Capture and retain heavy rainfalls in Jordan
Findings of a transdisciplinary German-Jordanian research project

Presented by the CapTain Rain project team

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CapTainRain

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Frequently used abbreviations

AFD	Agence Française de Développement
AZESA	Aqaba Special Economic Zone Authority
BGI	Blue-Green Infrastructure
CSOs	Civil society organizations
DEM	Digital Elevation Model
EBRD	European Bank for Reconstruction and Development
EIB	European Investment Bank
EWS	Early warning system
GAM	Greater Amman Municipality
GIZ	German Agency for International Cooperation
GCF	Green Climate Fund
GGGI	Global Green Growth Institute
GJU	German Jordanian University
HEC-HMS	Hydrologic Modeling System
INWRDAM	Inter-Islamic Network on Water Resources Development and Management
IUCN-ROWA	International Union for Conservation of Nature and Natural Resources – Regional Office for West Asia
JEA	Jordan Engineers Association
JICA	Japan International Cooperation Agency
JMD	Jordan Meteorological Department
JU	The University of Jordan
JVA	Jordan Valley Authority
KfW	KfW Development Bank
MoA	Ministry of Agriculture
MoE	Minister of Environment
MoEd	Ministry of Education
MoF	Ministry of Finance
MoI	Ministry of Interior
MoLA	Ministry of Local Administration
MoPH	Ministry of Public Works and Housing
MoPI	Ministry of Planning and International Cooperation
MoWI	Ministry of Water and Irrigation
NARC	National Agricultural Research Center
NCSCM	National Center For Security & Crisis Management
PDTRA	Petra Development Tourism Regional Authority
RRI	Rainfall-Runoff-Inundation model
RJGC	Royal Jordanian Geographical Center
RSS	Royal Scientific Society
SDC	Swiss Agency for Development and Cooperation
US-AID	U.S. Agency for International Development

UNFCCC	United Nations Framework Convention on Climate Change
UNDP	United Nations Development Programme
UNICEF	United Nations Children’s Fund
UNHabitat	United Nations Human Settlements Programme
WAJ	Water Authority of Jordan
WFP	World Food Programme
WMO	World Meteorological Organization. International cooperation entities
WP	Workpackages

Summary

The Middle East is particularly affected by climate change and extreme weather events such as droughts and heavy rainfall. In Jordan, repeated heavy rainfall events in recent years have led to flash floods that have caused enormous damage. Minimising such damage, but also maximising the benefits of heavy rainfall through improved water retention in one of the world's most water-scarce countries, was the research topic of the German-Jordanian project CapTain Rain ("*Capture and retain heavy rainfalls in Jordan*"; Duration: June 2021 – July 2024; website: www.captain-rain.de). The project was funded by the German Federal Ministry of Research, Technology and Space (BMFTR, former BMBF), as part of the funding measure "CLIENT II – International Partnerships for Sustainable Innovation" in the context of the framework program "Research for Sustainable Development" (FONA). The aim was to help improve current methods and tools for predicting flash floods and preventing of damage. The study areas included the capital Amman with its 4.3 million inhabitants in the metropolitan region and the more rural Wadi Musa region around the UNESCO World Heritage Site of Petra. Both regions have been severely affected by flash floods in the past. To this end, hydraulic and hydrological models were set up, along with a weather data portal. Vulnerability analyses were carried out, measures to reduce the damage caused by flash floods through the use of blue-green infrastructure were identified, and recommendations for urban planning and early warning systems were developed. Future scenarios were simulated for Amman and Wadi Musa to assess the impacts of climate change, urbanisation and how specific measures can help reduce vulnerability. CapTain Rain's transdisciplinary research methods enabled a holistic analysis of flash flood hazards and facilitated the transfer of scientific knowledge into practical climate change adaptation measures. Climate services (e.g. flash flood risk maps, weather data portal, vulnerability assessment and maps) were developed in close collaboration with Jordanian partners. The report at hand describes the project results and the CapTain Rain climate service products, which have also been made available in a Wiki.

Zusammenfassung

Der Nahe Osten ist vom Klimawandel und extremen Wetterereignissen wie Dürren und starken Regenfällen besonders betroffen. In Jordanien haben wiederholte Starkregenereignisse in den letzten Jahren zu Sturzfluten geführt, die enorme Schäden verursacht haben. Solche Schäden zu minimieren, aber auch die Vorteile von Starkregen durch eine verbesserte Wasserrückhaltung in einem der wasserärmsten Länder der Welt zu maximieren, war das Forschungsthema des deutsch-jordanischen Projekts CapTain Rain ("*Capture and retain heavy rainfalls in Jordan*"; Laufzeit: Juni 2021 – Juli 2024; Website: www.captain-rain.de). Das Projekt wurde durch das Bundesministerium für Forschung, Technologie und Raumfahrt (BMFTR, ehemals BMBF), in der Fördermaßnahme „CLIENT II – Internationale Partnerschaften für nachhaltige Innovationen" im Kontext des Rahmenprogramms Forschung für Nachhaltige Entwicklung (FONA) gefördert. Ziel war es, die aktuellen Methoden und Instrumente zur Vorhersage von Sturzfluten und zur Vermeidung von Schäden zu verbessern. Dabei wurden Starkregenereignisse und mögliche Klimawandeleffekte untersucht, die Auswirkungen von Sturzfluten auf Bevölkerung und Infrastruktur über hydraulische und hydrologische Modelle analysieren, sowie ein Wetterdatenportal eingerichtet. Es wurden Vulnerabilitätsanalysen durchgeführt, Maßnahmen zur Reduzierung von Schäden durch Sturzfluten durch den Einsatz von blau-grüner Infrastruktur ermittelt und Empfehlungen für die Stadtplanung und Frühwarnsysteme entwickelt. Für Amman und Wadi Musa wurden Zukunftsszenarien simuliert, um die Auswirkungen des Klimawandels und der Urbanisierung zu bewerten und zu ermitteln, wie spezifische Maßnahmen zur Verringerung der Vulnerabilität beitragen können. Die transdisziplinären Forschungsmethoden von CapTain Rain ermöglichten eine ganzheitliche Analyse von Lösungsoptionen und erleichterten den Transfer wissenschaftlicher Erkenntnisse in praktische Maßnahmen zur Anpassung an den Klimawandel. In enger Zusammenarbeit mit jordanischen Partnern wurden Klimadienstleistungen entwickelt (z. B. Risikokarten für Sturzfluten, Wetterdatenportal, Vulnerabilitätsbewertung und Karten). Der vorliegende Bericht beschreibt die Projektergebnisse und die CapTain Rain Klimadienstleistungsprodukte, die auch in einem Wiki ausführlich dargestellt werden.

1 Introduction

Authors: Katja Brinkmann and Dörte Ziegler

The Middle East is characterised by a hot and arid desert climate, which renders it highly susceptible to climate change and extreme climatic events (Lelieveld et al. 2012; Lelieveld et al. 2014). Of these, flash floods are particularly prevalent and destructive (Kundzewicz 2002). Flash floods are caused by intense rainfall occurring suddenly and at a high rate over a short period of time, and such floods often result in significant damage to people and the environment (Gruntfest & Handmer, 2001). A global analysis of record-breaking heavy rainfall events (Lehmann et al., 2015) and flash floods revealed that extreme rainfall increased by between 5.9% and 7.7% for every 1°C of global warming between 1990 and 2009. However, this increase was found to vary significantly by latitude (Westra et al. 2013). The complex interplay between anthropogenic watershed changes and climate change makes it difficult to predict the impact of climate change on the frequency and intensity of flash floods (Field et al., 2012; Kundzewicz et al., 2013). This is particularly the case in the Middle East, where there is keen interest in understanding heavy rainfall events and their predictability (Vries et al., 2018). Between 1950 and 2019, there were 45 flash flood events in Jordan, Egypt, Israel and Saudi Arabia, resulting in 1,573 deaths and over $1.8 billion worth of damage (Emergency Events Database, 2022).

Jordan is one of the Middle Eastern countries most affected by climate change and serves as an illustrative case study in this regard. The Ministry of Environment has identified flash flooding as a significant climate change-related risk (Hashemite Kingdom of Jordan, 2014). Over the past 50 years, the country has experienced a considerable number of such floods, resulting in substantial property damage and loss of life (Alhasanat, 2014; Al-Qudah, 2011). Despite their destructive nature, heavy and recurrent rainfall events play a pivotal role in the hydrological cycle of semi-arid regions by replenishing scarce freshwater resources, which are particularly important for agriculture (Amin et al., 2016; Al-Qudah, 2011). However, the rapid growth of Jordan's population, coupled with the influx of refugees from neighbouring countries, has resulted in significant alterations to land use and ineffective urbanisation management in areas prone to flash floods. Processes such as land sealing, agricultural intensification, deforestation, and the decline of traditional terraced agriculture (Al-Qudah et al., 2016) have reduced water infiltration and accelerated runoff rates. These changes have increased the probability of flash floods and made people and the environment more vulnerable to risk (Acosta-Coll et al. 2018). Continued poorly regulated urban development is placing an increasing number of areas at risk, and damage caused by heavy rainfall is anticipated to increase in the near future unless forecasts, early warning information and preparedness measures are significantly enhanced. However, the country lacks the capacity to build and maintain appropriate climate services, including early warning systems (EWS), and to implement measures to mitigate the effects of climate change and extreme weather events (CADRI, 2018). Jordan is also one of the world's most water-scarce countries, with limited renewable water resources (Ministry of Water and Irrigation, 2023). Consequently, optimising the use of heavy rainfall for water harvesting and minimising flash flood damage are key objectives in Jordan's climate change adaptation strategy.

One prerequisite for minimising disaster losses is the ability to accurately predict disaster events, enabling precautionary measures to be taken. Such 'climate services' for risk prevention are a high political priority in Jordan, but they have not yet been put into practice sufficiently. There is a lack of the basic hydrological and meteorological knowledge needed to predict the occurrence and intensity of flash floods in Jordan's wadis more accurately. The successful development and implementation of climate services also requires cooperation with future users and decision-makers. Transdisciplinary research methods enable holistic analysis of flash flood hazards and prevention, facilitating the transfer of scientific knowledge into practical climate change adaptation measures.

2 Objectives and project structure

Authors: Katja Brinkmann and Dörte Ziegler

2.1 Relevance and objectives

Over the past ten years, Amman has experienced a total of six flash floods, occurring on 14 and 15 November, 18 January, 18 April, 18 October, and 19 February. The November 2014 flood was particularly severe, resulting in three fatalities in Amman. Similarly, the November 2015 flood resulted in four deaths and extensive property damage. Another flash flood occurred in 2019, causing significant damage (The Jordan Times, 2019). Overall, the risk of flash flooding in Amman has increased considerably due to rapid urbanisation in recent decades.

In the Wadi Musa region, which encompasses the UNESCO World Heritage Site Petra, a severe flash flood occurred in 1963, resulting in the inundation of significant portions of the UNESCO World Heritage Site and the deaths of approximately 20 tourists. Several tourists were evacuated in the flash floods that occurred in 1991, 1995 and 1996 (Al-Weshah/El-Khoury, 1999). The most recent severe flash floods in Petra occurred in November 2018 and December 2022, resulting in 12 fatalities in total.

This list of extreme events shows that flash floods pose a significant threat to Jordan’s population, infrastructure and economy. Consequently, adapting climate change strategies to reduce Jordan’s vulnerability is of paramount importance.

CapTain Rain aims to improve the current methods and tools used to predict flash floods and prevent damage in Jordan. To this end, CapTain Rain:

(1) analysed the social-ecological drivers of flash floods in Jordan’s wadi and entangle the complex interactions between climate and land use change, in order to enable a better simulation and prognosis of flash flood events;
(2) assessed the social-ecological risk of flash floods using an integrated vulnerability analysis, that takes into account the spatial exposure of flash floods, sensitivity, and adaptive capacity;
(3) developed web-based climate services for flood-related decision making based on stakeholder dialogue and participatory approaches;
(4) and identified promising measures to improve the adaptive capacity of local communities, including methods and technologies to capture and retain water from heavy rainfall, but also to prevent damage.

The complex interactions between climate and land use changes and adaptation measures were elucidated in Jordan’s wadi systems. The study areas included Amman, the capital with a metropolitan population of 4.3 million, and the more rural region around Wadi Musa, which includes the UNESCO World Heritage Site of Petra (Figure 1). Both regions have been severely impacted by flash flooding in the past.

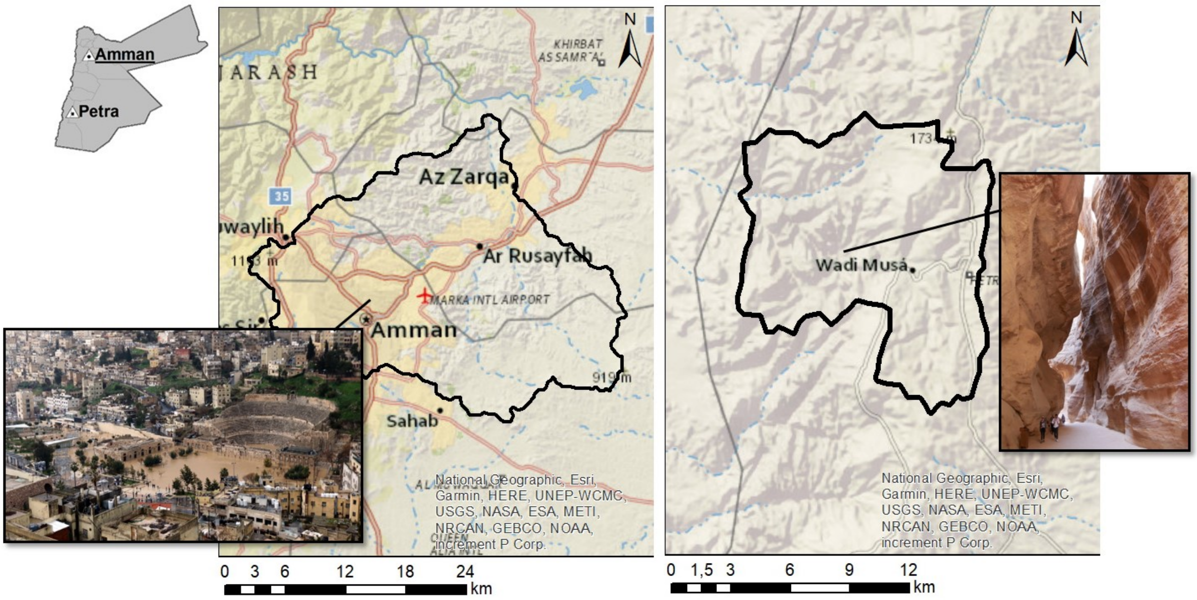


Figure 1. Overview of the selected study areas in Jordan: The capital Amman as urban region (left, Photo: flooded Roman theatre @Al Ghad Newspaper) and the more rural region of Wadi Musa (right, Photo: Siq entrance, Petra valley @Captain Rain 2023).

Climate services were developed in close collaboration with Jordanian stakeholders, taking into account both scientific and practical knowledge. These services include flash flood risk maps, near real-time early warning systems and recommendations for preventing the risks associated with heavy rainfall. CapTain Rain's transdisciplinary research methods enabled a holistic analysis of flash flood hazards and prevention measures. This approach facilitated the transfer of scientific knowledge into practical measures for adapting to climate change.

2.2 Project structure

Altogether, six work packages (WPs), comprising researchers from Germany and Jordan, contributed to the analysis of flash floods, including an integrated vulnerability analysis, and provided a revision of current methods for predicting and preventing flash floods (see Figure 2). All WPs were closely linked in a network that enabled synergistic interactions. At the same time, a transdisciplinary approach was adopted to ensure the early integration of stakeholders and the alignment of the project with the situation on the ground. WP 1, 'Coordination & Communication', encompassed central project management, including scientific and technical coordination, stakeholder integration, and communication. WP 2, 'Heavy rainfall hazard', focused on improving understanding of flash flood hazards in wadis and investigated how heavy rainfall events have changed in the past and may continue to change in the future due to the effects of climate change. WP 3, 'Exposure & Sensitivity', analysed the spatial and temporal impacts of flash floods on people and infrastructure along an urban-rural gradient. WP 4, 'Adaptive Capacity', investigated local knowledge of severe flash flooding and adaptation strategies, as well as the potential to improve methods and technologies for capturing and retaining heavy rainfall events. The results of WPs 2–4 were combined to perform an integrated vulnerability assessment and scenario analysis of various adaptation strategies in WP 5, 'Vulnerability'. The simulated scenarios were discussed and evaluated with local stakeholders. Promising adaptation strategies involving traditional and improved methods and technologies were identified that can help increase resilience to flash floods and climate impacts. This formed the basis for the development of web-based decision support tools, such as the water and weather data portal in work package 6 (WP 6), 'Climate Services and Knowledge Transfer'. This work package also comprised recommendations and related training.

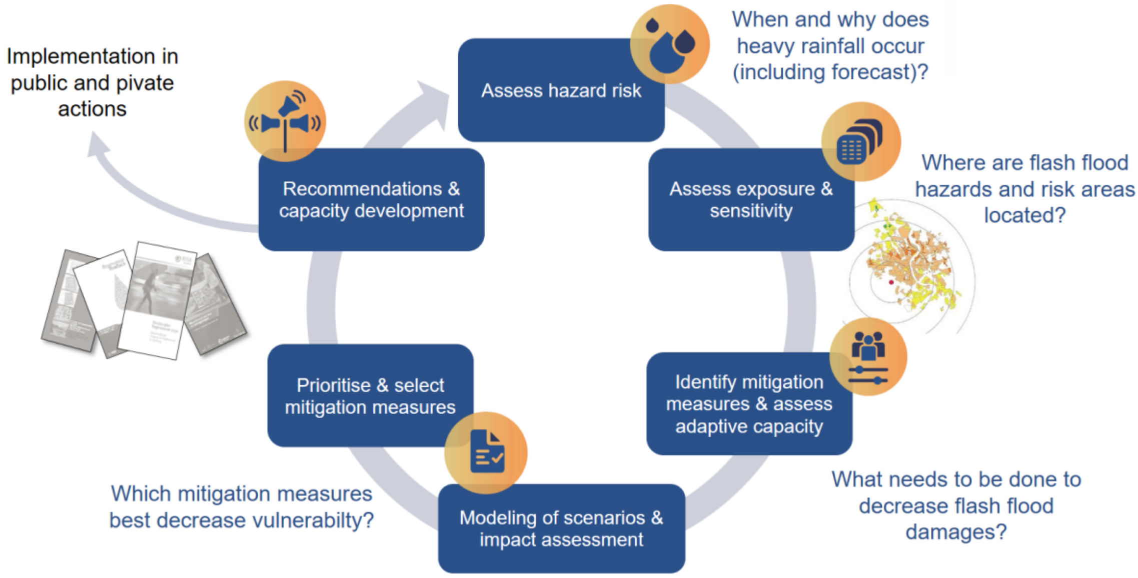


Figure 2. Conceptual framework for the integrated vulnerability analysis of flash floods and associated work packages.

3 Stakeholder dialogue and transdisciplinary integration

Authors: Katja Brinkmann, Markus Rauchecker, Dörte Ziegler and Martina Winker

3.1 Research objectives and methods

The development of practical and useful climate services for flash flood prediction and prevention relies on the participation of stakeholders involved in climate-related decision-making, and requires a transdisciplinary approach. To effectively promote the dialogue and collaboration necessary for co-production and co-design, relevant stakeholders need to be engaged (Thaler and Levin-Keitel, 2016; Schück-Zöller et al., 2018), as well as to facilitate the transfer of scientific results to climate-smart actions (Niyibizi et al., 2013).

The aim of stakeholder engagement was therefore to integrate the opinions, relevant practical knowledge, experience and needs of social actors and stakeholders into the project, thus facilitating external communication between science and society, and ensuring the transfer of knowledge beyond the project's lifespan. To this end, a stakeholder analysis and mapping were carried out at the beginning of the project, supplemented by expert interviews in Jordan. Knowledge integration and active involvement in the findings and techniques for predicting and preventing flash flood risks took place via annually coordinated stakeholder workshops. This laid the foundation for the transfer of knowledge into practice and enabled the early dissemination of the project results. Capacity building was crucial in this context and was carried out at different levels, with formats specifically tailored to stakeholders. This supported the training of local decision-makers and users in scientific and technical competences to enable them to use the climate services and products developed in CapTain Rain.

Expert interviews were conducted to gain an in-depth and well-informed perspective on various aspects of flash flood management in Jordan, such as structural challenges, relevant stakeholders, the drivers of flash floods, and mitigation measures. Unlike surveys, expert interviews are not standardised; they are open conversations based on pre-fixed questions and topics. This makes it possible to discuss relevant topics in depth to gain deeper insights. However, fewer interviewees can be included than in a survey. Between October 2021 and February 2023, we conducted 15 expert interviews with representatives from ministries, local authorities, international organisations, entities involved in international cooperation, scientific bodies, NGOs and consulting companies. We used a qualitative content analysis (Mayring, 2010) to analyse the interviews, identifying relevant text sections and grouping them into sub- and metacategories.

3.2 Key findings

3.2.1 Stakeholder analysis and mapping

For the stakeholder analysis and mapping, the stakeholders mentioned by the expert interviewees were categorised and their influence on flash flood management was estimated. The results of the stakeholder mapping (Figure 3) showed that state entities were the largest group (22 actors), and were named as key actors, albeit to varying degrees. At the national level, the key actors are the National Center for Security and Crisis Management, the Ministry of Water and Irrigation, and the Jordan Meteorological Department. For the local cases (Amman and Petra), the key actors are the Greater Amman Municipality and the Petra Development and Tourism Region Authority (PDTRA). The second largest group comprises international organisations and international cooperation entities (20 actors), with donor funding always being mentioned as crucial for measures and actions regarding flash floods.

Consulting companies and scientific entities are small groups (four actors each), but are considered important for measures and projects. Local citizens (six groups of actors) are divided by area (urban, camps, rural and flood-prone areas) and function (shop owners, residents and local leaders), and are given low actual influence but high potential. Several interviewees emphasised the importance of local citizens' participation. Only a few NGOs were mentioned, and of these, only the Inter-Islamic Network on Water Resources Development and Management (INWRDAM) was considered important for flash flood management.

The interview analysis revealed that the respondents' answers contained valuable information for the different work packages, which was used for further WP-specific analyses as follows: Information on land use planning was used in WP3, while information on traditional knowledge and measures was used in WP4. Information on local perceptions of flash floods and their causes was integrated into WP5, and technical and operational information on early warning systems enabled the emergency response chain to be graphically represented in WP6.

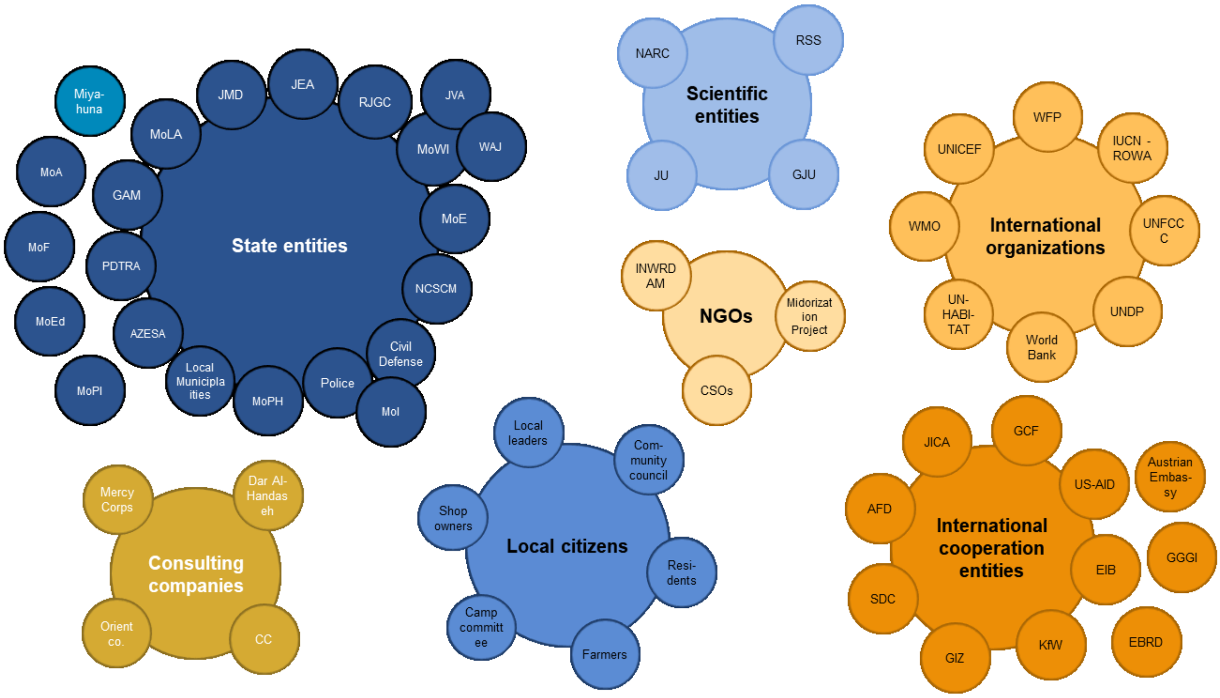


Figure 3. Results of the stakeholder mapping: Stakeholders mentioned in the interviews who play a role in CapTain Rain's research topics, and their assignment to stakeholder groups. See list of abbreviations.

3.2.2 Stakeholder engagement during project implementation

Knowledge transfer at the science-policy interface, and active stakeholder involvement in findings and techniques for predicting and preventing flash flood risks, was facilitated through annual stakeholder workshops (SW). Additionally, key stakeholders were represented on a steering committee, where significant decisions regarding project activities, the timing of the workshops and the workshops' agenda were reached collectively. The results of the stakeholder workshops were documented and regularly disseminated to all participants

The **kick-off event and first stakeholder workshop** were designed to align knowledge levels and facilitate a joint refinement of the research design, as well as the formulation of a strategy for disseminating findings to the target audience. Held at the Geneva Hotel in Amman on 3 October 2021, the workshop was attended by over 50 participants. All collaborative partners participated in the stakeholder workshops, as did additional Jordanian stakeholders who were identified based on recommendations from Jordanian partners, the initial results of the stakeholder analysis and previous experience (e.g. preparatory work in the context of the application process). After the introductory remarks and welcome addresses from the Jordanian project partners and the German funding agency, the CapTain Rain team presented their findings on the flash flood catastrophe in Germany in July 2021. They then engaged in a discussion with the participants about the potential transferability of these findings to Jordan. The research approach and preliminary results of the CapTain Rain project were then presented and discussed. During a group work session, flash flood hotspots in Amman and Petra were identified using a participatory mapping approach in Google Earth. Available studies on flash floods were compiled for each study site, along with a list of knowledge gaps and required actions. The workshop fostered transdisciplinary collaboration and enabled the fine-tuning of project activities and products to the needs of stakeholders.

The **second stakeholder workshop**, which took place on 30 January 2023 at the Geneva Hotel in Amman, was attended by 42 participants. The interim results were validated through a participatory process with the aim of refining the model results subsequently. The workshop also aimed to identify promising adaptation strategies for scenario development through a collaborative process. Alongside the presentation and discussion of the latest research results and the selection of focus areas, group work was conducted to discuss planning goals for reducing flash flood damage as well as potential measures in Amman and the early warning chain in Jordan.

The **third stakeholder worksho**p took place on 11 December 2023 at the Al-Hussein Cultural Centre in Amman. Around 30 project partners and Jordanian experts attended the event. Of particular significance were the discussions on scenarios and vulnerability assessment, and the consensus on completing and transferring the CapTain Rain products in collaboration with Jordanian partners. A further workshop was also held at the PDTRA office in Wadi Musa, focusing on the joint selection of planning objectives for the Wadi Musa region and the discussion of potential measures to reduce flash flood damage.

The **final event** took place on 30 June 2024 at the Al-Hussein Cultural Centre in Amman and was attended by over 70 people. After the project results for the various work packages were presented and discussed, an exhibition of the CapTain Rain products was held. Participants gained a comprehensive understanding of the flash flood risk and vulnerability maps, and had the opportunity to engage with climate and water data portals and a digital touch table for urban planning. This was followed by a final event in Wadi Musa on 2 July 2024. A key focus of this event was exploring the potential for further use of CapTain Rain's products in successfully implementing climate change adaptation measures.

Figure 4. Group work on planning goals at the second stakeholder workshop in 2023 (left), preparation of the exhibition for the CapTain Rain project’s final event in 2024 (right).

Further dialogues and collaboration were held between the stakeholder workshops, including with key donors such as UN-Habitat, the Swiss Development Corporation, GIZ and KfW.

3.2.3 Capacity development

To strengthen understanding of flash flood risk reduction in relation to the different work package aspects, online seminars (webinars) were held between 17 March and 8 June 2022 (see Table 1). The stakeholder workshops did not allow enough time to go into sufficient detail, whereas the online format enabled broader participation from both Germany and Jordan. During these capacity development events, the German project partners presented their research activities and discussed potential approaches with interested participants from Jordan. A total of five research topics from different work packages were presented. In the first seminar, German company KISTERS AG presented a powerful data management tool for early warning systems. The second seminar featured itwh GmbH, who provided information on data requirements and possible approaches for analysing flood hazards. Together with Koblenz University of Applied Sciences, they gave an overview of hydrological and hydraulic models for flash flood risk assessment in the third seminar. A particular highlight of this online seminar was the presentation by Dr Qasem Abdelal of the German-Jordanian University, who shared insights into his research in the Wadi Musa catchment area. The fourth seminar was hosted by the Potsdam Institute for Climate Impact Research (PIK), who introduced predictors for heavy rainfall events in Jordan. The series concluded with the fifth online seminar, which was hosted by the German company Hamburg Wasser. They provided an overview of potential measures to mitigate flash flood damage and presented the Sponge City approach.

Further training measures (both online and face-to-face) on individual products (e.g. hydraulic modelling, the water and weather data portal and the implementation of adaptation measures) took place in specific work packages in 2023 and 2024, and are explained in the relevant chapters.

Table 1. Overview of online-Trainings (webinars) conducted in spring 2022 on WP-specific research topics.

Date	Topic	Presenter
17.03	Features of the state-of-the-art Demonstrator for climatic variables	KISTERS AG
11.04	Flood hazard analysis tools – Data needed and possible approaches	itwh
16.05	Overview of hydrological and hydraulic models for flash flood risk assessment	Koblenz University, GJU, itwh
30.05	Introduction to predictors for heavy rainfall events in Jordan under climate change	PIK
08.06	Measures to reduce flash flood risks and examples from the Sponge City Hamburg	Hamburg Wasser, ISOE

3.2.4 Structural challenges for flash flood management in Jordan

To better integrate flash flood management into the governance structure and develop efficient management solutions, the structural challenges must first be identified and their interrelationships understood. The results of the expert interviews showed that the experts focused more on structural challenges relating to government agencies and international donors than on issues relating to local communities. The main challenge identified was the fragmentation and overlap of responsibilities caused by an increase in flash flood management activities. Stakeholders stated that there was no overarching strategy for dealing with flash floods and that many activities were reactive. A lack of funding for flash flood prevention measures was identified as a problem affecting not only government agencies, but also municipalities. Although flash flood prevention measures are mandatory for new buildings in Jordan, construction companies and the local population often do not comply because the measures are costly. Several experts mentioned the dependence on international donors and projects due to the lack of government funding for flash flood management. Flash flood management projects were considered unsustainable because government agencies did not continue them after completion due to a lack of funding and a lack of links between projects and government agencies. Furthermore, it was found that international donors had their own agendas and capacities when setting up projects. This exacerbates the existing fragmentation and overlap of responsibilities between government agencies. Stakeholders also mentioned that the proliferation of project activities not taken up by government agencies after projects end, coupled with the lack of local community participation in project design and decision-making, would lead to mistrust and result in low compliance, hindering efficient flash flood management. Figure 5 displays the interrelations of the structural challenges mentioned by the experts.

The stakeholder analysis showed that decision-makers, the public and research institutions are well aware of the significance of flash floods and the risks they pose due to the frequency of heavy rainfall events. However, the analysis revealed a lack of effective strategies and tools for reducing risk and damage. Although improving flash flood forecasting and risk management is a high political priority in Jordan, it has not yet been sufficiently implemented in practice. The development and implementation of technical and social measures for flash flood prevention and disaster management depends not only on funding and the technical applicability of the measures in a specific flood-prone area, but also on political and administrative support, and on being anchored in the local community of the flood-prone area. The results of the stakeholder analysis demonstrate how structural challenges can hinder the effective management of flash flood risk and highlight the difficulties that research projects encounter when attempting to implement their findings.

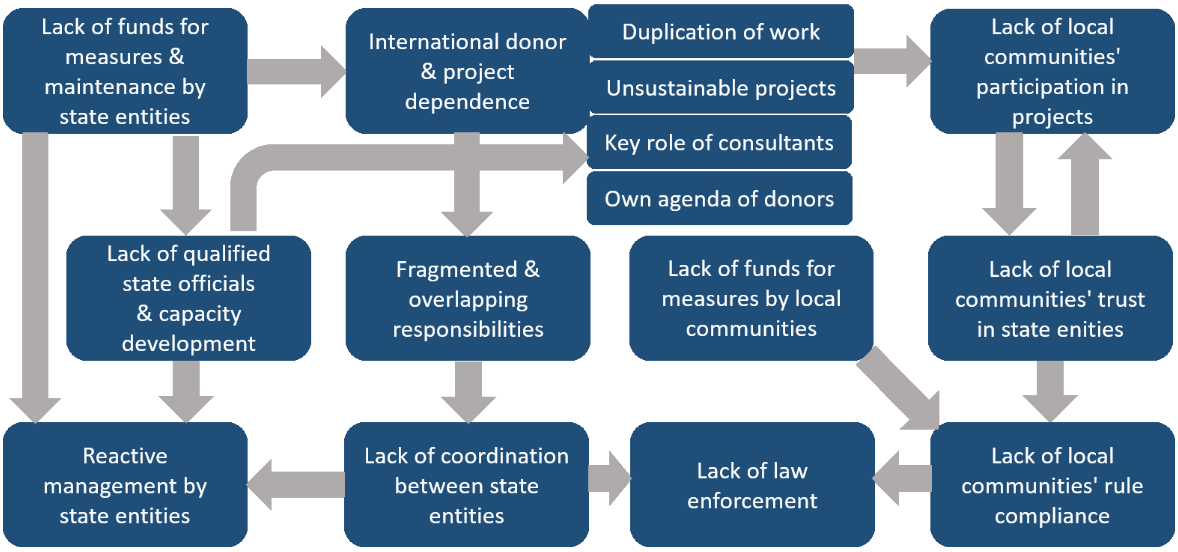


Figure 5. Interrelations of structural challenges for flash flood management (based on 15 expert interviews).

The interviewed experts highlighted a number of measures that could be taken to address the structural challenges. Several of these measures are already partly implemented. To avoid duplication of work, an overarching strategy for flash flood management is needed to better coordinate projects and activities in this area. More recent flash flood management projects, as well as CapTain Rain, have implemented steering and technical committees to improve coordination between state entities and projects. It is important for projects to provide capacity-building opportunities for state officials (see Chapter 3.2.3) to ensure they take ownership of the project results and to strengthen their qualifications so they can build on these results. Very few projects have integrated local communities into their designs and decision-making processes. Some state entities provide incentives for local communities to implement flash flood measures. However, it is important to further strengthen the relationship between state entities and local communities, which can be achieved through projects. Furthermore, it is important to improve coordination between state entities, which is achieved for flash flood events by the NCSCM. However, coordination for proactive management is still needed.

