sandbag systems. However, the additional requirement for labour is comparatively low and was therefore neglected.

3.2 Costs of deployment

The overview of the total cost of installing and dismantling the flood protection systems shows that under the assumed conditions the costs resulting from the one-off use of the SBRSs are around 30 %-50 % higher than for ~~a comparable sandbag system~~sandbagging. However, since the SBRSs, in contrast to ~~the sandbag systems~~sandbags, are largely reusable, the higher investment costs of the SBRSs are already amortized during their second application. Table 4 shows the cost estimates for the temporary flood dams (case 1) and Table 5 for the load drain (case 2) and the ring dam (case 3). In each case, the costs incurred for installing the systems exceed the costs for their dismantling. Whereas the costs for dismantling the sandbag dam amount to approx. 70 % of the costs of installation, in the case of SBRSs the dismantling costs are in the low single-digit percentage range compared to their installation.

Table 4: Comparison of the costs for installation and dismantling of ~~sandbag systems~~sandbagging and SBRSs – temporary flood dam, protection length 100 m (case 1).

	Sandbag dam	**Flutschutz -DCTKS**	**aqua defence**	**AQUARIWA**
Helpers, incl. lower command	10	2.5	2.5	2.5
Sandbag requirement [40 x 60 cm, empty]	16 500	-	400	400
Installation				
Time per dam [h]	61.88	7.50	8.48	10.71
Costs of helpers [€]	13 612.50	412.50	466.40	523.05
Costs of materials, incl. replacements [€]	5 898.75	42 930.33	47 400.15	51 758.87
Costs of trucks, incl. fuel [€]	641.47	35.06	37.56	28.02
Total installation costs without materials [€]	14 253.97	447.56	503.96	617.07
3% sundry costs [€], based on total operating costs: 15 € - 150 €	150.00	15.00	15.12	18.51
Total costs of installation [€]	20 302.72	43 392.89	47 919.23	52 416.95
Dismantling				
Time per dam [h]	20.63	16.55	12.96	9.10
Costs of helpers [€]	4 537.50	907.50	712.8	390.61
Costs of materials [€]	8 250.00	-	200.00	200.00
Costs of trucks, incl. fuel [€]	641.47	35.06	37.56	28.02
Total dismantling costs without materials [€]	5 178.97	942.56	750.36	418.63
3% sundry costs [€] based on total operating costs: 15 € - 150 €	150.00	28.28	22.51	15.00
Total costs of dismantling [€]	13 578.97	970.83	972.87	633.63
Installation and dismantling				
Total costs [€]	33 881.69	44 363.72	48 892.10	53 050.58

Table 5: Comparison of the costs for the installation and dismantling of sandbag and sandbag replacement systems load drain (case 2) and ring dam (case 3).

	Load drain		**Ring dam**	
	Sandbag	**Flutschutz**	**Sandbag**	**Flutschutz**
Helpers, incl. lower command	10	2.5	10	2.5
Sandbag requirement [40 x 60 cm, empty]	980	-	900	-
Installation				
Time per element [h]	4.90	0.50	4.50	0.50
Costs of helpers [€]	1 078.00	27.50	990.00	27.50
Costs of materials, incl. replacements [€]	350.53	3 046.28	321.75	3 726.01
Costs of trucks, incl. fuel [€]	41.31	6.93	38.18	6.93
Total costs without materials [€]	1 119.31	34.43	1.028.18	34.34
3% sundry costs [€] based on total operating costs: 15 € - 150 €	33.58	15.00	30.85	15.00
Total costs of installation [€]	1 503.24	3 118.21	1 380.78	3 748.51
Dismantling				
Time per dam [h]	2.45	1.10	2.25	1.10
Costs of helpers [€]	539.00	60.50	495.00	60.50
Costs of materials [€]	490.00	-	450.00	-
Costs of trucks, incl. fuel [€]	41.31	6.93	38.18	6.93
Total operating costs without materials [€]	580.31	67.43	533.18	67.43
3% sundry costs [€]based on total operating costs: 15 € - 150 €	17.41	15.00	16.00	15.00
Total costs of dismantling [€]	1 087.72	82.43	999.18	82.43
Installation and dismantling				
Total costs [€]	2 590.96	3 200.63	2 379.96	3 880.36

