water

MDPI

Article

Living with Urban Flooding: A Continuous Learning Process for Local Municipalities and Lessons Learnt from the 2021 Events in Germany

Bert Bosseler [1,*], Mirko Salomon [1], Marco Schlüter [1] and Matteo Rubinato [1,2,3,*]

[1] IKT-Institute for Underground Infrastructure, Exterbruch 1, 45886 Gelsenkirchen, Germany; salomon@ikt.de (M.S.); schlueter@ikt.de (M.S.)
[2] Faculty of Engineering, Environment and Computing, School of Energy, Construction and Environment, Coventry University, Coventry CV1 5FB, UK
[3] Centre for Agroecology, Water and Resilience, Coventry University, Coventry CV1 2LT, UK
* Correspondence: bosseler@ikt.de (B.B.); ad2323@coventry.ac.uk (M.R.); Tel.: +49-(0)209-1780614 (B.B.)

Abstract: In 2021, heavy precipitation events in Germany have confirmed once again that pluvial flooding can cause catastrophic damage in large, medium, and small cities. However, despite several hazard-oriented strategies already in place, to date there is still a lack of integrated approaches to actually preventing negative consequences induced by heavy rainfall events. Furthermore, municipalities across the world are still learning from recent episodes and there is a general need to explore new techniques and guidelines that could help to reduce vulnerability, and enhance the resilience, adaptive capacity, and sustainability of urban environments, considering the already predicted future challenges associated with climate variability. To address this gap, this paper presents the outcomes of the research project "*Heavy Rainfall Checklist for Sewer Operation*" which was conducted by IKT Institute for Underground Infrastructure, to involve all the stakeholders affected by pluvial flooding within cities, and implement a series of documents that can be adopted by municipalities across the world to support organizations and their operational staff in preventing problems caused by heavy rainfall incidents. More in detail, three different rainfall scenarios have been deeply analysed, and for each of them a list of specific tasks and suggestions has been provided for aiding decision-making.

Keywords: climate change; increased urbanization; flood adaptation; flood mitigation; resilient cities

Citation: Bosseler, B.; Salomon, M.; Schlüter, M.; Rubinato, M. Living with Urban Flooding: A Continuous Learning Process for Local Municipalities and Lessons Learnt from the 2021 Events in Germany. *Water* **2021**, *13*, 2769. https://doi.org/10.3390/w13192769

Academic Editor: Momcilo Markus

Received: 10 September 2021
Accepted: 28 September 2021
Published: 6 October 2021

1. Introduction

Urban flooding is one of the most frequent natural hazards affecting many cities across the world, leading to increasing life and property losses every year [1–3]. In Asia, for example, during the last decade, Vietnam was one of the world's most exposed countries to natural disasters, with an average of 650 deaths, damage to 340,000 ha of paddy rice and destruction of 36,000 houses each year [4]. Furthermore, Bangladesh is another country that had to deal multiple times with floods caused by monsoons, which can however be seen both as resources and hazards [5]. In Africa, developing countries suffer the most in terms of flood losses and damages because they have inadequate capacity to handle, prepare, prevent, and recover [6,7]. In America, results show that that in the United States an average of 6520 floods have occurred per year from 1996–2016, with annual mean economic losses up to 3986 million US dollars [8], while the economic, social, and environmental cost of urban floods in Mexico is continuously growing [9–11]. In Europe, Germany has been the latest country majorly affected by record rainfall which caused a devastating flood in western Germany, unfortunately causing a number of several fatalities and injuries. It was reported that at least 40,000 people have been affected by these recent floods in the wine-growing Ahr valley and regions in neighbouring North-Rhine Westphalia. In England and Wales, damage due to flooding exceeded £1 billion [12], and this figure is predicted to increase by 60–220% in the future [13].

Due to ongoing urbanization and phenomena linked with incessant climate change which will increase the frequency and magnitude of future flooding events [14–22], especially if linked with the formation of landslides [23,24], municipalities are strongly focusing on new techniques and challenges to improve existing flood management techniques and plans with the final aim to make cities more resilient to urban flooding [25,26]. Assessment measures and practical strategies have been suggested to increase flood resilience [27–32], however there is still a huge amount of information to process to learn from flooding events to increase the resilience of environments affected enhancing their adaptability to reduce negative consequences [33,34]. Achieving resilience is not a task to undermine: a resilient system responds to a disturbance by changing the relative amounts of its different parts and how they interact, thereby changing the way it functions [35]. Based on this definition, it is possible to affirm that it is a joint duty to better prepare for such events in the course of climate adaptation; this applies equally to the global, regional and local levels, as previously suggested by Article 7 (2) of the Paris Agreement: "*adaptation is a global challenge faced by all with local, subnational, national, regional and international dimensions*" [36,37]. The local level is clearly more important in the context of climate mitigation, because local measures can have an immediate protective effect, while reducing emissions is a challenge that needs to be coordinated globally.

Locally, urban drainage companies play a special role as experts in questions of urban water runoff; they are also attributed a high level of technical responsibility. Accordingly, the European standard EN 752 [38–40], which serves as a technical guideline for urban drainage companies, comprehensively addresses water management issues in Section 5.2.1: "*Drain and sewer systems are part of the urban drainage system. Urban drainage systems comprise all infrastructures for the management of wastewater and rain water in the built environment. The extent and role of the drain and sewer system within the urban drainage system depends on local circumstances for each system. Urban drainage systems are part of a wider system of water management.*"

While international, national and river basin measures are usually regulated at the legal level, local tasks must be organized largely independently by the municipalities and wastewater utilities. In addition to the sewage company, which represents a single but essential actor, numerous other departments within the city are typically involved with heavy rainfall prevention tasks and can basically be distinguished from each other based on their specific duty as follows:

- ***Wastewater***: this concerns the collection, conveyance and purification of water contaminated by use as well as contaminated water that runs off paved surfaces (e.g., Water Resources Law of the Federal Republic of Germany (WHG); Water Law of the State of North Rhine-Westphalia (LWG NRW);[41–43]). Sewer planning, construction and rehabilitation serve to build and maintain the network. Sewer operation, on the other hand, ensures continuous functionality. In the event of heavy rainfall, this means that the sewer system must reliably provide the discharge capacity foreseen in the design, even under heavy rainfall conditions, and there must be no disruptions or even failure of the network performance, e.g., due to blockage of the pipelines or the obstruction of inlets.
- ***Green space***: in the event of heavy rainfall, this relates to the prevention of soil runoff (litter, debris, branches), which can lead to run-off disturbances on the surface or also in the sewage system further down the line. In addition, green spaces can also be used from the outset as space for the retention and infiltration of rainwater.
- ***Road***: this concerns in particular the functionality of road inlets, but also the use of roads as a retention area in the event of heavy rainfall.
- ***Fire***: this concerns the prevention of danger in the event of a specific incident to be dealt by the fire brigade.

- ***Order and safety***: among other things, the consideration and enforcement of building planning recommendations in urban land use planning and the development plans of the municipalities.
- ***Building construction***: this refers to the protection of buildings, both through structural precautionary measures and measures in the event of an incident.
- ***Electricity/gas/water***: this focuses on safeguarding of infrastructure performance even in the event of heavy rain. Similar to the sewerage system, which must also safely provide its intended service in the event of heavy rain, this also applies to all other infrastructures.
- ***Water bodies***: this concerns particular protection against supra-regional flood events characterized by the overflowing of water bodies.
- ***Urban development***: planning concepts for dealing with rainwater through large-scale structural solutions, often also discussed as the "sponge city" concept.

The wastewater company and its sewer operation department play a special role. As a general unwritten rule, this is where the greatest expertise on the topic of "water in the city" lies and there is great proximity to citizens, since drainage systems technically always include property drainage and therefore offer a direct interface to private property.

During extreme heavy rainfall events, the impacts of surface runoff increase rapidly and necessary measures in sewer operation are barely predictable and must be adapted to the situation in each individual case. Each crisis management requires rapid and appropriate action, and most of the time people in charge within the categories listed above have only limited resources at their disposal, which have to be used optimally to deal with the most diverse situations [44–47]. Consequently, optimal crisis management requires intensive preparation [48–51], and many municipalities across the world are still seeking more information to make their urban drainage systems more resilient to urban flooding and more adaptable to unpredicted disturbances [52,53].

To address this gap, IKT (Institute for Underground Infrastructure in Germany), identified a list of essential tasks that could commonly arise during flooding events after having analysed outcomes obtained with comprehensive research conducted to date [54]. Therefore, this paper illustrates a series of steps for urban drainage companies that can facilitate urban flood disaster management within adjacent municipalities. The ideas proposed have been also recently reinforced and modified based on the lessons learnt from the summer 2021 flooding events in Germany, which led to severe flooding, particularly in North Rhine-Westphalia and Rhineland-Palatinate.

2. Methodology

In this section, all operators involved in the project are presented and all scenarios identified by the members are summarized. Furthermore, their characterization is provided together with an explanation of the duties and tasks that are associated and required for each one of these familiar scenarios.