3.3 Outlook: Stakeholder dialogue and transdisciplinary integration

CapTain Rain’s transdisciplinary research approach integrated scientific as well as practical knowledge of German and Jordanian actors through stakeholder dialogues and contributed to the transfer of scientific results into practice. Examples of this transfer include ‘climate services’, including flash flood risk maps, tools to improve flash flood forecasting, and recommendations for promising adaptation strategies and early warning systems. CapTain Rain’s ongoing stakeholder dialogue and capacity building activities enabled the participatory design of climate services in an understandable and user-friendly form. Although CapTain Rain was a time-limited research project, the continuous stakeholder engagement enabled the results to be prepared for future practical use by local decision-makers, and significant knowledge transfer has already taken place during these interactions and phases of intensive collaboration.

4 Rainfall hazard risk: Analysis of heavy rainfall scenarios in Jordan

Author: Peter Hoffmann

4.1 Research objectives and methods

The objective of this work package was to gain further insight into the natural hazard of heavy rainfall in Jordan by analysing a number of aspects. The preliminary phase of the research involved the identification of critical large-scale weather patterns over the eastern Mediterranean that were identified as the underlying cause of localised heavy rainfall events in Jordan. This approach enables the causal relationship between the large-scale transport of air masses and local weather to be identified and used as a proxy. Based on this, a prototype early warning system was established and tested in collaboration with the Jordan Meteorological Department (JMD), which evaluates operational weather forecasts. In addition, real-time data from satellite-based rainfall estimates for Jordan have been processed and made available in a radar design. In the context of climate change, simulation data from global and regional climate models were then analysed from a number of perspectives. (a) *How might the frequency of critical weather patterns change?* (b *How might heavy rainfall patterns in Jordan change in the future for different return periods?* (c) *Are there differences in the duration of rain events?* (d) *What plausible scenarios for possible heavy rainfall events can be derived and used for hydraulic simulations?* To implement the results and current climate services, an existing portal was extended to include Jordan.

4.2 Key findings for Amman and Wadi Musa

The following subchapters summarise and explain the main results and products of analysing heavy rainfall patterns and trends in Jordan. We start with some general climatological aspects concerning the seasonal distribution of precipitation and trends, followed by specific results. The main results of the heavy precipitation analysis can be summarised as follows:

- A causal linkage between local heavy rainfall events in Amman and Petra and critical large-scale weather patterns over the eastern Mediterranean was demonstrated.
- Regarding climate projections for the future until 2100, the long-term trends in annual mean precipitation is decreasing while the annual maximum precipitation is increasing in most parts of Jordan
- In terms of extreme rainfall, there is little differentiation between Amman and Petra: heavy rainfall can occur anywhere in Jordan.
- The heavy rainfall events in the eastern Mediterranean in 2023 (more specific: Libya and Greece) have demonstrated the considerable volume of water that can be discharged in a single day when low-pressure systems develop over the warm Mediterranean Sea. Similar events could also happen in Jordan in the context of climate change.
- A detection and monitoring of the critical circulation patterns that may result in intense rainfall should be integrated in operational weather forecasts. This would enable experts to better assess predicted developments of possible extreme rainfall conditions in Jordan days in advance.
- Open data of satellite rainfall estimates are suitable proxies to monitor approaching areas of rainfall in near real-time.
- Convective and short-term rainfall intensities of several hours in Amman and Petra show a positive climate sensitivity in contrast to longer-term events of 12 hours and more.
- Observed extreme events were defined as baseline scenario. Considering a progressive climate warming, such extreme events will be moderately increased by 15% to 20% (on average), however higher values cannot be excluded.
- Analysis of climate model simulations showed robust decreasing in the number of extreme rainfall events in Jordan, however the potential for an intensification of single events would increase according to those simulations.

- A climate service portal was developed for Jordan. The climate service portal enables users to inform about possible future scenarios of different climate indicators (e.g. seasonal mean temperature, number of hot days, maximum precipitation, etc.).

4.2.1 Climatology of Precipitation in Jordan

An overview of the seasonal distribution of rainfall events in the Greater Amman area was derived based on UERRA regional reanalysis data (Copernicus, 2019b). This was supplemented by analyses of long-term trends of mean and extreme precipitation. Open data were used due to the difficulty of accessing long-term meteorological measurements in Jordan. Although there may be inconsistencies at the level of individual events, the analyses provide a consistent overall picture at the national level.

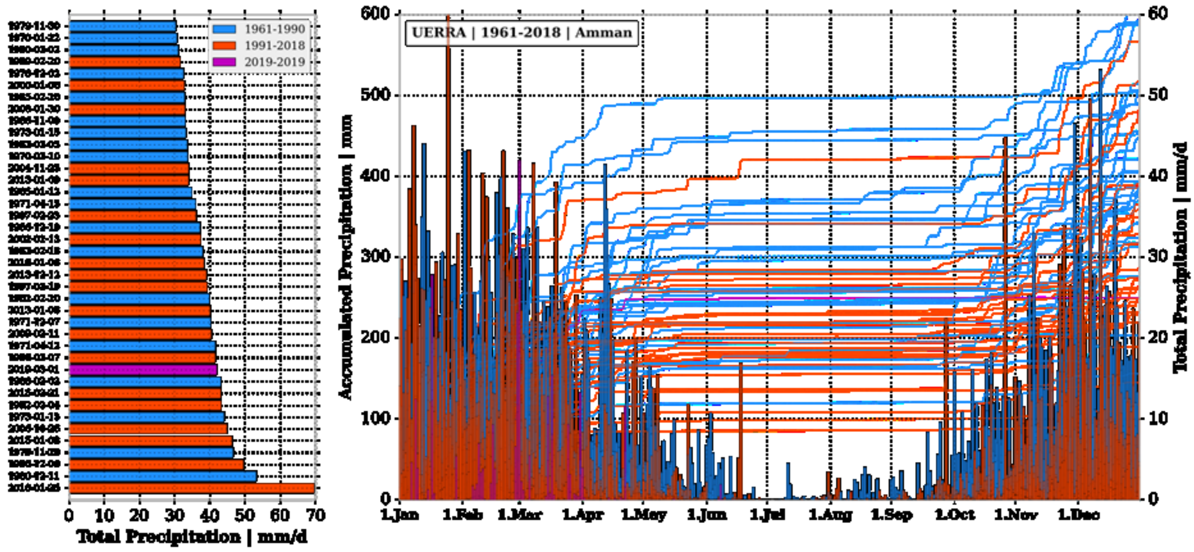


Figure 6. Seasonal cycle of daily total and accumulated precipitation in Amman from 1961-2019 extracted from the UERRA regional reanalysis data: 1961–1990 (blue) and 1991–2018 (red).

The seasonal distribution of daily precipitation values is representative of the typical climatological pattern observed in the eastern Mediterranean region. In Amman, there is minimal precipitation during the summer months, spanning the period from June to September (Figure 6). Maximum values are within the range of 50–70 mm per day. Two distinct periods have been delineated by colour: 1961–1990 (blue) and 1991–2018 (red). The accumulated rainfall totals demonstrate a clear trend towards drier conditions in recent years, with the heaviest events represented by red bars. This is to some extent an expected consequence of climate change, as recently noted by Zittis et al. (2022) in their analysis of changes in extremes in the Mediterranean and Middle East.

The region experiences a lower average precipitation level throughout the year; however, when precipitation does occur, it is at a higher intensity. This is supported by the trend analysis shown in Figure 7. Over most of Jordan, annual precipitation has decreased significantly in recent decades (negatively correlated with time). Conversely, there are predominantly increasing trends in annual maxima, particularly in the west, where the highest precipitation levels of about 300 mm per year are recorded. The large-scale weather patterns over the eastern Mediterranean and their changes have a significant influence on the trends. Therefore, the critical weather patterns were also examined in further analysis steps.

A recent report on weathering risk in Jordan in 2022 (WeatheringRisk, 2022) describes the current state of the climate and projected future trajectories. As a result of climate change, water stress is expected to increase, with prolonged dry periods becoming more severe as temperatures rise. Meanwhile, rainfall patterns are becoming less evenly distributed, increasing the likelihood of localised flash floods under current and future climate conditions.

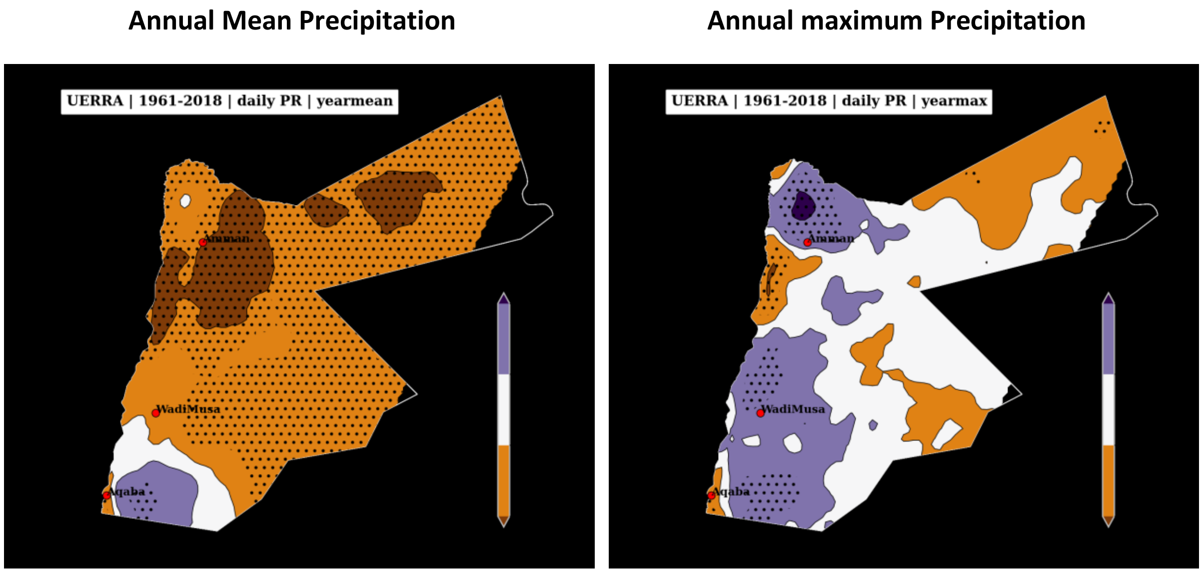


Figure 7. Long-term trends (time correlations) of the annual mean/maximum daily precipitation (left/right) in Jordan from 1961–2018 derived from UERRA regional reanalysis data.

4.2.2 Contextualization of Heavy Rainfall in Jordan

Any extreme rainfall event in Jordan and elsewhere occurs within a larger-scale atmospheric context, which is defined by the movement of air masses across different geographical regions. Using ERA5 global reanalysis data (Hersbach et al., 2020), we have retrospectively identified the critical circulation pattern associated with extreme local rainfall in Amman (nearest grid cell) for the past (1961–1990) and present (1991–2020) climate periods. A standard atmospheric field in synoptic meteorology is the geopotential height at 500 hPa (Z500), which represents the circulation conditions in the middle troposphere at a height of about 5 km. The curvature of the contour lines is a good indicator of the origin and transport path of air masses. Improving our understanding of the dynamical drivers of local extreme weather events could enhance existing early warning systems and long-term climate risk assessments.

Figure 8 shows the basic approach, in which local daily time series (PR_d) are combined with the corresponding atmospheric ($Z500_{x,y,d}$). For 30-years climate periods, we filter out days (t) where daily precipitation exceeds the 99th percentile (N = 110d).

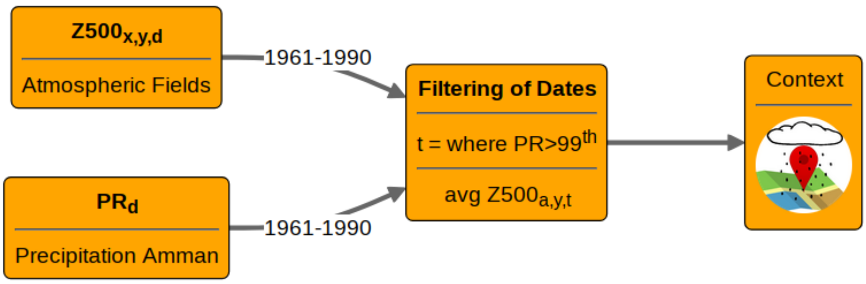


Figure 8. Scheme of contextualization

For these days, we normalised the Z500 and calculated the composite patterns using averaging. This approach was applied to the past (1961-1990) and the present (1991-2020) climate period, separately. Comparison of the patterns indicate possible changes in dynamical drivers. Comparing the patterns indicates possible changes in the dynamical drivers. Changes in intensity can also be identified and attributed by looking at the respective values of precipitation above the 99th percentile. Changes in frequency were identified by applying the 99th percentile threshold to both the past and present periods. Figure 9 illustrates the critical weather patterns associated with extreme rainfall in Amman in both the past and present.

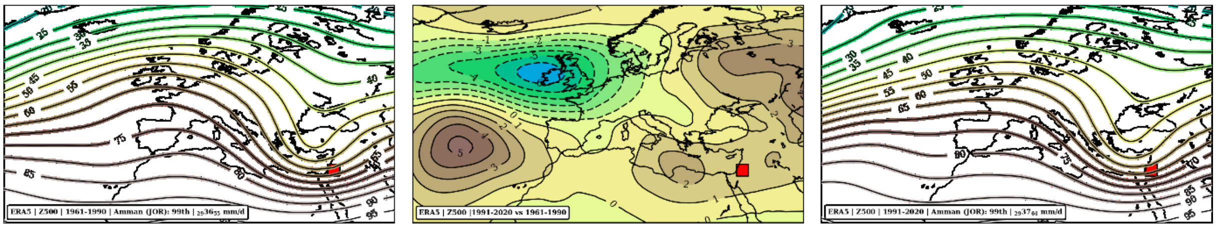


Figure 9. Causal linkage between local extreme rainfall (red) and the large-scale atmosphere circulation (contours): past (left), present (right) and present-past (center).

A trough-like pattern over the eastern Mediterranean transports cold air masses from north to south, favouring the formation of low-pressure systems and convective rainfall patterns in the Near East region (Dayan, 2015). The difference pattern in the center of Figure 9 shows a slight decrease in frequency in recent years, but not in intensity. This is probably related to higher blocking activity over Eurasia.

Similarly, we examined the global climate model ensemble CMIP6 (Copernicus, 2021) up to 2100 for the high-end scenario (SSP585). We find that the models agree on a reduction in the frequency of such events. However, there are larger uncertainties in the changes in intensity. This is not surprising, given that these are global models with coarse spatial resolution. That’s why we also examine regional models with high spatial and temporal resolution from the Coordinated Downscaling Experiment (CORDEX, 2019), in order to capture local phenomena and resulting precipitation patterns more realistically.

4.2.3 Data Products in a Design of Radar

The design format of data products is essential for providing user-oriented information. This product integrates operational services combining different open data products (reanalysis data, satellite rainfall estimates and weather forecasts) into a unified design of a radar for Jordan. This enables areas of accumulated rainfall to be monitored and assessed in terms of retrospective analysis of heavy rainfall maps and forecasts for the next 3 days.

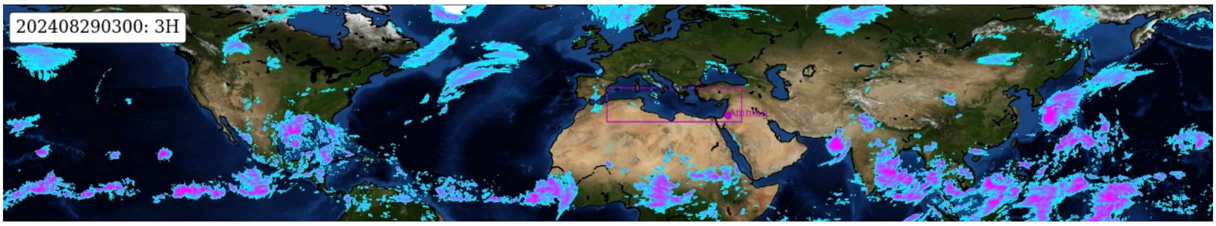
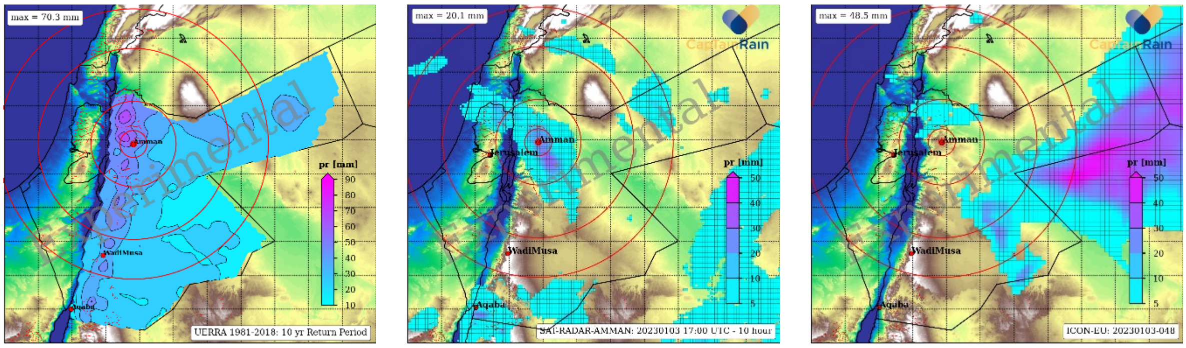


Figure 10. Real-time rainfall estimates from GSMaP satellite product (Kubota et al. 2020).

In practice, the product looks like this (see Figure 11). Heavy rainfall maps are shown on the left. These are derived from regional reanalysis data (UERRA) and illustrate the spatial distribution of heavy rainfall with a return period of 10 years. The range of values extends up to 70 mm/d in the north-west of the country. Following this logic, other real-time data (satellite and forecast) have been integrated. Please note that the data comes from different sources and has not been adjusted for bias. The current status remains experimental beyond the scope of the project. Ideally, it would be possible to monitor and assess the potential risk of expected or predicted rainfall areas and rainfall totals.

Heavy Rainfall Maps	Satellite Rainfall Estimates	Weather Forecast



10-yr return level	Nowcast of 12-hr acc. precipitation	DWD-ICON 48-hr acc. precipitation

Figure 11. Heavy rainfall maps in a design of a Radar: reanalysis (left), satellite (center) and forecast (right).

4.2.4 Heavy Rainfall Maps

Local heavy rainfall exhibits considerable diversity and is highly sensitive to long-term temperature increases. To demonstrate this, nine 30-year regional climate simulations were evaluated and compared. The initial dataset is available with a temporal resolution of three hours. From this, a variety of event classes, ranging in length from three to 24 hours, were considered. As shown in Figure 12, these are regionalisations of selected global climate model simulations (CMIP5) from 1981 to 2100 under the high-end RCP85 emissions scenario. The data are available in the Copernicus portal's climate data store (CORDEX, 2019a). The selection process was necessarily pragmatic, taking into account a number of factors, including the choice of domain, the availability of runs, temporal and spatial resolution, and the meteorological phenomenon under consideration. In addition, aggregation over several hours allowed for the recognition that local heavy rain events occur predominantly on a sub-daily basis, thus allowing for the consideration of different influencing factors. The shorter the duration of the events, the more dominant the temperature effect, which is likely to lead to an increase in precipitation intensity.

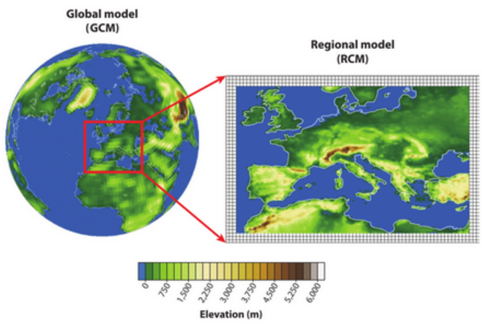
Simulations	**Domain**
Database[1]: rcp_8_5_mpi_m_mpi_esm_lr_smhi_rca4_1976-2099.nc rcp_8_5_ipsl_cm5a_mr_smhi_rca4_1976-2099.nc rcp_8_5_mohc_hadgem2_es_smhi_rca4_1976-2099.nc rcp_8_5_ichec_ec_earth_smhi_rca4_1976-2099.nc rcp_8_5_ncc_noresm1_m_smhi_rca4_1976-2099.nc rcp_8_5_miroc_miroc5_clmcom_clm_cclm4_8_17_1976-2099.nc rcp_8_5_cccma_canesm2_clmcom_clm_cclm4_8_17_1976-2099.nc rcp_8_5_cnrm_cerfacs_cm5_clmcom_eth_cosmo_crclim_1976-2099.nc rcp_8_5_mpi_m_mpi_esm_lr_clmcom_eth_cosmo_crclim_1976-2099.nc Euro-Cordex: *rcp8.5, 12 x 12 km, 3-hourly*	

Figure 12. Overview of the available high-resolution climate scenarios for the Euro-Cordex-11 domain having 3-hourly precipitation.

Figure 13 shows maps illustrating the sensitivity of 3-hour heavy rainfall in the regional climate ensemble. In most of Jordan, the intensity of precipitation is increasing. The magnitude is estimated to be between 10 and 15 percent for events occurring on average once every 50 years. This magnitude is consistent with that which can be expected on average from theoretical derivations.

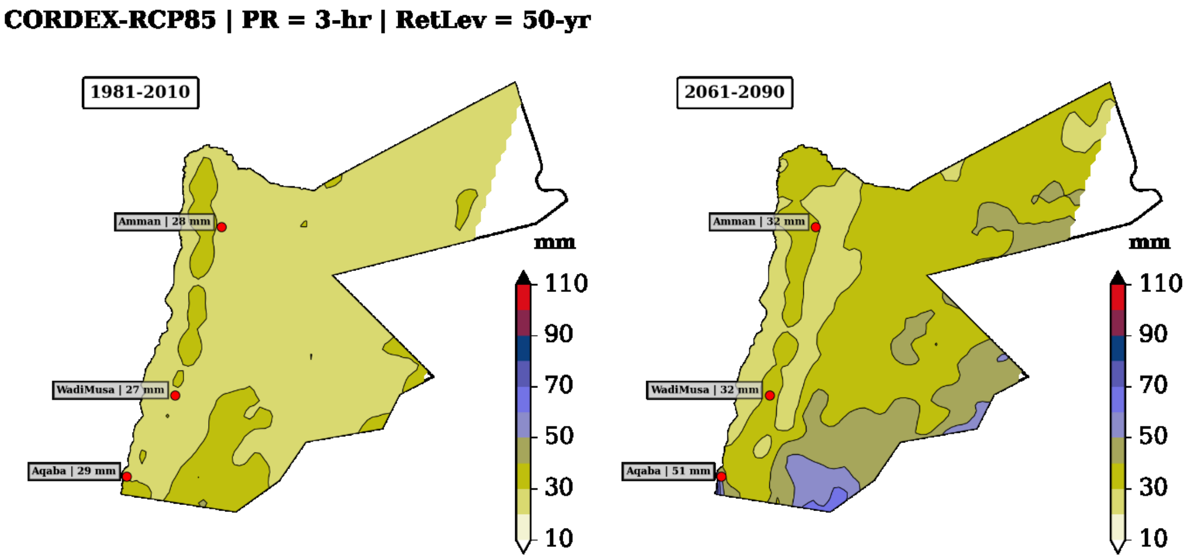


Figure 13. Derived heavy rainfall maps for past (left) and future (right) conditions: 3-hourly and return period 50-yr.

Heavy precipitation can occur anywhere, even in regions that have previously experienced minimal rainfall. It is important to note that Jordan is situated at the border of the domain. It is possible that edge effects may distort the results in this instance. However, this applies equally to both the historical and future simulations. Additional maps for different return periods and duration levels were considered (not shown). In comparison, the short-term events show the strongest climate sensitivity (shown in Figure 14). This finding is relevant for the future planning and adaptation strategies of critical infrastructure in Amman and Petra.

The duration of rainfall events significantly impacts the strength of the interaction between dynamic and thermodynamic effects. Consequently, opposing trends may emerge, such as a reduction in the number of events (critical weather conditions) coupled with an increase in their intensity. These are processes and phenomena whose future development is difficult to predict using current climate model simulations. Uncertainties remain because the scale of the phenomena considered varies in space and time. Underestimates of possible developments cannot be ruled out because models, despite their complexity, do not capture all interactions in the climate system. Even the slightest shift in the position of critical weather patterns can distort the results.

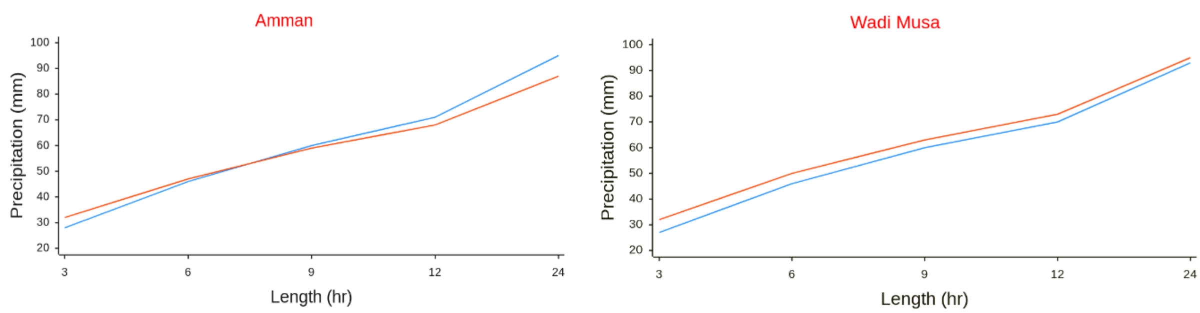


Figure 14. Sensitivity of heavy rainfall scenarios 3-hr to 24-hr under past (blue) and future (red) climate conditions.

4.2.5 Climate Service Portal

Climate Impacts Online is a climate service portal for countries run by the Potsdam Institute for Climate Impact Research (PIK), with the aim of putting climate change knowledge into practice. As part of the CapTainRain project, Jordan has been added as a new country. The service provides users with information on the latest climate projections for selected climate indicators up to 2100, for different SSP emission scenarios. This information is presented as zoomable maps, charts and tables in different languages. The baseline scenarios are derived by the ISIMIP initiative at PIK (https://www.isimip.org/). They provide bias-adjusted global climate model simulations (Copernicus, 2021) to researchers studying the impact of climate change worldwide. However, the mesh size of the data is relatively coarse. As a result, Jordan's regional characteristics are not well represented. The situation is different for the regionally higher resolution climate simulations used in the project to produce heavy precipitation maps. In contrast, the regional distribution of precipitation patterns is particularly evident in the western part of the country. Ensemble simulations at this scale are very large and time-consuming. Here we have accessed and processed available runs.

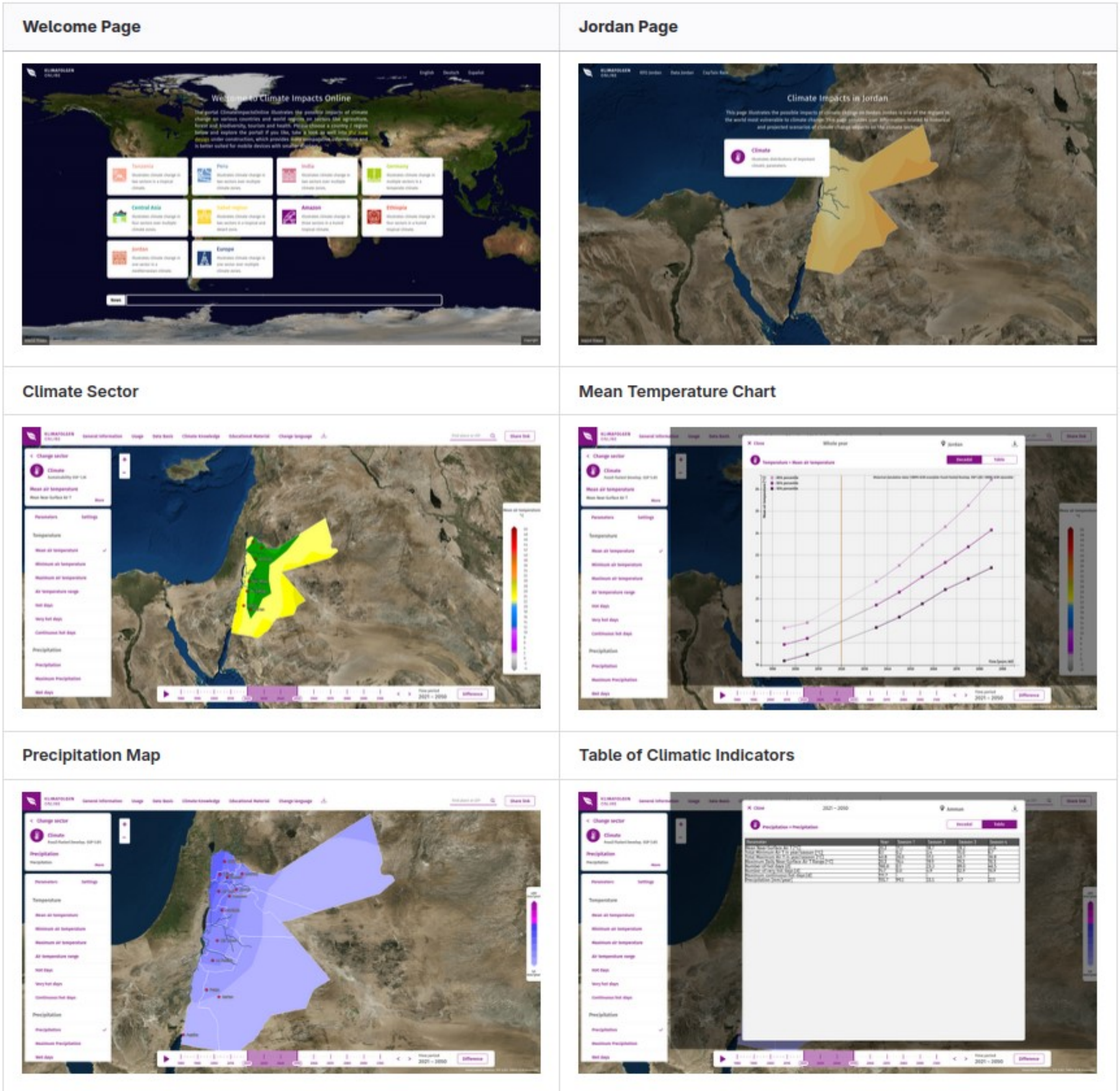


Figure 15. Screenshots of the climate service portal for Jordan (https://climateimpactsonline.com).

4.2.6 Early Warning of Critical Weather Types

To facilitate the early detection of developing extreme weather conditions (e.g. extreme rainfall), the Jordan Meteorological Department (JMD) conducts a daily review of ensembles of model forecasts. While some processes are automated, additional tools could facilitate expert monitoring. A tool of this kind was developed and evaluated in collaboration with the JMD during the second phase of the project. The underlying principle is outlined briefly below.

A retrospective analysis of the past decades has enabled the identification and classification of the meteorological conditions that have historically led to heavy precipitation in Jordan. The recurrent weather conditions were classified into 20 different categories using image comparison techniques related to atmospheric geopotential height fields. Consequently, each day in the past is assigned one of the 20 predefined weather conditions (WT01-WT20). Combining this with local measurement data enables the determination of the seasonal weather characteristics of each weather condition and which are prone to extremes. As illustrated in Figure 16, the seasonal characteristics of the weather types in Jordan are evident, with regard to precipitation and high temperatures.

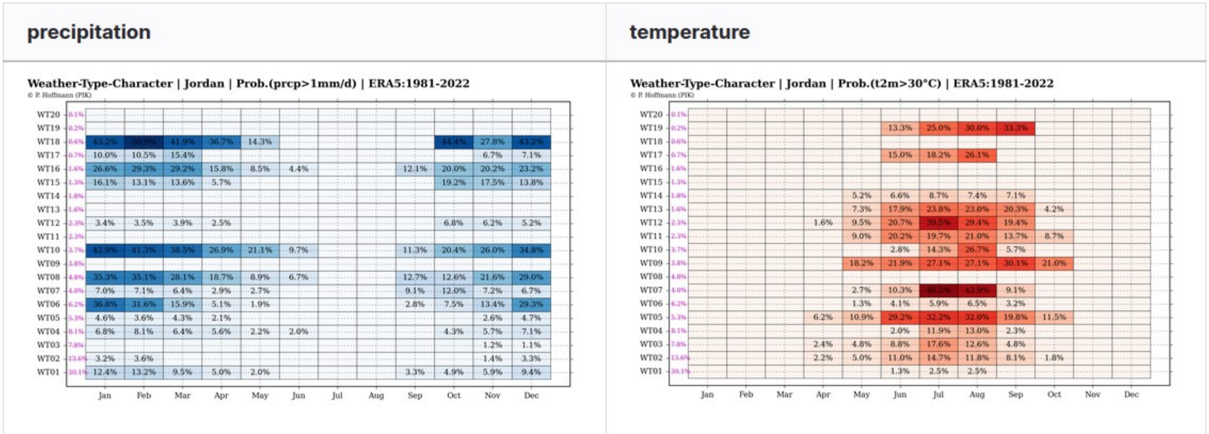


Figure 16. Long-term monthly mean weather-type characteristics for days above 1 mm (left) and days above 30°C (right) in Jordan.

The system for forecasting large-scale weather patterns and their relationship to local weather conditions in Jordan uses historical reanalysis data of atmospheric fields to objectively categorise recurring circulation patterns over the eastern Mediterranean. An established image comparison method is used to determine the degree of similarity between daily fields over a 30-year period. The resulting similarity matrix is then subjected to a hierarchical clustering procedure. Given the maximum number of sequences (N = 20), a sequence of daily sequences of recurring weather conditions is obtained, designated WT01 to WT20. WT01 represents the most frequent class. The corresponding sequences differ mainly in the curvature of the contour lines used to characterise the large-scale air mass transport. A random forest model is then trained to identify the relationships between the corresponding fields and the weather conditions. These relationships are then presented as a decision tree for further processing.

