FLOODS IN FOCUS

MEACAM Research Report

April 2025

MERCY CORPS

Contents

About MEACAM Research Reports

The Middle East Anticipatory Climate Action Model (MEACAM) is an online platform that provides geographically disaggregated agricultural drought and flood predictions, and estimates of how many people, communities, and internally displaced person (IDP) camps will be affected by these events. Currently, the platform provides national-level coverage of drought and flooding hazards for Iraq, Syria, and Yemen.

The MEACAM research report series covers drought and flooding risks in Iraq, Syria, and Yemen; methods of communicating early warning information in these countries; and how information and predictions provided by MEACAM can be applied to early action and disaster risk reduction efforts. This report focuses on flooding and presents case studies of affected communities, highlighting both the challenges they have faced and their successful adaptation strategies. The report contains technical information on MEACAM's statistical prediction model, and the thresholds used to determine the location of future flooding in Iraq, Syria, and Yemen. The report also contains a spatial analysis of flood vulnerability, and estimates of the population exposed to and displaced by potential future flooding scenarios in these countries.

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or DG ECHO. Neither the European Union nor the granting authority can be held responsible for them.

Funded by European Union Humanitarian Aid

Introduction

Caused by environmental and human-induced factors, floods pose a complex risk, particularly at the local level.[1] Already one of the most common environmental hazards globally,[2] flooding has increased due to extreme weather patterns brought on by climate change, leading to the destabilization of economies due to infrastructure damage, social disruption, deaths, injuries, and disease.[3] Urbanization is a key driver of flood risk, especially in low and middle-income countries.[4] Seasonal floods hit affected areas repeatedly, worsening vulnerabilities in impoverished communities.[5]

	Fluvial Flooding	**Pluvial Flooding**	
Definition	Overflowing rivers, streams, wadis	Flooding independent of an overflowing water body; worsened and hastened by poor drainage	
		Surface Water Flooding	**Flash Flooding**
Primary cause	Heavy or prolonged rainfall, sudden upstream water release	Accumulation of surface water from rainfall	Torrential rainfall, upstream dam/levee breakage, or rushing water from steep slopes
Time to develop	1 to several days, faster in smaller catchment areas	1 to 2 days, less than 24 hours in urban areas	Minutes to hours, generally less than six hours
Structural Mitigation	Dams, levees, floodwalls	Ditches, drains, retention areas, weirs	Retention basins, culverts, drains

Table 1. Overview of the most flood types in Iraq, Syria, and Yemen.[6,7]

Pluvial (river) and fluvial (flash and surface water) floods are the two most common types of floods in Iraq, Syria, and Yemen, each of which has its own risk factors and mitigation measures, which are outlined in Table 1. Flash floods begin within hours after a trigger event, such as torrential rains or the sudden release of water from the failure of a dam or levee.[8] These floods, which are the deadliest of all natural disasters, come with little warning. Forecasting flash floods is highly challenging, requiring systems that both detect and predict rainfall. Mitigation efforts focus on reducing exposure to flooding, including implementing and enforcing land use and building construction policies, issuing public warnings, and utilizing emergency systems as well as maintaining existing infrastructure and developing new infrastructure to control the flow of surface water.[9]

1 UNDRR, Global Assessment Report on Disaster Risk Management 2022
2 UNDRR, Ponding (Drainage) Flood March 10, 2025
3 UNDRR, Global Assessment Report on Disaster Risk Management 2022; UNDRR, Flash Flood March 10, 2025
4 Salika, I. et al., Impact of Urbanization and Climate Change on Urban Flooding: A case of the Kathmandu Valley Journal of Natural Resources and Development, July 2017; World Bank, Tracking urban flood exposure: Global trends since 1985 October 4, 2023
5 UNDRR, Global Assessment Report on Disaster Risk Management 2022
6 NOAA, Types of Floods 2025
7 Coastal floods in Yemen are caused by storm surges and therefore fall outside the scope of the current MEACAM platform's flood prediction models. However, the current MEACAM model can account for flash flooding caused by torrential rains during a tropical storm.
8 UNDRR, Flash Flood March 10, 2025
9 ibid.