In the case of ~~sandbag systems~~sandbagging, both sand and sandbags must first be procured. These are usually only stocked in ~~small~~ limited quantities, and in the event of procurement during a flood event, it must be expected that prices will rise sharply, so that they can even exceed the here assumed cost of sandbags. The sandbags must then be filled and laid with a great deal of time and effort. These aspects must be weighed against the investment costs for the respective SBRS, which, however, can be used several times. In order to replace damaged systems after use, an average new procurement requirement of 5% is assumed within the system service life. The sandbags required to weigh down and seal the upstream skirt of an SBRS are comparatively insignificant. The logistics costs for installation and dismantling are quite the same owing to the equally long travel distance: for ~~the sandbag system~~sandbagging~~s~~ they are higher compared to SBRSs, owing to the greater bulk. Basically, the logistics costs for all systems are comparatively low, which is also due to the comparatively low costs for the here assumed use of THW vehicles. When dismantling, the costs for ~~the sandbag system~~sandbagging~~s~~ are higher than for the SBRSs, owing to the extra need for helpers and the disposal of ~~the~~ sandbags. However, if it is possible to deploy heavy equipment for the dismantling of a sandbag dam, these costs can be lower than estimated in the present calculation because of the lower requirement for helpers and the shorter time involved. Overall, the largest cost items for ~~the sandbag systems~~sandbagging are the costs for the deployment of helpers and the procurement of materials (sand, sandbags), and for the SBRSs the procurement of the systems. If, in addition to the costs for installation, the costs for dismantling are also taken into account, from a financial point of view and under the assumed conditions, the purchase of SBRSs makes sense as they are amortised already during the second deployment. The investment costs did not include a quantity discount for the purchase of larger system lengths.

From a financial point of view, the use of SBRSs as a temporary flood dam is particularly worthwhile for protection against higher flood levels. If the protective height is reduced, the installation costs for the temporary sandbag dam decrease owing to the lower sandbag requirement. SBRSs, on the other hand, can rarely be flexibly adjusted in height, so that with lower system heights, the cost amortization in comparison to sandbag dams of low height only takes place after a number of deployments. For example, the costs for constructing a sandbag dam with a height of 0.50 m and a length of 100 m are only approx. 8 090 € for installation, approx. 5 352 € for dismantling and approx. 13 442 € for installation and dismantling. If an SBRS is offered in different system heights, savings can also be expected if lower system heights are used, but these are less significant. It should also be noted that the procurement costs of SBRSs supplied by other manufacturers may differ from those of the manufacturers considered here.

If there should be insufficient water available from natural sources (e.g. river water) in the immediate vicinity of where water-filled systems are to be installed, the costs for the water filling of hydrants are comparatively low (approx. 400 € Flutschutz-DCT~~KS~~ and 150 € AQUARIWA). If tank trucks have to be used, however, the logistical effort increases. Notwithstanding, the time, material and helper advantages of SBRSs remain in all of the cases considered here.

The calculations did not take into account the costs for upper command or travel, meals, overnight accommodation and sanitary requirements of the helpers. For upper command, i.e. the disaster control management, technical incident command and platoon, 5 € per helper in the lower command and day can be assumed. The costs for upper command are realistic overhead costs related to the number of helpers in action. With an ~~If one furthermore~~ estimate~~s~~ of 25 € per day for overnight accommodation, food and sanitary needs of the helpers, then with a helper day of 12 hours per sandbag system in cases 1, 2 and 3 approx. 6 %, and per SBRS approx. < 1 % more costs are incurred.