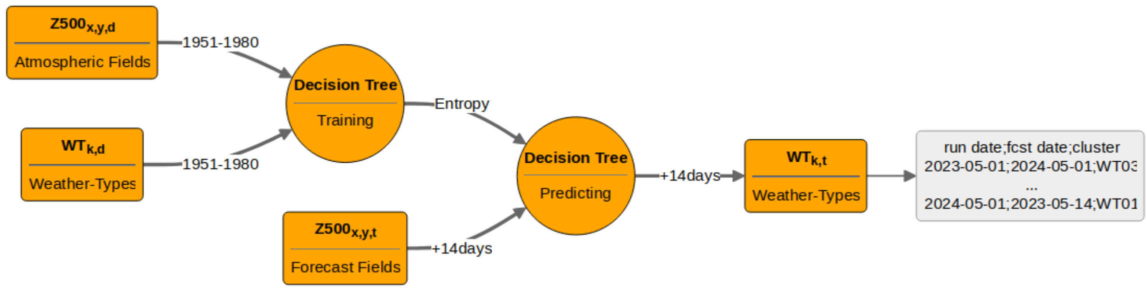
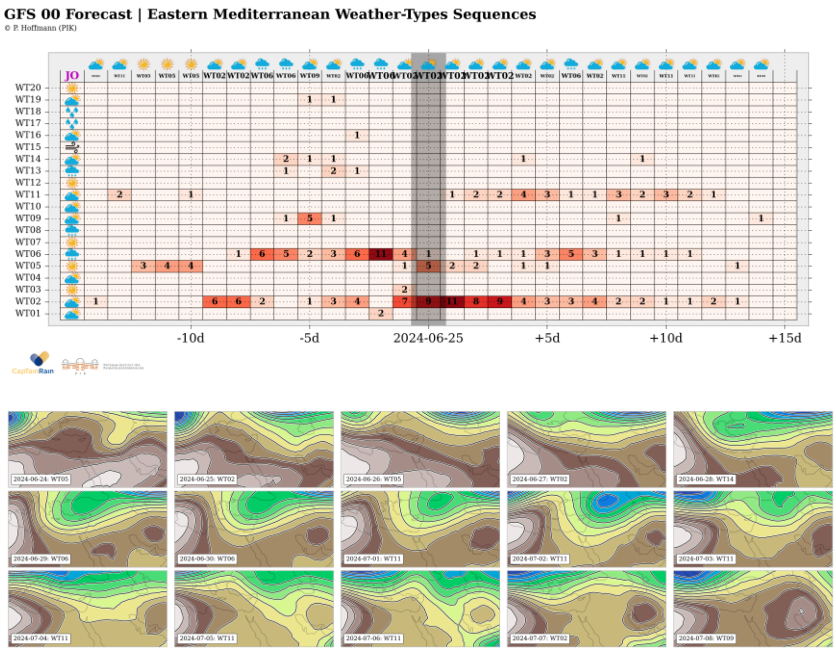


Figure 17. Scheme of data processing for training and predicting weather-types in weather forecasts.

The tool is employed exclusively on Global Forecast System (GFS) from the previous 14 days. The data is stored in an archive and is provided by the National Oceanic and Atmospheric Administration (NOAA) on a continuous basis. Each individual run simulates the global weather developments for the subsequent 14-day period and beyond, based on different initial conditions from the preceding days. The diagram then synthesises the similarities in the timing of the individual weather conditions, providing an update on a daily basis. The colouring of the boxes indicates which meteorological conditions will determine the weather, while the icons represent which local weather phenomena may be associated with them. Moreover, tables and maps are generated for the purpose of monitoring and controlling the corresponding assignments. Consequently, the capacity to discern the emergence of critical conditions at an early stage is enhanced. The optimisation process will extend beyond the duration of the project.



GFS_Global_onedeg_2024-06-24_0000

Initial Date	Forecast Date	GWL
2024-06-24	2024-06-24	WT05
2024-06-24	2024-06-25	WT02
2024-06-24	2024-06-26	WT05
2024-06-24	2024-06-27	WT02
2024-06-24	2024-06-28	WT14
2024-06-24	2024-06-29	WT06
2024-06-24	2024-06-30	WT06
2024-06-24	2024-07-01	WT11
2024-06-24	2024-07-02	WT11
2024-06-24	2024-07-03	WT11
2024-06-24	2024-07-04	WT11
2024-06-24	2024-07-05	WT11
2024-06-24	2024-07-06	WT11
2024-06-24	2024-07-07	WT02
2024-06-24	2024-07-08	WT09

1 20240625
1 2024-06-25 missing
0 20240626

GFS_Global_onedeg_2024-06-26_0000

Initial Date	Forecast Date	GWL
2024-06-26	2024-06-26	WT05
2024-06-26	2024-06-27	WT11
2024-06-26	2024-06-28	WT11
2024-06-26	2024-06-29	WT14
2024-06-26	2024-06-30	WT06
2024-06-26	2024-07-01	WT06
2024-06-26	2024-07-02	WT06
2024-06-26	2024-07-03	WT06
2024-06-26	2024-07-04	WT02
2024-06-26	2024-07-05	WT02
2024-06-26	2024-07-06	WT05
2024-06-26	2024-07-07	WT05
2024-06-26	2024-07-08	WT02
2024-06-26	2024-07-09	WT02
2024-06-26	2024-07-10	WT09

Figure 18. Resulting maps, tables and charts of the early warning tool for critical weather-types in Jordan.

The software tool is provided as standalone window application that is available under the GIT repository (https://gitlab.pik-potsdam.de/peterh/gfswt) hosted at PIK. After download it can be executed. The output generated is given in Figure 18. The main innovation is to convert atmospheric fields to a sequence of recurring weather-types. This clearly reduces complexity in the monitoring of ensemble forecast. Other target regions are Germany and Pakistan.

4.3 Outlook: Rainfall hazard risk

The occurrence of heavy rainfall is sensitive to variations in climatic conditions. However, the relationships are complex because the effects of temperature change and those of dynamic processes such as evaporation and rainfall are not mutually exclusive. On the one hand, rising temperatures of land masses and oceans lead to an exponential increase in the moisture content of the atmosphere through evaporation. In the event of a perfect storm, the precipitation levels would be significantly higher, potentially resulting in catastrophic consequences. Conversely, this process is controlled by large-scale factors related to the transport of air masses, which show considerable variability in both space and time. Long-term trends are therefore difficult to detect, with long-term climate projections including high insecurities. In conclusion, recent heavy rainfall events, such as those that occurred in Greece and Libya in 2023, have the potential to reach Jordan if the location and track of the controlling low-pressure system shifts just a little. It is therefore possible that rainfall in a single day could reach levels that would otherwise be expected over the course of an entire year. Understanding these relationships offers the potential for early detection of critical developments in forecasts and trends in long-term climate projections. While the frequency of such events does not currently indicate an increase, individual events in a warmer climate have the potential to trigger larger amounts of rainfall, leading to greater accumulations of rainwater in urban centres such as Amman or wadi systems such as Petra.

5 Exposure and Sensitivity: Flood hazards and risk areas

Authors: Clara Hohmann, Christina Maus, Hanna Leberke, Ahmad Awad, Ahmad Bariq Allemyar, Dörte Ziegler and Lothar Fuchs

5.1 Research objectives and methods

Closely linked to the quantification of heavy rainfall events under climate change, this work package analysed the resulting flash floods, with a focus on their spatial impacts on humans, infrastructure, and ecosystem services for the two pilot areas, Amman and Wadi Musa. To determine the exposure to flash floods as spatial occurrence of inundations, a hazard analysis was developed for different intensities and probabilities of rainfall scenarios. A flash flood risk assessment was conducted for the watersheds in Amman and Wadi Musa, incorporating a sensitivity analysis to determine the damage potential in the event of flooding. The resulting hazard and risk maps were used as climate services in stakeholder dialogues. Figure 19 shows the approach for flash flood risk assessments. The resulting hazard and risk maps as well as information about hydrological flow paths lay the foundation for the vulnerability analysis (WP 5) and the allocation and implementation of adaptation measures (WP 4). The hazard and risk maps were also used for risk communication (WP 6).

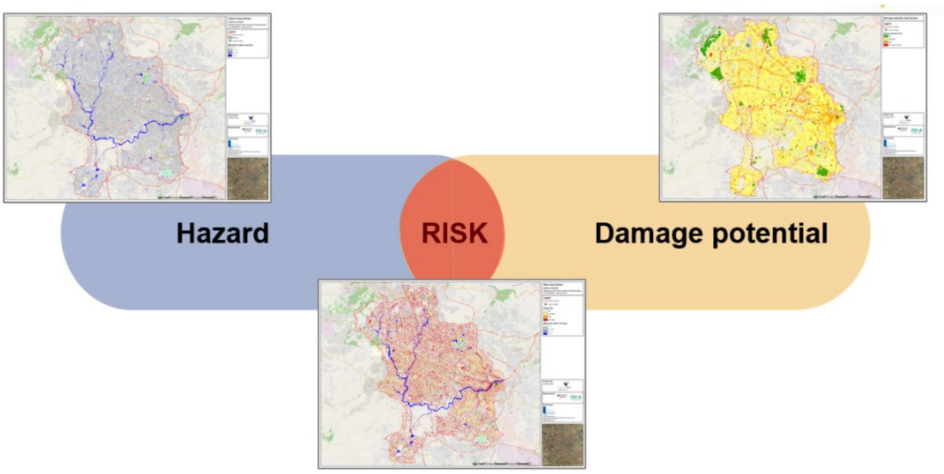


Figure 19. Flash flood risk assessment approach within CapTain Rain. Risk is the overlay of hazard and damage potential.

5.2 Key findings for Amman and Wadi Musa

The key findings and products of the flash flood hazard and risk analyses for the study regions Amman and Petra/Wadi Musa are listed here and further described in the following sections.

- Data scarcity is the most challenging aspect when assessing risks from flash floods in the MENA region.
- Hydrologic and hydraulic modelling is applicable in both urban Amman and rural Wadi Musa, with the quality of results depending on the quality of input data. Modelling was suitable to analyse the influence of climate and land use changes.
- The application of standard methodologies on flash flood risk assessment from Germany was possible, but requires adaptations regarding modelling (e.g. limited data access, hydrological processes of semi-arid areas) and damage categories (e.g. cultural heritage).
- The hydraulic modelling combined with the spatial analysis of damage potentials allowed to develop flash flood hazard maps, damage potential maps and flash flood risk maps.
- While hydraulic modelling shows inundation areas and the impact of different measures to reduce them, the regional extension is still limited to smaller basins due to time and resource requirements for this methodology. More rapid results can be achieved with hydrological models, also for larger watersheds. However, hydrological modelling focuses on runoff curves rather than inundation areas.

For data-scarce arid regions like Jordan, simple hydrological models such as HEC-HMS can provide initial assessments on strategies to assess and to retain flash flood. Multi-model approaches with comparison of hydrological and hydraulic models for Wadi Musa showed the quality of modelling results (Hohmann et al., 2024).

- Hydrological models cannot be validated and calibrated in Jordan due to lack of runoff data. A multi-model approach helped to check the quality of the models, comparing two hydrological models HEC-HMS, RRI and the hydraulic model HE2D/FOG2D results regarding peak flow rates and water levels.
- The quality of hydrological modelling would most profit from runoff data to allow calibration. Soil information and information about infiltration capacities would improve the results of both hydrological and hydraulic models. Hydraulic modelling would profit most from a more accurate, quality-proven digital elevation model (DEM), and by integrating data on the sewer system.
- Any rainfall and flash flood analysis require 5 minute- resolution rainfall data. Such data would be important for analysis of past events and help to assess the hazard and risks of future events.
- The quality control of data is important, as is the collection of data itself in Jordan.

5.2.1 Flash flood hazard

To model flash flood hazards, i.e. water flows and water levels resulting from heavy rain, hydrological and hydraulic modelling was used. Hydraulic models give the potentially inundated areas with spatially distributed information about water levels and flow velocity. Hydrological models provide runoff curves as hydrographs for certain outlets of watersheds, with hydrographs depicting flow rates and peak flows. Both hydrological and hydraulic models can be used to analyse the potential changes in climate by integrating heavy rainfall data. They also can be used to assess the impacts of urbanization and changes in land use land cover (LULC) and the integration of adaptation measures on flash flood events. The model results demonstrate the impacts of LULC and adaptation measures by illustrating changes in inundation areas and depths, flow velocities, and peak flow rates.

5.2.1.1 Watersheds of urban Amman and rural Wadi Musa

As a first step, the watersheds that should be investigated were delineated in Digital Elevation Models (DEM) with pour points at the outlet. A flow path sink analysis was carried out for this purpose. This analysis also gives a first overview about possible hotspot areas of inundations. In the case of Amman, a Digital Elevation Model (DEM) with a resolution of 1 m was utilised, provided by the Royal Jordanian Geological Survey (RJGC). With regard to Petra, a Digital Elevation Model (DEM) with a resolution of 2 m was utilised, which was provided by the PDTRA.

The watershed of central Amman has an area of 150 km². The area is characterised by high population density, with significant development of buildings and infrastructure, including roads, which collectively dominate the watershed. The mean annual precipitation is 245 mm. The central Amman watershed exhibits pronounced variations in altitude, with a range of up to 400 metres, and elevations extending from 700 to 1100 m. Towards the outlet of the watershed, the Roman theatre is located, a cultural heritage site and a hotspot of flash floods. The location is indicated on the maps by a star symbol, denoting its designation as an orientation point. In Amman, the former watercourse of this watershed has been covered by roads, and is only visible towards the outlet. The watershed contributes to the Zarqa river basin.

The studied watershed in Wadi Musa and Petra is much smaller with 75 km², but has a much higher difference in height with 1200 m. The climate is very dry, with an average annual rainfall of 172 mm. The region is mostly unpopulated with the exception of Wadi Musa, a community with about 6.800 inhabitants. The soils are rocky or sandy, with low permeability. Agriculture is characterised by small irrigated plots and livestock farming, primarily of goats and sheep. Wadi Musa is the community that manages the nearby Petra World Heritage Site. This watershed is characterized by the Siq, a narrow rocky canyon leading towards the Petra cultural heritage site. The entrance to the Siq is marked with a yellow star on the map above. The canyon is about 1 km long. If water entered this canyon, people would unable to escape. A tunnel adjacent to the Siq entrance has been constructed to divert rainwater. It dates back to Nabatean times.

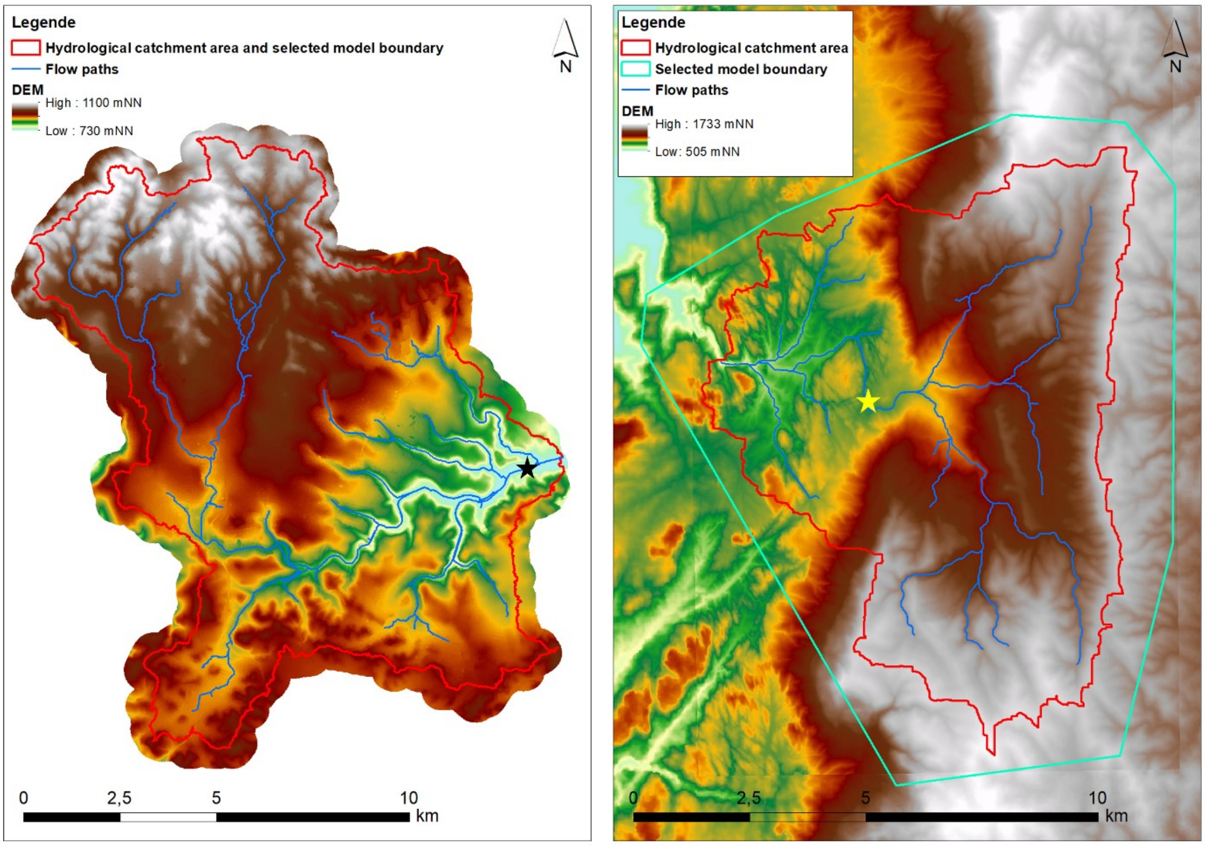


Figure 20. Left: Overview of the study area Amman with the hydrological catchment area and selected model boundary (red polygon) and the flow paths (blue lines). Right: Overview of the study area Wadi Musa with the hydrological catchment area (red polygon) and the selected model boundary (cyan polygon) and the flow paths (blue lines).

5.2.1.2 Hydrological modelling

A hydrological model transforms rainfall events into runoff and simulates hydrographs. After consideration of diverse models, we decided to use the HEC-HMS model in the CapTain Rain project, based on the following selection criteria:

- The model allows for short-term event modelling of minutes to hours.
- The model can integrate natural and urbanized areas, changes in LULC, as well as changes in rainfall due to climate change (e.g. Schoener, 2022; Zhang et al., 2019).
- Access is free: Open source model, with user manual (HEC-HMS, 2024).
- The model is often used in semi-arid regions with scarce data (e.g. Schoener, 2022, UN-Habitat, 2020; El Alfy, 2016).

The HEC-HMS model can be configured in a number of different ways. In the CapTain Rain project, we used the modules shown in Figure 21, which are ideal for modelling heavy rainfall events in regions where data is scarce.

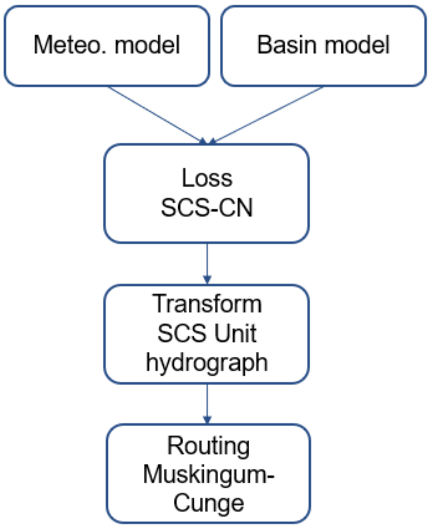


Figure 21. HEC-HMS modules used in the hydrological model setup of the CapTain Rain project.

Further delineation steps, such as sub-basin definition and stream identification, can be performed directly in HEC-HMS based on a DEM. For the meteorological model, we calculated the gauge weights of the rainfall stations using the Thiessen polygon function in ArcGIS. The curve number (CN), which is an empirical parameter used to predict infiltration versus direct runoff, is derived from soil and land cover maps (Awad, 2023). Literature values from USDA (USDA, 2010) were used for the different parameters of the transform and routing modules. The following table provides an overview of the input data used for the HEC-HMS models in Amman and Wadi Musa, respectively.

Table 2. Input data for the hydrological modelling in the study areas Amman and Wadi Musa respectively.

Input data	Amman	Wadi Musa
DEM	1 m (RJGC)	2 m (PDTRA)
Rainfall	Time series for five stations in/close to our study region in 5 min resolution for the event in Feb. 2019 (JMD, UN-Habitat 2020)	Time series for nine stations in event dependent resolution (PDTRA) and for one station in hourly resolution (MWI) in our study region for the event in Dec. 2022
Land cover	2021: Land cover classification of Sentinel-2 images (Awad 2023)	2021: Land cover classification of Sentinel-2 images (Awad 2023)
Soil information	HYSOGs250m (Ross et al., 2018)	HYSOGs250m (Ross et al. 2018)

5.2.1.3 Hydraulic modelling and flash flood hazard maps

Two methods were applied to analyse the flash flood hazards in our study regions of Amman and Wadi Musa: First, a flowpath sink analysis was performed (see Figure 20). This rapid methodology allows watershed and water flow paths to be analysed using GIS software and a DEM. Secondly, hydraulic modelling was performed. This required a software package and input data such as a DEM, buildings and rainfall events. Using personnel and computer resources, the hydraulic modelling produced GIS maps showing flash flood areas, flow velocities and inundation depths. The flash flood hazard was then interpreted in terms of inundation area and depth resulting from a rainfall event of a certain intensity and probability. The hydraulic models and simulations were created using the “Urban Flash Floods” software package (HE2D/FOG2D) from ITWH GmbH, version 8.6.2. The “HE2D” hydraulic model uses 2D shallow water equations to calculate surface flooding processes. These flow equations are solved in space using cell-centred finite volumes and in time using the explicit Euler approach. The model calculates inundation areas with water levels and surface flow velocities.

HE2D performs the discharge calculations on an irregular triangular grid. This is generated on the basis of the DEM (1 m respectively 2 m grid) and the buildings using the FOG2D model generator. To ensure that the simulation of the model runs is as efficient as possible, the size of the triangles is defined differently depending on the location. Each triangular element has a constant height value (Z-value), which is determined using a smoothing process. Building polygons are considered as non-flow gaps in the 2D calculation mesh. For the rainfall-runoff calculations, a distinction is made between paved and unpaved areas. Infiltration losses are considered for infiltration on unpaved surfaces using the Horton approach. HE2D uses the Manning-Strickler roughness approach. The roughness coefficients (k_{St} values) are determined based on the LULC.

Flash flood hazard maps, which are produced using 2D hydraulic modelling, show areas that are particularly at risk during periods of heavy rainfall. They illustrate where water accumulates and which areas may be particularly susceptible to flooding. These maps are essential for urban planning, disaster management and risk assessment. Alongside the analysis of damage potential, they provide a foundation for analysing flood risks.

For Amman, the area selected for hydraulic modelling is around 120 km². For performance reasons, the hydraulic model boundary was chosen to be slightly smaller than the watershed identified in the flow path–sink analysis. However, it still encompasses key urban areas such as the Roman Theatre. The Wadi Musa hydraulic model area, on the other hand, was chosen to be slightly larger than the watershed and is also approximately 120 km² in size.

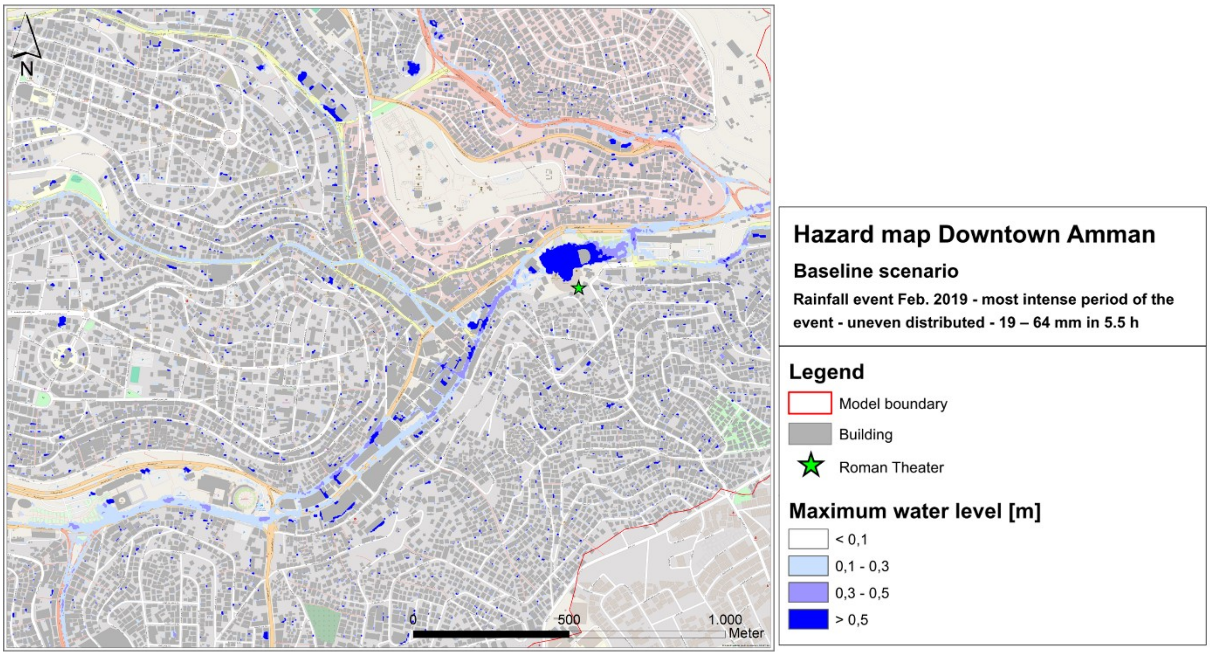


Figure 22. Hazard map for Downtown Amman modelled with HE2D/FOG2D with recorded rainfall from five stations during the February 2019 event (most intense period). Water levels are classified according to the German DWA-M 119 standard.

The results of our model depend heavily on the resolution and quality of the DEM. The 1 m resolution DEM for Amman (RJGC) shows some unrealistic depressions where water accumulates. Furthermore, detailed information on Amman's sewer systems is lacking. Regarding the hydrological models, data on water levels for calibrating and validating the model results was mostly lacking, except for photographic documentation of the heavy rainfall event that flooded the Roman theatre in 2019.

For Wadi Musa we had a DEM with a resolution of 2 m (PDTRA) and of good quality. Only some adjustments were necessary in the area of the Siq. In some parts, the top of the canyon is so narrow that we had to adjust the DEM to create a flow path of the correct size. We used the same approach for the tunnel at the beginning of the Siq.

For the subsequent risk assessment, we needed to determine four hazard classes. We opted for a classification according to the DWA-M 119 guideline: *low* = water depths < 0.1 m, *medium* = water depths ≥ 0.1 and < 0.3 m, *high* = water depths ≥ 0.3 and < 0.5 m, and *very high* = water depths > 0.5 m.

5.2.2 Flash flood damage potential

In addition to the hazard analysis, a comprehensive risk assessment requires an analysis of the damage potential, which categorizes buildings and other elements according to their type of use (e.g. residential, commercial, critical infrastructure etc.). The assessment of the damage potential considers the possible impact of heavy rainfall events on various sectors or aspects of life. These include people, particularly vulnerable groups such as children and people with restricted mobility; infrastructure, including critical infrastructure, but also residential, industrial and agricultural areas; the environment, including protected areas; and other aspects such as cultural heritage. The aim of assessing the damage potential is to determine, localise and illustrate protection requirements and damage susceptibility and to assign damage potential classes. Damage potential is evaluated independently of the hazard assessment. Where a high damage potential is present within a hazard area (i.e. an inundation area), a flash flood risk arises. Therefore, the damage potential assessment, together with the hazard assessment, forms the basis of the risk and vulnerability analysis.

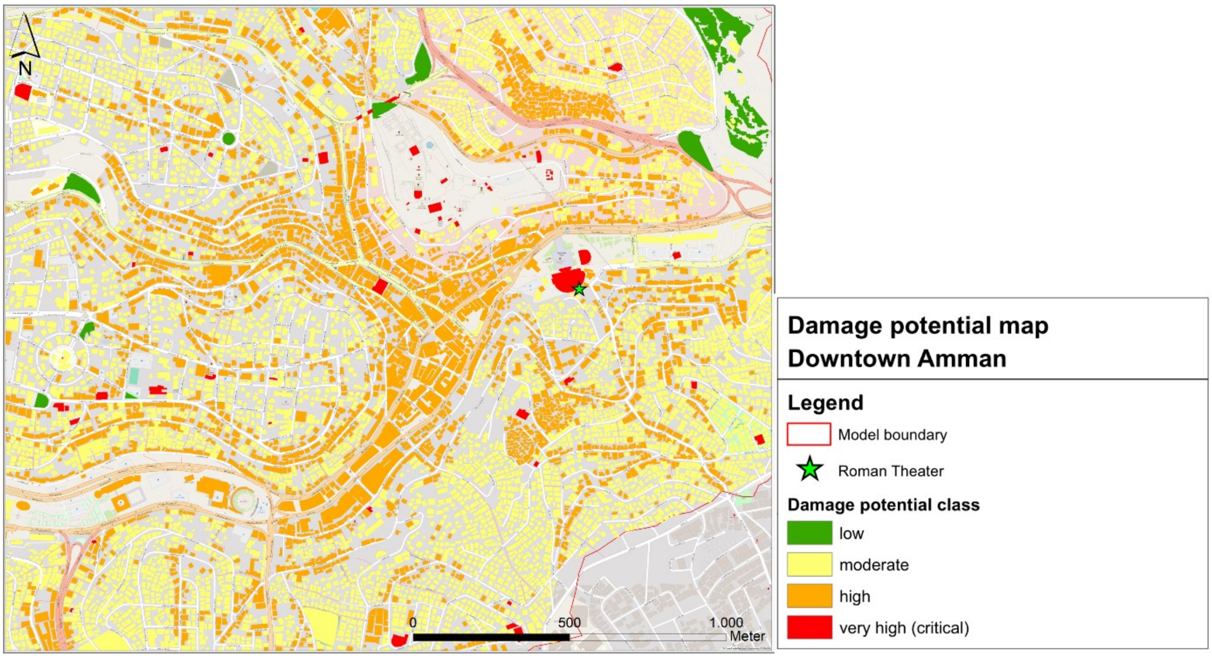


Figure 23. Damage potential map for Downtown Amman, showing buildings with a damage potential class for flash floods without consideration of flooded areas.

In CapTain Rain, the classification of the damage potential was based on the German standard DWA-M 119 (DWA 2016), adapted to the local situation through the expert opinion of selected Jordanian stakeholders (n = 5). Four classes were used to categorise the damage potential: 1 – low, 2 – moderate, 3 – high and 4 – very high (critical). Buildings within the study areas were classified based on their predominant use. The data basis for Amman comprised shapefiles from GAM and OpenStreetMap (OSM) datasets, and for Wadi Musa a shapefile from PDTRA, OSM datasets. For Wadi Musa, the data basis comprised a shapefile from the PDTRA and OSM datasets. Additionally, information was added using digitised buildings based on an aerial photograph (PDTRA) and building usage information from

Google Maps and Google Earth. However, little information about critical infrastructure was available for Amman and Wadi Musa.

The results of the damage potential assessment indicate that densely built-up urban areas are at high risk of damage, since floods can affect many buildings and escape routes can easily become flooded or blocked. The damage potential increases to very high if buildings have basements. The damage potential also increases if people are less mobile and thus less able to leave flooded areas. Therefore, hospitals and childcare facilities are assigned a very high damage potential. The damage potential is also classified as ‘high’ for critical infrastructure, including emergency services and energy infrastructure.

As the classification of damage potential can be subjective to a certain degree, it is recommended that it is assessed by expert groups and/or stakeholder workshops. Such a joint assessment can reduce subjectivity. Also, as the determined damage potential is based on a snapshot in time, it should be reviewed at regular intervals to take into account future developments, as well as possible changes in land use and infrastructure.

5.2.3 Flash flood risk

The aim of the flash flood risk analysis is to assess the degree of risks in potentially flooded areas through the combined consideration of hazard and damage potential. By identifying high-risk areas and objects, the risk analysis points out existing needs for action and provides the basis for the development of precautionary measures. Particular attention is paid to critical infrastructures and objects.

Table 3. Flash flood risk matrix (combination of hazard and damage potential).

risk		damage potential			
		low	medium	high	very high
flood hazard	low	low	medium	medium	high
	medium	medium	medium	high	very high
	high	medium	high	very high	very high
	very high	high	very high	very high	very high

A location is considered to have a high flood risk if it has a high flood hazard (e.g. high water levels) and an object or area with a high or very high damage potential (e.g. a hospital) is present. The assessment of risks to human health, the environment, cultural heritage, infrastructure facilities and other assets is based on qualitative analysis in four categories according to DWA-M 119 (2016): low, moderate, high and very high. The risk class is determined using a combination matrix in which the flood hazard and damage potential are considered together; see the table below.

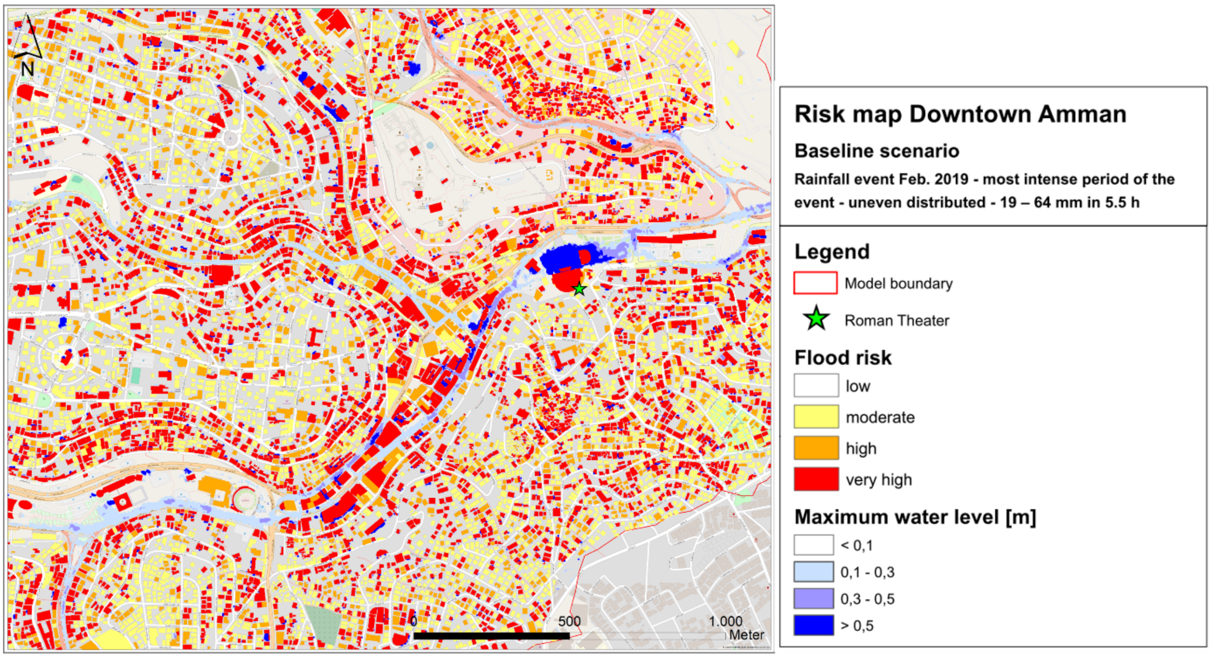


Figure 24. Flash flood risk map for Downtown Amman.

5.2.4 Multi-model approach to analyse runoff peaks from flash floods

The aim of the hydrological modelling was to assess potential runoff curves resulting from heavy rainfall events. Runoff curves enable the modelling of scenarios with regard to climate adaptation measures in larger basins. Based on runoff peaks, it would be possible to evaluate the potential reduction in water levels and inundation areas in these scenarios. However, due to lacking runoff data, it was not possible to calibrate or validate the hydrological models. However, due to a lack of runoff data, it was not possible to calibrate or validate the hydrological models. To ascertain the plausibility of the models' results, we adopted a multi-model approach for the Wadi Musa study area. By simulating the December 2022 flash flood event with three very different models, we aimed to gain insight into the uncertainty of the results. For this, we used the aforementioned HEC-HMS (hydrological) and HE2D/FOG2D (hydraulic) models, as well as the Rainfall-Runoff-Inundation (RRI) model.