2.1. Case Study: Operators Involved in North Rhine-Westphalia

In order to record and further develop the tasks and processes that wastewater companies and their sewer operation department should be dealing with during heavy rain events, the entire research project conducted by the IKT was closely aligned with network operators located in the federal state of North Rhine-Westphalia, Germany. All data were largely collected via online (due to restrictions for Covid19) and face-to-face interviews and reports filled and completed by responsible employees. All interviews (they usually lasted two to four hours) were conducted in two stages. The first one included a list of standard questions prepared in advance that the employees had to answer. After gathering the answers of the employees (wastewater company), who were asked whether heavy rainfall events had already occurred in the respective municipality in recent years, research was conducted with existing (internal) documents provided by the municipalities, online newspaper articles and weather databases to determine the extent to which these experiences of the employees were also documented. Then, within the second part of the interview process, there was a discussion to expand certain details found to be very interesting to enhance the acquisition of the information gathered. When completing the interviews of the employees, the information provided was double checked where possible with the documentation of the events found in literature or on online reports. If there were differences between what was gained from the employee's experience and the documentation online, then an additional interview was organized to further discuss the topic with the employees asking for more specific details. Interviews were conducted at 13 wastewater companies and the questions related, among other things, to experiences, whether a heavy rain event had already taken place in the municipality, whether there was damage or how attempts were made to cope with the heavy rain event (open answers were possible). For the individual measures on the checklist, questions were asked about the extent to which the measures had already been implemented and the answers proposed were for example "*A: not yet implemented*", "*B: already in planning/partially implemented*" and "*C: fully implemented*". In some cases, even two to three employees were interviewed together, which made it possible to compare results, which were finally presented in 4 project meetings with all municipalities and discussed among the interviewees, enabling verification and validation of the interview results. Since the participating wastewater companies took part in the research projects out of self-interest, these meetings were generally open and genuine. In cases where there were some initial reservations (e.g. operational staff or other departments), these were often quickly resolved by the presentation provided by the research team explaining carefully the aims and results of the project, convincing those doubtful about the importance and significance of the entire projects which only aimed at providing support and constructive results.

Three steering levels (panels) were used to discuss the interim results and to check their significance and quality:

- ***User panel***: This group consists of all approximately 70 members of the Municipal Wastewater Network KomNetAbwasser, which is organised by the IKT as a permanent community of wastewater companies [55]. Among other things, this group meets weekly online to continuously exchange information, evaluating new circumstances and recent flooding episodes.
- ***Expert panel***: This group partly consists of 13 members of the KomNetAbwasser, who supported the research project in an independent project funding. The group is supplemented by representatives of the Detmold district government and the North Rhine-Westphalian Environmental Agency, which funded the research project.
- ***Pioneer Panel***: This group includes 5 members of the expert panel who, as pioneers, have already helped to develop and implement essential measures on site independently.

The user and the expert panel (all members in North-Rhine-Westfalia are listed in Figure 1) played a central role in terms of quality assurance. Further data on the members of the expert panel and their experience with recent heavy rainfall events are listed in Table 1.

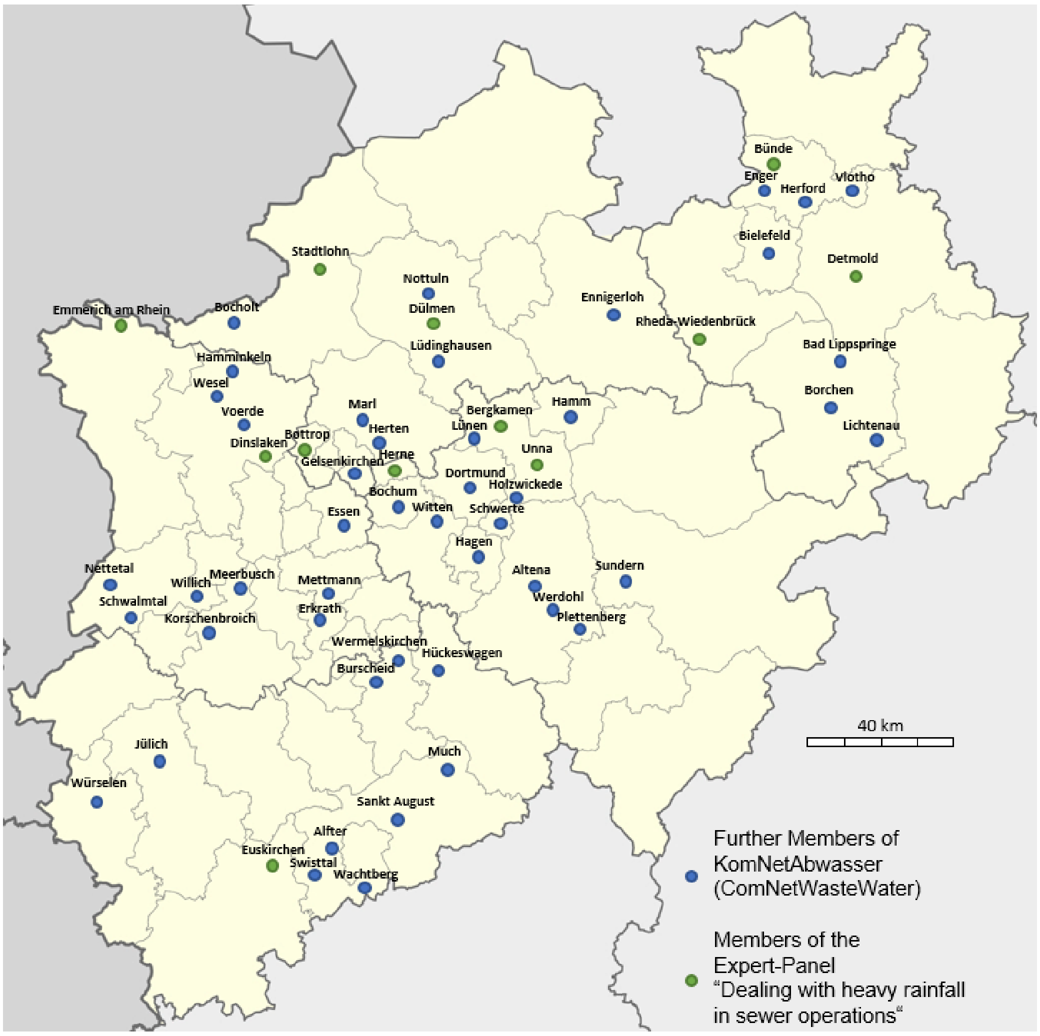

Figure 1. KomnetAbwasser members (including expert panel).

Table 1 displays information on heavy rainfall events, mainly gathered from press reports, recorded at each of the locations involved within this project. Unfortunately, due to the random nature of the latest events and the locations not in the near proximity of the stations available, accurate rainfall datasets are not available yet. As displayed, the population density of the participating municipalities ranged between 252 and 3031 inhabitants/km^2, so both rural and densely populated municipalities were represented. Within the framework of the research project and in the course of the current activities in the aftermath of the catastrophic rainfall events occurring in Germany during the summer of 2021 [56], the following three scenarios were distinguished: (i) stormwater drainage; (ii) dealing with heavy rainfall; and (iii) dealing with catastrophic rainfall. The methodological procedure for each of these three focal points is explained below. As available in the literature [57–59], flood risk is a result of the combination of flood hazard and flood vulnerability [60–62]. Flood risk emerges from the convolution of the probability of inundation (i.e., flood hazard) and the probability of associated negative consequences for the environment, economic activity, and human health (i.e., flood vulnerability).

Table 1. Municipal members of the expert panel dealing with rainfall during recent years.

City	Heavy Rainfall Events Recorded	Type of Operation	Area [km²]	Population	Population Density (Inhabitants per km²)
Bergkamen	**18/19.09.2014 (70 L/m² in 60 min)**	Municipal enterprise/Eigenbetrieb	44.9	48,829 (31 December 2017)	1065
Bottrop	**27.05.2018 (46.3 L/m² in 30 min)** 23/24.06.2016 07.06.2016, 30.05.2016, **23.05.2012 (41.8 mm)** 18.08.2011, 28.04.2011, 14.11.2010, 17.07.2010, 23.07.2009	Managed by the municipality/Regietrieb	100.6	117,364 (31 December 2017)	1164
Bünde	23/24.06.2016 01.06.2016 29/30.07.2014 10.07.2014	Public law institution/AöR	59.3	45,712 (31 December 2017)	769
Detmold	20.07.2017 06.09.2014 26.08.2010 21.08.2007 08.06.2003	Managed by the municipality/Regietrieb	129.39	74,353 (31 December 2017)	578
Dinslaken	**30.05.2016 (70 L/m² in 60 min)** 03.07.2009 10.06.2003	Managed by the municipality/Regietrieb	47.66	67,489 (31 December 2017)	1.415
Dülmen	01.06.2018 **20.06.2013 (65 L/m² in 180 min)** 01.05.2004	Quasi-public utility/Eigenbetriebsähnliche Einrichtung	184.83	46,507 (31 December 2017)	252
Emmerich on the Rhine	15.08.2015 23.05.2012 31.10.1998	GmbH	80.4	30,845 (31 December 2017)	385
Euskirchen	20.08.2002 03.06.2000	Managed by the municipality/Regietrieb	139.49	57,715 (31 December 2017)	407
Herne	20.06.2013 23.07.2009 **03.07.2009 (71.6 mm)** 10.06.2003	GmbH & Co. KG	51.42	156,490 (31 December 2017)	3.031
Rheda-Wiedenbrück	18.08.2011 21.08.2007	Municipal enterprise/Eigenbetrieb	86.72	48,685 (31 December 2017)	553
Stadtlohn	**20.06.2013 (80 L/m² in 90 min)**	Managed by the municipality/Regietrieb	79.25	20.367 (31 December 2017)	257
Unna	23.05.2012 28.07.2008	Quasi-public utility/Eigenbetriebsähnliche Einrichtung	88.56	57,158 (31 December 2017)	667

2.2. Scenario 1: Stormwater Drainage (Design Rainfall)

These are mainly regular recurring tasks and activities that any sewerage company needs to maintain to ensure the usual performance of the networks, and these are derived from the general legal and technical requirements for sewerage operation. These tasks are generally organized independently and are the responsibility of the wastewater company.