3.3 Time, helper and logistics requirements

For cases 1, 2 and 3, the estimated time, helper and logistics requirements are shown in Table 6 and Table 7. Time 'materials' refers to the time needed to fill the sandbags – aqua defence and AQUARIWA need sandbags in order to weight down the upstream skirt. Time 'logistics' contains the time for loading respectively unloading the trucks as well as time for the outward and return journey between the filling station respectively storage and the site of operation, which is tightly calculated as one hour per truck. It is assumed that there is an unrestricted amount of trucks available, which is of course a theoretical value, resulting in an overall time for logistics of one hour. In reality, the overall time would increase depending on the actual available amount of trucks. Time 'installation' refers to the installation of the specific system, if necessary, including additional time for a sandbag chain. According to this, time 'dismantling' refers to the dismantling of the individual systems as well as time for cleaning of the SBRSs, if necessary also including additional time for a sandbag chain. Time for disposal or stowage of SBRSs was not taken into account.

The time, materials and helper advantages of the SBRSs are clearly visible. In case 1, the use of SBRSs requires approx. 25 %-30 % of the time, approx. 5 %-7 % of the helper hours and approx. 5 % of the trucks compared to the sandbag dam. If more helpers or trucks are used, the respective proportions shift, but the total effort remains the same. In case 2 and case 3, approx. 40 % of the time and approx. 6 % of the helper hours are required when using SBRSs. The logistics data in case 2 and case 3 were rounded up to fully loaded trucks. Eight Flutschutz-load drains or Flutschutz-ring dams can be transported per truck, so that when using these SBRSs there is a need for only approx. 8 %-9 % of the trucks required for ~~sandbag systems~~sandbagging.

When sandbag~~-systems are~~ging is used, poor access — and thus the need for sandbags being passed on over longer distances by means of a sandbag chain (see Figure 2) — may result in a significant additional need for helpers or the use of alternative means of transport such as helicopters or boats, which can only transport sandbags in small amounts~~.~~ This can also considerably increase the time required for transport as well as the costs incurred. The possible scenarios are manifold and could therefore not be considered in detail. SBRSs do not need additional helpers in case of poor accessibility, because due to their relatively low weight they can be put in place with much more easy means in the required amount, e.g. by the use of special vehicles which can access even wet ground but which cannot carry a lot of weight.

Table 6: Comparison of time, helpers and logistics requirements for the installation and dismantling of sandbag and sandbag replacement systems - temporary flood dam (case 1).

	Sandbag dam	**Flutschutz -D~~KS~~CT**	**aqua defence**	**AQUARIWA**
Helpers, incl. lower command	10	2.5	2.5	2.5
Trucks	26	2	2	1
Installation				
Time materials [h]	41.25	-	2.00	2.00
Time logistics [h]	1.00	1.00	1.00	1.00
Time installation [h]	20.63	7.50	6.48	8.71
Total time, incl. logistics [h]	62.88	8.50	9.48	11.71
Total helper hours [h]	618.75	18.75	21.20	26.78
Dismantling				
Time materials [h]	-	-	-	-
Time logistics	1.00	1.00	1.00	1.00
Time dismantling, incl. cleaning SBRS [h]	20.63	16.50	12.96	7.10
Total time, incl. logistics [h]	21.63	17.50	13.96	8.10
Total helper hours [h]	206.25	41.25	32.40	17.76
Installation and dismantling				
Total time, incl. logistics [h]	84.50	26.00	23.44	19.81

	Sandbag dam	Flutschutz -D~~KS~~CT	aqua defence	AQUARIWA
Total helper hours [h]	825.00	60.00	53.60	44.53

Table 7: Comparison of time, helpers and logistics requirements for the installation and dismantling of sandbag and sandbag replacement systems – load drain (case 2) and ring dam (case 3).