Fluvial floods occur when water flowing in a river exceeds the capacity of a stream channel, leading to run-off over natural banks and artificial embankments into flood plains.[10] These floods normally follow periods of extended precipitation and snowmelt or the failure of flood control structures.[11] Such flooding can be mitigated with integrated flood management that maximizes the natural and beneficial impact that flood water has on enriching floodplains while minimizing loss of life and property.[12] Rapid and unplanned urbanization elevates the hazards of river floods by replacing natural permeable soil with artificial impermeable surfaces, blocking natural water flows with construction, and obstructing channels with waste and debris, among other factors.[13] While the frequency and magnitude of riverine floods has not increased worldwide, areas near rivers have become more urbanized, leading to higher death rates and property destruction from these recurring events.[14]

Hazard predictions for riverine floods use a combination of spatial data, including land-use and terrain models, as well as meteorological and hydrological information.[15] Hydrologists describe floods in their forecasts by recurrence intervals. For example, a "100-year flood" means a flood is of such a magnitude it has a 1% chance of occurring any year but could still happen two years in a row (albeit statistically unlikely).[16]

MEACAM: A potential solution

The MEACAM platform provides geographically disaggregated flood predictions, including locations of flooding events and the number of people affected by them. The platform predicts floods at different time windows, which allows users to anticipate rapidly developing flash floods as well as slower-developing surface water and river flooding. These predictions are presented on an interface designed to be easily accessible to the public, aid actors, and government agencies, which serves as a hub for additional vulnerability layers and flood predictions produced by other actors.

Flooding in the MENA region

While the Middle East and North Africa (MENA) region is characterized by worsening droughts and water scarcity,[17] it is becoming increasingly vulnerable to flooding. For example, northwest Syria suffered from floods in 2021 and 2022 as other parts of the country experienced drought.[18] Flash floods have grown more extreme in the region, including in its arid regions.[19] Episodes of heavy rainfall and flooding have increased, including in the Arabian Peninsula, while significant proportions of the MENA region's population are situated in flood-risk zones.[20] The highlands of Yemen, Syria, Lebanon, Palestine, and Iraq's Tigris-Euphrates River system are expected to be affected by the increased frequency of torrential downpours, driving up flood risks even as average

10 UNDRR, Fluvial (Riverine) Flood March 10, 2025
11 FEMA, Types of Flooding March 10, 2025
12 UNDRR, Fluvial (Riverine) Flood March 10, 2025;Associated Program of Flood Management, What are the beneficial impacts of floods? March 10, 2025
13 Lema-Burgos, S., Urban development consequences of the riverine floods in the western Balkans Lund University Press, 2020
14 UNDRR, Fluvial (Riverine) Flood March 10, 2025
15 World Bank, Flood hazard and risk maps: A key instrument for flood risk management December 6, 2022
16 USGS, The 100-year flood June 7, 2018
17 UN Climate Summit News (COP28), What the IPCC Synthesis Report means for Middle East countries 2023
18 UN OCHA, Syria: Facing the dual challenge of climate change and conflict November 10, 2023
19 Loudyi, D. et al., Flood Risk Management in the Middle East and North Africa (MENA) region Urban Water Journal, June 18, 2020
20 Carnegie Endowment for International Peace, The Looming Climate and Water Crisis in the Middle East and North Africa April 19, 2024; One UN Climate Change Learning Partnership, Adapting to a new climate in the MENA region January 2023

amounts of rainfall are expected to fall.[21] Yemen and Oman will also likely be more heavily affected by coastal storms, including flooding from torrential rainfall and storm surges.[22]

The humanitarian impacts of flooding and other natural disasters in the MENA region are not easily disaggregated from other factors such as conflict, poor governance, and economic challenges. In recent years, floods in Iraq, Syria, and Yemen have led to loss of life, a deterioration of living conditions for people already displaced by conflict, and damage to infrastructure and agriculture.[23,24] Using the JRC Global Flood Hazard map[25] and 2025 Global Human Settlement population estimates,[26] the MEACAM team estimates approximately 1.5 million people are at risk of being displaced by pluvial flooding per-year in Iraq, Syria, and Yemen (see Annex: Displacement Methodology).

Country-level drought across studied areas

Iraq

Trends and geography

Flooding in Iraq is a recurring environmental and humanitarian challenge, exacerbated by the country's physical geography, climate variability, socio-political instability, and underdeveloped water management system.[27] Iraq suffers from riverine flooding, prevalent along the Tigris and Euphrates rivers, peaking from January through March due to snowmelt from northern highlands and prolonged rainfall.[28] Regions such as Wasit and Maysan in the south are particularly prone to flooding due to flat terrain and limited drainage infrastructure.[29] Flash floods are frequent in the northern and northeastern regions – such as Duhok, Sulaymaniyah, and Erbil – where steep slopes amplify runoff.[30] Unlike riverine floods, flash floods are difficult to predict during intense rainfall events.[31] Recent studies indicate increasing variability in rainfall patterns, with both intensity and distribution shifting,