The RRI model was setup in a 100 m grid resolution based on the data shared with us by Dr. Sameh Kantoush, Kyoto University. The following figures show the modelled runoff curves at the Siq entrance for all three models.

For the model comparison, we used the rainfall data from ten stations, for the event in December 2022 (28 hours), which was selected based on data availability. The models reacted differently to the event: the HEC-HMS model showed the fastest and strongest reaction, while the RRI and HE2D/FOG2D models showed their highest peaks up to two hours later. Runoff modelled with RRI is more inert, with a late peak and a slow descending curve. The hydraulic model HE2D/FOG2D reacts more slowly, showing the first flow nine hours later.

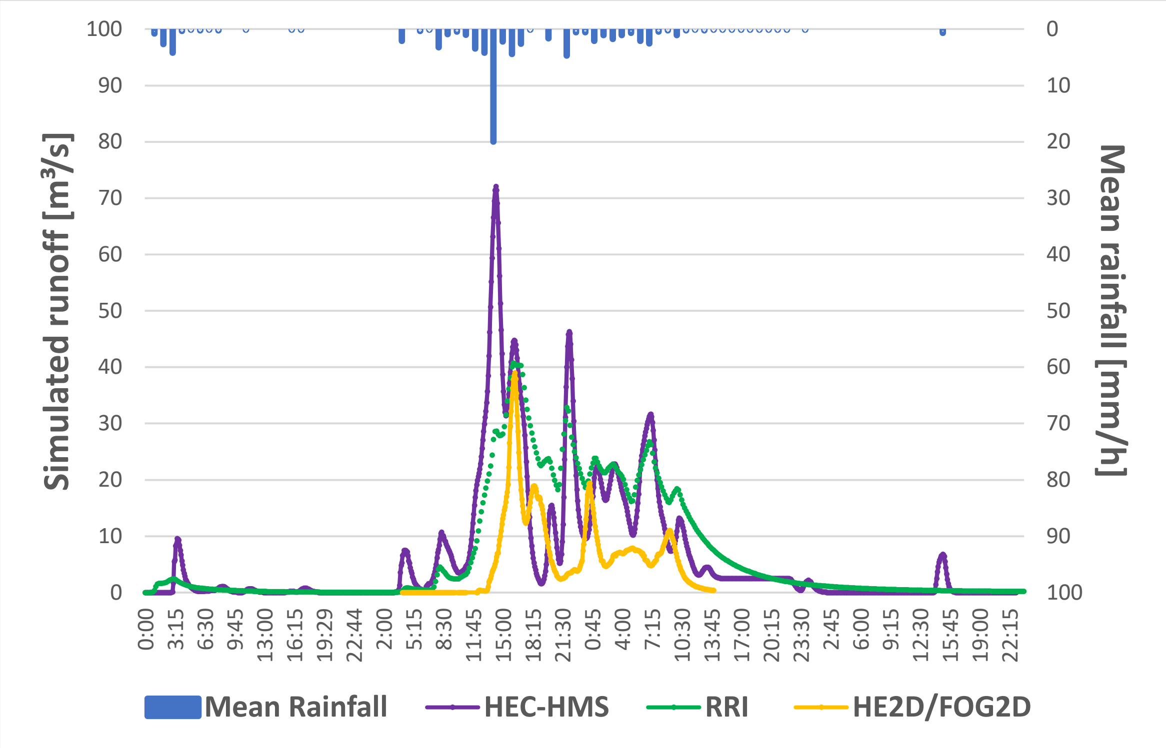


Figure 25. Simulated runoff at the Siq entrance, Wadi Musa with the models HEC-HMS (purple), RRI (green) and HE2D/FOG2D (yellow), as well as the mean input rainfall (blue) for the event of December 2022.

The models are set up with the same input parameters regarding DEM, slope, soil information, and rainfall. However, the output runoff curves differ due to variations in the model setups and internal processes. While all models provide water level variations at key points within a range of 8 to 30%, the runoff peaks vary between ~ 40 m³/s and > 70 m³/s, i.e. ~ 75% variation. For the December 2022 event, the water levels are almost identical, differing by only 8 %. In the intense rainfall scenario, the water levels of the three models differ up to ~30 %, with the RRI model showing the lowest values (0.8 m), and HE2D/FOG2D the highest water levels (1.2 m). Still all water level results represent a quite close range (0.84 m – 1.21 m). Striking is the behavior of RRI which shows similar water levels for the two rainfall inputs, a behavior which we cannot explain yet.

Table 4. Simulated water at the bridge near the Petra entrance in Wadi Musa for two different rainfall inputs.

Event	HEC-HMS	RRI	HE2D/FOG2D
Dec 2022, 28 h	0.78 m	0.85 m	0.81 m
Intense scenario	1.00 m	0.84 m	1.21 m

5.3 Outlook: Flood hazards and risk areas

The model results and produced maps are important tools for the Jordanian partners and are now ready to be used for planning purposes. Further refining the hydraulic model for Amman would be beneficial, for example by integrating detailed sewer and stormwater network information and/or an improved DEM. Partners working with data such as DEMs and building information, such as the GAM for Amman and the PDTRA for Petra, should link this data to flash flood hazard and risk maps. They should also actively update these maps and use them to inform other institutions and the public. The HE2D/FOG2D hydraulic model developed by ITWH for Amman and Wadi Musa has been set up so that hazard and risk maps can be easily updated. Other hydraulic models could also be utilised for Amman and Petra, bearing in mind potential licence costs, the resources required to set up the hydraulic models, and the resources required for data proofing.

In order to calibrate the models and increase their reliability, runoff data is required. Therefore, staff gauges should be installed and maintained, and monitored during periods of rainfall. Suggestions for installing staff gauges have been provided to both GAM and PDTRA. Also, the quality of rainfall data should be improved. For heavy rainfall events, high-resolution (approximately 5-minute) rainfall data should be available. Ground station data needs to be coupled with radar data to obtain special distributed heavy rainfall data. Such quality-controlled rainfall radar data is not currently available in Jordan. Processing radar data and coupling it with ground station rainfall data would require additional resources. Furthermore, the southern part of Jordan is not covered by the Jordan Meteorology Department's radar system. In future, the quality of rainfall data should be improved to provide a reliable basis for more accurate modelling. This would reduce infrastructure adaptation costs, since this infrastructure could be adapted to quantified rainfall events.

6 Adaptive capacity: Selection and localisation of adaptation measures

Authors: Daniel Schuhmann-Hindenberg, Linnéa Fölster, Martina Winker and Katja Brinkmann

6.1 Research objectives and methods

Adaptive capacity refers to a system's potential or capability to adapt to flash flood risk. Technical measures alone are insufficient to mitigate the damage caused by flash floods in urban areas. To significantly reduce the damage potential, an integrated set of adaptation measures is needed in both public and private areas. A change of mindset is needed towards jointly assessing promising adaptation measures, involving officials and local stakeholders with different areas of responsibility. In addition to structural measures and property protection, innovative measures for the retention, safe discharge, storage and use of heavy rainfall were identified, evaluated, allocated and approved on the basis of feasibility. The aim was to expand the portfolio of adaptation options to prevent flash flood damage by evaluating innovative measures for the discharge and use of heavy rainfall, and to deliver recommendations for the planning process and implementation of measures. Appropriate and innovative measures to mitigate flash flood risks were identified through literature surveys, GIS-based analysis and participatory methods. Additionally, expert interviews (Chapter 3) were considered. Identifying planning objectives, suitable areas for future implementation ('focus areas') and the appropriate measures is an iterative process. In CapTain Rain, we conducted a stepwise participatory planning process divided into three main steps: Data collection and analysis; planning and localisation; and development and strategy (Figure 26).

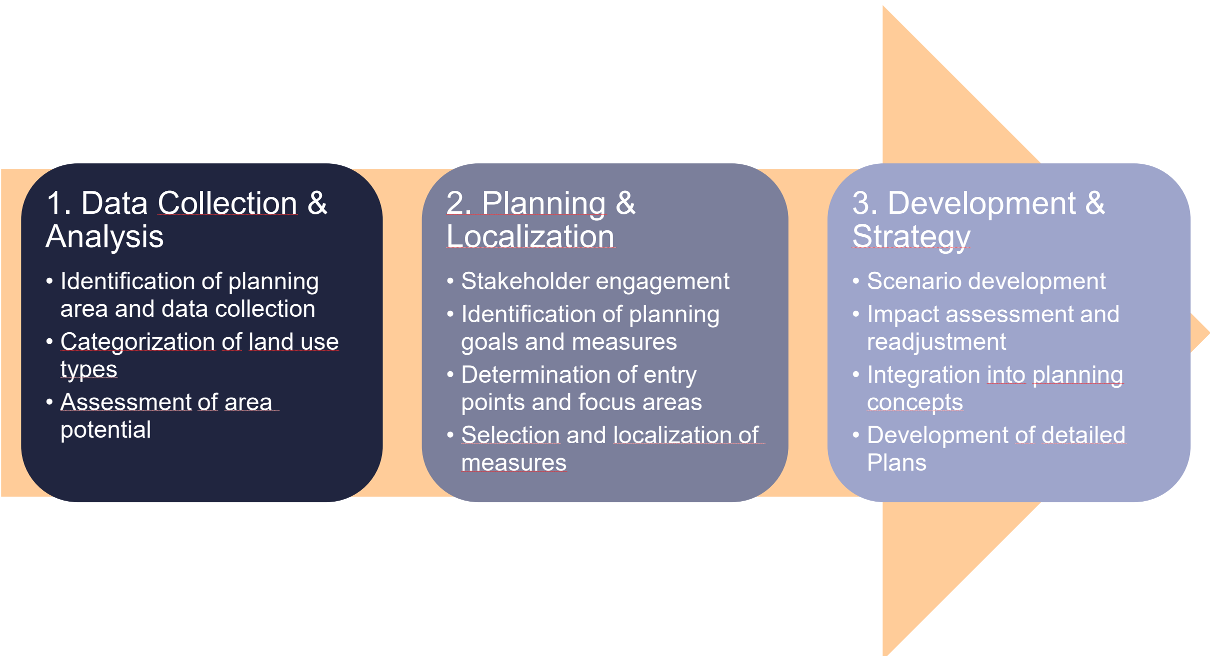


Figure 26. Overview of the stepwise planning process comprising data collection & analysis, planning and localization, and the development & strategy.

The process started with the identification of the planning area, followed by collecting and analysing spatial data and field information. All the collected GIS data and relevant information were integrated into a GIS database for analysis. To enable spatially explicit planning and allocation of measures, we used baseline data and maps provided by our Jordanian partners, as well as the results of the hydrological and hydraulic analyses (Chapter 5) and vulnerability assessments (Chapter 8). Successful implementation of flash flood mitigation measures also requires stakeholder involvement. We used the results of the stakeholder analysis (Chapter 3) to consider the different responsibilities, roles and tasks in the planning processes according to the different urban areas and sectors involved such as roads, green areas, private and public areas. We also considered water resources and urban structures. Additionally, we analysed the perceptions and knowledge of the local population to identify knowledge gaps and recommend knowledge transfer. To this end, structured interviews were conducted in flash flood hotspot areas in Amman (n = 52) and Wadi Musa (n = 15). In the second phase, ‘Planning & Localisation’, further stakeholder needs were elaborated upon, and focus areas, planning goals, and suitable measures were identified in close collaboration with stakeholders through the second stakeholder workshop, virtual planning workshops, and bilateral exchange. To integrate scientific and practical knowledge, we compiled a database of measures and their potential contribution to flash flood protection and water retention in the MENA region through a literature review, expert interviews and utility experience.

The subsequent selection and allocation of measures was carried out in a co-creation process with stakeholders and local decision-makers. To support the participatory planning processes, a multi-touch table was introduced. The multi-touch table (Figure 27) is located at GAM and is the responsibility of the Strategic Planning Department. In the third phase, an impact assessment was conducted based on the integrated scenario analysis within CapTain Rain. The effects of the selected and allocated measures were simulated using the hydraulic models presented in Chapter 5. These results are summarised in Chapter 9.

Figure 27. Multitouch table introduced at GAM in Amman and at the final workshop.

6.2 Key findings

6.2.1 Increased knowledge of blue-green infrastructure

Measures for rainwater management and flash flood protection encompass a blend of innovative and traditional approaches to effectively manage stormwater and, in this case, reduce the damage caused by flash floods. These measures include:

- Blue-green infrastructure, which leverages natural elements such as wetlands, green/blue roofs, and rain gardens to manage rainwater through absorption, filtration, and storage.
- Technical measures, or grey infrastructure, which uses engineered solutions like pipes, culverts, and dams to control and direct the flow of stormwater.
- Multifunctional tools in which various of the above-mentioned measures as well as other urban requirements (parking lots, playgrounds, sports activities) are integrated on the same plot.

A comprehensive literature review and expert interviews (data from stakeholder analysis) were conducted to identify innovative measures for the retention, safe discharge, storage and use of heavy rainfall in arid and semi-arid regions. The results were summarised in a database/catalogue, covering two main aspects: traditional water harvesting methods in arid and semi-arid regions and the types and possibilities of rainwater management in terms of Blue-Green-Infrastructures (BGI). Each measure has unique characteristics and performance, and can be selected according to which planning goal it best addresses, ensuring an effective, tailored rainwater management strategy. While some measures address flash flooding directly, others focus more on the impacts of climate change, such as heat or drought. However, all measures can serve more than one objective.

The set of measures was discussed, refined and prioritized in several meetings with the Jordanian partners. In addition, an in-depth analysis of the expert interviews was conducted to gather information on overall challenges and knowledge of, and experience with, flash flood adaptation measures. Based on these results and further expert evaluation, 12 measures were selected from the catalogue for the subsequent planning process and the preparation of information material (*infocards,* Figure 28) for each measure. The *infocards* (Schumann-Hindenberg et al., 2025) contain a short description of each measure, its contribution to planning goals and selection criteria such as costs, maintenance needs and implementation conditions.

In addition to these *infocards*, capacity development was conducted for local stakeholders based on a webinar "Measures to reduce flash flood risks/Sponge City Hamburg" in June 2022, which provided insights into possible measures and a practical example for a participatory planning process in Hamburg, Germany. Several online workshops were also conducted as part of the participatory planning process in 2023 and 2024.

Figure 28. Infocard example for the measure "Raingarden".

6.2.2 Increased knowledge through geospatial analysis

Geospatial analysis was used to examine land use data and the topography of the catchment area, with the aim of identifying opportunities to integrate BGI into urban landscapes. The sub-catchment areas of Amman were derived from hydraulic and topographic data and used for further processing of the land use data and the potential analysis. The land use map depicts a series of grouped land use categories derived from the GAM typology. These were labelled according to their degree of development and the availability of open space (i.e. undeveloped, non-built-up areas). The latter was derived from land use and land cover maps in a recent study by Awad (2023). Information on flood-prone areas from hydraulic and hydrological models (see Chapter 5) and documentation of actual flooding events were combined with land use information and other cadastral data in a GIS. In this way, potential fields of action were identified and measures assigned. An overall analysis helped to recognise how much space could be available for the implementation of measures per catchment area, whereby a distinction is made between public and private areas (Figure 29). The analysis of potential area in public spaces showed that most of the sub catchment does have enough space (public) available.

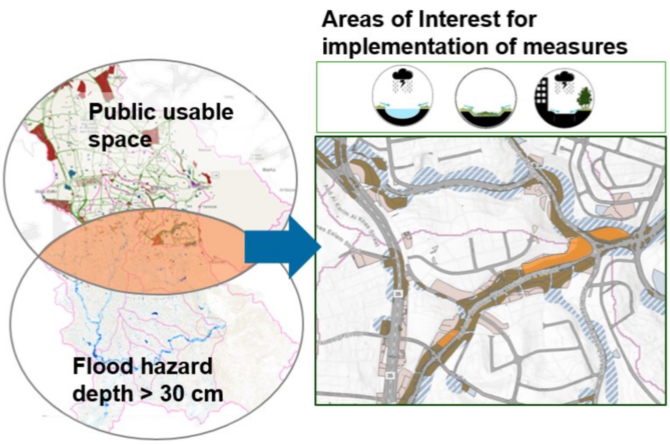


Figure 29. Analysis of landuse overlayed with flood prone map.

Figure 30 shows an example of the overlaid maps. The orange plots overlap with an area at risk of flooding, where the water level could rise by up to 30 cm in the event of a flash flood (left). Undeveloped and open areas affected by flooding offer great potential for the realisation of BGI measures (right). Further analysis of these potential areas is required in terms of their availability and boundary conditions (e.g. slope and soil type), as well as additional indicators (including overlap with strategic master plan concepts, flood-prone areas and risk zones). The area’s potential for implementing measures between public open spaces and transport routes was particularly promising.

Figure 30. Analysis of landuse overlayed with flood prone map (detailed view).

6.2.3 Identifying focus areas and planning goals

Geospatial analysis was used to identify suitable locations for implementing different measures. These focus areas can be catchment areas, neighbourhoods, streets or urban development areas. They can also result from urban planning or be areas of special interest in terms of critical infrastructure. The focus areas were determined using various criteria, including the availability of open spaces and the potential for implementing blue-green infrastructure, flood risk and vulnerability, and the availability of (geo)data. Based on this, three focus areas were selected for a more detailed analysis in the subsequent participatory planning process (see Figure 31).

- **Eastern part of Marj Al Hamam:** This sub-catchment was selected for hydraulic reasons and comprises a variety of land uses. Upon closer inspection, the Royal Village Project and a preschool were identified as specific neighbourhoods for detailed planning.
- **Sports City and later b. Jordan University:** This public area has many green spaces and significant potential for blue-green infrastructure. Initially, the focus was on Sports City, but it later shifted towards Jordan University, as it offers more public space.
- **Al Abdali:** This area includes critical infrastructure, such as hospitals, making it a priority for flood mitigation measures to protect these essential services.

The next step was to identify planning goals for each focus area. These planning goals can inform further decisions regarding the feasibility of measures, as these differ in their contribution and intensity. This is particularly important in areas with very limited space, where clear focus and consequent decision-making for the most appropriate measures can be supported. In our study regions, the main planning goal was flash flood protection. However, demonstrating what else can be achieved simultaneously, such as additional water provision, increased groundwater recharge, or improved quality of stay, can garner more support and acceptance. Furthermore, planning goals are transparent to everyone involved and can be negotiated openly.

The following planning goals were determined within CapTain Rain (based on Winker et al., 2022, a detailed description is provided in Schumann-Hindenberg et al., 2025):

- Reduction of flash flood damage
- Water supply (provision)
- Groundwater Recharge
- Erosion Reduction
- Urban Climate
- Quality of Stay
- Water Protection
- Biodiversity
- Health Promotion
- Environmental Education
- Production of food and renewables
- Urban Gardening and Agriculture
- Cultural Heritage

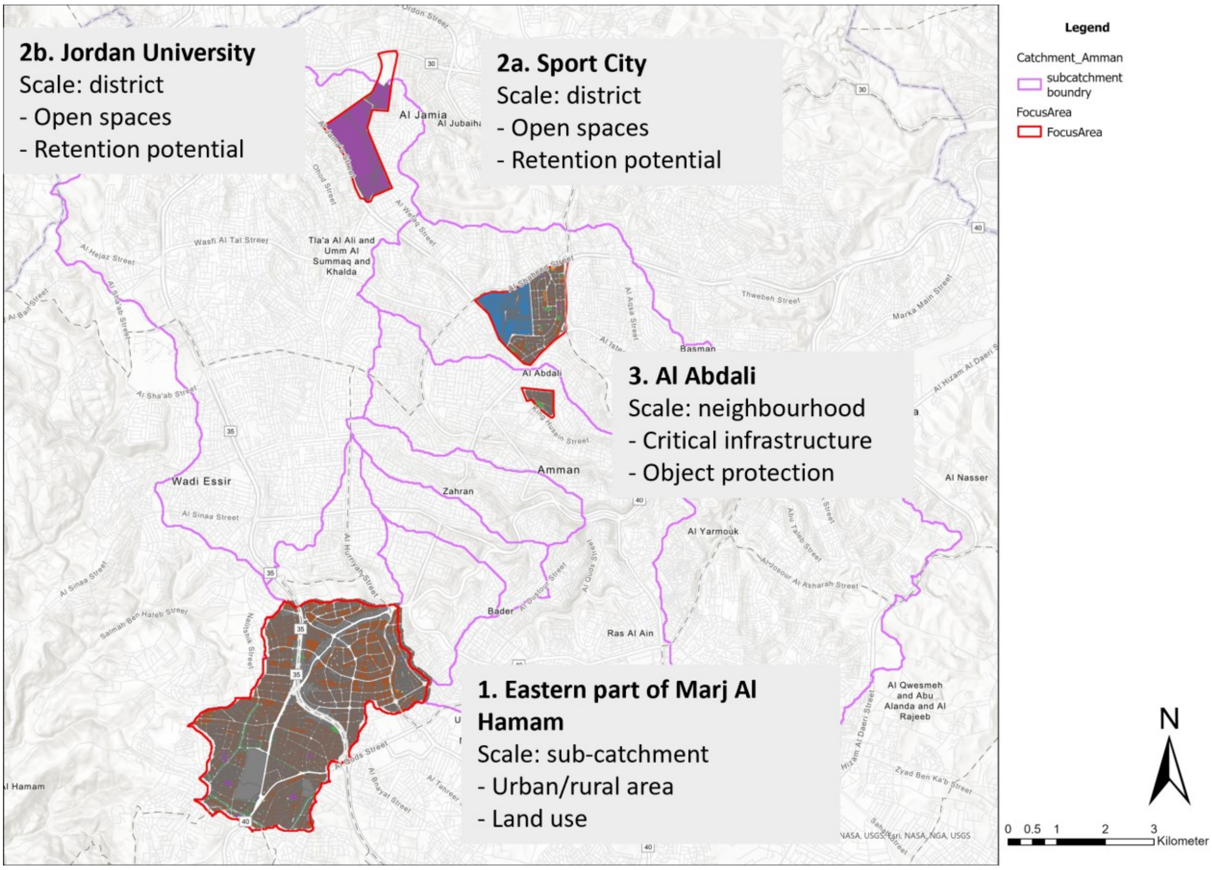


Figure 31. Location of the focus area within the catchment of downtown Amman.

During the stakeholder workshop held in Amman in January 2022, planning goals and measures were identified for each focus area (Table 5). The following figure illustrates the impact that the selected measures will have on the planning goals.

Table 5. Planning goal for each focus area and a pre-selection of measures.

Focus Area/Group	Eastern part of Marj Al-Hamam	Sports City	Al Abdali
Selected planning goals	• Groundwater recharge • Quality of stay • Health promotion • Protection of food & renewable raw materials	• Urban climate • Biodiversity • Quality of stay • Health promotion	• Reduction of flash flood damage • Health promotion • Erosion control • Urban gardening (general greening)
Possible measures	• Rooftop harvesting (Enjasa) • Rain gardens • Bioswales • Infiltration trenches • Diversion channel/culvert	• Rain gardens • Green roofs • Bioswales	• Green roofs • Bioswales • Rain gardens • Porous roads (new) • Higher curb stones and small walls (new)
Remarks/Comments	• Strong interconnection of measures and goals • Appropriate focus area	• Avoid measures which decrease planning goals or other important functions • Introduction of additional planning goal “cultural heritage” • Area is not a public space	• Very dense and steep area • Heavy rainfalls caused landslides in the past • Development of existing stairs to provide a terracing effect • Focus area interesting for further investigations

Icons	Measures	Reduction of flash flood damage	Water supply (provision)	Groundwater recharge	Erosion reduction	Urban climate	Quality of stay	Water protection	Bio-diversity	Health promotion	Environ-mental education	Production of food and renewables	Urban gar-dening and agriculture
	Water harvesting:												
	Terracing	low	low	low	low	no	low	low	low	no	low	low	low
	Roof top harvesting (Enjasa)	low	low	no	no	no	no	low	no	no	low	no	low
	Blue-green infrastructure:												
	Rain gardens	high	no	low	low	high	high	low	high	low	high	low	low
	Green roofs	high	no	no	no	high	high	low	high	high	high	low	low
	Blue roof	high	low	no	low	low	no	low	no	no	low	no	high
	Bioswale	high	no	high	high	high	low	low	low	low	low	low	no
	Infiltration trench	high	no	high	low	low	low	no	low	no	no	no	no
	Detention basin	high	low	no	low	no	no	low	no	no	no	no	low
	Multifunctional Area	high	no	low	no	low	low	low	no	no	no	no	low
	Rainwater harvesting	high	high	no	no	no	low	low	low	no	no	low	high
	Urban Forest	low	no	no	high	high	high	low	low	low	low	no	low
	Object protection:												
	Mobile flood protection elements	low	no	no	low	no	no	no	no	no	no	no	no
	Controlled flooding	low	no	no	no	no	no	no	no	no	no	no	no
	Structural measures:												
	Check Dams	low	low	low	low	no	no	low	low	no	low	no	no
	Dike/Flood barriers	high	low	low	low	no	no	low	no	no	low	no	no
	Diversion channel / culvert	high	no	no	no	no	no	low	no	no	no	no	no
	Expansion of canalisation	high	no	no	no	no	low	low	no	low	no	no	no

no = no impact   low = low impact   high = high impact

Figure 32. Overview of the different measures and their benefits regarding different planning goals. Base for the development of overview was Winker et al. (2019).

6.2.4 Allocation of measures of blue-green infrastructure in the map

Several participatory planning workshops were conducted to facilitate the spatial allocation of blue-green infrastructure measures with local stakeholders.

- Kick-off workshop on measures to reduce flash flood damage (online), 05/07/2023
- Planning workshop on allocating measures with a special focus on blue-green infrastructure (online), 21/11/2023.
- Training and workshop entitled 'From planning goal to implementing measures for storm water management'. Important knowledge about the planning process for implementing measures was imparted and discussed using participatory GIS approaches (multi-touch table), 17/04/2024 (GAM, in-person and online).

During the kick-off workshop, stakeholders engaged in general brainstorming to exchange knowledge and information on urban planning in the focus areas and blue-green infrastructure, as well as other measures. During the second and third workshops, the available information and maps were visualised either at a multitouch table or online on a whiteboard. For each of the selected focus areas, participants discussed existing knowledge and experiences relating to flash flood events and damage, as well as existing or planned infrastructure. Possible locations for measures were then discussed and allocated directly on the maps using specific icons for each measure. The following figures show the allocation of measures alongside comments from the participants, who were Jordanian stakeholders from GAM, PDTRA and research institutions. The drafted measures were integrated into the GIS and the models from Work Package 3 for the impact assessment. A comprehensive multi-scenario analysis was conducted for Amman, integrating the results of various research activities (see Chapter 11).

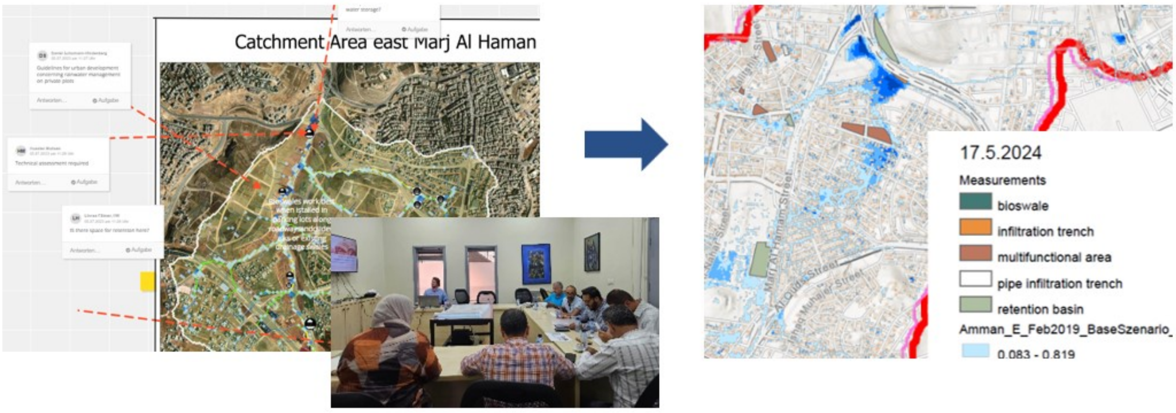


Figure 33. Photo (CapTain Rain 2024) and examples of results from the workshop entitled “From planning objective to implementation of rainwater management measures”; maps show the results for the selection and localization of measures.

6.2.5 Two detailed concepts for neighbourhood development

As part of a master’s thesis, an example of a detailed concept was developed for our case study (Sharma, 2024). One such concept was developed for Royal Village, an undeveloped plot of land in the lower part of the focus area within the Marj Al-Hamam catchment (see Figures 35 and 36). The proposal is for a mixed-use development comprising a hospital and sports area at one end and a retail centre at the other, with various commercial outlets in between. The design also incorporates different types of residential villas and apartments to the west. While this design could meet future housing needs, the development is located in an area at high risk of flash flooding. The increased imperviousness of new constructions would further endanger existing structures.

Overview of the developed concept:

- Each building is surrounded by green spaces, and the potential exists to reduce stormwater runoff from these buildings through green or blue roofs, rainwater harvesting, and on-site storage.
- The public commercial buildings have good potential for implementing green roofs.
- The space between the commercial buildings, initially proposed as a plaza, could be converted into a ‘green corridor’, which would be a multifunctional space used to retain stormwater from the entire development above or below ground. This space would greatly enhance the aesthetics, biodiversity, and quality of life.
- The streets can be redesigned to incorporate bioswales and infiltration trenches to slow the flow of stormwater and convey it to the green corridor for retention.
- Parking spaces have good potential for permeable paving to increase infiltration in these areas.

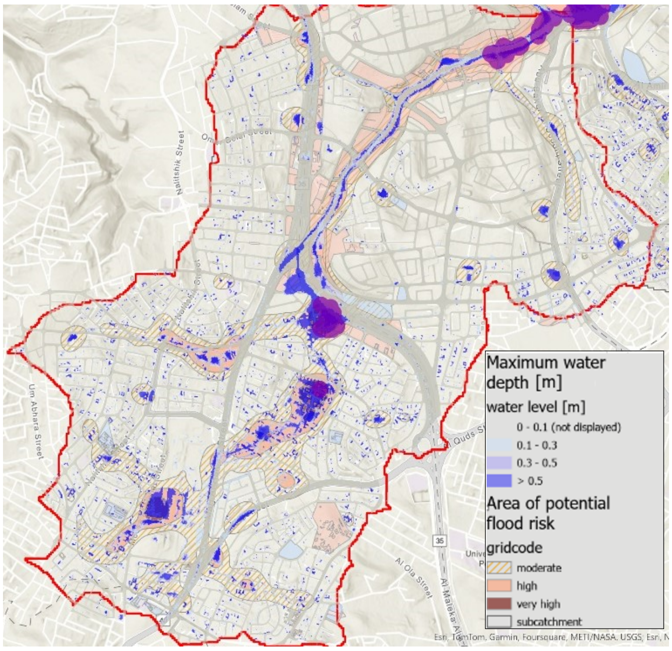


Figure 34. Map of the focus area Marj Al Hamam showing flood risk zones and max water depth.

Figure 35. Concept design for the Royal Village Project (© alnasser + partners, architectural and engineering firm, https://alnasserpartners.com).

Another detailed example illustrates a concept incorporating public and private land. This area is located in the south-western part of the catchment (the eastern part of Marj Al Hamam). This mixed-use area comprises multistorey apartment buildings, a secondary school and a mosque. Around 70% of the area is sealed, while 12% remains undeveloped. Parts of the area, mainly the school, are located within a potential flood hazard zone. In terms of vulnerability and sensitivity, a high risk has been evaluated (mainly due to critical infrastructure). Therefore, this example is not very effective in minimising the risk of flash flooding at existing building sites. To integrate sufficient measures to meet the objective of reducing flooding risk, about 30% of the total area would need to be used to implement various measures. The following examples could be considered:

- Blue or green roof on suitable buildings.
- A combination of swales and infiltration trenches along the streets, which also refer to bioswales, to improve infiltration as well as facilitate conveyance of runoff from streets and surrounding areas towards the open green space created in the school grounds.
- Rain gardens at the school to detain rainwater and enhance quality of stay.

The exemplary illustration of measures at the secondary school (Figure 36) shows the integration of BGI in existing buildings and sites.

Figure 36: Conceptual design of measures in public areas, example secondary school (Source: Sharma, 2024).

A multi-scenario analysis was carried out to demonstrate the impact of the measures outlined in these concepts (see Chapter 9.2). To this end, a series of blue-green infrastructure measures were developed within the focus areas, comprising the detailed concepts shown in Figures 36 and 37. The effects of these scenarios, simulated using hydraulic models (see Chapter 5), are summarised in Chapter 9.

6.3 Outlook: Selection and localisation of adaptation measures

The planning tools and manuals that have been developed will provide the Jordanian partners with a foundation on which to initiate a participatory process and implement blue-green infrastructure. The adaptive capacity measures and strategies can be applied to other areas and, with the help of technology, provide an innovative approach to reducing the risk of flash flooding.

The multi-touch table has been designed to serve as a valuable instrument in future stakeholder meetings, with the Strategic Planning Department and the GIS Department already familiar with its functionalities. The table is intended for use in various urban planning processes in Amman and other regions of Jordan, including the planning of new roads, urban development, green roof strategy, and the implementation of climate change measures. It can be utilised for both stakeholder exchange and internal planning meetings.

There is a significant opportunity for impact in deeper collaboration with Miyahuna on comprehensive rainwater management. Miyahuna is involved in the Captain Rain project as a collaborating partner and participated in the stakeholder workshop in January 2023. Several additional meetings have been held to discuss further collaboration within CapTain Rain. Integrating Miyahuna’s data into the hydraulic model, as discussed in WP3, is expected to improve the model’s accuracy. However, this integration was not yet completed, and GAM has been tasked with completing it. Another notable outcome is the identification of synergies between stormwater management and groundwater recharge, an initiative that appears to already exist in Amman.

According to GAM, the results of this project will inform further strategic planning processes and climate adaptation strategies, such as ‘Future Amman’ (Three Strategies for Climate-Smart Spatial Transformation) and the Amman Green City Action Plan. They will also inform programmes run by UN-Habitat, such as the development of a preliminary design for flood mitigation and flood risk assessment and flood hazard mapping for Downtown Amman, and by INWRDAM, such as flood water management and risk reduction. These initiatives will enable the city of Amman to effectively reduce the risk of flash floods and establish a more resilient and sustainable urban environment. The tools developed, along with the guidelines containing recommendations for the urban planning process for selecting and implementing measures (Schumann-Hindenberg et al., 2025), will enable GAM to consider alternative options for improving rainwater management.

7 Adaptive capacity: Water and weather data portal for Jordan to improve early warning

Author: Michael Thiemann

7.1 Research objectives and methods

Proactive flood risk and damage assessments, as well as flood impact reduction measures, are critical to managing the occurrence and impact of floods, as investigated in CapTain Rain. Nevertheless, flooding will continue to pose a real risk to Amman and Petra, even if all economically viable measures are implemented. This risk will be exacerbated by rising rainfall variability due to climate change. Therefore, real-time monitoring of the weather and weather forecasts, along with the timely mobilisation of first responders, plays a vital role in managing flooding and its impacts in Amman and Petra.