	Load drain		**Ring dam**	
	Sandbag	**Flutschutz**	**Sandbag**	**Flutschutz**
Helpers, incl. lower command	10	2.5	10	2.5
Trucks	2	1	2	1
Installation				
Time materials [h]	2.45	-	2.25	-
Time logistics [h]	1.00	1.00	1.00	1.00
Time installation [h]	2.45	0.50	2.25	0.50
Total time, incl. logistics [h]	5.90	1.50	5.50	1.50
Total helper hours [h]	49.00	1.25	45.00	1.25
Dismantling				
Time materials [h]	-	-	-	-
Time logistics	1.00	1.00	1.00	1.00
Time dismantling, incl. cleaning SBRS [h]	2.45	1.10	2.25	1.10
Total time incl. logistics [h]	3.45	2.10	3.25	2.10
Total helper hours [h]	24.50	2.75	22.50	2.75
Installation and dismantling				
Total time, incl. logistics [h]	9.35	3.60	8.75	3.60
Total helper hours [h]	73.50	4.00	67.50	4.00

4 Conclusion

Tests of various SBRSs with the focus on stability, functionality and handling were carried out. The experiences from the test setups show that SBRSs, owing to their functionality and their labour and time-saving characteristics as well as the lower requirement for materials, offer the potential to make operational flood defence more efficient than with the use of sandbags alone. Since SBRSs are technical systems whose functional capability must be proven before they can be used, the introduction of a test and certification system is urgently recommended. A basis for the development of a certification system according to the German standard is already available in the BWK leaflet 'Mobile Flood Protection Systems' (BWK, 2005), the international certification systems such as FM Approvals (2019) or BSI Kitemark (2019a) as well as the test results described here and in Massolle et al. (2018).

Further aspects have to be considered using SBRSs instead of sandbagging. These include the lower flexibility of SBRSs, higher demands on trained personnel, the creation of hazards by assembly errors, defects in the construction, mechanical influences due to flotsam, vehicles, and persons as well as by vandals, the possibility of collective failure (domino effect), or the influences of currents, winds and waves. The hazards introduced through the use of SBRSs cannot entirely be ruled out, but the hazard can be minimized by taking appropriate precautions. Also SBRSs easily allow to impound higher flood water levels, which is on the one hand an advantage but on the other hand results in greater probability of subsoil failure if high water levels are impounded. In general, the use of SBRSs can lead to higher requirements on a suitable subsoil. Many of the aspects mentioned can be laid down in guidelines to support decision-makers with regard to the possible use of SBRSs. However, taking into account possible catastrophic consequences in the event of failure, the installation of SBRSs should be planned and executed under the supervision of specialists and under special observation during the flood event. From the authors' point of view SBRSs are rather a suitable supplement to than a full replacement of sandbagging. Especially because of their easy, flexible handling and their reliable usability within the scope of its possibilities, sandbags are an essential mean in the operational flood defence. No matter whether SBRSs find increasing application in future, sandbags will continue to play an important role in flood defence owing to their simple application and high flexibility — even if, for example, they are only used to close gaps for which prefabricated systems of a certain length are not suitable.

In addition to certification of the systems, other factors such as costs, local operating conditions (subsurface properties, current, wind, waves, etc.), handling, necessary measures to minimise the risk of failure owing to mechanical defects and vandalism, sufficiently trained personnel, logistics and storage of the systems play an important role when considering the use of SBRS. Many of these aspects can be laid down in guidelines to support decision-makers with regard to the possible use of SBRS. The cost issue can be offset by the resulting increase in the efficiency of flood protection – and thus ultimate savings through damage reduction.

Kommentiert [II3]: These paragraphs originate from the manuscript nhess-2019-164 - Sandbag Replacement Systems - Stability, Functionality and Handling. Track changes relate to changes made in that document.