All regular recurring tasks and activities of sewer operation according to the state of the art (listed in Table 2) are also usually examined for their relevance to heavy rainfall prevention. The legal regulations of Germany's most populous federal state (North Rhine-

Westphalia, approximately 18 million inhabitants) were used as an example and discussed and evaluated with the expert panel.

Critical operating points were already identified from the experience of the standard operation "stormwater drainage", e.g., cleaning-intensive sewer sections, frequently flooded areas, sensitive pumping stations operating at full capacity. These operating points were then included in further consideration of the study focusing on dealing with heavy rainfall.

2.3. Scenario 2: Dealing with Heavy Rain

These are recurring tasks of sewer operations that are related to irregular heavy rainfall events that can no longer be handled by the sewer network, but require regulated surface runoff. These tasks are usually designated by the technically competent wastewater companies and must be borne by the municipality and its specific departments.

The core of the research project undertaken and analysed in this manuscript was the development of continuous improvement for the tasks of preparation, warning, management, and aftercare in the event of heavy rainfall. The basic procedure was based on the requirements of EN 752 (Section 6.4.4.5 of this document "*Contingency and emergency plan*").

This approach aims to learn from heavy rain events and to continuously improve the knowledge of the system behaviour and the necessary measures. In addition, all phases of the process should also be practiced through regular training of the operating personnel and, if necessary, should also be continuously adapted to changing boundary conditions, as they may arise, for example, through new equipment purchases, personnel turnover, organizational adjustments in the company or the reconstruction of the network structure (Figure 2).

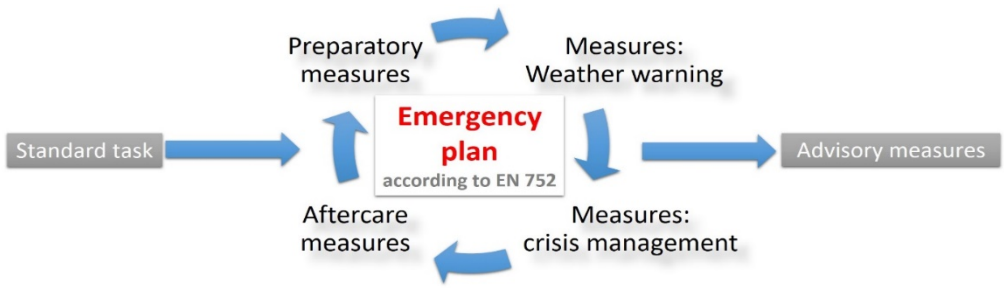

Figure 2. The process of "dealing with heavy rainfall".

Workshops were held with staff involved in the management of the sewer operation and sewer maintenance, and the aim of these meetings was to gather the knowledge of the employees about critical points in the urban area during heavy rainfall events and, on this basis, to jointly develop priority lists and contents for control and maintenance lists. Each workshop lasted two to four hours and was held at the sewer company on site, i.e., at the depot or the sewage treatment plant. This was decided so as to make the employees interviewed feel comfortable within their familiar and pleasant working environment. In addition, this allowed the project team to inspect and document the equipment available for heavy rain prevention and management. Furthermore, each workshop was split into two parts: firstly, the project's objectives and results were presented. Then, city maps were used to identify and mark the flooding focal points from staff's experience. These flooding focal points were matched with the operating points of the sewer network. Subsequently, a discussion among staff was conducted to prioritize the operating points (pump stations, pipe culverts, street drains, etc.).

Organizational procedures and responsibilities are crucial during heavy rainfall events and emergency plans need to be established as a priority. For example, in the event of a heavy rainfall event outside office hours, it could be required that immediate measures are to be managed independently by the head on-call duty staff, until they hand over the management to another person, e.g., the head of sewer operations. Furthermore, preparatory measures include, in particular, the organisation of procedures and reporting routes. Access requirements, including interfaces to other stakeholders' offices, are identified and fixed in writing in contingency and emergency plans because the creation of master lists for immediate measures to be taken in the event of storm warnings is also an essential part of precautionary measures. Pipe culverts, special structures and, if necessary, road drains that should be checked and, if necessary, cleaned before a heavy rainfall event, should be listed and recorded. In addition, key infrastructure should be prioritised in order to be able to take rapid and targeted measures in the event of heavy rainfall, with the purpose of maintaining operations as efficiently as possible, and to keep the extent of damage as minimum as possible. Additionally, an increased standby service should be organised to ensure that sufficient personnel are available to cope with heavy rainfall.

If a weather warning is reported, the reinforced standby service should be activated and coordinated. Employees from sewer operations and other employees from the administration should be put on standby. By doing this, the operations team is ready to be available outside their normal service hours in order to carry out necessary measures. The control list should then be actioned after the weather warning and the work carried out documented, involving (i) emergency measures during crisis management; (ii) aftercare measures; and (iii) advisory measures.

If a heavy rainfall event actually occurs, any incidents that occur must be documented and classified according to the prioritisation list. With this help, fast, efficient, targeted measures for coping with the event can be carried out. If necessary, contact will be sought with the control centre in order to carry out assistance missions for the city community.

As aftercare, faults in the sewage system identified during the rainfall event should be documented in an accident register. In addition, further emergency activity in the urban area (e.g., fire brigade operations) should be archived and the experience of the employees deployed collected. Based on the documentation of the measures taken and incidents in the urban area, a joint review of the precautionary measures should be carried out, as possible ways to optimise future responses are generally derived from this.

The ability to share the knowledge and expertise gained by sewer operations with other relevant departments is essential, through continuous exchange, so that sewer network operators can contribute significantly to municipal flood prevention. These competencies include, among other things, writing up operational experience on emergency water pathways, barriers, and retention in urban areas and presenting it in lists or risk maps. For example, the road construction department and the fire brigade can be informed by the sewer network operator about defective road drains requiring attention in the event of heavy rainfall.

Finally, zones particularly at risk in the event of heavy rainfall/flooding in urban areas should be surveyed and marked (e.g., underpasses, pipe culverts, bridges, special locations of underground car parks). The selection of endangered areas can be then recorded on maps and used to calibrate and validate the performance of numerical models in continuous development.

2.4. Scenario 3: Dealing with Catastrophic Rainfall

These are tasks related to a single event that entails catastrophic consequences, especially personal injury and high property damage, which should only affect a generation in rare individual cases, if at all.

During and immediately after the catastrophic rainfall events in July 2021, the members of the Municipal Network Wastewater KomNetAbwasser on the expert panel were faced with the question of how to organize rapid supra-regional assistance for the affected wastewater companies in such an extreme situation. The following process was established:

- ***Pilot operations***: Direct contact with the most affected members of KomNetAbwasser, which had already been reported in the media (e.g., what happened to the cities of Hagen and Altena). Direct interaction between the known contact persons and coordination of first relief operations.
- ***Public relations***: Dissemination of the experiences from the pilot interventions via the press and direct call to all members of KomNetAbwasser to concretise offers of assistance.
- ***Data collection***: Establishment of a structured data pool with information from helpers on mobile numbers, available personnel and equipment, possible deployment times as well as information from those seeking help on mobile numbers and starting point in the town.
- ***Matching of those offering and seeking help***: The main contact persons in suitable wastewater companies should be connected with each other, usually via their mobile numbers. Further coordination should take place directly in 1:1 contact.
- ***Monitoring***: The operations were centrally documented by the IKT and the lists of resources still available were constantly updated. During the online weekly KomNetAbwasser meetings, both the IKT and the helpers reported on the current situation so that the experience gained in the field could be used directly for improvements.

Parallel to the above-mentioned process, the findings and contact options were also passed on to the crisis teams of the districts deployed for immediate hazard prevention with the support of the North Rhine-Westphalian State Environmental Agency. This is a procedure that should be followed by adjacent municipalities in case of similar catastrophic events.

3. Results

3.1. Stormwater Drainage

Based on the legal regulations, all standard tasks of sewer operation were scrutinized to determine whether they contribute to heavy rainfall prevention. Table 2 shows an overview of the regular tasks according to the NRW Self-Monitoring Ordinance [63] in conjunction with the requirements from the corresponding circular on the operation of sewer networks [64], which could be used as a comparison with regulations in other countries. The points of particular importance for heavy rainfall prevention are marked accordingly (indicated as X within Table 2). Successful prevention of heavy rainfall was based on criteria according to the NRW Self-Monitoring Ordinance and the NRW Operations, and all the tasks involved were summarised in Table 2. Below, the most crucial points are highlighted and discussed separately and explained accordingly.

Deposits in wastewater structures reduce the hydraulic cross-section or the capacity of these structures, which means that the intended drainage and storage capacities can be weakened. Unfortunately, during heavy rainfall events, reduced capacity can have a particularly detrimental effect [65–68]. Deposits that exceed a height specified in the NRW circular must therefore be removed by cleaning or clearing, and this procedure could be implemented as prevention in those municipalities where it is not adopted at the moment because cleaning the structures involved contributes to the prevention of heavy rainfall. As shown in Table 2, cleaning measures should be regularly adopted within (i) sewers (No. 1.1); (ii) siphons (No. 3.1); (iii) stormwater overflows (No. 7.2); (iv) stormwater clarification, stormwater overflow and stormwater detention basins, storage sewers (No. 8.1) and discharge structures (No. 9.2).