We assessed the current state of flood warning activities in Amman and Petra, analysing the strengths and weaknesses of existing early warning systems (EWS), including their underlying data sources, methodology, and dissemination tools. Recommendations were developed for an EWS adapted to users' needs. The user-friendliness of Petra's existing EWS was evaluated through expert interviews and focus group discussions with local stakeholders (including questions such as: *What information should be included? What media channels should be used? Do warnings reach all people at risk? Are the risks and warnings understood? Are the warnings clear and usable?)*. This information was used to develop recommendations for the creation of early warning apps for the population. These recommendations formed the basis for the design and implementation of a water and weather EWS portal as a demonstrator.

7.2 Key findings

7.2.1 Assessment of Flood Warning in Amman and Petra

Flood warning activities are already performed in Jordan. In order to best implement adaptive capacity measures, we assessed the current status of Flood Warning in Amman and Petra.

7.2.1.1 Amman

In Amman, the first step was to document the governmental agencies involved in the event of flooding incidents. There is no early warning system in Jordan or Amman at a national scale. Furthermore, the emergency response chain in the event of flash floods differs at regional (Amman: Greater Amman Municipality, GAM) and national levels (excluding PDTRA). The resulting responsibility and communication diagram is presented in Figure 37.

The Jordan Meteorological Department (JMD) sends a climate report twice a day to various institutions. Once the JMD identifies a high risk of extreme rainfall that could cause significant local flooding, the National Center for Security and Crisis Management (NCSCM) implements an overarching emergency response plan. The NCSCM coordinates activities between MWI, MoE, Civil Defense, and also GAM in case of flash floods in Amman. In the case of flash flood incidents in Jordan, the Ministry of Water and Irrigation, the Ministry of Environment, Civil Defense, as well as Police and Military act on the ground. MWI hereby acts according to its emergency response plan and through field teams at at-risk locations. Evacuations and related management during events are to a large degree performed by the Police, the Military and Civil Defense. The MoE only acts in case of the flooding of areas with hazardous materials, which could lead to water pollution, based on its emergency response plan.

Amman is a special case because the GAM has its own emergency response structure. According to the GAM emergency response plan, the emergency unit, comprising a main centre, 22 district centres, field teams, the Building Observation Department and the Media Department, is activated in case of flash flood risk, especially during winter. The emergency unit deploys pumps, mobile dams and other equipment to areas at risk of flash flooding in Amman, which GAM has identified based on experience of prior incidents. The GAM Media Department provides information to the population. The Building Observation Department assists the field teams in evacuating people. Three different lines of decision-making exist: one for the emergency level (GAM only), one for warning the population (GAM and NCSCM) and one for evacuating people (GAM mayor and minister of the interior). It is important to examine the decision-making lines in more detail, including more than one actor, to determine whether a more efficient structure is required. GAM is responsible not only for emergency response, but also for cleaning out canals before events and cleaning up after them.

The key to a successful emergency response is an accurate, timely and location-specific rainfall warning. Using a questionnaire, WP6 assessed flood warning activities in Amman. These were then compared to a set of ideal actions and, based on a gap analysis, recommendations were prepared.

Key recommendations include cross-agency integration of real-time rainfall observations, use of the Amman weather radar to identify areas at risk of local flooding, and establishment of a regional, high-resolution weather forecast model. Such information would greatly enhance the agencies' situational awareness before and during extreme rainfall events, making the planning and execution of emergency management measures more effective.

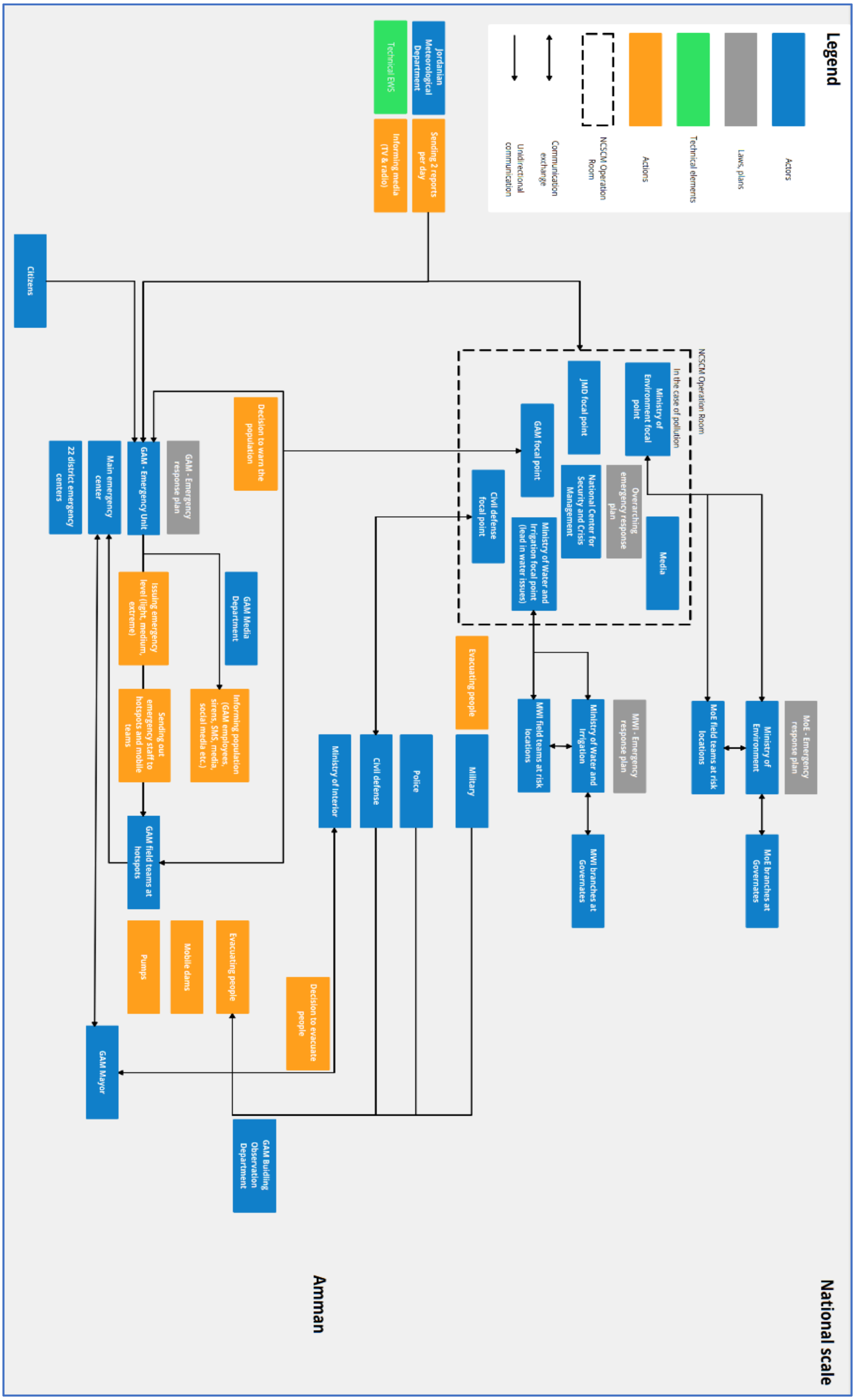


Figure 37. Actors during flood emergencies in Amman and at the national scale.

7.2.1.2 PDTRA

PDTRA operates a network of rainfall observation stations in the Petra area to assess the risk of extreme rainfall and local flooding (Alhasanat, 2017). PDTRA itself primarily handles the coordination, especially within the Petra Archaeological Park. Work Package 6 conducted a status assessment and gap analysis, providing recommendations. These recommendations are similar to those for the Amman area.

7.2.2 Water and Weather Portal for Jordan

The Water and Weather Data Portal for Jordan (WWDPJ) was developed to demonstrate the implementation of some of the recommendations via the cloud-based KISTERS datasphere tool for data management & operation. Datasphere provides easy access to real-time weather observations and forecasts via any web-browser and was expanded during the CapTain Rain project to efficiently and reliably manage and visualize open (and free) weather observations and forecasts for use in Amman and Petra. As such it can be used by the Jordanian stakeholders to gain awareness of current weather and to prepare for emergency management activities. In that realm the WWDPJ covers the functionalities marked in yellow in Figure 38. The related access and training were offered to MWI, JMD, GAM, WAJ, and PDTRA.

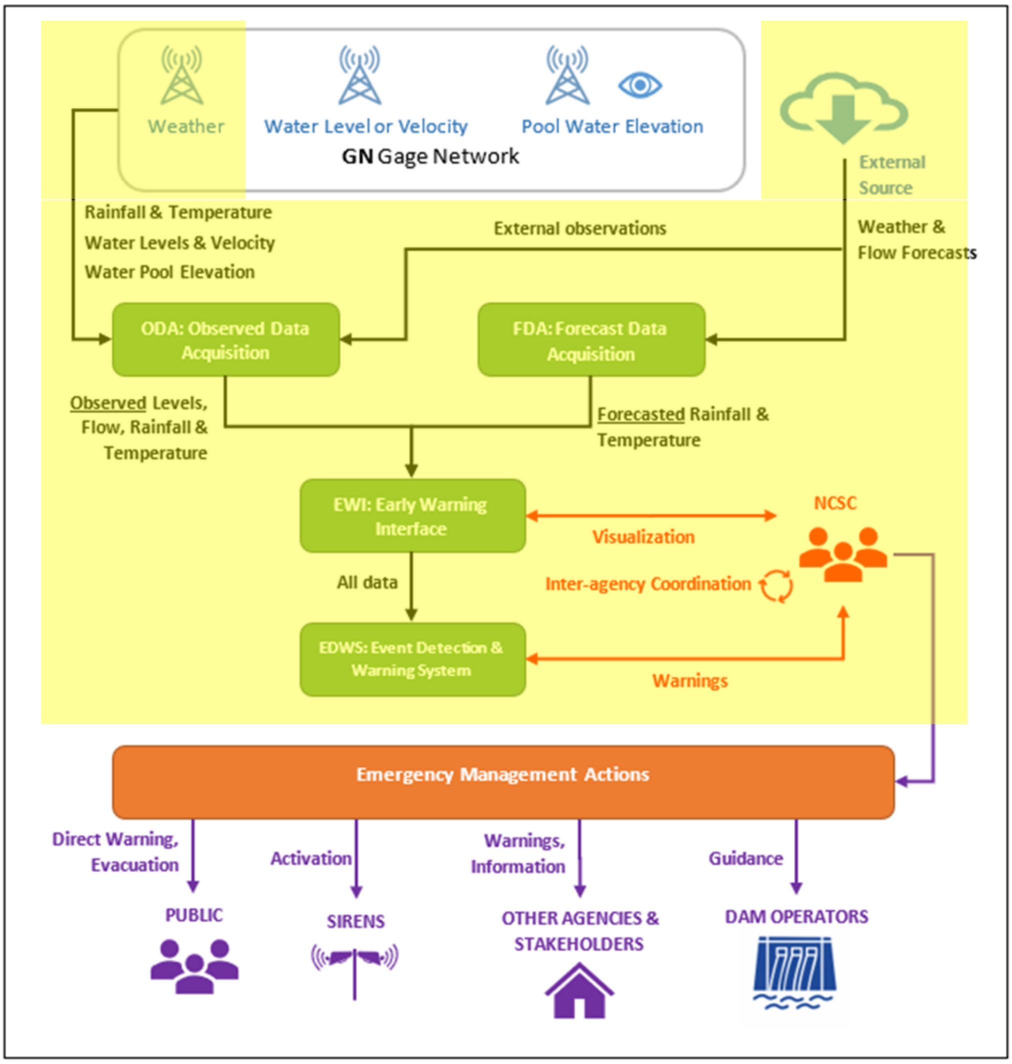


Figure 38. Functionalities covered by the WWDPJ (yellow highlights) as Part of the Overall Emergency Management Activities.

7.2.2.1 Historical Data Products

While the main purpose of the WWDPJ is to provide situational awareness of current and future weather, it can also manage historical data that can be downloaded for further study purposes. The Jordanian stakeholders provided the historical data listed in Table 6, which was made accessible via the portal. Figure 40 depicts locations for which historical data were made available in the WWDPJ map interface. Figure 41 provides an example data graph of historical precipitation at one site.

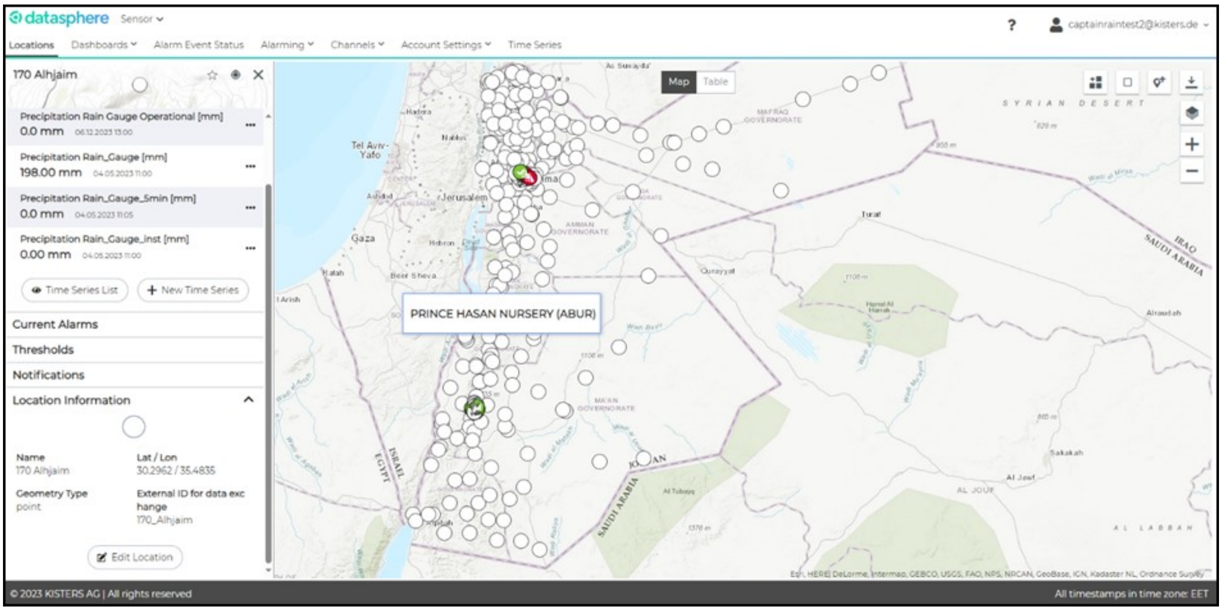


Figure 39. Historical Data Locations shown in the WWDPJ Map Interface.

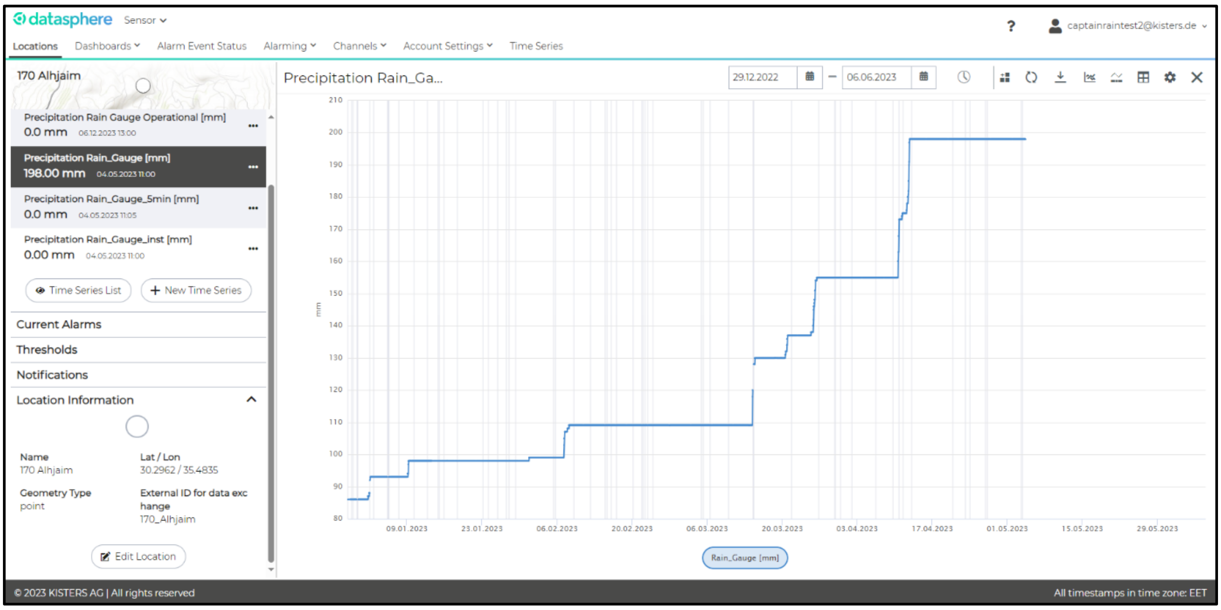


Figure 40. Example Graph of Historical Data in the WWDPJ.

Table 6. Historical Data available in the WWDPJ

Parameters	Period	Spatial resolution	Area	Provided By
Temperature Max, Temperature Min, Temperature Mean, Wet and Dry Bulb Humidity, Vapor Pressure, Dew Point Temperature, Relative Humidity, Wind Direction, Windspeed, Wind Distance, Evaporation, Radiation, Sunshine Hours	1964 to 2017	daily	total Jordan	Ministry of Water and Irrigation (MWI)
Precipitation, Temperature, Relative Humidity		daily	total Jordan	MWI
Precipitation, Evaporation, Temperature, Relative Humidity, Radiation, Wind Direction, Windspeed,Pressure		hourly	2 stations	Mutah University
Max Temperature, Min Temperature, Precipitation, Windspeed, Relative Humidity, Radiation	1979 to 07/2014	daily	3 stations	USA National Centers for Environmental Prediction (NCEP)
Precipitation, Relative Humidity, Temperature, Wind Direction, Windspeed	2022	6H	total Jordan	World Meteorological Organization (WMO)

7.2.2.2 Observed Remotely Sensed Weather Products

Ground observations of weather and water level data can provide a valuable assessment of the local situation. However, larger weather patterns can be analysed via remotely sensed data, typically obtained via satellite observations. Table 7 lists the satellite remote sensing data available through WWDPJ.

Table 7. Satellite Data Products in the WWDPJ

Provider	Products	Cover	Spatial Resolution	Temporal resolution	Update Interval
Eumetsat H SAF	Precipitation (H03B and H60)	Global	0.05 ° (~5km)	5 min	Every 15 min.
Japan Meteorological Agency (JMA)	Precipitation (NRT gauge-calibrated und real-time gauge-calibrated)	60°N to 60°S	0.1 ° (~10km)	1 hour	NRT every 2 hours; real-time every 6 hours
Meteosat IODC (Middle East)	Brightness temperature (various) RGB Composite (various) Reflectance (various)	Indian Ocean	0.05 ° (~5km)	5 min	Every 15 min.

These are downloaded from the providing organizations and imported into the WWDPJ at the intervals described. They can then be immediately visualized by the user (Figure 42 and 43).

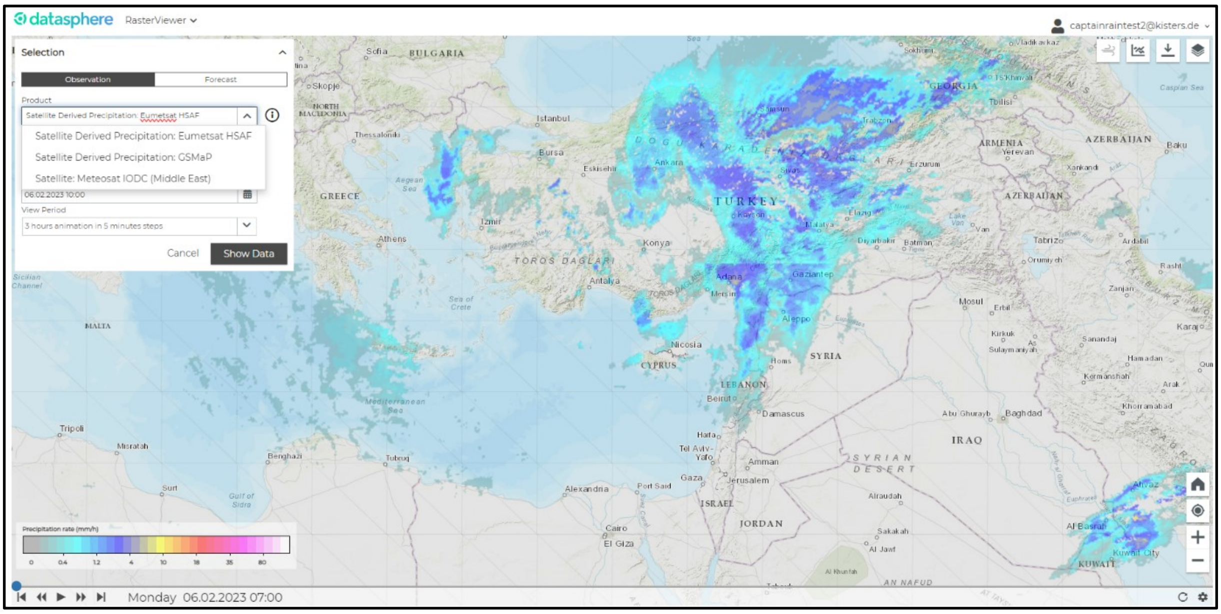


Figure 41. Selection of Satellite Observations Products via the WWDPJ Interface.

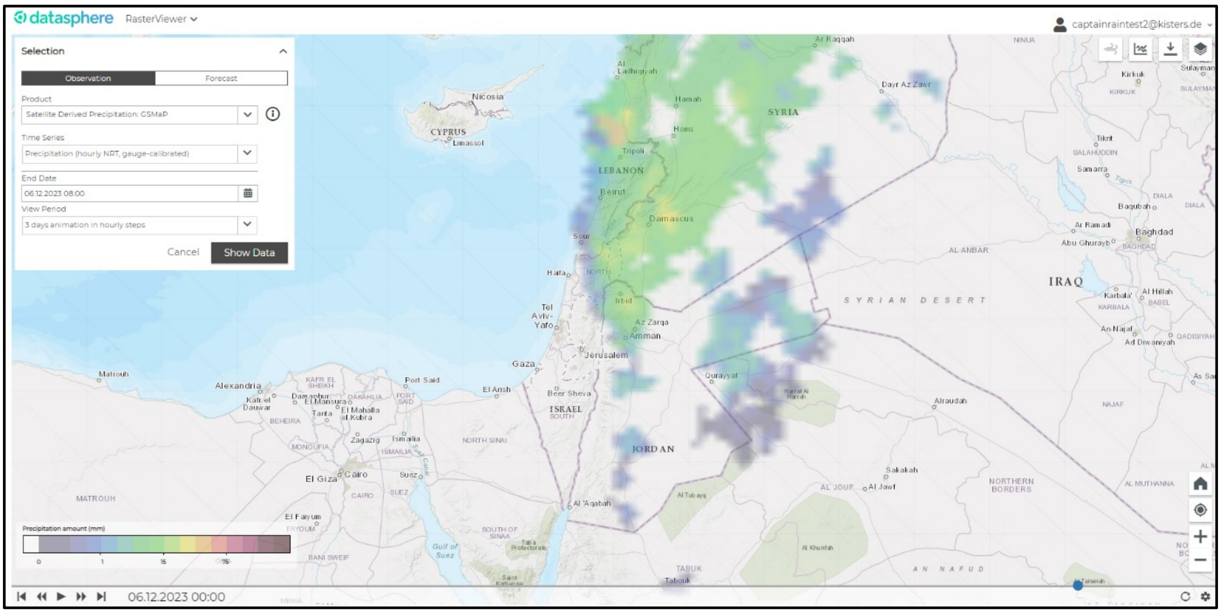


Figure 42. Animating a Selected Satellite Observations Product in the WWDPJ Interface.

Ground Rainfall Observation Products

As part of the project, the WWDPJ was coupled with the existing rainfall station network operated by PDTRA in the Petra area. Near-real-time rainfall observations at nine rainfall stations (Figure 43) are imported hourly into the WWDPJ and provided to the end user.

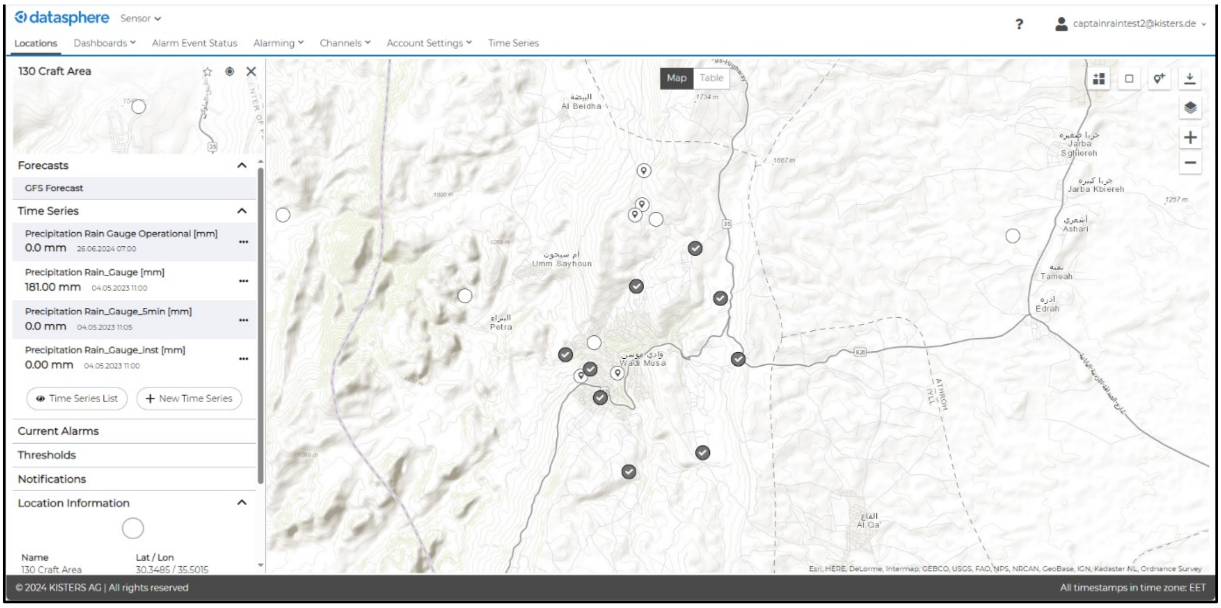


Figure 43. PDTRA's rainfall observations sites shown in the WWDPJ Interface.

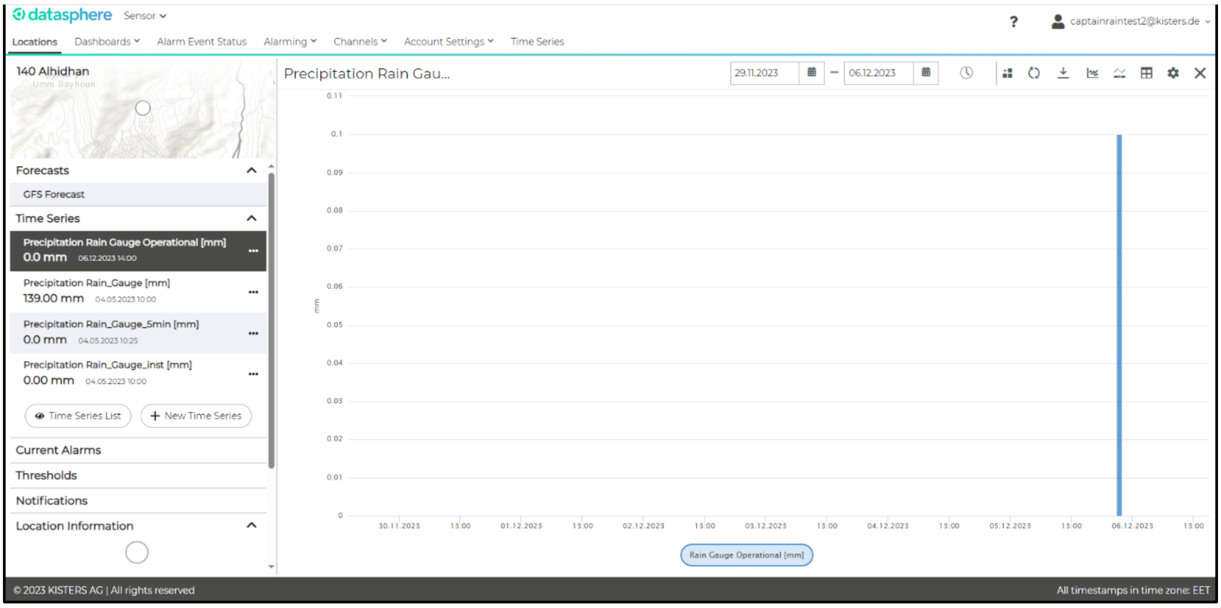


Figure 44. Displaying Rainfall Observations in the WWDPJ Interface.

7.2.2.3 Rainfall Nowcast Product

Rainfall nowcasts provide very short-term forecasts of rainfall by moving observed rainfall fields into the future. This can aid in the rapid mobilization of emergency management personnel as well as in the warning of the population just ahead of extreme rainfall events.

Ideally, these rainfall fields are observed by local weather radars that provide rainfall estimates in near-real time at high spatial and temporal resolutions and with good accuracy. However, such data were not available through JMD and rainfall nowcasting was hence implemented using an existing nowcasting scheme applied to the Eumetsat H SAF satellite precipitation product (Figure 45).

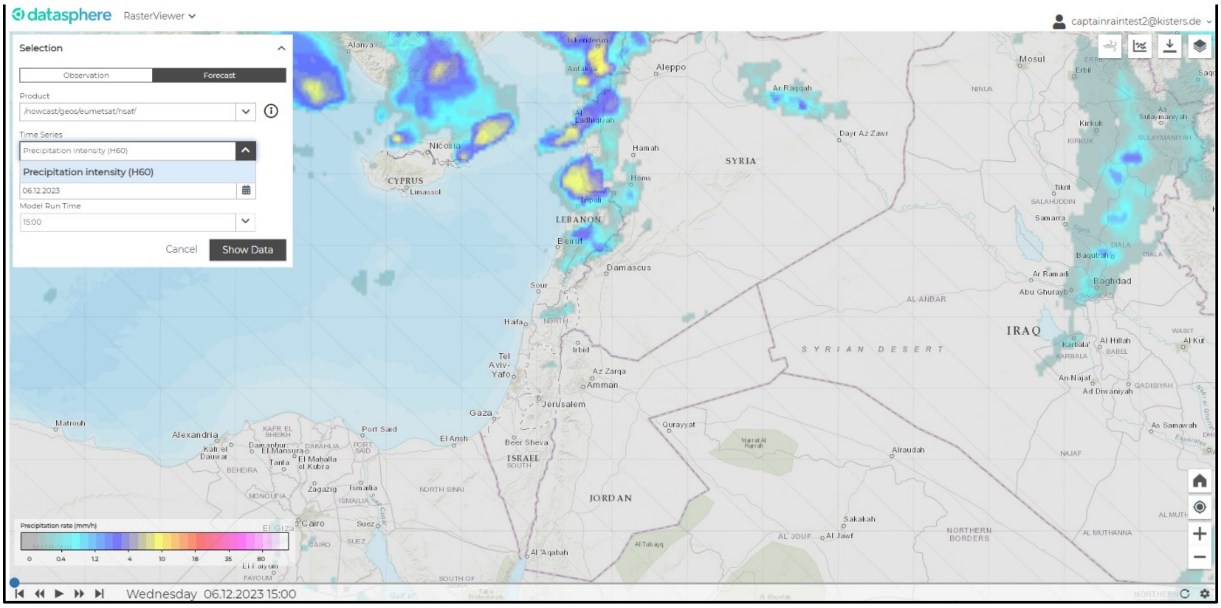


Figure 45. Selecting the WWDPJ Rainfall Nowcast Product.

7.2.2.4 Weather Forecast Products

Rainfall nowcasting can provide forecasts of rainfall for a maximum of 2 hours into the future, often less. In order to gain awareness further out in the future, weather forecasts based on numerical weather models must be used. Such forecasts are provided, often for free, by a variety of national and transnational weather forecast agencies. Table 8 lists the weather forecast data available through the WWDPJ.

The weather forecast data includes deterministic as well as probabilistic products. Figure 46 shows the available products in the WWDPJ. Figure 47 demonstrates the selection of forecast parameters available as part of the ECMWF weather forecast – this can then be animated (Figure 48). Figure 49 shows the extraction of forecast data at arbitrary points.

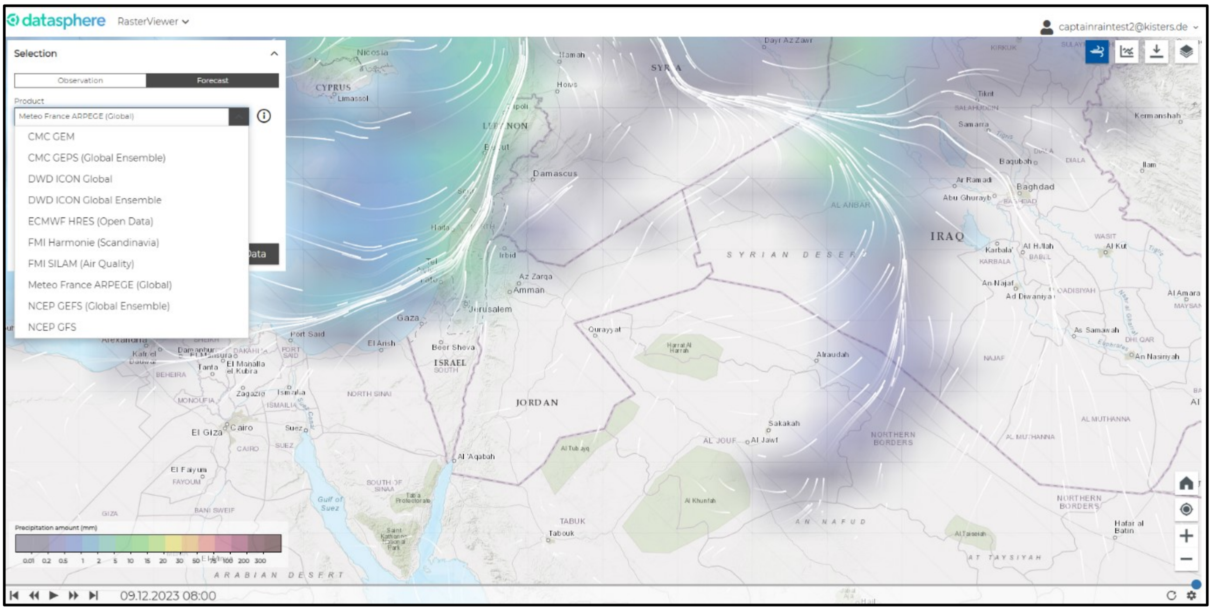


Figure 46. Selecting Weather Forecast Products in the WWDPJ.