The authors' determination of the operational costs was carried out for specific scenarios and with several simplifications, but nevertheless allows an approximate estimate of the operational costs of sandbagging and SBRSs under realistic conditions. When used once, all SBRS show higher overall costs, including costs for investment, logistics, installation and dismantling. Considering the help of the German disaster relief system, the total costs range from 44 364 € to 53 051 € for the linear SBRSs respectively 33 882 € for the sandbag dam and from 3 201 € to 3 880 € for the Flutschutz dyke defence measures respectively from 2 591 € to 2 380 € for the corresponding sandbagging measures. The higher total costs result from the higher acquisition costs of the investigated SBRSs. SBRSs are reusable, therefore, with regard to amortization of the higher acquisition costs of SBRSs, the number of times a system can be used within its service life plays a decisive role, since the acquisition costs of the investigated systems are amortized during their subsequent reuse. Since SBRSs can be transported with comparatively low logistical effort, a more centralised storage system is conceivable, so that in the event of flooding, the systems can also be transported from more distant regions that are not immediately affected by the flood. This would be in the interest of a cross-municipal and therefore cost-effective acquisition.

All investigated SBRSs show clear time-, material- and personnel-saving advantages. In case of the temporary flood dam, under the simplifications assumed here, the use of SBRSs requires approx. 25 %-30 % of the time, approx. 5 %-7 % of the helper hours and approx. 5 % of the trucks compared to the sandbag dam. For the load drain and the ring dam, approx. 40 % of the time, approx. 6 % of the helper hours and approx. 8 % - 9 % of the trucks are required when using SBRSs as assumed under the conditions set forth herein. In particular, the time but also material and personnel saved during operation must be taken into account here, which may even be crucial to providing protection in the first place. The time, material and personnel saving characteristic of SBRSs might offer the possibility to use SBRSs during heavy precipitation events, respectively flood events with only short early warning times. Such events can come along with high flow velocities, resulting in high potential dynamic loads. Further investigations and a special testing routine would be necessary in order to make reliable statements about a SBRSs' functionalities during such events.

From a technical point of view decision makers are confronted with the question of the reliability of SBRSs, which in general show a good functionality comparable to sandbagging, and in terms of time, personnel and material need show better results than sandbagging alone. The question of the functionality of SBRSs can be addressed by introducing independent test routines and certifications. From an economic point of view, decision makers are confronted with the question of higher investment costs if SBRSs are purchased. The here done investigations indicate that only if SBRSs are subsequently reused, this is not connected to economic losses. In addition to the economic aspects, however, it should also be noted that SBRSs can be set up in a significantly shorter time, which often can be the basis for effective protection.

Irrespective of this, owing to their time-, material- and personnel-saving characteristics SBRS offer the potential to make operational flood protection considerably more efficient than a system based solely on sandbagging. In particular, the time saved during operation must be taken into account here, which may even be crucial to providing protection in the first place.

No matter whether SBRS find increasing application in future, sandbags will continue to play an important role in flood defence owing to their simple application and high flexibility — even if, for example, they are only used to close gaps for which prefabricated systems of a certain length are not suitable.

In addition to further technical examination of the functionality of SBRS in realistic tests and subsequent certification, in order to promote the use of SBRS in operational flood protection and for the protection of populations, it is necessary to overcome the financial hurdles to their procurement. In particular, it is necessary to provide financial support to the municipal authorities responsible for the purchase of the systems. This could, for example, entail eliminating the difference in the financing of the contingency costs of protection systems and the costs of using the systems, because in the event of a disaster event the costs for operational flood defence are generally borne by the federal states or the federal authorities, but the costs for maintaining a minimum quantity of protection systems are borne by the municipalities. Whereby sandbags and the filling material can still be procured at very short notice in the event of flooding, it is not so easy to procure SBRS that may still have to be produced.

Kommentiert [II4]: These paragraphs originate from the manuscript nhess-2019-165 – Sandbagging versus Sandbag Replacement Systems: Costs, Time, Helpers, Logistics. Track changes relate to changes made in that document.

Appendix

Table A1: System dimensions and further properties of tested SBRSs.