Table 2. Operational measures of the wastewater utility with contribution to flood prevention: X.

	Institution	No.	Result of the Inspection According to	Measure	Implementation	Post
1	Sewers (incl. the integration of the connecting sewers)	1.1	Deposits with a height >15% of the profile height (estimated) up to DN 1000 greater than DN 1000	Cleaning	according to cleaning schedule, otherwise within 3 months 6 months	X
		1.2	Impairment of the structural or operational condition of a sewer section	Rehabilitation	/	☐
		1.3	Impairment of stability	/	without delay	☐
		1.4	Impairment of the function of the sewer section	/	within 5–10 years	☐
		1.5	Exfiltration	/	immediately until within 10 years	☐
		1.6	Rat infestation	Combat	according to rat control plan	☐
2	Shaft structures	2.1	Damage to manhole covers, mud flaps, crampons	Replacement, repair	without delay	X
		2.2	Leakages at the manhole body	Waterproofing	like sewers	☐
		2.3	defective general condition	Repair	sewer rehabilitation	☐
3	Inverted Siphons	3.1	Deposit with backwater	Eviction	without delay	X
		3.2	Malfunctions of the facility	Removal	without delay	X
		3.3	Visible damage to the material	Repair	like channels	☐
4	Wastewater and flood pumping stations	4.1	Faults in the function of the pumps, pump control, signalling and alarm devices, remote monitoring and remote-control systems.	Repair, exchange	without delay	X
5	Pressure lines without pressure network	5.1	Visible damage (e.g., corrosion)	Repair, Renewal	case-by-case decision	☐
		5.2	defective fittings for venting, draining, pressure surge protection, control devices	Repair, exchange	without delay	X
6	Pressure and vacuum drainage networks	6.1	Repair of defects and damage in accordance with the manufacturer's specifications			☐
7	Stormwater overflows	7.1	Error in the quantity control	New setting, repair	without delay	X
		7.2	Throttle blockage	Cleaning	without delay	X
		7.3	Measuring device	New hire		☐
8	Stormwater clarification and overflow basins, storage sewers, stormwater detention basins	8.1	Deposition in individual subareas >20 cm height (estimated)	Clearance	within 1 week in dry weather	X
		8.2	Error in the throttle/flow rate control	New setting, repair	without delay	X
		8.3	Error in the function of the mach system	Repair, exchange	without delay	X
		8.4	Faults in the function of mechanical equipment such as fittings, cleaning equipment, etc.	New setting, maintenance, repair	without delay	X
		8.5	faulty measuring equipment	Calibration, readjustment	within 1 month	☐
		8.6	Deviation of the throttle water quantity >20% of the setpoint	Rehabilitation of the throttle system	Within a year	X
		8.7	Visible damage to the material	Repair	like channels	☐
9	Discharge structures	9.1	Visible damage to the material	Repair	within 5 years	☐
		9.2	Deposits with a height > 5% of the cross-sectional height (estimated)	Eviction	within 3 months	X
10	Flood closures	10.1	Defects in the function of the closure organs	Repair	without delay	X
11	Separation systems	11.1	Condition in need of emptying	Emptying	without delay	X
		11.2	defective general condition	Repair, exchange	without delay	☐
12	Emergency power generators	12.1	Error in the function	Repair, exchange	without delay	X

According to the circular of the Ministry of the Environment "Requirements for the operation and maintenance of sewerage networks" (1995). Supplementary literature source: https://komnetabwasser.de/blog/kh-170327-starkregen-und-ueberflutungsvorsorge-im-kanalbetrieb/, accessed on 3 September 2021.

Additionally, when dealing with manhole structures, damage to manhole covers and strainers could imply that they cannot be opened with short notice in flooded streets and areas in order to temporarily discharge more surface water into the sewer network. If manhole structures are also used as inlet points for rainwater as planned (e.g., manhole structure with grating at low points), damage to covers and strainers can reduce the discharge capacity. Therefore, it is suggested to replace damaged manhole covers and strainers and, if necessary, each sewer company should monitor their status. As shown in Table 2, the repair of manhole covers can be found within the category No. 2.1 (shaft structures).

Malfunctions or even failures of wastewater and flood pumping stations can have a major impact with flooding consequences, especially during heavy rainfall. If signal and alarm devices fail, the sewer operation may not be informed or not precisely informed about pump malfunctions and cannot react appropriately. The same applies to the failure of remote monitoring (remote data transmission). If a malfunction of the remote monitoring occurs, manual intervention at the pumps on site is necessary, which leads to delays. However, particularly in the case of heavy rainfall, sewerage companies need to react as quickly as possible depending on the situation. Therefore, the repair or replacement of faulty system parts contributes to heavy rainfall prevention. For rapid responses to incidents, quick deliveries or stockpiling of important replacement components can be helpful. Table 2 discusses wastewater and flood pumping stations under category No. 4.1 (sewage and flood pumping stations).

In case of malfunctions of culverts, flow rates can be reduced. This can also occur with pressure pipes if they cannot be operated optimally, for example due to faulty venting. This can exacerbate the problem of backwater, overtopping, and sewer-induced flooding in sewer system at the rear or in pumping stations in the event of heavy rainfall. Therefore, these measures contribute to heavy rainfall prevention in sewer operations as shown in Table 2, for No. 3.2 (siphons) and 5.2 (pressure lines without pressure network).

The throttle discharge of spillways and storage structures can also influence the behaviour of the sewer system during heavy rainfall. If the correct function of the throttle is not guaranteed in the case of a rainwater overflow, either too much or too little water is discharged into the receiving watercourse or too much or too little water is conveyed to the connected sewer system. A deviation of the throttle discharge can lead to a backwater into the sewer system, thus reducing discharge capacities of the sewers in the case of heavy rainfall, especially if the discharge quantity is too low in the case of storage structures (without relief). In addition, if the available storage volume of the structures is exceeded, an undesirable discharge and overflow of the basin may occur if the inflow volume is greater than the volume of water that can be discharged (input > output). A deviation of the throttle discharge, if the discharge volume is too high, can lead to an overload of the downstream sewer network and block volumes there which buffer a heavy rain event.

The measures of readjustment, repair or, if necessary, replacement of a throttle device, as well as its cleaning, are therefore evaluated as measures that contribute to heavy rainfall prevention and can be processed by the sewer companies if necessary. However, this also depends on the complexity of the throttle device and the qualification of the personnel of the sewer company. Therefore, the following measures in Table 2 contribute to heavy rainfall prevention in sewer operations: (i) stormwater overflows (No. 7.1 and 7.2); and (ii) stormwater clarification, stormwater overflow and stormwater detention basins, storage sewers (No. 8.2 and 8.6).

If the function of the existing mechanical or mechanical cleaning equipment of storm water tanks, storm water overflows, storm water retention tanks and storage sewers is defective, cleaning cannot be carried out by the sewerage company. Therefore, maintenance or repair of the cleaning equipment must be carried out immediately as highlighted in Table 2 for points 8.3 and 8.4 (stormwater clarification, stormwater overflow and stormwater detention basins, storage sewers).

Flood gates are also particularly important for smaller watercourses, which can rise rapidly during heavy rainfall events, and water pushing back from the watercourses can lead to backwater in the sewer network and thus to sewer-induced flooding. Therefore, the repair of closure elements of flood gates contributes to heavy rainfall prevention in sewer operations (flood closures: No. 10.1).

Depending on the type of system, the emptying of separation systems is relevant for the prevention of heavy rainfall from an environmental point of view. For example, in the case of decentralised rainwater treatment chambers, the emptying of separation systems can prevent environmentally harmful light substances from entering the sewer network and water bodies as a result of an overflow. Therefore, the emptying of separation systems contributes to heavy rainfall prevention in sewer operation (separation systems: No.11.1).

Especially for the operation of pumping stations in the event of a power failure caused by heavy rain, the reliable functioning of emergency power generators is crucial. For this purpose, mobile devices are often kept in stock by the sewer companies. Keeping the available fixed and mobile emergency power generators in an operational condition is therefore also to be assigned to the obligatory tasks with a contribution to heavy rainfall prevention. Therefore, the following measure in Table 2 contributes to the prevention of heavy rainfall in the sewer system: emergency generators (No. 12.1).

3.2. Heavy Rain

In the research project conducted within the municipalities involved presented in Section 2.1 (Table 1), the essential operational and organisational measures for implementing the model shown in Figure 2 were worked out in detail. Table 3 displays an overview of each sub-category identified for each specific main topic.

Table 3. Dealing with heavy rainfall—overview of essential measures in sewer operation.