Table 8. Weather Forecast Products in the WWDPJ

Provider	Products	Cover	Spatial Resolution	Temporal resolution	Update Interval
Canadian Meteorological Centre (CMC)	GEM / GDPS Standard Deterministic Products	Global 240 hours into the future	0.15 ° (~15 km)	3 hrs	Every 12 hours
	GEPS Probabilistic air pressure MSL, air temperature (2m), precipitation; 21 time series	Global 360 hours into the future	0.5 ° (~50 km)	6 hours	Every 12 hours
German Weather Service (DWD)	ICON Global Standard Deterministic Products	Global 120 hours into the future	0.25 ° (~25km)	3 hrs or 6 hrs	Every 6 hours
	ICON Global EnsembleProbabilistic air temperature (2m), precipitation; 40 time series	Global 120 hours into the future	0.25 ° (~25km)	6 hours	Every 6 hours
Meteo France	ARPEGE (Global) Deterministic Air pressure MSL, Dew point (2m), Air temperature (2m), Precipitation	Global 102 / 60 hrs into the future	0.5 ° (~50 km)	3 hrs	Every 12 hours
National Centers for Environmental Prediction (NCEP) – USA	GFS Standard Deterministic Products	Global 240 hours into the future	0.25 ° (~25km)	3 hrs or 6 hrs	Every 6 hours
	GEFS Probabilistic air pressure MSL, wind gusts, air temperature (2m), relative humidity (2m), precipitation; 30 time series	Global 384 hours into the future	0.5 ° (~50 km)	6 hours	Every 6 hours

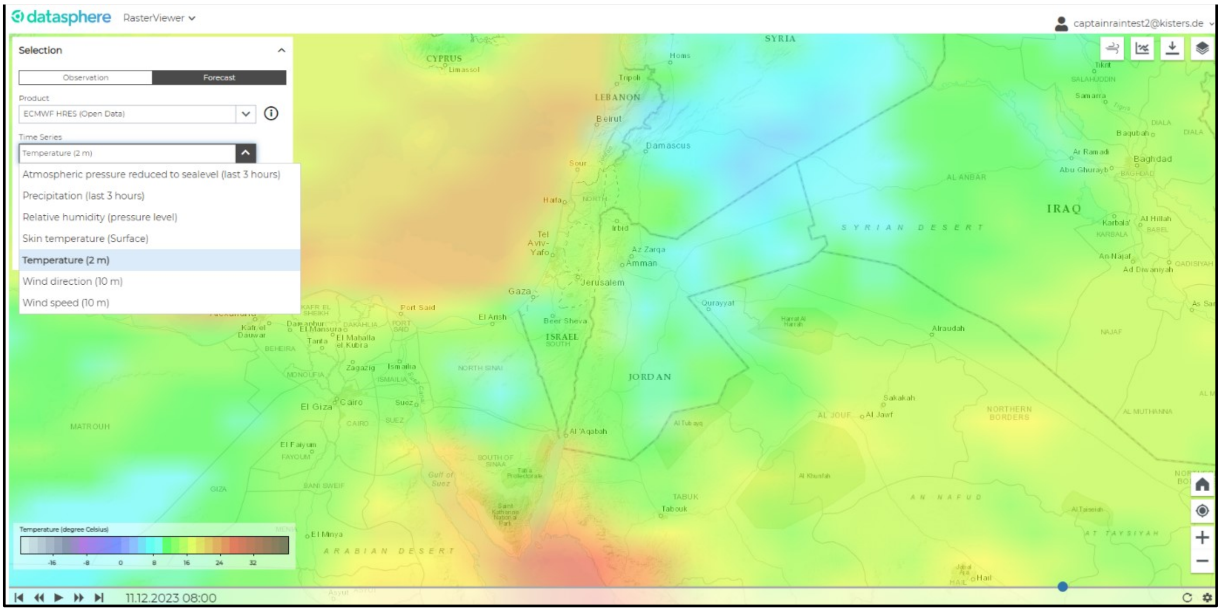


Figure 47. Selecting a Parameter (here Temperature) of a Weather Forecast Products in the WWDPJ

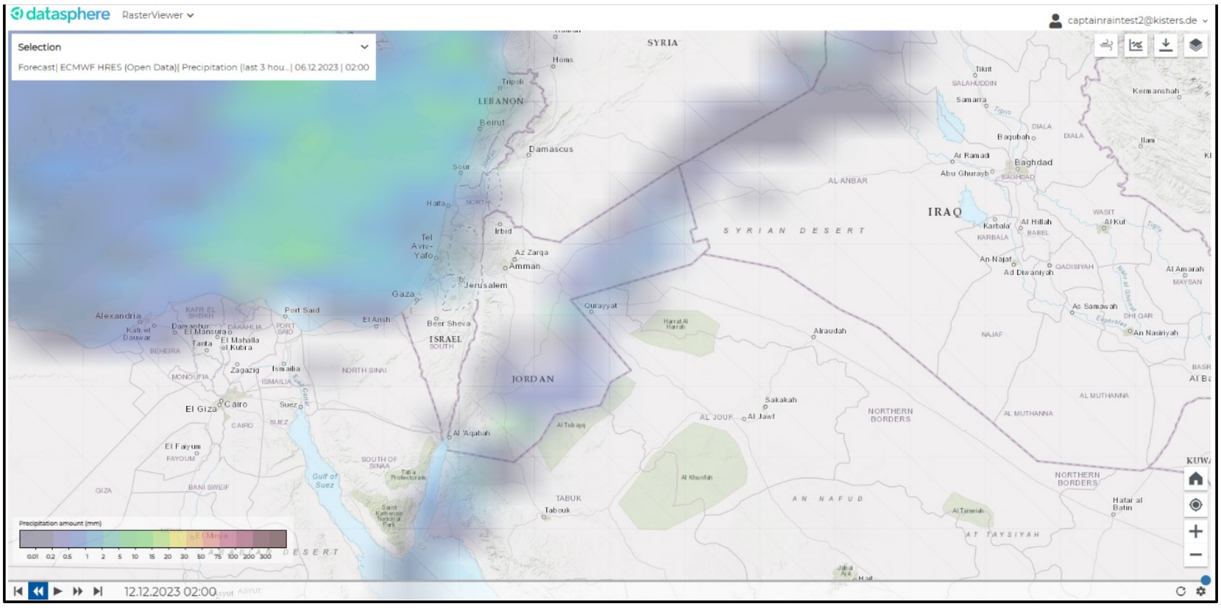


Figure 48. Animating a Selected Weather Forecast Parameter in the WWDPJ Interface.

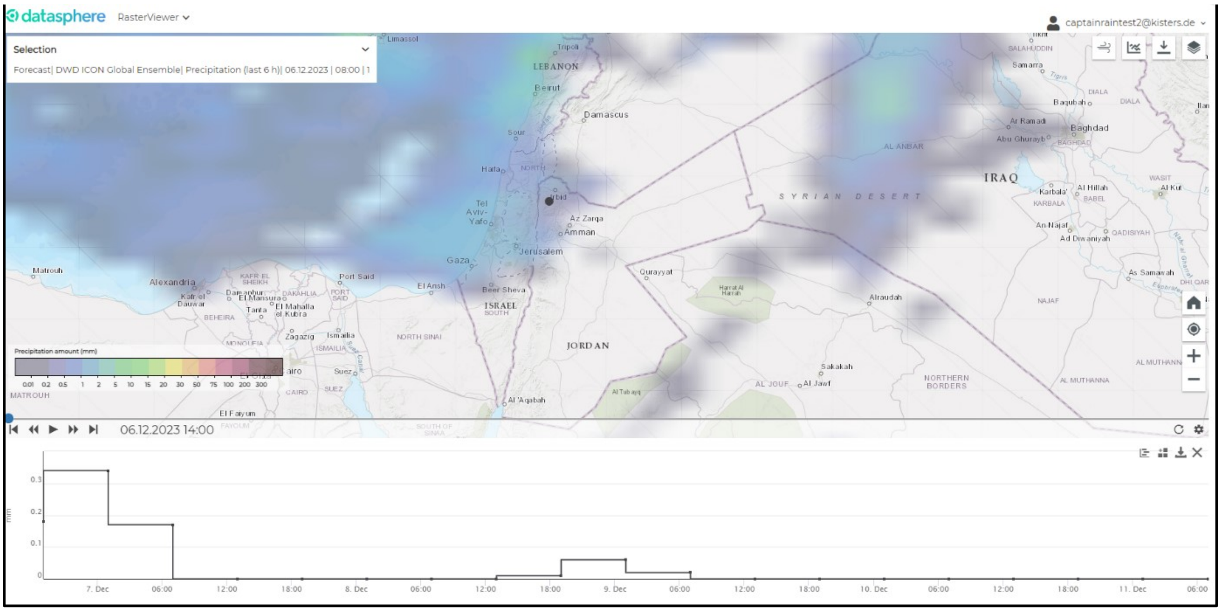


Figure 49. Showing a Forecast of Rainfall at an Arbitrary Location in the WWDPJ Interface.

7.2.2.5 Hydrological Modelling

One focus of WP6 was to integrate the models developed under WP3 into the WWDPJ. In this regard the KISTERS real-Time Analytics Framework (RTAF) was further developed and the WP3 HEC-HMS model for Amman integrated. Figure 50 depicts forecasted flows during a small rainfall event in Amman at three locations (J.1, J.2, and J.3, respectively).

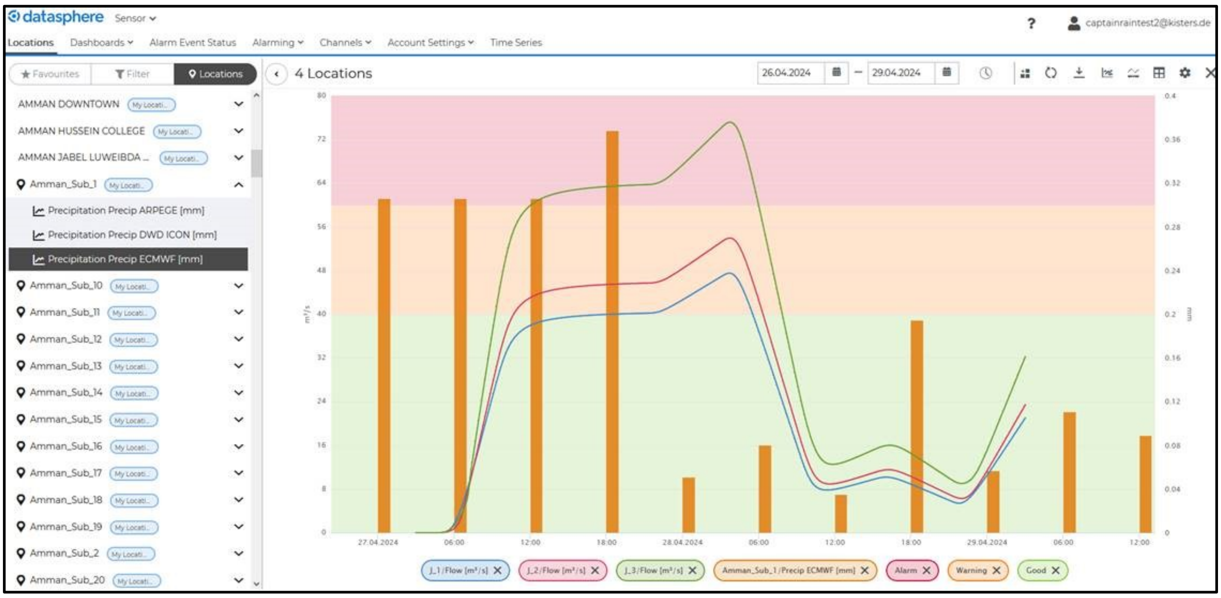


Figure 50. Forecasted Flow at Three Locations in Amman, shown in the WWDPJ Interface.

7.2.2.6 Extreme Events Detection

A key feature of the WWDPJ is its ability to automatically inspect all weather observations, nowcasts, and forecasts to determine a risk of extremely high rainfall exists. This can be performed both on point data (such as the observations made at the PDTRA weather stations) and raster data (such as the satellite observations and weather forecasts). Large flow events can also be detected on the forecasted flows in Amman (see Section 7.2.2.5).

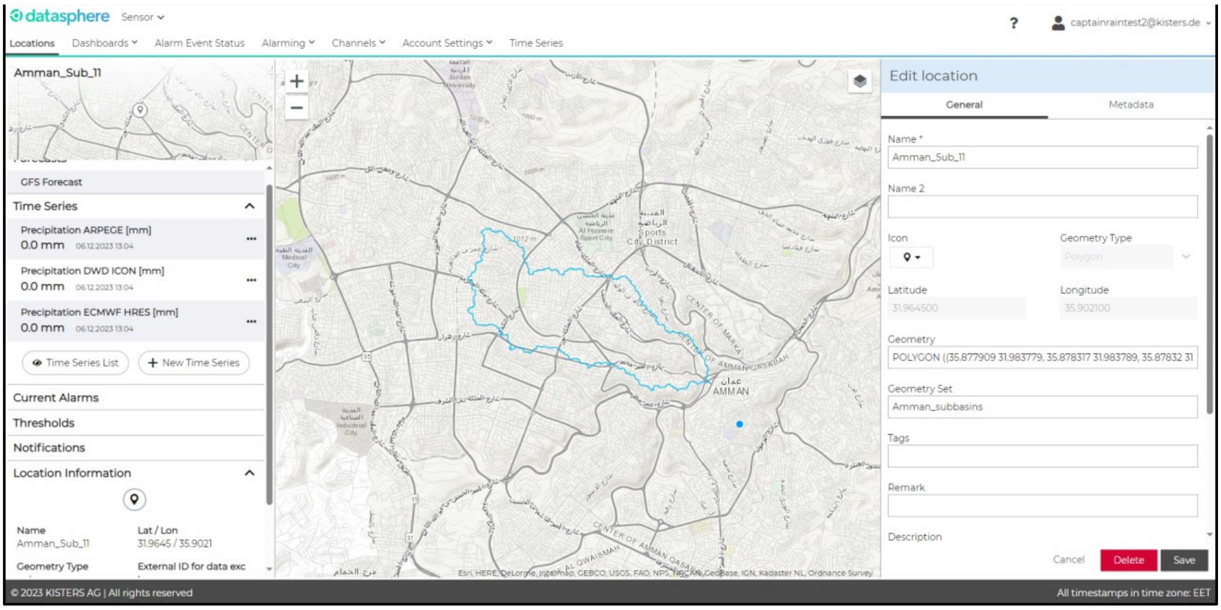


Figure 51. Example Sub-Basin Area (blue polygon) for which Rainfall is Averaged in Amman.

For Amman, observed and forecasted rainfall is averaged from the raster data over the local tributary sub-basins of the Zarqa River. One such sub-basin is shown in Figure 51. For the PDTRA area, rainfall is spatially averaged over a circle centered on the Petra Archeological Park (Figure 52).

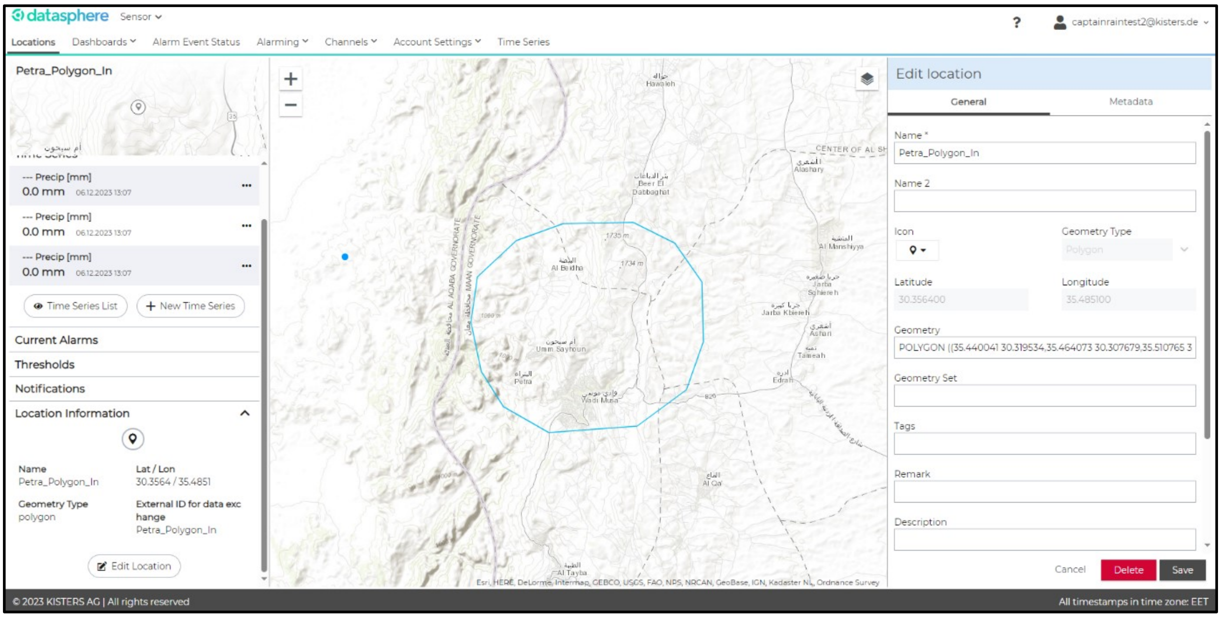


Figure 52. Area (blue polygon) for which Rainfall is Averaged in the Petra Area.

Thresholds are defined for each such area. The WWDPJ classifies the related spatially averaged rainfall data (Figure 53) and detects if thresholds are exceeded (Figure 54).

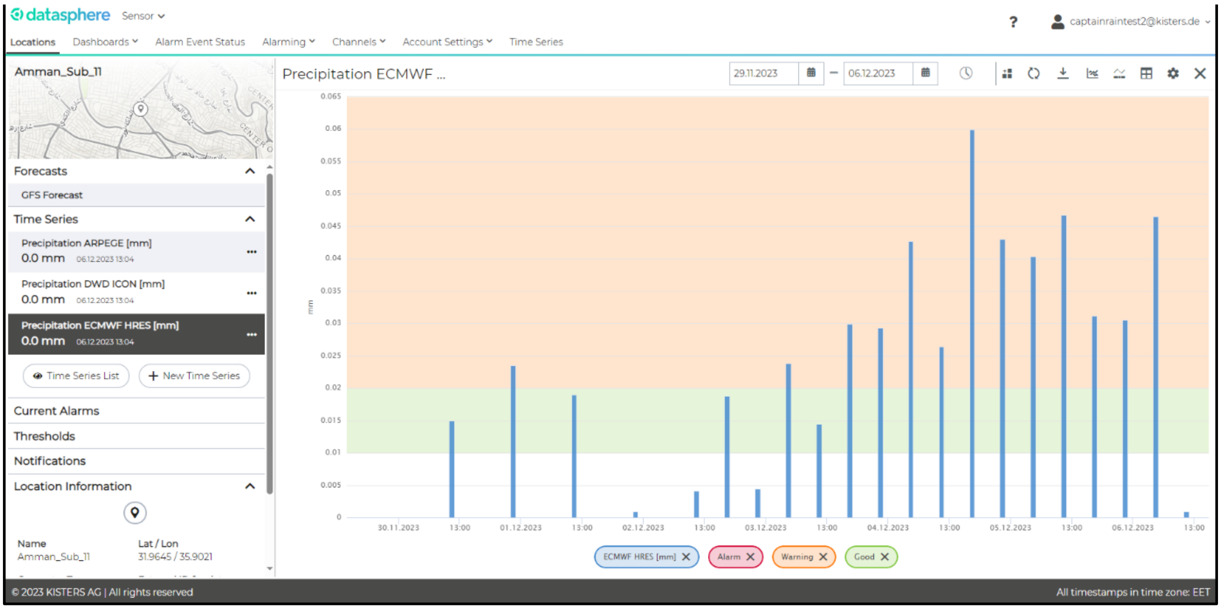


Figure 53. Depiction of Classified Forecasted Rainfall Averaged over a Sub-basin in the WWDPJ.

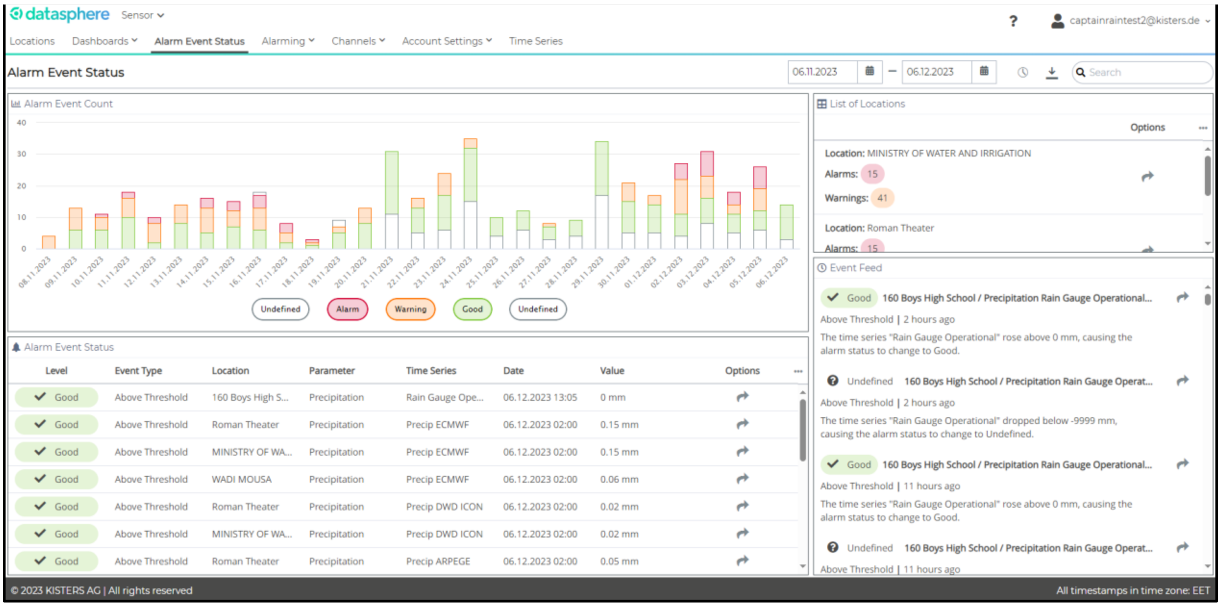


Figure 54. History of Threshold Exceedances Shown in the WWDPJ Interface.

7.2.2.7 Alarming

The WWDPJ is set up to send notification emails to pre-defined individual recipients (Figure 55) or groups of recipients (Figure 56) if extreme observed or forecasted rainfall events have been detected.

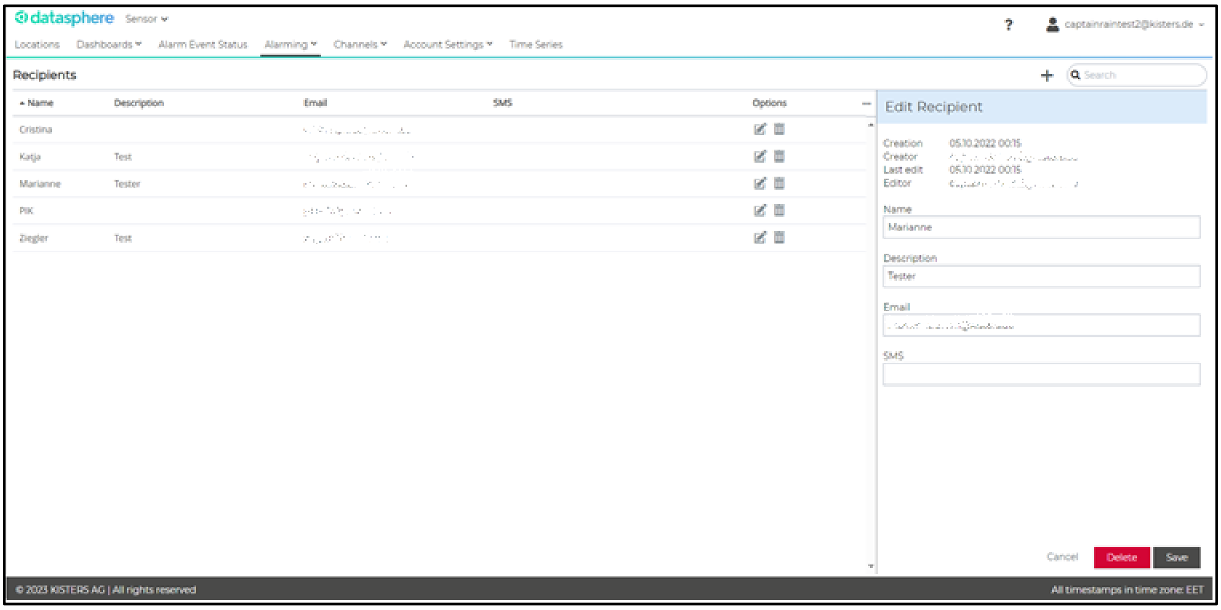


Figure 55. Definition of Alarm Recipients in the WWDPJ.

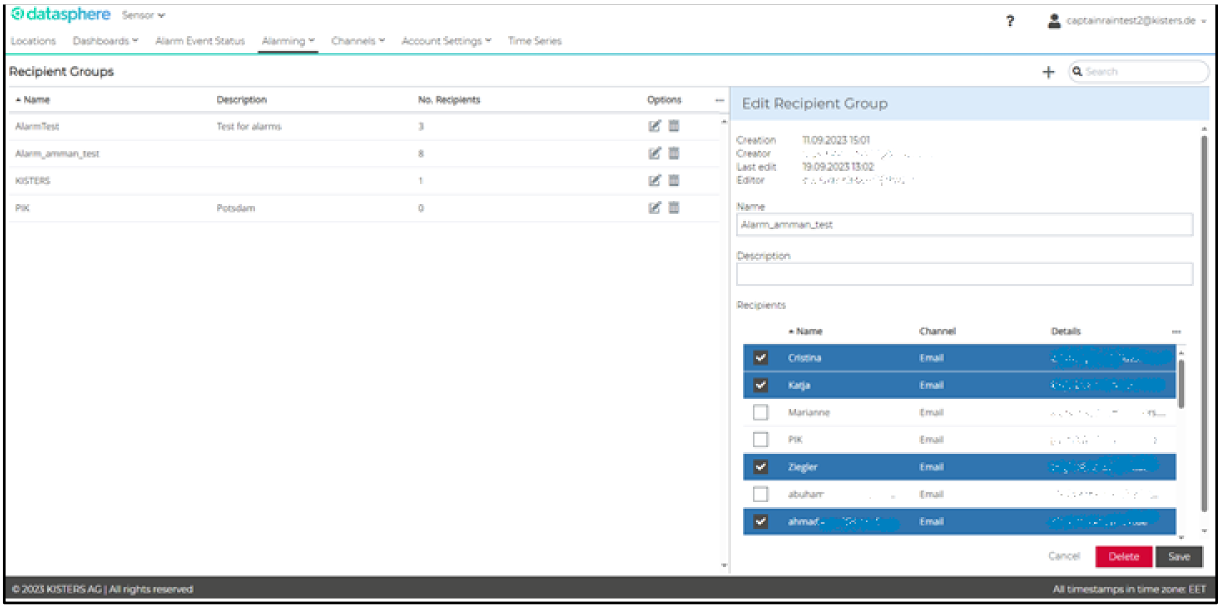


Figure 56. Definition of Alarm Recipient Groups in the WWDPJ.

7.3 Outlook: Climate and water data portal for Jordan to improve early warning

Flood warning and related emergency management is well established in Jordan. However, the data to make data driven decisions ahead of possible extreme rainfall (and possibly flooding) events is somewhat sparse due to the limited availability of real-time rainfall observations and high-resolution radar and weather forecasts. The WWDPJ demonstrates how the use of high-resolution open data and the sharing of weather observations and forecasts among the Jordanian government agencies could improve flood warnings and thus mitigate flood damage during extreme events.

The main stakeholders in the project, and especially JMD, utilized the WWDPJ during the project period and voiced interest in continued access to the information provided by the system.

The next steps should hence be to explore ways to continuously provide such access. WP 6 is in related discussions with the GIZ, the German Embassy in Amman as well as Swiss and US development agencies to explore the related funding. CapTain Rain project partners are also participating in the Jordanian Water Risk / Flood Mapping Working Group, which coordinates donor funded activities in this field.

8 Integrated vulnerability assessment

Authors: Katja Brinkmann, Ahmad Awad and Clara Hohmann

8.1 Research objectives and methods

Flood vulnerability analysis and assessment is urgently needed to improve urban risk management, reduce flood damages and risks, and protect the local population. The aim of the analysis was to identify vulnerable areas and those with high adaptive capacity. Vulnerable areas and areas with high adaptive capacity were prioritised for the future implementation of flash flood mitigation measures. To identify such areas, we carried out an integrated assessment at different spatial and temporal scales summarizing the results of the various work packages, particularly those relating to heavy rainfall hazards (Chapter 4), flash flood risk (Chapter 5) and adaptive capacity (Chapter 6). The resulting flash flood vulnerability assessment will serve as a decision-support tool for urban planning, helping to identify risk areas and select adaptation strategies (maps, assessments and reports)..

Our integrated (spatially explicit) vulnerability assessment (Brinkmann et al., in preparation) has been adapted for data-scarce areas by combining different disciplinary perspectives with local knowledge. An integrated way of understanding vulnerability can be carried out through a Social-Ecological Vulnerability Assessment (SEVA). SEVA is defined "*as the extent to which environmental degradation and climate change cause negative changes in exposure, susceptibility and in the capacity of the social-ecological system to anticipate, cope with and recover from the hazard*" (Depietri, 2020).

This approach was based on the general framework promoted by the Intergovernmental Panel on Climate Change (IPCC), which has been widely adopted for vulnerability assessments. In the IPCC definition, vulnerability is defined as the propensity or predisposition to be adversely affected (Ara Begum et al., 2022), often understood as a function of the component's exposure, sensitivity and adaptive capacity (Thiault et al., 2021). Understanding these components is crucial for effective risk management and resilience building. For each of these components, several indicators were selected to capture the different social, physical and ecological domains (Table 9).This selection was based on data availability, expert opinion and stakeholder needs. Stakeholder perspectives and needs were incorporated into the vulnerability assessment through expert interviews (n = 7) and focus group discussions during three stakeholder workshops. In addition, interviews were conducted with local residents (n = 52) to gather additional information on adaptive capacity in terms of local knowledge of measures to reduce flash flood damage and willingness to implement measures on private land.

For the calculation and mapping of indicators we conducted spatial analysis within ArcGIS 10.8 using available GIS data (e.g. buildings, land cover, population statistics at the neighborhood scales) provided by the Municipality of Greater Amman (GAM) and own analysis on exposure and land cover within WP 3. Data gaps, especially on buildings and green spaces, were filled by available open source data and by manual digitization based on recent Google Earth images. To estimate the social domain of sensitivity, which was based on population data at the neighborhood scale, we combined various demographic (very young or very old people, disabled people, refugees) and economic factors (low income, low level of education). To reduce data dimensions of this multivariate dataset, we performed a principal component analysis (PCA) and then used the results of the first principal component as an indicator, which is strongly correlated with the number of refugees and low income. Each indicator map was transformed to a 2 m raster file and classified within ArcGIS 10.8 using natural breaks (Jenks) from 1 = low; 2 = moderate, 3 = high and 4 = very high.

Table 9. Selected Indicators for the SEVA for Amman for each component (exposure, sensitivity and adaptive capacity) and domain (social, physical and ecological).

Domains:	**Components:** **Exposure**	**Sensitivity**	**Adaptive capacity**
	Degree to which a subject (inhabitant, building, ecosystem) is exposed to flooding in case of a flash flood event	Degree to which a subject/object is affected by a given (flash flood) exposure	Ability of a subject/object to adjust to the hazard event. It reduces the overall level of vulnerability and thus the effects of a flash flood
Social	Determined based on the proximity of residential buildings to flood prone areas. Classification was based on the risk analysis of WP 3 using the expected water level (cm) during a flash flood event (Baseline Scenario).	Estimated based on demographic (very young or very old people, disabled people, refugees) and economic factors (low income, low level of education) as well as building types (Potter et al. 2009; Ababsa and Daher, 2011)	Assessed based on the economic capacity of residents to implement measures on their land.
Physical	Determined based on the proximity of critical infrastructure to flood prone areas. Classification was based on the simplified risk analysis of WP 3 using the expected water level (cm) during a flash flood event (Baseline Scenario).	Estimated based on the analysis of damage potential in WP 3 classifying critical infrastructure as sensitive objects (worship places, energy and water infrastructure, cultural heritage sites, schools, kindergarten)	Assessment was based on the availability and suitability of open space for the potential implementation of measures to decrease flash flood damages. We considered impermeable open space (non-build up) on public and private land.
Ecological	Determined based on the proximity to flood prone areas of larger green spaces used for leisure activities and habitats for flora and fauna (parks, floodplain, woodland). Classification was based on the simplified risk analysis of WP 3 using the expected water level (cm) during a flash flood event (Baseline Scenario).	Estimated based on the limited capacity for water infiltration. For this we used the impermeable surfaces (build-up areas extracted from Awad, 2023 6) as a proxy, as no detailed soil map data was available.	

The combination of the individual indicators maps combining exposure (E) and sensitivity (S) resulted in a map of vulnerable areas. All indicators were weighted equally in the following way:

Exposure & Sensitivity = $E_{social} + E_{physical} + E_{ecological} + S_{social} + S_{physical} + S_{ecological}$

For the assessment of adaptive capacity, we categorized land use parcels within the studied catchment of Amman based on the use (e.g. residential area, road, commercial area), ownership (private, public), residential type (residental villas A/B of better well-off inhabitants, others) and the level of development (developed, undeveloped, see Table 10).

Besides the vulnerability assessment for the current situation, we also explored vulnerability for possible future pathways with regard to changes in heavy rainfall events (WP 2), as well as measures to decrease flash flood damages. These scenarios were simulated with hydraulic and hydrologic models (WP 3) and assessed using vulnerability indicators.

Table 10. Categorization of the adaptive capacity based on physical (availability of open space), social (open space in private land of well-off residents) and ecological (permeable surfaces with high water infiltration) aspects

Category	Description	Average open space on the parcel (m^2)
1 (low)	Little space for the implementation of measures (mainly built-up areas)	250
2 (moderate)	Medium-sized open spaces on developed private land	950
3 (high)	Large open spaces on developed parcels in public space and on private land belonging to wealthy residents (GAM class: residential A/B), as well as on undeveloped parcels in private land (GAM classes: commercial and residential C/D)	3000
4 (very high)	Large open areas on undeveloped parcels in public space and on private land belonging to wealthy residents (GAM class: residental villas/A/B)	2000

8.2 Key findings for Amman

8.2.1 Co-creation of vulnerability indicators and assessment

To integrate stakeholders' perspectives on vulnerability indicators and gain insight into the assessment of these indicators, expert interviews and focus group discussions were conducted. The vulnerability indicator "physical sensitivity" classifies the damage potential of critical infrastructure based on the German standard DWA-M 119 (DWA, 2016). Thus, high damage potential is associated with energy and water infrastructure, hospitals, schools, kindergartens, basements or underground infrastructure. This classification was adapted to the local context by incorporating expert opinion from Jordanian stakeholders and adding the categories of 'cultural heritage sites' and 'places of worship'. To this end, semi-structured interviews were conducted with local experts (n = 5) to elicit their views on the potential damage that flash floods could cause in Amman, with particular reference to the different land uses in the city.