Manufacturer/ distributor	Product name	Water height [m]	System height [m]	Length [m]	Width [m]	Weight (unfilled) [kg]	Diameter [m]	System	Main material	Fill material	Water permeable	Anchoring	Material requirements	Homepage
Basin system														
Aquariwa GmbH	Aquariwa	0,5-1,0 (water filled) 1,0-1,5 (sand filled)	0,9-1,5	-	-	15,0-39,0	1 - 1,5	Cylindrical containers bent too open plates filled with water, sand or gravel	Glass fibre-reinforced board with grid	Water, sand, gravel	No	None	Tarpaulins, sandbags, hoses, pumps or wheel loaders, dumpers	http://www.aquariwa.de/home/
Indutainer	Indutainer	N.s.	1,05	0,93	0,93	7,0	-	Waterfilled basin system	Polypropylene fabric, polyurethane foam	Water	No	None	Pumps, hoses, if necessary filling aid	http://www.indutainer.com/
Quick Damm GmbH	Quick Damm	1,0	1,0	2,0	1,0	50,0	-	Open, collapsible steel frame with a geotextile container filled with sand or gravel or a plastic container filled with water	Steel frame, geotextile, plastic-coated fabric tarpaulin	Water, sand, gravel	No / Yes	None	Wheel loaders, dumper or pumps, hoses	http://www.quick-damm.de/start.html
Trestle system														
ALTRAD Plettac assco GmbH	aqua defence	1,3	1,3	1,3	1,71	app. 41,5 per m	-	Hard foam panels covered with tarpaulin on collapsible support elements	Hard foam panels, galvanized support elements, tarpaulin	-	No	N.s.	Sandbags	https://plettac-assco.de
RS Stepanek KG	Aqua Barrier	0,65-1,8	0,65-1,8	1,23	N.s.	N.s.	-	EUR pallets covered with tarpaulin on foldable collapsible elements	Wooden pallets, galvanised support elements, polypropylene foil	-	No	N.s.	Wooden pallets, tarpaulins, sandbags	http://hochWaterschutz-rs.de/a/hochWaterschutz/aqua-barrier/
Dam system														
NOAQ Flood Protection	NOAQ Boxwall	0,5	0,528	0,705	0,68	3,4	-	Boxes connected to each other	ABS (acrylonitrile butadiene styrene)	-	No	None	None	http://noaq.com/de/home-2/
Tube system														
European Flood Control GmbH	Tiger Dam	0,4;0,75;1,0	0,5 per tube	15,0	-	30 per tube	0,5 per tube	Closed, water filled tube system; pyramid-shaped strapped	PVC	Water	No	For additional protection against slipping possible	Tarpaulins, sandbags, pumps, hoses	http://www.eu-floodcontrol.eu/
HochWaterschutz Agentur	Hydrobaffle	0,23-1,83	0,31-2,44	3,0-32,0	0,7-5,49	2,61-20,32	0,7-5,49	Closed, water filled tube system	Plastic-coated fabric tarpaulin	Water	No	None	Pumps, hoses, square wrenches for the seals	http://www.hochWaterschutz-agentur.de/de/mobiler-hochWaterschutz-details
Mobildeich GmbH	Mobildeich	0,45-2,6	0,45-2,6	10,0-50,0	0,4-2,6	5-56 per m	0,45-1,5	Closed, water filled tube system held together as 2- to 3-tube packages with net sheathing and sealing tarpaulin	PVC coated polyester fabric	Water	No	None	Pumps, hoses, Y-piece	http://www.mobildeich.de/de/index.php
optimal Planen- & Umwelttechnik GmbH	FLUTSCHUTZ-Doppelkammerschlauch	0,6	0,9	10,0;15,0; 20,0	-	110,0-220,0	1,5 / 0,9	Closed, water filled tube system	Polyester fabric coated on both sides	Water	No	None	Leaf blower, pumps, hoses	http://www.alles-optimal.de/index.php/produkte-fuer-feuerwehr-und-katastrophenschutz/hochWaterschutz/doppelkammerschlauch-flutschutz/75-doppelkammerschlauch-flutschutz
Öko-Tec Umweltschutz-systeme GmbH	Öko-Tec Schlauchwall	0,5-1,5	0,5-1,5	5,0-20,0	1,5-2,3	4,0-9,5 per m	0,5-1,5	Closed, air filled tube system	PVC	Air	No	If necessary, with wind on the side of the protection zone or with current on the water side	Blower	http://noaq.com/de/home-2/
Load drain														
optimal Planen- & Umwelttechnik GmbH	FLUTSCHUTZ-Auflast	-	0,6	7,0	3,5	70,0	-	Closed, water filled tube system	Polyester fabric coated on both sides	Water	No	None	Pumps, hoses	http://www.alles-optimal.de/index.php/produkte-fuer-feuerwehr-und-katastrophenschutz/hochWaterschutz/schlauchlastfilter-flutschutz/77-schlauchlastfilter
Temporary ring dam														
optimal Planen- & Umwelttechnik GmbH	FLUTSCHUTZ-Quellkade	1,0	1,0	2,9	2,9	35,0	-	Closed, water filled tube system	Polyester fabric coated on both sides	Water	No	None	Leaf blower, pumps, hoses	http://www.alles-optimal.de/index.php/produkte-fuer-feuerwehr-und-katastrophenschutz/hochWaterschutz/schlauchkade-flutschutz/76-schlauchkade-flutschutz