No.	Measures in Sewer Operation *
I	**Standard tasks with contribution to heavy rainfall prevention according to SüwVO Abw NRW**
1.	Implement and document self-monitoring (cf. § 5 Para. 1 SüwVO Abw).
2.	Keep mobile equipment and emergency tools ready for use (cf. § 3 (2), § 5 Operational Decree).
3.	Clarify responsibilities and contact lists (cf. § 4 (2) SüwVO Abw; § 3 (2) Operational Decree).
4.	Activate and coordinate on-call duty (cf. § 3 para. 2 Operational Decree)
5.	Visual inspection of the operating points after heavy rainfall (cf. § 4 (2) Operating Decree)
II.	**Precautionary measures for rare and extreme heavy rains**
1.	Communicate higher-level disaster control plans in sewer operations
2.	Create incident and emergency plans, service and operating instructions, risk assessment
3.	Organize increased heavy rainfall on-call service
4.	Install and introduce weather forecasting instrument
5.	Introduce checklist for immediate measures in case of severe weather warnings
6.	Operational hazard analysis with prioritization of structures, comparison of heavy rainfall map
7.	Carry out coordination with the flood protection plan
8.	Conduct regular drills on emergency operations and behaviour during heavy rainfall
II.	**Precautionary measures for rare and extreme heavy rains**
1.	Communicate higher-level disaster control plans in sewer operations
2.	Create incident and emergency plan, service and operating instructions, risk assessment
3.	Organize increased heavy rainfall on-call service
4.	Install and introduce weather forecasting instrument
5.	Introduce checklist for immediate measures in case of severe weather warnings
6.	Operational hazard analysis with prioritization of structures, comparison of heavy rainfall map
IIIa.	**Immediate measures as soon as a severe weather event is forecast**
1.	Check severe weather warning, compare with other forecasts if necessary.
2.	Activate and coordinate increased heavy rainfall on-call service
3.	Work through checklist of prioritized control and maintenance tasks
IIIb.	**Immediate measures in the emergency situation (during/shortly after severe weather event)**
4.	Prioritize and process incidents

5.	Establish communication with fire brigade control centre, provide coordinated assistance if necessary.
6.	Inspect neuralgic points of the sewer network, maintain and clean if necessary
V	**Organisational aftercare measures**
1.	Compile and publish emergency aid passport and resource lists
2.	Draw up lists/risk maps of endangered localities, watercourses, emergency waterways, barriers, retention according to operational experience and prepare them in writing for other departments.
3.	Inform street planning about precarious street processes (priority list)—if necessary, coordinate support services for control and cleaning
4.	Provide guidance on materials for heavy rainfall information and advice for citizens.

* Note: Regular review and optimization of the measures is necessary. Higher-level disaster management plans are reviewed every two years; adjustments can be taken over from there, e.g., updated contact lists and reporting channels.

For further support, a series of documents was developed and made available [69] for all the German municipalities involved, and for any other municipality across the world seeking assistance and guidance. These documents include (and can be found at https://www.komnetabwasser.de/arbeitsdokumente/, accessed on 3 September 2021, all documents are in German):

- Checklist "*Heavy Rainfall Management in Sewer Operations*";
- Emergency and incident plan for heavy rain;
- Emergency assistance passport for tools, equipment and personnel deployment;
- Priority list of potentially endangered operating points and localities list.

In addition, structural measures have also been identified that can be implemented directly by the Sewer Operations Department at low cost to improve the robustness of the system in the event of heavy rainfall. These include, for example, the use of hinged and daywater-tight or backwater-proof manhole covers, the protection of culverts and the relocation of power switching devices.

3.3. Catastrophic Rain and Lessons Learnt from the Flood in Summer 2021

Storm BERND devastated parts of North Rhine-Westphalia in the period of 13 to 15 July 2021, in some cases to catastrophic proportions. This resulted in 49 deaths, immense property damage, and great suffering in the southern parts of the state. The Eifel and Bergisches Land regions in particular were affected by extraordinary precipitation with subsequent flooding. Between 19 to 26 July, a total of 13 assistance interventions coordinated by the IKT took place by municipalities for other ones. The map in Figure 3 shows an overview of the affected municipalities; it is possible to observe the links of assistance interventions.

The following key points have been identified following the flooding events that caused severe damage in Germany during summer 2021.

Sewerage companies are very specialised companies with specific responsibilities for protecting and managing existing infrastructure. During a critical event, the measures taken by sewerage companies are aimed at restoring the functionality of the drainage networks in order to protect areas affected by heavy rainfall from future imminent events, because even an event with lower precipitation could have negative effects on a system that is in its recovery phase. This is particularly important, because citizens living in the affected areas are usually very traumatized by catastrophic events and need to be reassured and protected from further mental issues.

Drainage companies are generally not seen by the state crisis teams as direct actors in acute hazard prevention, such as the army, the Red Cross, technical relief organisations and police, but predominantly only as supplementary supporters/helpers. The role as an affected party, which itself needs help and support to repair infrastructure, was hardly seen. Accordingly, it is important to establish direct contact between the wastewater managers of the affected and the assisting municipalities, so that concrete relief operations can be coordinated directly between them.

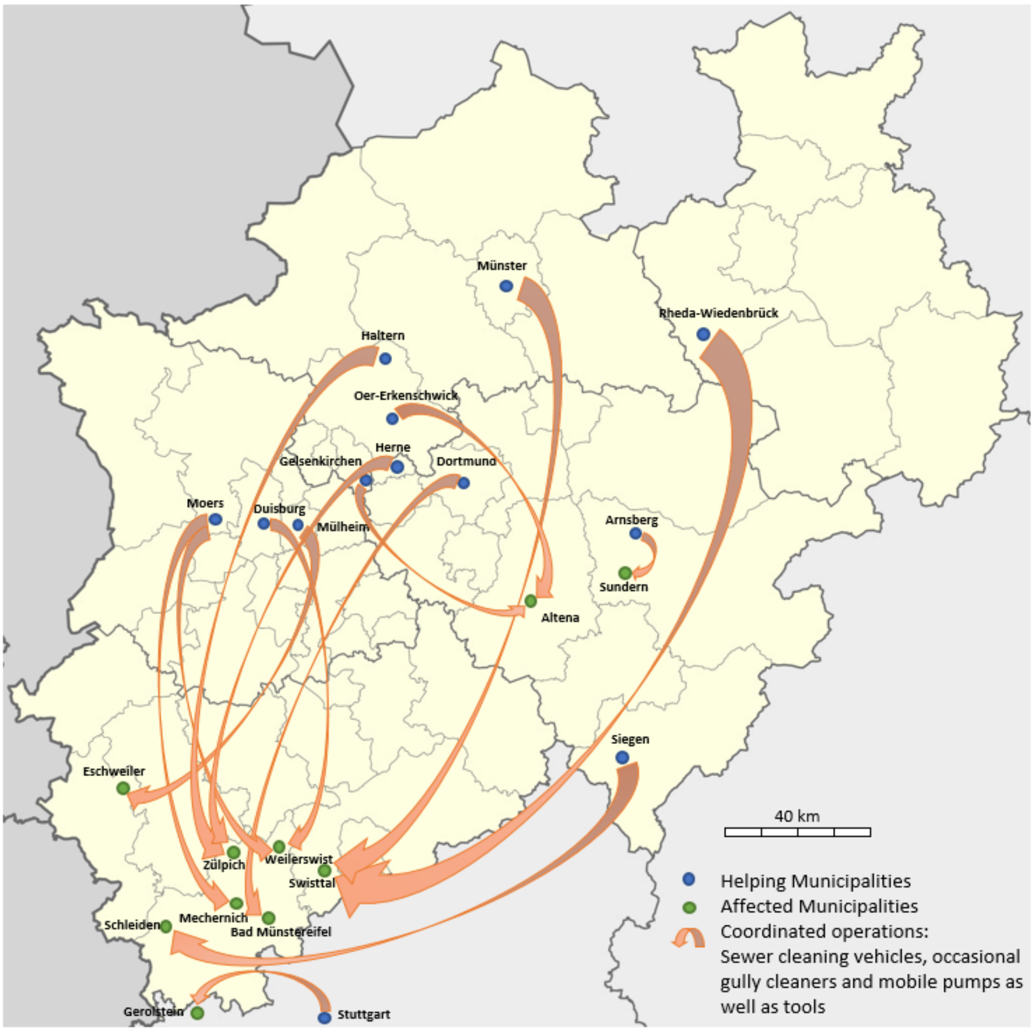

Figure 3. Emergency operations/deployments (first week).

In many cases, contact between the wastewater experts was only possible because those involved in the municipal network KomNetAbwasser have many personal contacts with those affected and potential helpers. Many contacts only came about via mobile phone numbers that were not publicly accessible or rather random social media connections. This shows an immense need for the systematic collection of contact data at the working level, e.g., in the sense of an emergency assistance passport. Optimally, the provision of such data should already be required in legal self-monitoring obligations, and it should be possible to retrieve the data centrally from a trustee office like IKT in the event of a crisis.

Unlike normal heavy rainfall events, which lead to local flooding but not to catastrophic effects, the affected localities were overwhelmed by the speed and force of the catastrophic events. Although those affected were basically prepared for flooding events, due to the initially rather unspecific warnings they did not expect such an extreme exceptional situation, also due to previous experience with lesser events. Thus, private protective measures were usually limited to simple, proven, and well-known measures, such as the protection of material goods by, for example, securing basement rooms. However, this did not do justice at all to the upcoming event and its dangers to human life. In the future, extreme scenarios should be specified in warnings and trained in exercises. Currently existing flood warning systems across the world are not reaching enough people considered at risk, aggravating the impacts when those affected are those most vulnerable over the flood incident cycle. Furthermore, there is a recognition that one size of flood warning will not "fit all" [70], both in terms of the characteristics of the flood e.g., rapid response vs. slow onset and in terms of the difference within communities. Flood warning systems must be integrated to a greater degree with response and recovery, as well as planning and awareness, and even if they are designed considering a technology perspective, communication, trust, and credibility of the sources of warnings must be attended. Municipalities should be prepared for worst case scenarios, like for example flooding at night or even during weekends or bank holidays. Finally, existing flood warnings can see their benefits optimized if linked to awareness raising efforts. Staff should get to know social characteristics of their area and work with local people to raise awareness and do emergency planning because once a warning is issued and received, it is fundamental for it to be understood, acted on to make all the actions effective. A key issue for improving flood warnings is to stop thinking about the warning as an 'end', because they should start a chain of events that will result in people taking action to protect themselves, their family, neighbours or wider community so that there is no threat to life or property.