To find out which type of vulnerability indicators (components and domains) are most important for the integrated assessment from the stakeholders' perspective, we conducted a focus group discussion during the Captain Rain workshop in December 2024. This was done through an Analytic Hierarchy Process (AHP) where participants rated the relative importance of the different vulnerability indicators. Each participant completed a matrix in which they compared the importance of the vulnerability indicator in pairs. Based on the ratings given, the weight for each indicator was calculated. A total of seven expert judgements were made. The results showed that social and physical exposure as well as social and physical sensitivity were weighted higher than social and physical adaptive capacity. Indicators related to the ecological domains were consistently assigned lower importance/ priority in the context of Amman city (Table 11).

Table 11. Results of the AHP approach showing the relative importance of the different vulnerability indicators (components and domains) from the stakeholders' perspective (n = 7).

Vulnerability indicator	Priority ranking	Avg. Weight
Social exposure	**1**	0.228
Physical exposure	**2**	0.150
Social sensitivity	**2**	0.150
Physical sensitivity	**3**	0.114
Social & physical adaptive capacity	**4**	0.083
Ecological exposure	**5**	0.037
Ecological adaptive capacity	**6**	0.015
Ecological sensitivity	**7**	0.013

8.2.2 Vulnerability assessment of the current situation

Our results for the current situation (baseline scenario) showed that especially the sub-districts of the larger Qasabah Amman area in the east of the study catchment are highly vulnerable. This is particularly true for the districts of Al Yarmouk, Basman and Al Madeenah, where more than 20% of the area was classified as very vulnerable to flash floods (Figure 57).

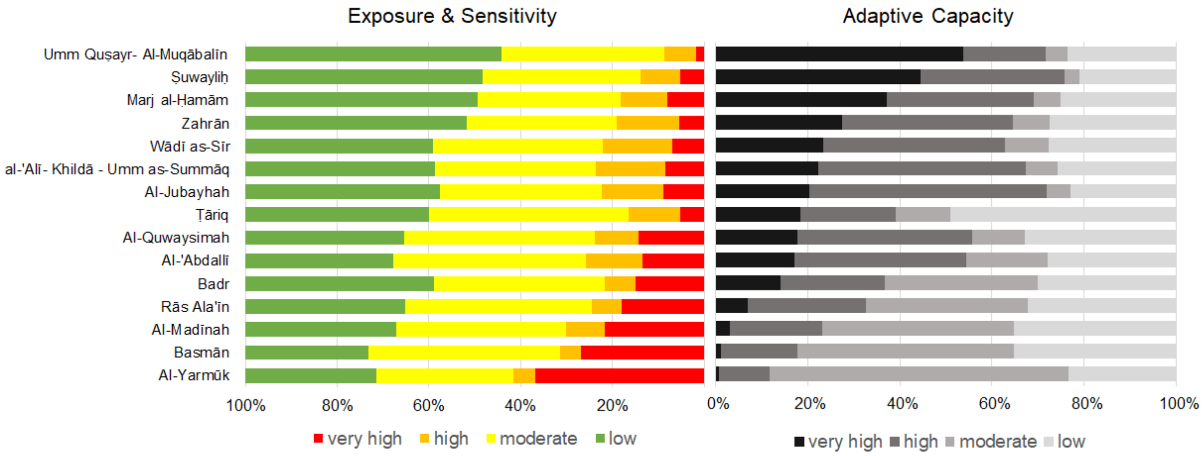


Figure 57. Distribution (%) of vulnerability categories for Exposure + Sensitivity and Adaptive Capacity for the districts of the study catchment in Amman.

This area is characterized by a high degree of urbanisation, a highly vulnerable resident population (high sensitivity) with many disadvantaged individuals and refuges, and many physically exposed areas (areas in close proximity to a flood path). This is particularly the case for the downtown area of Amman, which is situated in a low-lying basin, surrounded by higher elevations. In addition to the topographical conditions that result in a generally higher exposure (see chapter 5) this area is also characterised by an inadequate drainage infrastructure and the highest proportion of impermeable surfaces (Awad, 2023), which prevent water from being absorbed into the ground, thereby increasing surface runoff. The urban development of downtown Amman has taken place over centuries without the implementation of modern flood management planning. The area has also become a settlement for refugees and a residential area for working class families (Potter et al., 2009; Ababsa and Daher, 2011), a social development linked to the relatively lower cost of living in the older parts of the city. The comparatively low income of residents in these areas results in a comparatively high social sensitivity to flash flood damage.

Special attention was given to adaptive capacity, which in our assessment indicates the availability of open space for future implementation of measures. The highest adaptive capacity was found in the southwest in the districts of Umm Quṣayr- Al-Muqābalīn and Marj al-Ḥamām with 54% and 37% of the area respectively, and in the northwest in the district of Ṣuwayliḥ with 45%. These areas have open space on public land, but also on private land owned by more affluent residents. Although these districts have less open land than in the past due to rapid urbanisation (Awad, 2023), there are still some undeveloped areas, especially on the outskirts of the city or in areas reserved for future projects. These small, scattered pockets of open land are often used for a variety of purposes, such as small-scale agriculture, informal recreational areas, or are left as vacant plots awaiting future development. On the outskirts of Marj al-Ḥamām, some land remains in its natural state or is used for small-scale agriculture. These areas are more common on the periphery, where urban development has not yet fully encroached.

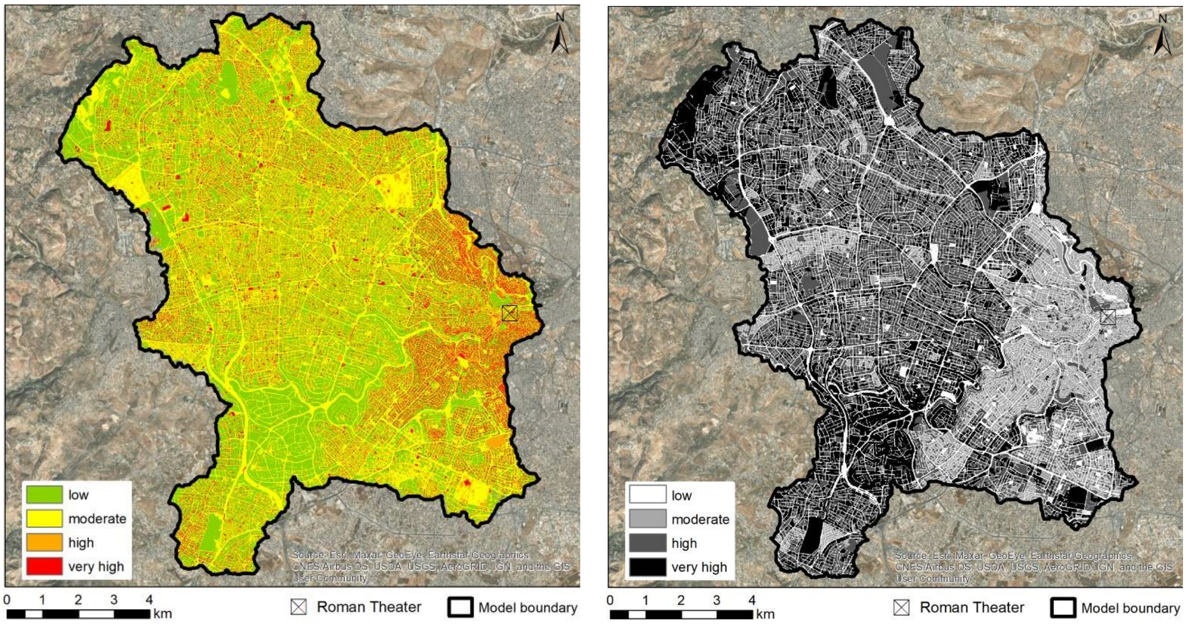


Figure 58. Combined vulnerability maps showing all domains for sensitivity and exposure (left) and for adaptive capacity (right) for the study area in Amman.

In Amman, some open spaces are privately owned and reserved for future development, but open spaces are also available on already developed private properties belonging to better-off residents. This indicates great potential for the implementation of future measures in the private sector if sufficient incentives are created here. Our interviews with residents of Amman revealed that many citizens (37%) have already experienced flash flood damage to their property (Figure 59). Many are aware of possible measures (54%) to reduce the damage potential, and some have already implemented them (40%). Overall, the willingness to take further measures to reduce flash flood damage to their own properties in the future is very high (85%), provided it is financially feasible.

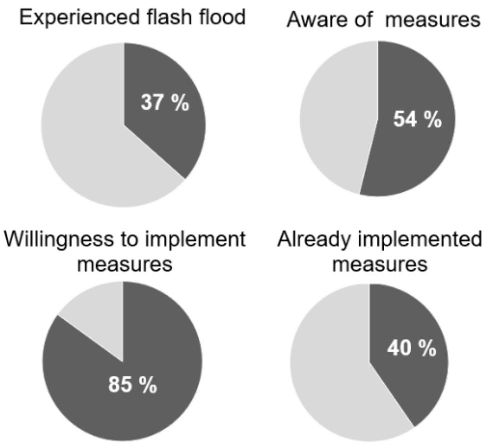


Figure 59. Results of the Interviews with residents in Amman (n = 52) on local knowledge of flash floods and mitigation measures

8.3 Outlook: Vulnerability assessment

Our integrated, spatially explicit vulnerability assessment combined different disciplinary perspectives with local knowledge. Despite the challenges posed by scarce data, we identified the areas most vulnerable to flash flooding, as well as those with the greatest adaptive capacity, for future implementation. The lack of data on critical infrastructure was offset by OpenStreetMap (OSM) data and our own measurements. However, basic data on critical infrastructure, social aspects and environmental aspects is still scarce and needs to be improved for a more detailed risk and vulnerability analysis.

The SEVA results highlighted that the most vulnerable areas are located in the east of the studied watershed, including downtown Amman (the highest built-up area, with the highest sensitivity of residents and many exposed areas), whereas the highest adaptive capacity was detected on the outskirts of the city in the northwest and southwest (with open spaces on public and private land). Given the great potential of open spaces on private property and the willingness of citizens to implement measures, it is suggested that more incentives should be created to promote the implementation of future measures to reduce flash flood damage. However, given the high demand for housing and commercial space in Amman, any remaining open spaces are under pressure from real estate developers. This suggests that open spaces may continue to decrease as development progresses. Careful urban planning is therefore required to ensure that these areas retain some level of open space and that the development of such areas incorporates the future implementation of measures to reduce flash flooding and green infrastructure solutions. Blue-green infrastructure solutions help to manage and retain rainfall runoff, improving water infiltration. Our results can serve as a decision support tool for ongoing sustainable urban planning in the Amman Green City Action Plan (GCAP 2021), which seeks to enhance the city's resilience to climate change by implementing measures to mitigate the impacts of extreme weather events, such as flooding.

9 Integrated multi-scenario analysis

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Besides the rainfall hazard, exposure, sensitivity, adaptive capacity and vulnerability analysis for the current situation, we also explored possible future scenarios for the study region Amman integrating the results of the various research activities. Using a multi-scenario analysis, the effects of changes in heavy rainfall and land cover changes, as well as measures to decrease flash flood damages were simulated with hydraulic and hydrologic models (Figure 60). These results serve as a decision-support tool for urban planning, showing what could happen in urban areas if the effects of climate change and urbanisation intensify, and demonstrating the opportunities that implementing measures such as blue-green infrastructure could provide in reducing the risk of flash flooding. The scenarios were defined collaboratively within the CapTain Rain consortium, incorporating scientific expertise and practical knowledge from Jordanian stakeholders. The rainfall and land cover change scenarios were primarily based on scientific knowledge incorporating expert opinions from Jordanian stakeholders. In contrast, the measures scenarios were based on a participatory planning process (Schumann-Hindenberg et al., 2025) and co-created with Jordanian stakeholders.

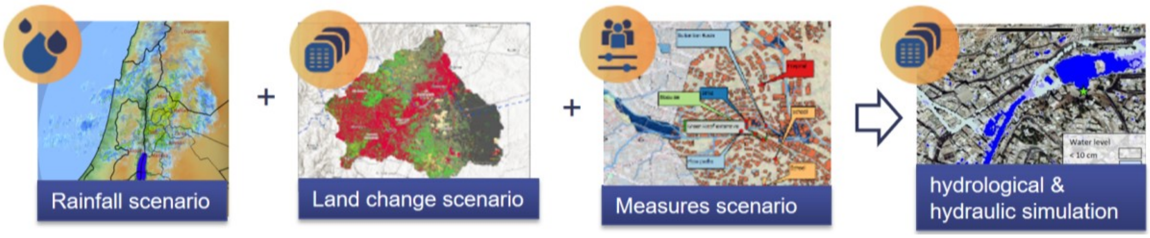


Figure 60. Overview of the different scenarios within CapTain Rain that have been simulated using hydrological and hydraulic models

9.1 Key findings for Amman

- Land use and land cover analysis showed that Amman´s urban and built-up surfaces increased 10-fold from 1968 to 2021 and that with further urban development the simulated built-up areas in 2050 are expected to increase by around 70 %
- The analysis on future changes in the distribution of precipitation showed a decrease of the total precipitation and an increase of extreme precipitation.
- Heavy rainfall events shorter than 6 hours show a much stronger reaction to global warming than longer durations.
- In future both the severity of intense rainfall and drought conditions in Jordan will have a higher impact on the humans in Jordan
- The results of hydrologic and hydraulic modelling show that both climate change and urbanization will increase the hazard of flash floods in Jordan, i.e. flooded areas, water volumes and peak flows.
- By relative comparisons, the hydrologic models could demonstrate past and future impacts of land use change on peak flow rates within Amman´s major watershed. Since the scarce soil data seems to indicate quite impermeable soil, the impact of urban development on peak flow rates is much smaller than anticipated. The results showed that changes of precipitation events (increases of intensity and/or duration, e.g. up to an annual rainfall amount in one event) influence the hazard of flash floods up to five times higher than land use changes (Hohmann et al. 2024).
- The hydraulic simulation of the measures scenarios indicated that the selected adaptation measures have the potential to reduce inundation areas and potentially flash flood risk for the moderate rainfall scenario by 75%).

9.2 Development of multi-scenarios

9.2.1 Rainfall scenarios

The rainfall scenarios should depict a range of frequent heavy rainfall events, e.g. once per year, but also the impact of future climate change. They should also demonstrate the consequences of a potential catastrophic event with a low probability, in order to evaluate the effectiveness of various adaptation measures. The German heavy rainfall index (Schmitt, 2015, DWA-M 119, 2018) was used as a reference point, for which rainfall data covering return periods from 1 to over 100 years would be required. However, the data available in Jordan is insufficient to link rainfall intensities to return periods. Therefore, the rainfall scenarios were limited to four: a “baseline” reference situation derived from a comprehensive analysis of historical heavy rainfall events; a climate change scenario derived from climate models (later defined as “moderate”); and two extreme events (one intense and one catastrophic) to cover a broad range of possible heavy rainfall events. To define the intensities and durations of heavy rainfall for these scenarios, a retrospective analysis of historical heavy rainfall events was conducted in AP 2. Then, the impact of climate change on the intensity and duration of heavy rainfall in Jordan was analysed. This enabled us to define the potential range of heavy rainfall intensities and durations in Jordan. The following section explains those analyses:

A comprehensive retrospective analysis of historical heavy rainfall events in Jordan was difficult to conduct due to the limited availability of high-resolution precipitation data. Various reanalysis products were used as a basis to identify recent extreme rainfall events including their spatial rainfall patterns and to compare them with available station data. This enabled a baseline scenario to be described for Amman and Wadi Musa, where a significant effect (flash flood) was observed on critical infrastructure and society. Figure 61 shows a screenshot of an event table sorted by date, derived in AP2 for Amman and Wadi Musa, which compares rainfall patterns extracted from different open data sets. The most recent event in Amman occurred on 28 February 2019.

Amman

DATE	UERRA	ERA5	W5E5	GWL	Z500	UERRA	ERA5	W5E5
2004-11-22	009.4	023.3	051.3	NWZ				
2002-12-20	008.1	031.7	045.2	HM				
2013-01-08	047.8	031.9	044.3	BM				
2019-02-28	-999.9	023.3	040.6	NWA				
2012-03-01	030.6	026.8	040.5	HM				
2006-04-02	017.1	027.7	035.9	WZ				
2010-01-18	012.2	023.5	035.0	WW				

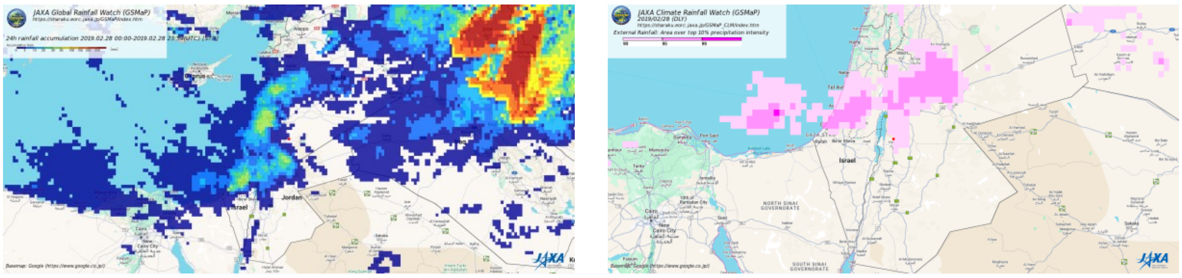
WadiMusa

DATE	UERRA	ERA5	W5E5	GWL	Z500	UERRA	ERA5	W5E5
2010-01-18	012.1	035.2	035.4	WW				
2016-03-26	001.1	027.9	035.1	WZ				
2002-12-20	002.8	011.9	025.3	HM				
2001-04-04	-999.9	008.7	024.4	SWA				
2004-01-14	014.2	011.1	024.3	WS				
2004-11-22	000.6	012.6	021.3	NWZ				
2001-01-25	000.7	006.6	021.2	SWZ				

Amman | Wadi Musa

Figure 61. Sorted table of heavy rainfall events given as values and patterns for Jordan using different reanalysis products: UERRA, ERA5, W5E5. In addition, the respective large-scale circulation patterns (Z500) are given.

For the **baseline scenario**, we selected the most intense 5.5 hours of the relatively short February 2019 event, which was recorded by five stations from the Jordan Meteorological Department (JMD) at an hourly resolution. Additionally, time series with a resolution of 5 minutes for this event were obtained from a study commissioned by UN-Habitat (2020). Such an event occurs approximately once a year in Amman. This event exhibited significant spatial and temporal variations; for instance, 58 mm of rainfall was recorded at the Amman Airport station in four hours, which is nearly equivalent to an event with a return period of 25 years, according to the UN-Habitat (2020) study (60 mm/3 h). At one station, however, only 19 mm of rainfall was measured in this time period. The timing and spatial pattern of the event are also accurately reflected in the GSMaP satellite rainfall estimates (see Figure 62). However, the magnitude of the event is clearly underestimated compared to rain gauges. Nevertheless, it was one of the top 10% of events in the last 20 years.



24h Accumulated Rainfall Pattern	*Area over top 10% precipitation intensity*

Figure 62. Baseline event in Amman on February 28th in 2019 represented by Satellite Rainfall Estimates (GSMaP, JAXA[1]) given as 24-hour accumulation (left) and as area over the top 10% precipitation intensity (right).

In the context of climate change, the nature of such events will change. Climate model simulations provide the basis for defining possible heavy rainfall scenarios. These simulations can be used to test how sensitive and responsive meteorological phenomena are to different climatic conditions. It should be noted, however, that models do not provide an exact representation of real conditions. By evaluating model ensemble data, we were able to demonstrate that short periods of intense rainfall (3 hours) in particular react with a greater response to warmer climatic conditions. On average, the effect of climate change on the intensification of heavy rainfall is expected to be around +20% by the end of the century. Future climatic conditions will correspond to an increase in local temperature of around 5°C by the end of the century (KNMI Climate Explorer[2]). The developments in models are within the expected horizon of the interaction of physical rules. However, there are also possible shifts in the large-scale weather patterns and local rainfall patterns that significantly determine the severity (e.g. Dayan et al. 2015). The source of uncertainty in climate models are often associated with such phenomena like atmosphere blocking over Eurasia and the North-Atlantic sector. The frequency change have a large impact on weather extremes in general (e.g. Kautz et al, 2022). In this case, experiences can sometimes help to construct possible stress test scenarios. It cannot be ruled out that even amounts of rainfall that are spread over several events over the year will rain down within just one day or even a few hours. There are recent examples for the MENA region (Greece, 2023 or Valencia, 2024).

For the **moderate scenario**, we aimed to demonstrate the average impact of climate change on the intensity of heavy rainfall. Based on our analyses of sub daily, high-resolution climate model simulations for the RCP8.5 emission scenario[3], we increased the baseline scenario's rainfall volume by 20% in this scenario. Although the return period of the baseline scenario is less than 100 years, we created this synthetic event bearing in mind the high uncertainty in the results of climate models for heavy rainfall events. To address this issue, we also designed two more intense and catastrophic extreme rainfall scenarios.

For the **intense scenario**, we chose the highest observed rainfall at one station (Amman Airport) during the entire February 2019 event (27 hours) and applied it uniformly across the entire area. The station recorded 136 mm rainfall over 27 hours. According to t UN Habitat statistics, this equates to a return period of 5–10 years.

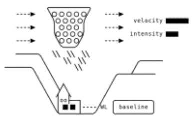
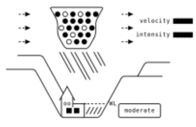
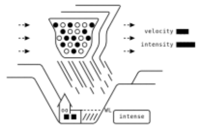
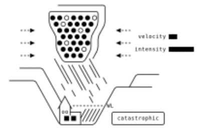
For the **catastrophic scenario**, we increased the rainfall volume to 300 mm, which is almost the mean annual rainfall total for Amman. In September 2023, Mediterranean countries such as Libya and Greece experienced a single heavy rainfall event that produced the yearly amount of rain, leading to devastating floods (WION, 2023). This would be about 3–5 times more rain than in the baseline scenario. Table 12 summarises the considered rainfall scenarios, along with their respective narratives and aspects.

1 https://sharaku.eorc.jaxa.jp/GSMaP/

2 https://climexp.knmi.nl/plot_atlas_form.py?id=someone@somewhere

3 https://cds.climate.copernicus.eu/datasets/projections-cordex-domains-single-levels

Table 12. Developed possible future extreme rainfall scenarios (baseline, moderate, intense, catastrophic) for the study areas Amman and Wadi Musa.

	baseline	moderate	intense	catastrophic
				
	thunderstorm	amplified thunderstorm	persistent thunderstorm	thunderstorm clusters
Amman	**Feb. 2019** 19 – 64 mm in 5.5 h 25-yr return period	**+20% Climate Change** 23 – 77 mm in 5.5 h	**Airport station** 136 mm in 27 h	**Annual Rainfall** 300 mm in 27 h
Wadi Musa	**Dec. 2022** 7 – 36 mm in 7 h	**+20% Climate Change** 08 – 43 mm in 7 h	**PDTRA station 180** 70 mm in 28 h	**Annual Rainfall** 126 mm in 28 h
Narratives	Significant heavy rainfall event whose course was sufficiently well characterized by measurements and reported	Increase in heavy rainfall intensity derived from model simulations due to higher temperatures in the context of climate warming	Consideration of neighboring stations with higher or longer-lasting rainfall events	Consideration of unlikely but not excluded rainfall events with real reference in other countries in the Mena region
Factor	~1.0	~1.2	~2.0	~3.0 – 5.0

9.2.2 Land cover change scenario

The land cover datasets for our catchment area in Amman for the past (1968) and present (2021) were derived from the results of a MSc thesis (Awad, 2023) carried out within the CapTain Rain project. High-resolution panchromatic CORONA satellite images (1968) and Sentinel-2 images (2021) were used for the object-based classification of past and present land cover conditions. The classification results have a spatial resolution of 10 m. The analysis revealed that built-up surfaces had increased tenfold between 1968 and 2021 (Awad, 2023). Such drastic urbanisation has also been observed in other MENA cities (e.g. Hamdy et al., 2023).

The key drivers of land cover changes were identified based on historical trends (Awad, 2023) and in collaboration with Jordanian stakeholders. These drivers were then used as predictors for the statistical model. Additionally, future urban development plans for the city of Amman were identified from the perspective of stakeholders and incorporated into the model based on expert interviews with urban planners in Amman. Land cover prediction modelling was performed with IDRISI TerrSet's Land Change Modeler (LCM) on the study's watershed area using a Multilayer Perceptron neural network and Markov Chain model (MLP-MC) (Awad et al., in preparation). The MLP-MC model is an inductive pattern-based statistical model that performs a non-parametric regression or classification analysis between input variables and the output dependent variable (Camacho Olmedo et al. 2018). The spatial resolution of the 2050 land cover map is 100 m. Simulated built-up areas in 2050 are expected to increase by around 70 % mainly at the expense of rangelands.

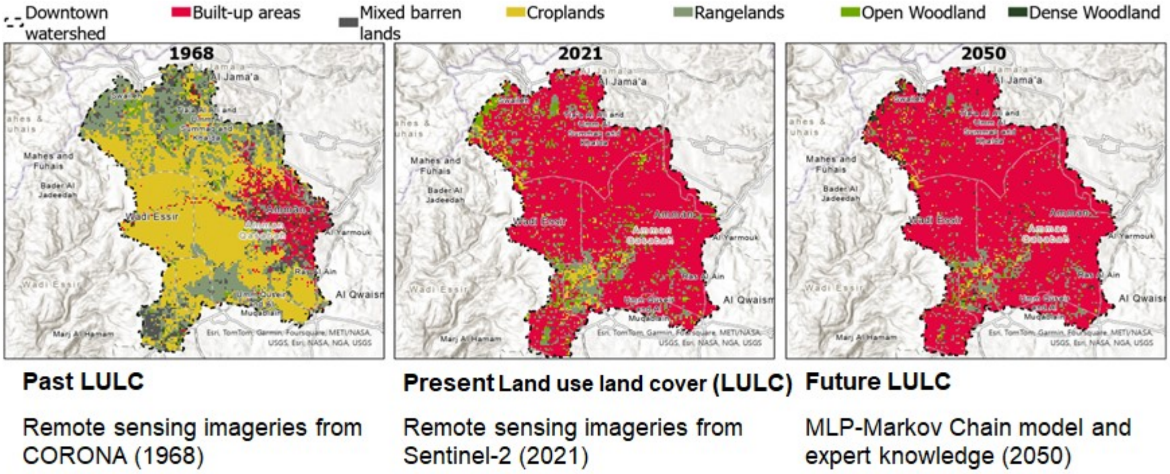


Figure 63. Land use and land cover datasets for our catchment area in Amman for the past (1968), present (2021) and future scenario (2050), based on satellite images and predicted LULC changes (Hohmann et al. 2024).

9.2.3 Measures scenarios

The measures scenarios (Table 13) were developed in a participatory manner during two stakeholder workshops and then refined on an expert basis (see Chapter 8 and Schumann-Hindenberg et al. 2025). Based on these results, a variety of potential adaptation measures were allocated to the different focus areas. These also include the draft concepts presented as examples in Chapter 6.2.5. Hydrological and hydraulic simulations, which allow a quantitative impact assessment of the allocated measures were only conducted for the focus area Eastern part of Marj Al-Hamam. Depending on the ownership structure of the available land, two different scenarios were defined. The first scenario focused on public space, where it is assumed that measures can be implemented more easily and quickly by the planning municipality. The second scenario includes private land. In this scenario, it is assumed that implementating measures requires more negotiation and takes much more time, but offers much greater potential in terms of land availability.

Both scenarios had two focal points: firstly, ensuring the reduction of flash flood risks and damage to downstream areas and central Amman, and secondly, considering potential improvements to the focus area itself, based on water flow characteristics during flash floods.

Table 13. Description of the selected measures scenarios.

	Land use categories	Measures	Description
Public space scenario	Public areas such as streets, plazas, public and municipal plots of land, undeveloped municipal areas, public green spaces	retention basin, infiltration trenches, bioswales	Easy access, as only a limited number of stakeholders need to be involved (the city administration), planning and implementation from a single source, direct start and implementation in the near future possible.
Public and private space scenario	Public areas as well as private land (developed and undeveloped)	retention basin, infiltration trenches, bioswales, multifunctional areas, pipe infiltration trenches	Access is more complicated because various professional and private stakeholders have to be involved, the municipality is more in the role of steering and guiding the process than implementing measures; process requires through preparation and a participatory element, also when starting directly, implementation will require time.

To achieve the goal of the 'public and private space' scenario, 291 hectares of land would be required for the integration of blue-green infrastructure. According to the analysis, the total amount of publicly usable land is 234 ha, while the total amount of privately usable land is 1,142 ha. This means that around 20% of private land would be required to achieve the goal of the 'public and private space' scenario.

9.3 Hydrological simulation of rainfall and land use scenarios

Using **the HEC-HMS hydrological model** (see Chapter 5), we modelled and assessed combinations of rainfall and land cover change scenarios (past, present and future) to analyse the interrelationship between climate change (i.e. changes in heavy rainfall events) and urbanisation trends (i.e. land cover changes). First, we simulated the heavy rainfall event that took place in Amman in February 2019, combining it with past (1968), present (2021) and future (2050) land cover scenarios. The results are depicted in Figure 64. The modelled runoff curves are close together, indicating that changes in land use and land cover (LULC) have a small influence on runoff generation for heavy rainfall events in Amman. This is due to the soil information used to set up the hydrological model having low infiltration capacities. The differences between 1968 and 2021 are much greater than those between 2021 and 2050 because a large proportion of the surface was built up in 2021. Near the end of the event, runoff is similar for all land use/land cover (LULC) states as the soil is saturated and behaves similarly to a built-up area.

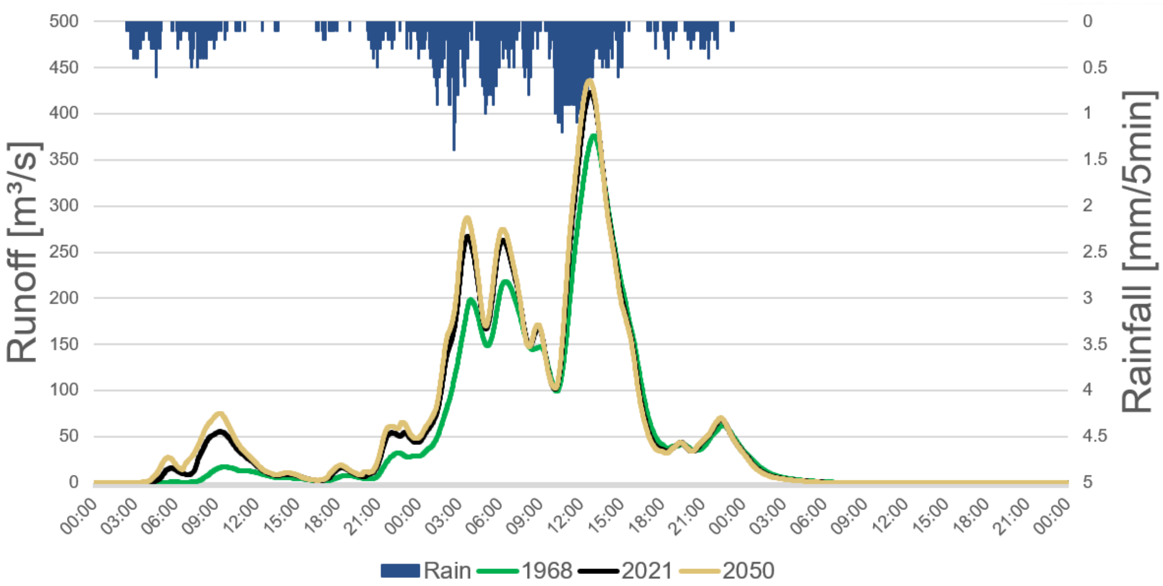


Figure 64. Modelled runoff curves at the catchment outlet near Downtown Amman from HEC-HMS for the heavy rainfall event of February 2019 and different land cover scenarios (past – 1968: green, present – 2021: black, future – 2050: yellow).

The results of our model are subject to high levels of uncertainty as they rely on global datasets for information on soil and land cover, as well as local rainfall station data whose accuracy is unknown. One of the biggest challenges was the lack of runoff data with which to calibrate and validate the model, which is one aspect of Jordan's data scarcity. Due to these uncertainties, we focused instead on relative changes between different model runs, i.e. those involving past, present and future land use and land cover (LULC) and possible future rainfall events. These relative changes provide an opportunity to gain insight into the potential impact of future developments.

Figure 65 shows that the model results for all rainfall scenarios and land use/land cover (LULC) states indicate that changes in heavy rainfall events due to climate change, as well as the effects of urbanisation, will drastically increase peak runoff and therefore flash flood risk. Under the catastrophic scenario with annual precipitation in one event, disastrous peak discharges might occur. Moreover, it can be seen that changes in rainfall influence the flash flood risk up to five times more than changes in land cover: The peak runoffs of the intense and catastrophic scenarios are more than 100 % (intense scenario) or more than 400 % (catastrophic scenario) higher compared to the baseline, whereas the land cover changes under the baseline scenario (first group of columns) are only around 40 % (changes from 1968 to 2021) respectively around 20 % (changes from 2021 to 2050).

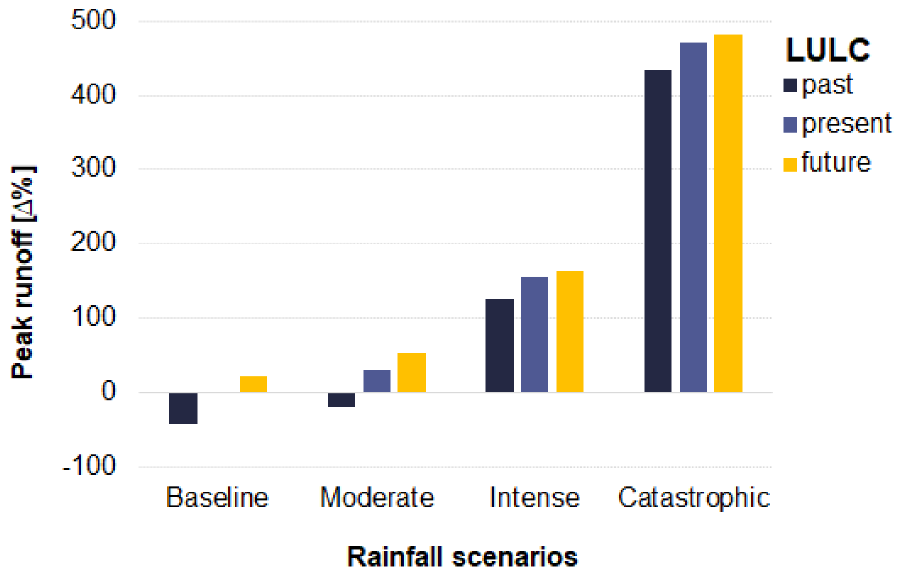


Figure 65. With HEC-HMS simulated rainfall scenarios (baseline, moderate, intense, and catastrophic) and respectively with the LULC datasets of the past – 1968, present – 2021 and future – 2050, calculated differences to baseline scenario (5.5 h rainfall event and present LULC) in percent change of peak flow at the catchment outlet (Hohmann et al. 2024).