---

21 Richardson, K. et al., Climate Risk Report for the Middle East and North Africa (MENA) Region 2021; IEA, National Climate Resilience Assessment for Iraq March 10, 2025; World Bank – Climate Knowledge Portal, Syrian Arab Republic – Extreme Events March 10, 2025

22 Richardson, K. et al., Climate Risk Report for the Middle East and North Africa (MENA) Region 2021

23 ReliefWeb, Syria: Floods - Feb 2023 February 2023; IOM, IOM Responds to Flooding in Iraq November 27, 2018; UNHCR, Yemen: Needs grow for millions displaced amid catastrophic flooding and prolonged humanitarian emergency August 30, 2024

24 Internal Displacement Monitoring Centre, A decade of displacement in the Middle East and Africa 2021

25 Joint Research Centre, Global River Flood Hazard Maps Version 1

26 Joint Research Centre, Global Human Settlement Layer: Population (1975-2030)

27 Gleick, P., Water as a weapon and casualty of armed conflict: A review of recent water-related violence in Iraq, Syria, and Yemen, WIREs Water June 4, 2019

28 Al-Hussein, A. et al., Flood Analysis Using HEC-RAS and HEC-HMS: A Case Study of Khazir River (Middle East-Northern Iraq) Water November 21, 2022; Sissakian, V. et al., Geological hazards in Iraq, classification and geographical distribution Iraqi Bulletin of Geology and Mining, January 2011; Al-Nassar, A. et al., Mapping Flash Floods in Iraq by Using GIS, Environmental and Earth Sciences Environmental Sciences Proceedings, July 22, 2021; Kadhum, J. et al., Synoptic and dynamic analysis of few extreme rainfall events in Iraq May 23, 2022

29 Al-Abadi, A. et al., A GIS-based integration of catastrophe theory and analytical hierarchy process for mapping flood susceptibility: a case study of Teeb area, Southern Iraq Environmental Earth Sciences, April 11, 2016; Abdulrazzaq, Z. et al., Flood modelling using satellite-based precipitation estimates and digital elevation model in eastern Iraq International Journal of Advanced Geosciences, January 2018; Rasn, K. et al., Designation of Flood Risk Zones Using the Geographic Information System Technique and Remote Sensing Data in Wasit, Iraq Geomatics and Environmental Engineering, June 2, 2021; Al-Abadi, A., Mapping flood susceptibility in an arid region of southern Iraq using ensemble machine learning classifiers: a comparative study Arabian Journal of Geosciences, May 8, 2018

30 Mohammad, J. et al., Determining the Surface Drainage Network Causing Flash Floods in Central Erbil Sub-Basins in Northern Iraq Using GIS and Geospatial Technique Iraqi Geological Journal, June 30, 2024; Mzuri, R. et al., Identification of Flood-Prone Areas Using Geo-informatics: A Case Study of Erbil City, Kurdistan Region, Iraq Iraqi Geological Journal, September 30, 2024; Amen A. et al., Mapping of Flood-Prone Areas Utilizing GIS Techniques and Remote Sensing: A Case Study of Duhok, Kurdistan Region of Iraq Remote Sensing, February 17, 2023

31 Shareef M., et al., River Flood Modelling For Flooding Risk Mitigation in Iraq Civil Engineering Journal, October 1, 2021

exacerbating the frequency and severity of floods.[32] For instance, unexpected heavy rainfall in 2018 and 2019 caused significant flooding in southern Iraq, which is traditionally considered less vulnerable.[33]

Rapid urbanization exacerbating flooding risks in Iraq

Growing hazards

Urban centers such as Erbil, Baghdad, and Mosul face compounded flood risks due to rapid urbanization, unregulated construction on floodplains, and outdated stormwater infrastructure, all of which intensify surface runoff during heavy rains. In these cities, poorly planned development and land use changes have disrupted existing natural drainage pathways and outpaced the capacity of existing infrastructure.[34]