Many relief operations were only possible because those responsible organized this spontaneously and initially left the legal and commercial processing unresolved, such as labour law conditions and commercial and fee accounting options for the operations. In other cases, assistance could not be activated at all because long decision-making processes led to delays lasting days or even weeks. Here, it seems indispensable to clarify the legal framework for assistance before possible events so that action can be taken quickly in the event of an incident.

While many sewer operators discuss the fact that the operation of strainers under the sewer covers is too costly, these very elements protected the sewers from excessive siltation. In many cases they were filled with sludge and completely closed the sewer access, but this also prevented the inflow of further sludge into the sewer system.

Destroyed heating oil tanks led to large oil inflows into the sewage system. As a result, it was no longer justifiable to walk in manholes and sewers. It is also to be expected that the water bodies will be affected by these inflows. Other waste also collected in the sewers, but there were no suitable temporary storage places for its disposal.

Basically, the organization of relief operations in the event of a disaster needs to be reconsidered. At present, the emergency systems of wastewater utilities are oriented solely to average flooding scenarios, but not to extreme events. This also applies to the holding of network and operational data. In the event of a disaster, all local systems can be destroyed, so that it should be possible to back up essential network data and make it available via simple communication channels, such as printouts and mobile phone information.

In the event of a disaster, the staff of smaller wastewater companies in particular need strategic as well as technical support. Many employees are also privately affected by the event and are physically and mentally hardly able to manage a complex disaster situation in the wastewater company.

3.4. Interpretation of the Findings within the International Context

This study focused on a case study (North-western Germany), however the insights obtained have potential implications for governments and communities across the globe. Flooding events do not follow geopolitical or administrative borders, and as previously mentioned, unfortunately tent to involve various sectors of society when they occur. This work confirmed that it is therefore not possible to identify a unique individual or organization that should be in charge to analyse, evaluate, and manage flood risk in society alone. On the other hand, this work demonstrated that it must instead be jointly governed by a net of different actors who are not independent of each other, but dependent on various resources and affected by the decisions and actions of others. Therefore, municipalities across the world cannot be unified under a unique group because they are all relatively large and complex organizations incorporating several departments with a broad range of responsibilities. The guidelines and procedures provided in this study could be a starting point for a better flood risk prevention and management, however it is fundamental for municipalities to investigate what external actors contribute and how they depend on them to achieve these objectives. Municipalities need to reinforce the importance of trust, of expectation to receive support in the moment of need and of willingness to provide it when somebody else requires it, sharing equipment available and working towards growing as a group rather than independently.

Traditional thinking is that resilient societies bounce back from the state they have fallen into after a devastating event. However, based on the lessons learned, instead of viewing the drainage design as a static process and to cope with floods of a certain recurrence, a contemporary interpretation of urban resilience needs to encompass a more flexible and adaptive approach to flood management. A flexible flood management system may be defined as measures for a given level of flooding, but with an integrated ability to modify it later. Urban resilience should be viewed as an adaptive process where society continuously learns how to cope with changing socioeconomic conditions and urban land use, as well as a changing climate.

4. Conclusions

Dealing with pluvial flooding is a major concern that all municipalities across the world are facing constantly nowadays. Due to continuous flooding events, despite several improvements in this field, there are still lessons to be learnt. With this paper, the IKT aimed to support this need, providing further insights discovered during heavy flooding events that happened in Germany in 2021 and developing a series of new guidelines to be followed. The key aspects to be drawn can be summarized as follows:

- The task of stormwater drainage is currently still underrepresented in the legal and technical requirements for the operation of the structures. For example, the self-monitoring ordinances in Germany mostly only regulate the regular inspection of the usual sewer network structures, such as manholes, pipes, and control elements. However, with the increased development of sponge city concepts to adapt to the consequences of climate change, numerous new construction elements are being developed and are already in use today, known under the collective term SUDS—Sustainable Urban Drainage Systems, such as green roofs. Operational requirements must also be set for these elements and, if necessary, must also be legally fixed. Scientific studies on the construction and operation of these systems can provide the necessary basis.
- Dealing with heavy rainfall that can no longer be absorbed by the sewage system requires better knowledge of the surface runoff that then occurs and its interaction with the sewage system. The interface between the sewer and the surface is of particular importance. This concerns the performance of inlets and manhole covers as well as their modelling in numerical simulation programmes. Here, further investigations are useful for better understanding these interactions.
- Dealing with catastrophic rains: ultimately, the sheer volume of runoff that occurs during a catastrophic rain and the foreign objects carried along by it led to the property damage and personal injury observed. Direct protection against these masses of water rarely seems possible. It is therefore all the more important to better understand the runoff formation and concentration at the surface occurring in the entire catchment area, because these initially still low runoffs only lead to the large dangerous water masses in total. Accordingly, reliable heavy rainfall risk maps can only be determined if the runoff formation in the area is known with certainty. Studies that precisely quantify runoff formation and concentration, both in-situ and in the laboratory, are therefore urgently needed.

The above-mentioned water management issues require a clever combination of laboratory tests, numerical analyses, and observations in reality. Laboratory tests on a 1:1

scale can supplement real observations with important, additional extreme scenarios, and thus ensure the selection of suitable parameters for the numerical simulation [2].

Author Contributions: Conceptualization, B.B. and M.Sal. (Mirko Salomon), M.Sch. (Marco Schlüter); methodology, B.B., M.Sal. (Mirko Salomon), M.Sch. (Marco Schlüter); validation, M.Sal. (Mirko Salomon), M.Sch. (Marco Schlüter); formal analysis, M.Sal. (Mirko Salomon), M.Sch. (Marco Schlüter); investigation, M.Sal. (Mirko Salomon), M.Sch. (Marco Schlüter); resources, B.B.; data curation, M.Sal. (Mirko Salomon); writing—original draft preparation, B.B., M.R.; writing—review and editing, B.B., M.R.; supervision, B.B.; project administration, M.Sal. (Mirko Salomon); funding acquisition, B.B. All authors have read and agreed to the published version of the manuscript.

Funding: The research was funded by 13 municipal sewer network operators lead by the city of Rheda-Wiedenbrück, and supported by additional funds from the Ministry for Environment, Agriculture, Conservation and Consumer Protection of the State of North Rhine-Westphalia (Grant N. AZ 54.08.0854.028/SR-01/17-RW).