Author contribution

Conceptualisation: B.K.; Methodology: L.L. and C.M.; Resources: C.M. and L.L.; Formal Analysis: L.L., C.M. and V.K.; Writing—original draft preparation: L.L.; Writing—review and editing: B.K., C.M. and L.L.; Visualisation: L.L. and V.K.; Supervision: B.K. and L.L.; Project administration: B.K.; Funding acquisition: B.K.

Conflicts of interest

The authors declare that they have no conflict of interest.

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References

American National Standards Institute (ANSI) and FM Approvals, American National Standard for Flood Abatement Equipment: ANSI/FM Approvals 2510, FM Approvals, Norwood, 2014.

Aquaburg Homepage: https://www.aquaburg.com/cropped-aquaburg-oben-aquawand-test-treibgutanprall-von-hinten-2-jpg/, last access: 25 September 2019.

AQUARIWA Homepage: http://www.aquariwa.de/die-einsaetze/aquariwa-in-gartow-juni-2013/#die-einsaetze/aquariwa-in-gartow-juni-2013/, last access: 25 September 2019.

Biggar, K. and Masala, S.: Alternatives to sandbags for temporary flood protection, Alberta Transportation and Utilities Disaster Services Branch and Emergency Preparedness Canada, Edmonton, AB and Ottawa, ON, Canada, 1998.

British Standards Institution (BSI): PAS 1188-2:2014 Flood protection products – Specification, Part 2: Temporary products, Third Edition, The British Standards Institution Group Headquarters, London, 2014.

British Standards Institution (BSI) Homepage: https://www.bsigroup.com/en-GB/, last access: 25 September 2019a.

British Standards Institution (BSI) product directory search Homepage: https://www.bsigroup.com/en-GB/Product-Directory/, last access: 25 September 2019b.

Bund der Ingenieure für Wasserwirtschaft, Abfallwirtschaft und Kulturbau (BWK) e.V.: Merkblatt: Mobile Hochwasserschutzsysteme – Grundlagen für Planung und Einsatz, BWK-Bundesgeschäftsstelle, Sindelfingen, Deutschland, 2005.

Egli, T.: Entscheidungshilfe Mobiler Hochwasserschutz, Vereinigung Kantonaler Feuerversicherungen, Bern und Bundesamt für Wasser und Geologie, Biel, 2004.

FM Approvals Homepage: https://www.fmapprovals.com/, last access: 25 September 2019.

Flutschutz Homepage: http://www.flutschutz.org/entwicklung/entwicklung-d.html, last access: 25 September 2019.