9.4 Hydraulic simulation of rainfall and measures scenarios

In addition to the hydrological simulation, the different rainfall scenarios were also simulated using the **hydraulic modelling** approach as summarized in Chapter 5. The land cover scenario was neglected in hydraulic modelling, since hydraulic models need detailed land use information including the spatial allocation of buildings which was not available for our past and future land cover scenarios. The following figure shows the inundated areas of the baseline scenario, i.e. of a flash flood similar to the event of February 2019 in Amman. The other maps depict how the three heavy rainfall scenarios would increase the water levels and inundated areas in comparison to the baseline scenario. The modelled inundation area of the baseline scenario comprises the area of the Roman Theater and the surrounding streets. This area was already flooded in 2018 and 2019. The moderate scenario, with 20% more rainfall, increases the modelled water levels by 10–50 cm in large areas. The intense scenario increases the inundated areas further, with water levels rising by 50 cm to over 1 m compared to the baseline. The catastrophic scenario shows very high water levels (over 1 m) and flooding of a much greater extent.

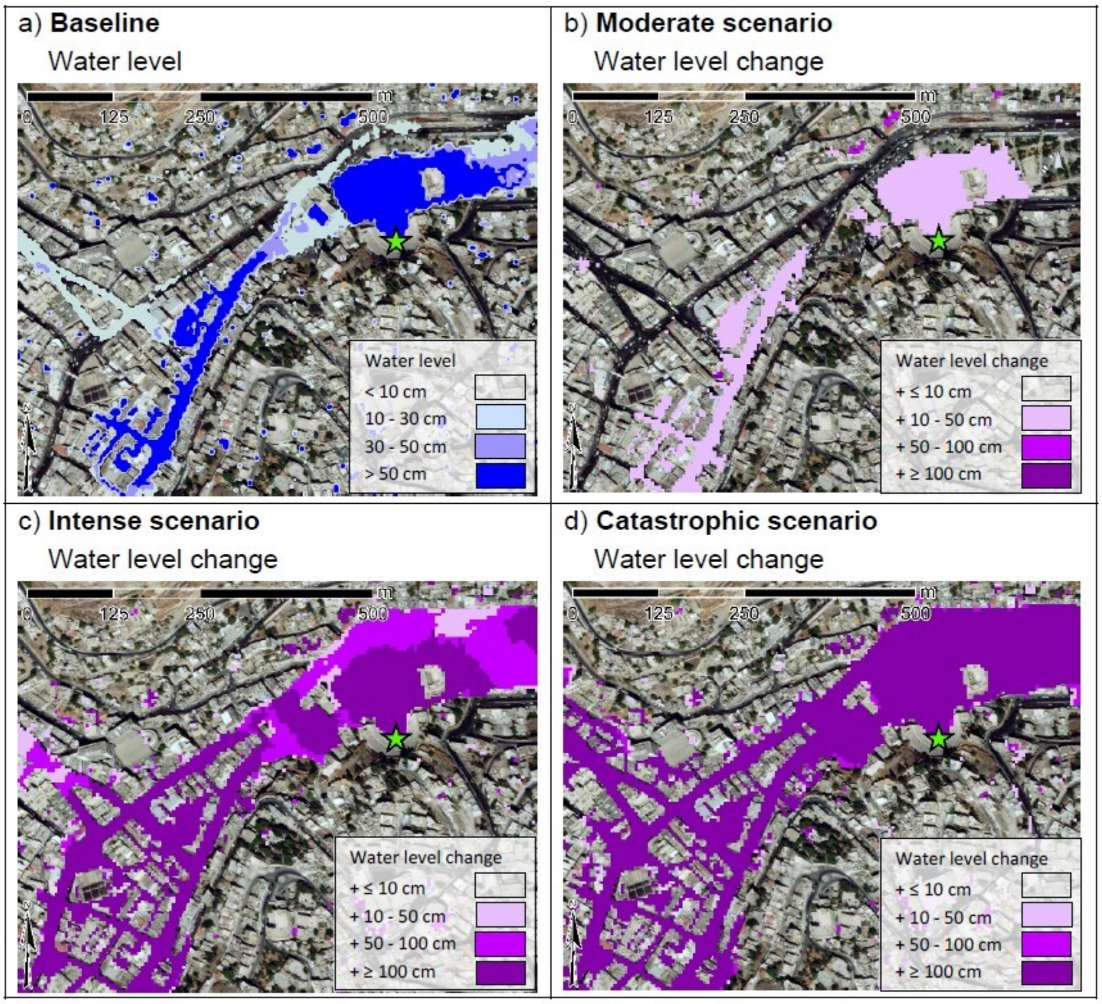


Figure 66. Focus area Downtown Amman with a) inundation map of the baseline simulation, water levels in blue, and the differences maps to the baseline in purple of b) moderate scenario (20 % more rainfall than baseline), c) intense scenario (maximum station for the whole catchment, 136 mm in 27 h), d) catastrophic scenario (300 mm in 27 h), the UNESCO world heritage site, Roman theater, is marked with a green star (Hohmann et al. 2024).

In order to demonstrate the impact of possible measures (impact assessment), the **measures scenarios** were simulated for the focus area Marj Al Hamam, a complete sub-catchment of the study region. The identified measures (see Table 13) were positioned along the main flow paths in available open spaces, e.g. beside streets. All measures provide a certain retention volume. This volume was calculated by multiplying the free area in m² by a theoretical depth of 0.5 m; however, real measures may differ from this depth, e.g. for technical and/or covered retention basins.

Results of the ‘public space’ scenario: In this scenario, only public spaces were used to allocate measures. The total potential usable space was 432,662 m², corresponding to 4% of the total focus area. Eleven measures were identified and allocated in public spaces: one retention basin, eight infiltration trenches and two bioswales. The measures require an area of 49,048 m² in total, corresponding to 11% of the potential usable space. Nearly half of this area is occupied by infiltration trenches situated along streets, particularly main roads. The measures are collectively capable of holding back a volume of 16,376 m³. Hydraulic simulations of different rainfall scenarios show peak runoff reductions of 34% for the baseline scenario, 21% for the intense scenario, and 6% for the catastrophic rainfall scenario. As most of the measures are located in the lower part of the focus area, the greatest impact in terms of reducing runoff volumes and flash flood damage is seen further downstream. Nevertheless, they also have an impact on critical areas within the focus area itself, such as the significant inundation potential at the intersection of Dead Sea Road and Airport Road.

Table 14. Summary of the results of the measures scenarios for the focus area 1 – Marj Al Hamam.

Character	Very high percentage of agricultural and open land.	
Focus	Public space scenario	Public and private space scenario
Identified measures	11 measures were identified: 1 retention basin, 8 infiltration trenches along roads and 2 bioswales.	23 measures were identified: the 11 one of the public space scenario as well as 12 additional ones on private land. Overall, they include 5 retention basins, 7 multi-functional areas, 8 infiltration trenches, 2 bioswales and 1 pipe infiltration trench
Required Area	49,048 m²	179,524 m²: out of this 130,476 m² located on private land, (multifunctional areas and retention basin have 82 % of 179,524 m²)
hold back a volume	16,376 m³	36,209 m³ (19,833 m³ only private)
Potential useable space	3 % of total CA%	26 % of the total CA
Implementation area	Implementation in 1% of total CA	Implementation in 10% of the potential area (2% of total CA)
Result simulation		
Peak run off reduction in rainfall scenarios	34 % for baseline, 21 % for intense, 6 % for catastrophic event	75 % for base scenario, intense 46 %, catastrophic event 13 %

Results of the 'public and private space scenario': This scenario focuses on private areas and public land. The potential usable space amounts to 2,001,832 m², corresponding to 20% of the focus area. Within this scenario, 23 measures have been identified: the 11 measures from the public space scenario, plus 12 additional measures on private land. The measures include five retention basins, seven multifunctional areas, eight infiltration trenches, two bioswales and one pipe infiltration trench. All of the measures require an area totalling 179,524 m², 130,476 m² of which are located on private land. The measures "multifunctional area" and "retention basin" are particularly noteworthy as they represent four new locations and require most of the area (82%). Overall, the measures require an area of 179,524 m², corresponding to 10% of the potential usable space and 2% of the focus area. The measures can hold back a volume of 36,209 m³. Hydraulic simulations of different rainfall scenarios show peak runoff reductions of 75% for the baseline scenario, 46% for the intense scenario and 13% for the catastrophic event.

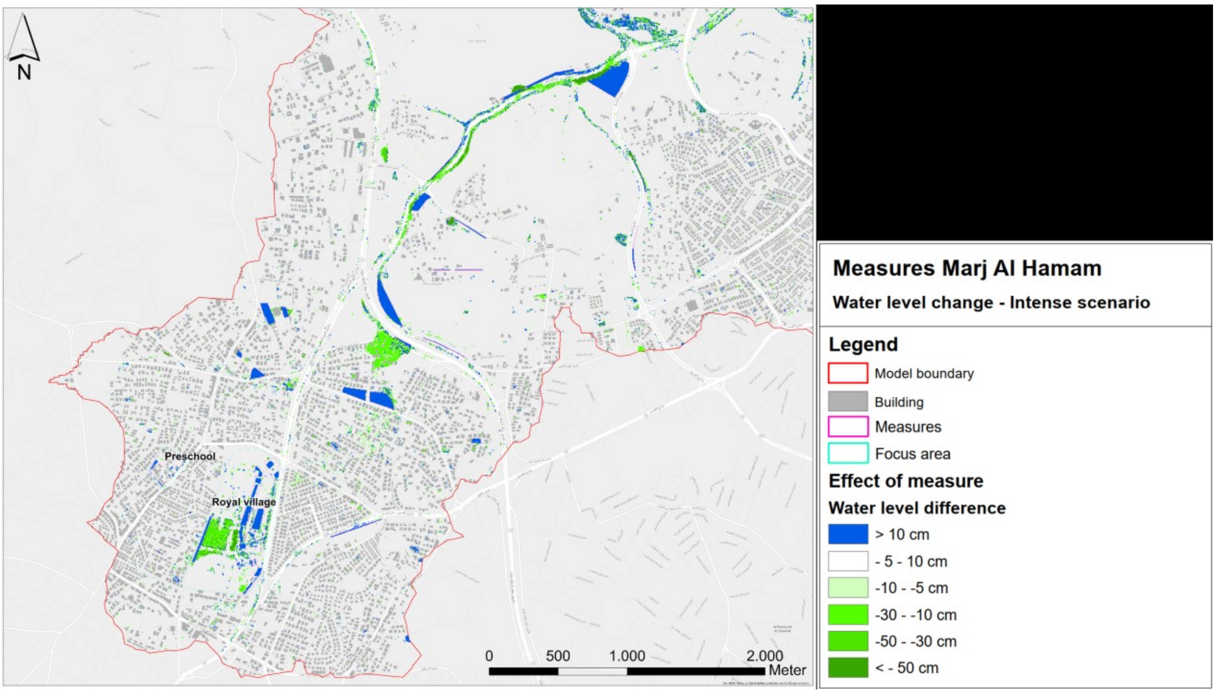


Figure 67. Impact (decrease of water level) of the 'public and private space scenario' in combination with the intense rainfall scenario modelled with the hydraulic model HE2D/FOG2D.

The results show that the measures in the 'public and private space scenario' have a positive impact. They reduce inundated areas within the sub-catchment. Regarding the runoff curves, a reduction is especially evident in the baseline rainfall scenario. However, looking at the catastrophic scenario with much more rainfall, the reduction is potentially small and does not reduce any of the larger runoff peaks. This highlights the importance of catastrophe management: protection against catastrophic flash floods is not possible, so early warning systems and evacuation measures are required instead.

9.5 Outlook: Multi-scenario analysis

The hydraulic simulation clearly showed how an increase in heavy rainfall events could affect inundation areas and put more urban areas at risk. These spatially explicit datasets and maps are extremely useful for storm water management, particularly for planning future measures to prevent flash flooding, as well as for early warning systems and evacuation planning. The rainfall and land cover change scenarios were primarily based on scientific knowledge incorporating expert opinions from Jordanian stakeholders. In contrast, the measures scenarios were developed through a participatory planning process in collaboration with Jordanian stakeholders. The resulting scenarios therefore reflect local possibilities and can be incorporated directly into urban planning work. The measures scenario incorporating blue-green infrastructure demonstrated significant potential for mitigating floodplain water levels, particularly when measures are implemented in both public and private spaces, where substantial open space is available (see Chapter 8). To promote the implementation of future measures on private property, incentives should be created and incorporated into urban planning.

The multi-scenario results serve as a decision-support tool for ongoing sustainable urban planning within the Amman Green City Action Plan (AECOM Limited, 2021). Combined with other modelling approaches and additional data on future demographic trends and land use changes with different building patterns, these simulation results could be further refined and improved. This would enable the two greatest challenges in future urban planning – urbanisation and the increasing risk of flash flooding – to be considered in an integrative way and taken into account in planning. To better assess the scenarios' potential to reduce vulnerability, the vulnerability assessment presented in Chapter 8 could be carried out for different future scenarios. For the vulnerability component 'Exposure', which depicts the degree to which a subject (inhabitant, building or ecosystem) is exposed to flooding in the event of a flash flood, this is feasible. However, detailed data on demographic and socio-economic characteristics and their modelling are required to project future demographic and economic trends for the other vulnerability components (sensitivity and adaptive capacity).

10 Key messages and further research need

Authors: Katja Brinkmann and Dörte Ziegler

CapTain Rain delivered methods and climate services for flash flood prediction and prevention in a participatory and target group-oriented manner. The overall objective was to improve climate change adaptation in Jordan and reduce vulnerability regarding flash flood events. The project focused on analysis and planning tools to identify options for improving flash flood management and thus climate change adaptation in Jordan. The analysis, planning and early warning tools were developed together with stakeholders so that they can be used in the future in the pilot areas of Amman and Wadi Musa, as well as in other cities in Jordan and in other semi-arid countries in the MENA region.

The transdisciplinary research approach integrated scientific and practical knowledge using different research methods such as climate analysis, hydrological and hydraulic modelling, remote sensing techniques, participatory GIS methods, integrated vulnerability assessment, stakeholder workshops, expert interviews and scenario analysis. Despite challenges such as scarce and poor-quality data, regionally adapted solutions for retaining heavy rainfall and reducing flash flood risks were developed in close cooperation with Jordanian stakeholders and practice partners, taking into account scientific and local, practice-oriented findings. These climate services include flash flood hazard and risk maps, tools to improve the prediction of flash floods and recommendations for promising adaptation strategies and early warning systems that are suitable for a semi-arid country with limited monitoring and modelling resources. In order to transfer and further develop the results obtained on climate services and products as decision support in practice, we recommend integrating the climate services on flash floods into urban planning processes. With regard to climate service products, the **key results and recommendation of CapTain Rain** can be summarized as follows:

Rainfall hazard	• A **climate service portal** and future **heavy rainfall scenarios** that incorporate climate change effects were developed for Jordan. • Analysis of climate model simulations showed a decrease in the number of extreme rainfall events in Jordan, while their intensity would increase. • The integration of critical circulation patterns in weather forecasts would improve the prediction of heavy rainfall events in Jordan.
Exposure and Sensitivity	• The **hydrological models** (HEC-HMS, RRI) displayed the runoff curves and allowed an initial assessment of possible changes in heavy rainfall events and impacts of urbanization. • The **hydraulic model** combined with the spatial analysis of damage potential allowed to show inundation areas and develop flood hazard maps, damage potential maps and flash flood risk maps; it can be used to model impacts of possible adaptation measures. • The hazard and risk maps should be used to communicate potential flooding areas to residents, the public, and to institutions of crisis management and to prioritize measures for climate adaptation.
Adaptive capacity: Adaptation measures	• A participatory process for the **selection and localisation of measures** in urban and landscape planning was applied showing the potential for the implementation of blue-green infrastructure • Maps, infocards on measures and a guideline were developed for local decision makers.

	• Blue-green infrastructure should be adapted to the dry climate in Jordan so that evaporation losses and irrigation requirements are minimized.
Climate and water data portal	• A **digital platform to manage rainfall data** and to include weather forecasts and improve early warning was adapted to Jordan. Data on climate predictions for Jordan were integrated in the climate service portal. • The use of high-resolution open data and the sharing of weather observations and forecasts among the Jordanian government agencies would improve flood warnings
Vulnerability assessment	• A trans-disciplinary approach to **assess vulnerability** towards flash floods was developed, integrating ecological, social and physical aspects. • Vulnerable areas are particularly located around Downtown Amman (highest built-up area, highest sensitivity of residents and many exposed areas); the highest adaptive capacity was found in the outskirts, where there is still space for the implementation of measures, especially on private land • The assessment results and maps serve as decision-support when selecting measures, but also for flood warning and alarm plans.
Multi-scenario analysis	• Changes of rainfall intensity and duration have the largest influence on runoff, since soils have low infiltration capacities. • The **catastrophic rainfall scenario** serves as **stress test** to prepare for potential catastrophes. • The simulated scenarios can be used for assessing the impacts of measures on risk reduction under different rainfall scenarios and serve as decision support

In Jordan, responsibilities and resources for the management of heavy rain and flash flood events have been assigned and largely clarified. However, there is a lack of resources and continuity, as well as limited access to data. In this context, **structural challenges** include donor and project dependency. It is crucial to reinforce the bond between state entities and local communities, a process that can be facilitated through the implementation of projects. For the proactive management of flash flood risks, it is essential to **establish effective coordination** between government agencies. The establishment of a leading agency or state entity would facilitate this process. Furthermore, a transdisciplinary understanding of data requirements and data access across different institutions is necessary. This can be achieved by integrating and sharing data in data portals. This approach would enhance prediction and early warning capabilities, as well as facilitate more targeted risk management and disaster management in the event of a flash flood.

Obtaining the **data necessary for flash flood risk management** remains challenging due to insufficient data analysis and maintenance processes, as well as difficulties accessing the data. Therefore, the quality of data, including rainfall data, digital elevation information, soil data and building information, should be enhanced.

However, this requires resources to be allocated to integrated data management and maintenance. For example, installing and maintaining gauges at designated points within watersheds would be a significant step towards improving data on peak flow rates and water tables. Furthermore, utilising open access data, including satellite and OpenStreetMap data, helps to overcome data barriers. It is imperative that existing data gaps are filled and that the data is standardised. This will ensure that future climate, hydraulic and hydrological models achieve a higher level of reliability in their modelling results.

Furthermore, the **establishment of standards and procedures** related to flash flood management is of paramount importance. This involves the development of methodologies into standards with regard to meteorological and hydrological monitoring, as well as the formulation of standards for urban planning and development and building codes for sewers, buildings, or streets.

The Greater Amman Municipality (GAM) and the Petra Development and Tourism Regional Authority (PDTRA) are currently implementing initiatives to adapt to climate change in Amman and Wadi Musa, respectively. These initiatives prioritise the **implementation of blue-green infrastructure**, with rainwater harvesting being of particular significance. When seeking to retain water during more extreme rainfall events, it is crucial to consider the complex effects and interactions of evapotranspiration and groundwater recharge. Given the current limitations of available data, it is recommended that further studies be conducted on soil conditions and groundwater recharge rates. A **participatory planning process** is advised to facilitate the implementation of blue-green infrastructure, commencing with a joint understanding of planning goals and extending to the utilisation of a comprehensive range of multifunctional measures to adapt to flash floods. This process requires the involvement of various stakeholders in formulating planning goals and measures, which are then formalised in flash flood risk management plans. Thereafter, recurrent assessment of the implementation of measures and their impacts is required.

The Jordanian partners and associated stakeholders involved in the CapTain Rain project benefited from capacity building, for example through webinars, which enabled them to enhance their tools and methods for managing heavy rain and flash floods. **Cooperation between Jordan and Germany** in addressing climate change was strengthened through various visits to Jordan, stakeholder workshops, meetings, virtual conferences and, finally, a joint study tour to Germany in August 2024. There is great interest in further cooperation with Germany, the MENA region and Europe in the future. To **secure knowledge transfer**, the CapTain Rain project has presented project results to institutions and stakeholders involved in development cooperation and flash flood and water management. These include a donor round moderated by the German Embassy in Jordan, KfW and GIZ, the Swiss Development Cooperation, UN-Habitat and USAID. This has resulted in the formation of a new network, and CapTain Rain is now part of the Water Disaster/Flood Mapping, Analysis and Mitigation Working Group of SDC, regularly attending its meetings.

11 References

Ababsa, M., Daher, R.F., 2011. Villes, pratiques urbaines et construction nationale en Jordanie. Presses de l'Ifpo, available at https://doi.org/10.4000/books.ifpo.1675.

Acosta-Coll, M., Ballester-Merelo, F.,Martinez-Peiró, M., de La Hoz-Franco, E., 2018. Real-Time Early Warning System Design for Pluvial Flash Floods – A Review. In: Sensors (Basel, Switzerland), 18, 7.

AECOM Limited, 2021. Amman Green City Action Plan. Available at https://www.amman.jo/site_doc/AmmanGreen2021.pdf.

Alhasanat, H., 2014. Flash Flood Assessment for Wadi Mousa City-Jordan. In: Procedia Economics and Finance, 18: 675–683.

Alhasanat, H. A., 2017. Early Warning System Guidance to Mitigate Flash Flood Impacts in Petra Region, Jordan. Salford, UK.

Al-Qudah, K. A., 2011. Floods as Water Resource and As a Hazard in Arid Regions – A Case Study in Southern Jordan. In: Jordan Journal of Civil Engineering, 5:148–161.

Al-Qudah, K. A., Abdelal, Q., Hamarneh, C., Abu-Jaber, N., 2016. Taming the torrents – The hydrological impacts of ancient terracing practices in Jordan. In: Journal of Hydrology, 542: 913–922.

Al-Weshah, R. A., El-Khoury, F., 1999. Flood Analysis and Mitigation for Petra Area in Jordan. In: Journal of Water Resources Planning and Management, 125: 170–177.

Amin, M. T., Mahmoud, S. H., Alazba, A. A., 2016. Observations, projections and impacts of climate change on water resources in Arabian Peninsula – Current and future scenarios. In: Environmental Earth Sciences, 75: 864.

Ara Begum, R., R. Lempert, E. Ali, T.A. Benjaminsen, T. Bernauer, W. Cramer, X. Cui, K. Mach, G. Nagy, N.C. Stenseth, R. Sukumar, and P. Wester, 2022. Point of Departure and Key Concepts. In: Climate Change 2022. Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 121–196, doi:10.1017/9781009325844.003.

Awad, A., 2023. Analysis of the spatial-temporal dynamics of land-use changes using a mixed-method approach: A Case study from Amman, Jordan. M.Sc. thesis at the faculty of life Sciences, technical university of Munich, Germany.

Awad, A., Hohmann, C., Maus, C., Abu Hamour, W., Al Naimat, M., Brinkmann, K. (in preparation). Understanding urbanization's impact on flash flood risks from past to future: A Case study of a rapidly growing MENA city.

CADRI Partnership Secretariat [ed.], 2018. Capacity Assessment of the Disaster Risk Management System in Jordan – Draft. Available at https://data2.unhcr.org/en/documents/download/67193.

Olmedo, C.M.T., Paegelow, M., Mas, J.-F., Francisco, F. (Eds.), 2018. Geomatric approaches fo modelling land change scenarios: Springer (Lecture Notes in Geoinformation and Cartography). Available online at https://doi.org/10.1007/978-3-319-60801-3.

Copernicus, 2021. Climate Change Service, Climate Data Store – CMIP6 climate projections. Copernicus Climate Change Service (C3S) Climate Data Store (CDS). DOI: 10.24381/cds.c866074c.

Copernicus, 2019a. Climate Change Service, Climate Data Store – CORDEX regional climate model data on single levels. Copernicus Climate Change Service (C3S) Climate Data Store (CDS). DOI:10.24381/cds.bc91edc3.

Copernicus, 2019b. Climate Change Service, Climate Data Store – Complete UERRA regional reanalysis for Europe from 1961 to 2019. Copernicus Climate Change Service (C3S) Climate Data Store (CDS). DOI: 10.24381/cds.dd7c6d66.

CORDEX: Copernicus Climate Change Service, Climate Data Store, 2019. CORDEX regional climate model data on single levels. Copernicus Climate Change Service (C3S) Climate Data Store (CDS). DOI: 10.24381/cds.bc91edc3 (Accessed on 31-May-2024).

Dayan, U., Nissen, K., Ulbrich, U., 2015. Review Article: Atmospheric conditions inducing extreme precipitation over the eastern and western Mediterranean. Nat. Hazards Earth Syst. Sci., 15: 2525–2544.

Depietri, Y. 2020. The social–ecological dimension of vulnerability and risk to natural hazards. Sustain Sci 15: 587–604. https://doi.org/10.1007/s11625-019-00710-y.

DWA, 2016. German Guideline, DWA-Merkblatt 119. Risikomanagement in der kommunalen Überflutungsvorsorge für Entwässerungssysteme bei Starkregen (Risk management in municipal flood prevention for drainage systems during heavy rain), DWA German Association for Water, Wastewater and Waste, e.V., Hennef, ISBN: 978-3-88721-393-0.

Emergency Events Database, 2022. Available at: https://www.emdat.be/

El Alfy, M., 2016. Assessing the impact of arid area urbanization on flash floods using GIS, remote sensing, and HEC-HMS rainfall–runoff modeling. Hydrology Research, 47: 1142–1160. DOI: 10.2166/nh.2016.133.

Field, C. B., Barros, V.; Stocker, T. F., Dahe, Q., 2012. Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation – Special Report of the Intergovernmental Panel on Climate Change, Cambridge University Press. New York.

Gruntfest, E., Handmer, J., 2001. Coping with Flash Floods, Springer Netherlands; Imprint: Springer. Dordrecht.

Hamdy, O, Abdelhafez, M. H. H., Touahmia, M., Alshenaifi, M., Noaime, E., Elkhayat, K., Alghaseb, M., Ragab, A., 2023. Simulation of Urban Areas Exposed to Hazardous Flash Flooding Scenarios in Hail City. Land 12: 353. DOI: 10.3390/land12020353.

Hashemite Kingdom of Jordan, 2014. Jordan´s Third National Communication on Climate Change. – Report, submitted to the United Nations Framework Convention on Climate Change. Deposit Number at the National Library (2014/11/5178).

HEC-HMS, 2024. Hydrological Modeling System of the Hydrologic Engineering Center within the U.S. Army Corps of Engineers (HEC-HMS), available at www.hec.usace.army.mil/software/hec-hms/

Hersbach, H., et al., 2020, The ERA5 Global Reanalysis, Quaterly Journal of the Royal Meterological Soceity 146: 1999-2049, doi: 10.1002/qj.3803

Hohmann et al. 2024. Hydrological approaches to assess flash flood risks in data scarce and climate-change affected regions like Jordan. Forum für Hydrologie und Wasserbewirtschaftung. Bd. 45, Berlin, S. 25 - 36., https://doi.org/10.14617/for.hydrol.wasbew.45.24

Itwh, 2024. Software package: Urban Flash Flood with FOG 2D and HYSTEM-EXTRAN 2D, Institute for technical scientific hydrology GmbH, https://itwh.de/en/software-products/desktop/urbane-sturzfluten/

Kautz, L.A., Martius, O., Pfahl, S., Pinto, J. G., Ramos, A. M., Sousa, P. M., Woollings, T., 2022. Atmospheric blocking and weather extremes over the Euro-Atlantic sector – a review, Weather Clim. Dynam., 3: 305–336, https://doi.org/10.5194/wcd-3-305-2022.

Kubota, T., K. Aonashi, T. Ushio, S. Shige, Y. N. Takayabu, M. Kachi, Y. Arai, T. Tashima, T. Masaki, N. Kawamoto, T. Mega, M. K. Yamamoto, A. Hamada, M. Yamaji, G. Liu, Oki, R., 2020: Global Satellite Mapping of Precipitation (GSMaP) products in the GPM era, Satellite precipitation measurement, Springer, https://doi.org/10.1007/978-3-030-24568-9_20.

Kundzewicz, Z. W., Kanae, S., Seneviratne, S. I., Handmer, J., Nicholls, N., Peduzzi, P., Mechler, R., Bouwer, L. M., Arnell, N., Mach, K., Muir-Wood, R., Brakenridge, G. R., Kron, W., Benito, G.; Honda, Y., Takahashi, K., Sherstyukov, B., 2013. Flood risk and climate change – Global and regional perspectives. In: Hydrological Sciences Journal, 59:1–28.

Lehmann, J., Coumou, D., Frieler, K., 2015. Increased record-breaking precipitation events under global warming. Climatic Change, 132: 501-515.

Lelieveld, J., Hadjinicolaou, P., Kostopoulou, E., Chenoweth, J., El Maayar, M., Giannakopoulos, C., Hannides, C., Lange, M. A., Tanarhte, M., Tyrlis, E., Xoplaki, E., 2012, Climate change and impacts in the Eastern Mediterranean and the Middle East. Climatic Change, 114: 667–687.

Lelieveld, J., Hadjinicolaou, P., Kostopoulou, E., Giannakopoulos, C., Pozzer, A., Tanarhte, M., Tyrlis, E., 2014. Model projected heat extremes and air pollution in the eastern Mediterranean and Middle East in the twenty-first century. Regional Environmental Change, 14: 1937–1949.

Mayring, P., 2010: Qualitative Inhaltsanalyse – Grundlagen und Techniken, 11. revised version. Beltz Verlag, Weinheim, Basel.

Niyibizi, A., Mpeirwe, A., Ajambo, S., 2013: Vulnerability assessment for rural settings: Applicability to developing countries, in: Leal Filho, W. (Ed.), Climate Change and Disaster Risk Management. Springer, Berlin, Heidelberg, pp. 273–292.

Potter, R.B., Darmame, K., Barhamb, N., Nortcliff, S., 2009. “Ever-growing Amman”, Jordan: Urban expansion, social polarisation and contemporary urban planning issues. Habitat International, 33: 81–92.

Ross, C.W., Prihodko, L., Anchang, J.Y., Kumar, S.S., Ji, W., Hanan, N.P., 2018. Global Hydrologic Soil Groups (HYSOGs250m) for Curve Number-Based Runoff Modeling. ORNL DAAC, Oak Ridge, Tennessee, USA. https://doi.org/10.3334/ORNLDAAC/1566.

Sharma, T., 2024. A comparative scenario analysis of WSUD measures for stormwater management in Amman, Jordan. M.Sc. thesis at the HafenCity Universität Hamburg, Germany.

Schoener, G., 2022. Impact of urbanization and stormwater infrastructure on ephemeral channel transmission loss in a semiarid watershed. Journal of Hydrology: Regional Studies, 41, DOI: 10.1016/j.ejrh.2022.101089.

Schmitt, T., Krüger, M., Pfister, A., Becker, M., Mudersbach, C., Fuchs, L., Hoppe, H., Lakes, I., 2018. Einheitliches Konzept zur Bewertung von Starkregenereignissen mittels Starkregenindex. Korrespondenz Abwasser, Abfall, 65: 113-12.

Schuck-Zöller, S., Cortekar, J., Jakob, D., 2018. Evaluation Transdisziplinärer Forschung und deren Rahmenbedingungen- Vorüberlegungen zur Nutzung im Bereich von Klimaservice. fteval Journal 45: 28–37.

Schumann-Hindenberg, D., Awad, A., Brinkmann, K., Fölster, L., Winker, M., 2025. Integrated planning for reducing flash flood risk through blue-green infrastructure: A guideline using the city of Amman in Jordan as an example. DOI: 10.5281/zenodo.17351802

Thaler, T., Levin-Keitel, M., 2016. Multi-level stakeholder engagement in flood risk management—A question of roles and power: Lessons from England. Environmental Science & Policy, 55: 292–301.

The Jordan times, 2019. Flooding results in road closures, complaints and rescues on Thursday. Aivailable at https://www.jordantimes.com/news/local/flooding-results-road-closures-complaints-and-rescues-thursday.

Thiault, L., S. D. Jupiter, J. E. Johnson, J. E. Cinner, R. M. Jarvis, S. F. Heron, J. M. Maina, N. A. Marshall, P. A. Marshall, Claudet J., 2021. Harnessing the potential of vulnerability assessments for managing social-ecological systems. Ecology and Society 26:1. https://doi.org/10.5751/ES-12167-260201

UN-Habitat, 2020. Developing a Preliminary Design for Flood Mitigation and Performing a Flood Risk Assessment and Flood Hazard Mapping for Downtown Amman. Report available at https://procurement-notices.undp.org/view_file.cfm?doc_id=219741.

USDA (United States Department of Agriculture), 2010. Natural Resources Conservation Service – Part 630 Hydrology – National Engineering Handbook – Chapter 15 Time of Concentration, available at https://rashms.com/wp-content/uploads/2021/11/TOC_NRCS-Part-630-Ch-15.pdf.

Vries, A. J. de, Ouwersloot, H. G., Feldstein, S. B., Riemer, M., El Kenawy, A. M., McCabe, M. F., Lelieveld, J., 2018. Identification of Tropical-Extratropical Interactions and Extreme Precipitation Events in the Middle East Based On Potential Vorticity and Moisture Transport. Journal of Geophysical Research: Atmospheres, 123: 861–881.

Westra, S., Alexander, L. V., Zwiers, F. W., 2013. Global Increasing Trends in Annual Maximum Daily Precipitation. In: Journal of Climate, 26: 3904–3918.

WeatheringRisk (2022): Climate Risk Profile for Jordan. Available at https://www.weatheringrisk.org/sites/default/files/document/Climate_Risk_Profile_Jordan.pdf.

Winker, M., Frick-Trzebitzky, F., Matzinger, A., Schramm, E., Stieß, I., 2019. Die Kopplungsmöglichkeiten von grüner, grauer und blauer Infrastruktur mittels raumbezogener Bausteine. Ergebnisse aus dem Arbeitspaket 2, netWORKS 4. netWORKS-Papers, 34. Berlin: Deutsches Institut für Urbanistik Difu, Germany. Available at https://networks-group.de/de/publikationen/networks-paper.html (accessed 6.12.2024).

Winker, M., Matzinger, A., Anterola, J., Frick-Trzebitzky, F., Pillen, J., Schramm, E., 2022. Infokarten für die Planung blau-grün-grauer Infrastrukturen. In: Forschungsverbund netWORKS (Hg.): Frankfurt am Main.

Ministry of Water and Irrigation, 2023. National Water Strategy 2023 – 2040. Available at https://www.mwi.gov.jo/EBV4.0/Root_Storage/AR/EB_Ticker/National_Water_Strategy_2023-2040_Summary-English_-ver2.pdf, last accessed on 20.06.2024.

WION, 2023. 'Unprecedented phenomenon': In just one day, Greece surpasses average annual rainfall in Magnesia region. Available at https://www.wionews.com/world/unprecedented-phenomenon-in-just-one-day-greece-surpasses-average-annual-rainfall-in-magnesia-region-633011, last accessed on 22.03.2024.

Zhang, Y., Wang, Y., Chen, Y., Liang, F., Liu, H.,2019. Assessment of future flash flood inundations in coastal regions under climate change scenarios-A case study of Hadahe River basin in northeastern China. The Science of the total environment, 693: DOI: 10.1016/j.scitotenv.2019.07.356.

Zittis, G., Almazroui, M., Alpert, P., Ciais, P., Cramer, W., Dahdal, Y., Fnais, M., Francis, D., Hadjinicolaou, P., Howari, F., Jrrar, A., Kaskaoutis, D.G., Kulmala, M., Lazoglou, G., Mihalopoulos, N., Lin, X., Rudich, Y., Sciare, J., Stenchikov, G., Xoplaki, E., Lelieveld, J., 2022. Climate Change and Weather Extremes in the Eastern Mediterranean and Middle East. Reviews of Geo-physics, 60: e2021RG000762.