Acknowledgments: We would like to thank the participating municipalities for their technical support within the framework of the research project and for their special commitment during the emergency measures during the heavy rainfall events in July 2021.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Rubinato, M.; Martins, R.; Kesserwani, G.; Leandro, J.; Djordjevic, S.; Shucksmith, J. Experimental calibration and validation of sewer/surface flow exchange equations in steady and unsteady flow conditions. *J. Hydrol.* **2017**, *552*, 421–432. https://doi.org/10.1016/j.jhydrol.2017.06.024.
2. Rubinato, M.; Lashford, C.; Goerke, M. Advances in experimental modelling of urban flooding. In *Water-Wise Cities and Sustainable Water Systems: Concepts, Technologies, and Applications. IWA Publishing*; Chapter 9; 2020; p. 235.
3. Willner, S.N.; Otto, C.; Levermann, A. Global economic response to river floods. *Nat. Clim. Change* **2018**, *8*, 594. https://doi.org/10.1038/s41558-018-0173-2.
4. Reynaud, A.; Aubert, C.; Nguyen, M.H. Living with Floods: Protective Behaviours and Risk Perception of Vietnamese Households. *Geneva Pap. Risk Insur.-Issues Pract.* **2013**, *38*, 547–579. https://doi.org/10.1057/gpp.2013.16.
5. Ferdous, M.R.; Wesselink, A.; Brandimarte, L.; Slager, K.; Zwarteveen, M.; Di Baldassarre, G. The Costs of Living with Floods in the Jamuna Floodplain in Bangladesh. *Water* **2019**, *11*, 1238. https://doi.org/10.3390/w11061238.
6. Abaya, S.W.; Mandere, N.; Ewald, G. Floods and health in Gambella region, Ethiopia: A qualitative assessment of the strengths and weaknesses of coping mechanisms. *Glob. Health Action* **2009**, 2, 1–10.
7. Haile, A.T.; Kusters, K.; Wagesho, N. Loss and damage from flooding in the Gambela region, Ethiopia. *Int. J. Glob. Warm*. **2013**, *5*, 483–497.
8. Zhou, Q.; Leng, G.; Peng, J. Recent Changes in the Occurrences and Damages of Floods and Droughts in the United States. *Water* **2018**, *10*, 1109. https://doi.org/10.3390/w10091109.
9. Zúñiga, E.; Magaña, V.; Piña, V. Effect of Urban Development in Risk of Floods in Veracruz, Mexico. *Geosciences* **2020**, *10*, 402. https://doi.org/10.3390/geosciences10100402.
10. Areu-Rangel, O.S.; Gómez, L.C.; Bonasia, R.; Espinosa-Echavarria, V.J. Impact of Urban Growth and Changes in Land Use on River Flood Hazard in Villahermosa, Tabasco (Mexico). *Water* **2019**, *11*, 304.
11. Valdes-Manzanilla, A. Effect of Climatic Oscillations on Flood Occurrence on Papaloapan River, México, during the 1550–2000 Period. *Nat. Hazards* **2018**, *94*, 167–180.
12. Environment Agency. *Flood and Coastal Erosion Risk Management Long-Term Investment Scenarios (LTIS)*; Environment Agency: Bristol, UK, 2014.
13. Adaptation Sub-Committee. *Climate Change—Is the UK Preparing for Flooding and Water Scarcity*; Committee on Climate Change: London, UK, 2012.
14. Nguyen, H.D.; Fox, D.; Dang, D.K.; Pham, L.T.; Viet Du, Q.V.; Nguyen, T.H.; Dang, T.N.; Tran, V.T.; Vu, P.L.; Nguyen, Q.H.; et al. Predicting Future Urban Flood Risk Using Land Change and Hydraulic Modeling in a River Watershed in the Central Province of Vietnam. *Remote Sens.* **2021**, *13*, 262. https://doi.org/10.3390/rs13020262.
15. Majidi, A.N.; Vojinovic, Z.; Alves, A.; Weesakul, S.; Sanchez, A.; Boogaard, F.; Kluck, J. Planning Nature-Based Solutions for Urban Flood Reduction and Thermal Comfort Enhancement. *Sustainability* **2019**, *11*, 6361. https://doi.org/10.3390/su11226361.
16. Fenner, R.; O'Donnell, E.; Ahilan, S.; Dawson, D.; Kapetas, L.; Krivtsov, V.; Ncube, S.; Vercruysse, K. Achieving Urban Flood Resilience in an Uncertain Future. *Water* **2019**, *11*, 1082. https://doi.org/10.3390/w11051082.
17. Valeo, C.; He, J.; Kasiviswanathan, K.S. Urbanization under a Changing Climate–Impacts on Hydrology. *Water* **2021**, *13*, 393. https://doi.org/10.3390/w13040393.
18. Yao, L.; Chen, L.; Wei, W. Exploring the Linkage between Urban Flood Risk and Spatial Patterns in Small Urbanized Catchments of Beijing, China. *Int. J. Environ. Res. Public Health* **2017**, *14*, 239. https://doi.org/10.3390/ijerph14030239.

19. Rubinato, M.; Nichols, A.; Peng, Y.; Zhang, J.; Lashford, C.; Cai, Y.; Lin, P.; Tait, S. Urban and river flooding: Comparison of flood risk management approaches in the UK and China and an assessment of future knowledge needs. *Water Sci. Eng.* **2019**, *12*, 274–283. https://doi.org/10.1016/j.wse.2019.12.004 .
20. Kesserwani, G.; Seungsoo, L.; Rubinato, M.; Shucksmith, J. Experimental and numerical validation of shallow water flow around a surcharging manhole. In Proceedings of the 10th Urban Drainage Modelling Conference, Mont-Sainte Anne, QC, Canada, 20–23 September 2015.
21. Shao, S.; Luo, M.; Rubinato, M.; Zheng, X.; Pu, J.H. Advances in Modelling and Prediction on the Impact of Human Activities and Extreme Events on Environments. *Water* **2020, ISBN 978-3-03936-803-7**. https://doi.org/10.3390/books978-3-03936-803-7.
22. Kitsikoudis, V.; Erpicum, S.; Rubinato, M.; Shucksmith, J.; Archambeau, P.; Pirotton, M.; Dewals, B. Exchange between drainage system and surface flows during urban flooding: Quasi-steady vs. dynamic modelling. *J. Hydrol.* **2021**, *602*, 126628. https://doi.org/10.1016/j.jhydrol.2021.126628.
23. Sardooi, E.R.; Azareh, A.; Mesbahzadeh, T.; Sardoo, F.S.; Parteli, E.J.; Pradhan, B. A hybrid model using data mining and multi-criteria decision-making methods for landslaide risk mapping at Golestan Province, Iran. *Environ. Earth Sci.* **2021**, *80*, 487. https://doi.org/10.1007/s12665-021-09788-z.
24. Cao, Y.; Wei, X.; Fan, W.; Nan, Y.; Xiong, W.; Zhang, S. Landslide susceptibility assessment using the Weight of Evidence method: A case study in Xunyang area, China. *PLoS ONE*, **2021**, *16*, e0245668. https://doi.org/10.1371/journal.pone.0245668.
25. Hegger, D.L.; Driessen, P.P.; Wiering, M.; van Rijswick, H.; Kundzewicz, Z.W.; Matczak, P.; Crabbe, A.; Raadgever, G.T.; Bakker, M.H.; Priest, S.J.; et al. Toward more flood resilience: Is a diversification of flood risk management strategies the way forward? *Ecol. Soc*. **2016**, *21*, 52. https://doi.org/ 10.5751/ES-08854-210452.
26. Liao, K.H. A theory on urban resilience to floods—A basis for alternative Planning Practices. *Ecol. Soc.* **2012**, *17*,(4), 48. https://doi.org/10.5751/ES-05231-170448.
27. Keating, A.; Campbell, K.; Szoenyi, M.; McQuistan, C.; Nash, D.; Burer, M. Development and testing of a community flood resilience measurement tool. *Nat. Hazards Earth Syst. Sci*., **2017**, *17*, 77–101. https://doi.org/10.5194/nhess-17-77-2017.
28. Lhomme, S.; Serre, D.; Diab, Y.; Laganier, R. Analyzing resilience of urban networks: A preliminary step towards more flood resilient cities. *Nat. Hazards Earth Syst. Sci.*, **2013**, *13*, 221–230. https://doi.org/10.5194/nhess-13-221-2013.
29. Restemeyer, B.; Woltjer, J.; van den Brink, M. A strategy-based framework for assessing the flood resilience of cities—A Hamburg case study. *Plann. Theor. Pract*. **2015**, *16*, 45–62. https://doi.org/10.1080/14649357.2014.1000950.
30. Lennon, M.; Scott, M.; O'Neill, E. Urban design and adapting to flood risk: The role of green infrastructure. *J. Urban Des*. **2014**, *19*, 745–758. https://doi.org/10.1080/ 13574809.2014.944113.
31. Schelfaut, K.; Pannemans, B.; Van der Craats, I.; Krywkow, J.; Mysiak, J.; Cools, J. Bringing flood resilience into practice: The FREEMAN project. *Environ. Sci. Pol*. **2011**, *14*, 825–833. https://doi.org/10.1016/j.envsci.2011.02.009.
32. Zevenbergen, C.; Veerbeek, W.; Gersonius, B.; Van Herk, S. Challenges in urban flood management: Travelling across spatial and temporal scales. *J. Flood Risk Manag*. **2008**, *1*, 81–88. https://doi.org/10.1111/j.1753-318X.2008.00010.x.
33. Carpenter, S.; Walker, B.; Anderies, J.M.; Abel, N. From metaphor to measurement: Resilience of what to what? *Ecosystems* **2001**, *4*, 765–781. https://doi.org/ 10.1007/s10021-001-0045-9.
34. Kuang, D.; Liao, K.H. Learning from Floods: Linking flood experience and flood resilience. *J. Environ. Manag.* **2020**, *271*, 111025. https://doi.org/10.1016/j.jenvman.2020.111schmidtt025.
35. Walker, B. Resilience: What it is and is not. *Ecol. Soc.* **2020**, *25*, 11. https://doi.org/10.5751/ES-11647-250211.
36. Banda, M.L. Global Adaptation Law: Optimizing Legal Design for Multi-Level Public Goods after the Paris Agreement. *Vanderbilt J. Transnatl. Law* **2018**. Available online: https://ssrn.com/abstract=3134172 (accessed on 3 September 2021).
37. Persson, Å.; Dzebo, A. Special issue: Exploring global and transnational governance of climate change adaptation. *Int. Environ. Agreem.* **2019**, *19*, 357–367. https://doi.org/10.1007/s10784-019-09440-z.
38. Schmitt, T.G.; Thomas, M.; Ettrich, N. Analysis and modeling of flooding in urban drainage systems. *J. Hydrol.* **2004**, *299*, 300–311. https://doi.org/10.1016/j.jhydrol.2004.08.012.
39. Toumazis, A.D. Flood resilience technology as a tool of adaptation of the built environment to increased flood hazard and risk. International Conference "Advanced methods for flood estimation in a variable and changing environment". In Proceedings of the Mid-Term COST Action ES0901, Volos, Greece, 24–26 October 2012.
40. DIN German Institute for Standardization. *DIN EN 752 Drainage Systems Outside Buildings—Sewer Management*; German version EN 752; Beuth Verlag GmbH: Berlin, Germany, 2017.
41. Law on the Regulation of the Water Resources (Wasserhaushaltsgesetz-WHG) of 31 July 2009 (BGBI. I, p. 2585), Last Amended by Article 1 of the Act of 18 July 2017 (BGBI I, p. 2771). Available online: https://www.gesetze-im-internet.de/whg_2009/BJNR258510009.html (accessed on 28 July 2018).
42. Water Law for the State of North Rhine-Westphalia (Landeswassergesetz-LWG NRW) of 8 July 2016, as Amended by Article 1 of the Act of 8 July 2016 (GV. NRW. p. 559). Available online: https://recht.nrw.de/lmi/owa/br_text_anzeigen?v_id=3920070525140450679 (accessed on 27 July 2018).
43. Thielbörger, P. The Current Legal Status of the Right to Water. In *The Right(s) to Water*; Springer: Berlin/Heidelberg, Germany, 2014. https://doi.org/10.1007/978-3-642-33908-0_2.
44. Vorobevskii, I.; Al Janabi, F.; Schneebeck, F.; Bellera, J.; Krebs, P. Urban Floods: Linking the Overloading of a Storm Water Sewer System to Precipitation Parameters. *Hydrology* **2020**, *7*, 35. https://doi.org/10.3390/hydrology7020035.