Gabalda, V., Garvin, S., Hunter, K., Florence, C., Salagnac, J.-L., Golz, S., ten Veldhuis, M.-C., Diez, J., Monnot, J. V.: Flood Resilience Technologies. SMARTeST. 2013. Available online: https://www.ioer.de/fileadmin/internet/IOER_Projekte/PDF/FB_R/Flood-Resilience-Technologies_SMARTeST-Project_D23-final-July13.pdf, last access: 25 September 2019.

Massolle, C., Lankenau, L., Koppe, B.: Emergency Flood Control: Practice-Oriented Test Series for the Use of Sandbag Replacement Systems, Geosciences, 8, 482, https://doi.org/10.3390/geosciences8120482, 2018.

Mc Cormack, S. M., Van Dyke, C., Suazo A., Kreis, D.: Temporary Flood Barriers, Research Report KYSPR-12-448, Kentucky Transportation Center, College of Engineering, University of Kentucky, Kentucky Transportation Cabinet Commonwealth of Kentucky and Federal Highway Administration U.S. Department of Transportation, Kentucky, 2012.

Mobildeich Homepage: https://www.mobildeich.de/de/referenz.php#filme, last access: 25 September 2019.

National Flood Barrier Testing & Certification Program (NFBTCP) Homepage: https://nationalfloodbarrier.org/products/#!/prodsub-peri-barriers, last access: 25 September 2019.

Niedersaechsischer Landtag: Antwort auf eine Grosse Anfrage. Niedersaechsischer Landtag – 17. Wahlperiode. Drucksache 17/1730, 2014. Available online: https://www.landtag-niedersachsen.de/drucksachen/drucksachen_17_2500/1501-2000/17-1730.pdf, last access: 25 September 2019.

Ogunyoye, F.; Stevens, R.; Underwood, S.: Delivering benefits through evidence. Temporary and Demountable Flood Protection Guide, Environment Agency, Bristol, 2011.

Österreichischer Wasser- und Abfallwirtschaftsverband (ÖWAV): Arbeitsbehelf 42: Mobiler Hochwasserschutz, Wien, 2013.

Pinkard, F., Pratt, T., Ward, D., Holmes, T., Kelley, J., Lee, L. T., Sills, G., Smith, E., Taylor, P. A., Torres, N., Wakeley, L., Wibowo, J.: Flood-Fighting Structures Demonstration and Evaluation Program: Laboratory and Field Testing in Vicksburg, Mississippi, U.S. Army Corps of Engineers, Washington, 2007.

Popp, F., Lehmann, S., Lehmann, B.: Flexibilität und Effizienz in der Deichverteidigung durch mobile Aufkadungssysteme. Wasserwirtschaft, 01, 29-33, 2019.

Simm, J.; Sharp, M.; Hemert, H. v.; Igigabel, M.; Pohl, R.; Tourment, R.; Wallis, M.; Drake, C.; Banks, J.; Bramley, M.; Chassé, P.; Conforti, T.; Jenkins, O.; Mallet, T.; Matheu, E.; Royet, P.; Verigin, S. (Editorial Steering Board): The international levee handbook, C731, Construction Industry Research and Information Association (CIRIA), London, 2013. Available online: https://www.ciria.org/ItemDetail?iProductCode=C731F&Category=FREEPUBS&WebsiteKey=3f18c87a-d62b-4eca-8ef4-9b09309c1c91,, last access: 25 September 2019.

Technisches Hilfswerk (THW): THW-pocket card *'Hochwasserschutz und Deichverteidigung'* ('flood protection and dyke defence'), status 02.08.2017, unpublished; THW Training Centre Hoya, Hoya, Germany, 2017.

VdS Schadenverhütung GmbH: Mobile Hochwasserschutzsysteme: Hinweise für die Beschaffung, den Einsatz und die Bereitstellung, VdS 6001 : 2014 – 02 (01), Köln, 2014.

Wagner, J.: AQUARIWA Test 100er Zylinder, Youtube, published on 11 February 2016: https://www.youtube.com/watch?v=JrYk6ymPcYk, last access: 25 September 2019.