45. Cai, X.; Haile, A.T.; Magidi, J.; Mapedza, E.; Nhamo, L. Living with floods—Household perception and satellite observations in the Barotse floodplain, Zambia. *Phys. Chem. Earth Parts A/B/C* **2017**, *100*, 278–286. https://doi.org/10.1016/j.pce.2016.10.011.
46. van Leeuwen, K.; Hofman, J.; Driessen, P.P.; Frijns, J. The Challenges of Water Management and Governance in Cities. *Water* **2019**, *11*, 1180. https://doi.org/10.3390/w11061180.
47. Goodrich, K.A.; Basolo, V.; Feldman, D.L.; Matthew, R.A.; Schubert, J.E.; Luke, A.; Eguiarte, A.; Boudreau, D.; Serrano, K.; Reyes, A.S.; et al. Addressing Pluvial Flash Flooding through Community-Based Collaborative Research in Tijuana, Mexico. *Water* **2020**, *12*, 1257. https://doi.org/10.3390/w12051257.
48. Powell, J.H.; Mustafee, N.; Chen, A.S.; Hammond, M. System-focused risk identification and assessment for disaster preparedness: Dynamic threat analysis. *Eur. J. Oper. Res.* **2016**, *254*, 550–564. https://doi.org/10.1016/j.ejor.2016.04.037 .
49. Miceli, R.; Sorgiu, I.; Settanni, M. Disaster preparedness and perception of flood risk: A study in an alpine valley in Italy. *J. of Environ. Psychol.* **2008**, *28*, 164–173. https://doi.org/10.1016/j.jenvp.2007.10.006.
50. Ikeda, S.; Fukuzono, T.; Sato, T. *A Better Integrated Management of Disaster Risks: Toward Resilient Society to Emerging Disaster Risks in Mega-Cities*; TERRAPUB, ISBN 9784887041400, 2006, 227–234.
51. Takao, K.; Motoyoshi, T.; Sato, T.; Fukuzondo, T.; Seo, K.; Ikeda, S. Factors determining residents' preparedness for floods in modern megalopolises: The case of the Tokai flood disaster in Japan. *J. Risk Res.* **2004**, *7*, 775–787. https://doi.org/10.1080/1366987031000075996.
52. Babovic, F.; Mijic, A.; Madani, K. Decision making under deep uncertainty for adapting urban drainage systems to change. *Urban Water J.* **2018**, *15*, 374–389. https://doi.org/10.1080/1573062X.2018.1529803.
53. Balsells, M.; Barroca, B.; Becue, V.; Serre, D. Making urban flood resilience more operational: Current practice. Proceedings of the Institution of Civil Engineers. *Water Manag.* **2015**, *168*, 57–65.
54. Salomon, M.; Schlüter, M. Abschlussbericht: Umgang mit Starkregenereignissen im Kanalbetrieb, IKT-Institut für Unterirdische Infrastruktur, 12/2018. (Translation: Final Report: Dealing with Heavy Rainfall Events in Sewer Operations. IKT Institute for Underground Infrastructure. 2018. Available online: https://www.ikt.de/wp-content/uploads/2019/04/f260-umgang-mit-starkregenreignissen-im-kanalbetrieb-abschlussbericht.pdf (accessed on 3 September 2021)).
55. IKT Institute for Underground Infrastructure. 2021. Available online: https://www.komnetabwasser.de/ (accessed on 3 September 2021).
56. Junghänel, T.; Bissolli, P.; Daßler, J.; Fleckenstein, R.; Imbery, F.; Janssen, W.; Kaspar, F.; Lengfeld, K.; Leppelt, T.; Rauthe, M.; et al. Hydro-klimatologische Einordnung der Stark- und Dauerniederschläge in Teilen Deutschlands im Zusammenhang mit dem Tiefdruckgebiet „Bernd" vom 12. bis 19. Juli 2021. Deutscher Wetterdienst. 2021. Available online: https://www.dwd.de/DE/leistungen/besondereereignisse/niederschlag/20210721_bericht_starkniederschlaege_tief_bernd.pdf?__blob=publicationFile&v=6 (accessed on 3 September 2021). (In German)
57. Murillo-García, F.G.; Rossi, M.; Ardizzone, F.; Fiorucci, F.; Alcántara-Ayala, I. Hazard and population vulnerability analysis: A step towards landslide risk assessment. *J. Mt. Sci.* **2017**, *14*, 1241–1261. https://doi.org/10.1007/s11629-016-4179-9.
58. Frigerio, I.; De Amicis, M. Mapping social vulnerability to natural hazards in Italy: A suitable tool for risk mitigation strategies. *Environ. Sci. Policy Elsevier* **2016**, *63*, 187–196.
59. Guillard-Gonçalves, C.; Zêzere, J.L. Combining Social Vulnerability and Physical Vulnerability to Analyse Landslide Risk at the Municipal Scale. *Geosciences* **2018**, *8*, 294. https://doi.org/10.3390/geosciences8080294.
60. Eini, M.; Kaboli, H.S.; Rashidian, M.; Hedayat, H. Hazard and vulnerability in urban flood risk mapping: Machine learning techniques and considering the role of urban districts. *Int. J. Disaster Risk Reduct.* **2020**, *50*, 101687.
61. Masood, M.; Takeuchi, K. Assessment of flood hazard, vulnerability and risk of mid-eastern Dhaka using DEM and 1D hydrodynamic model. *Nat. Hazards* **2012**, *61*, 757–770.
62. Koks, E.E.; Jongman, B.; Husby, T.G.; Botzen, W.J. Combining hazard, exposure and social vulnerability to provide lessons for flood risk management. *Environ. Sci. Pol.* **2015**, *47*, 42–52.
63. Verordnung zur Selbstüberwachung von Abwasseranlagen-Selbstüberwachungsverordnung Abwasser-SüwVO Abw: ("Ordinance on the Self-Monitoring of Wastewater Facilities-Self-Monitoring Ordinance on Wastewater-SüwVO Abw", 17. October 20213). Available online: https://recht.nrw.de/lmi/owa/br_bes_text?anw_nr=2&bes_id=24944&aufgehoben=N (accessed on 3 September 2021).
64. Anforderungen an den Betrieb und die Unterhaltung von Kanalisationsnetzen RdErl. d. Ministeriums für Umwelt, Raumordnung und Landwirtschaft-IV B 6-031 002 0201-v. 3.1.1995 (Requirements for the operation and maintenance of sewerage networks, Circular of the Ministry of the Environment, Spatial Planning and Agriculture-IV B 6-031 002 0201-3.1.1995). Available online: https://recht.nrw.de/lmi/owa/br_bes_text?anw_nr=1&gld_nr=7&ugl_nr=770&bes_id=1970&val=1970&ver=7&sg=0&aufgehoben=N&menu=1 (accessed on 3 September 2021).
65. Crabtree, R.W. Sediment in Sewers. *Water Environ. J.* **1989**, *3*, 569–578. https://doi.org/10.1111/j.1747-6593.1989.tb01437.x.
66. Ashley, R.M.; Fraser, A.; Burrows, R.; Blanksby, J. The management of sediment in combined sewers. *Urban Water J.* **2000**, *2*, 263–275. https://doi.org/10.1016/S1462-0758(01)00010-3.
67. Schellart, A.N.; Tait, S.J.; Ashley, R.M. Estimation of Uncertainty in Long-Term Sewer Sediment Predictions Using a Response Database. *J. Hydraul. Eng.* **2010**, *136* (10). https://doi.org/10.1061/(ASCE)HY.1943-7900.0000193.
68. Tang, Y.; Zhu, D.Z.; Rajaratnam, N.; van Duin, B. Sediment Depositions in a Submerged Storm Sewer Pipe. *J. Environ. Eng.* **2020**, *146* (10). https://doi.org/10.1061/(ASCE)EE.1943-7870.0001799.

69. IKT Institute for Underground Infrastructure. Starkregen-Check Kanalbetrieb: Basic Manual mit Störfall- und Notfallplan nach DIN EN 752; IKT: 2019. (Title in English: Heavy Rainfall Check Sewer Operations: Basic Manual with Contingency and Emergency Plan according to DIN EN 752. Available online: https://www.komnetabwasser.de/wp-content/uploads/2020/04/Umgang_mit_Starkregenreignissen_im_Kanalbetrieb-Anlage-1-Basic-Manual_mit_Stoerfall_und_Notfallplan.pdf (accessed on 3 September 2021).
70. Environment Agency. *Improving Flood Warnings: Final Report. Improving Institutional and Social Responses to Flooding*; Science Report: SC060019—Work Package 1a; 2019.