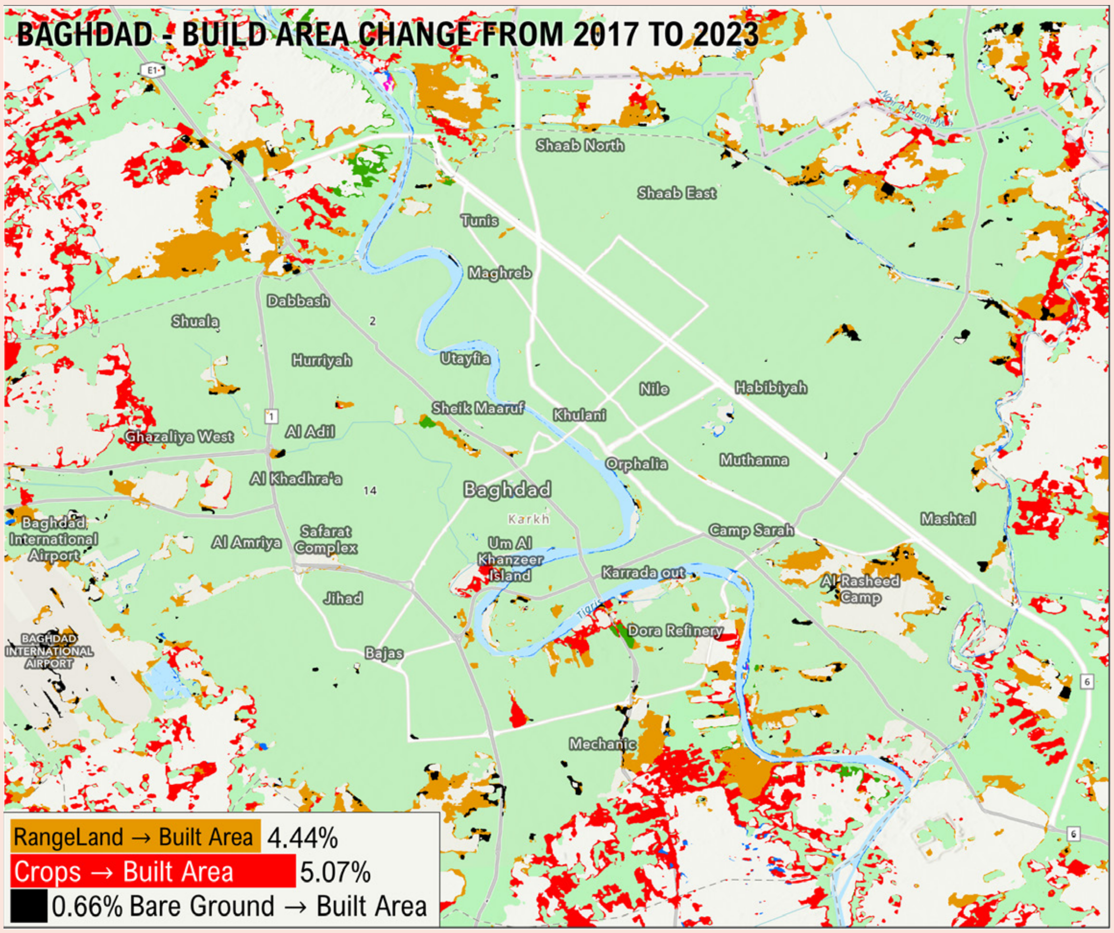

Figure 1: Built-up area expansion in Baghdad from 2017 to 2023 based on Sentinel-2 10m Land Use/Land Cover data.

32 Ahmad A. et al., Flood susceptibility mapping utilizing the integration of geospatial and multivariate statistical analysis, Erbil area in Northern Iraq as a case study Scientific Reports, July 24, 2023

33 Al-Hussein, A. et al., Flood Analysis Using HEC-RAS and HEC-HMS: A Case Study of Khazir River (Middle East-Northern Iraq) Water, November 21, 2022; Mustafa, A. et al., GIS-based hydrodynamic modeling for urban flood mitigation in fast-growing regions: a case study of Erbil, Kurdistan Region of Iraq Scientific Reports, June 1, 2023; Razavi -Termeh, S. et al., Application of genetic algorithm in optimization parallel ensemble-based machine learning algorithms to flood susceptibility mapping using radar satellite imagery Science of the Total Environment, May 15, 2023

34 Mustafa, A. et al., GIS-based hydrodynamic modeling for urban flood mitigation in fast-growing regions: a case study of Erbil, Kurdistan Region of Iraq Scientific Reports Scientific Reports, June 1, 2023

In January 2025, the MEACAM team interviewed experts in Iraq who highlighted the sharp rise of flood frequency and severity in cities, with Erbil, Duhok, and Zakho in northern Iraq among the worst affected.[35] For example, 12 people were killed by floods in Erbil city in late 2021 and early 2022, which caused over USD 14 million in damages.[36] Erbil city's unplanned urban expansion has significantly altered natural drainage patterns, reducing the capacity to absorb rainfall. According to key informants in the city, buildings in some areas have been constructed too close to riverbanks and flood-prone zones, obstructing natural water flow. The situation is similar in Dohuk, which, as noted by an engineer, is geographically "sandwiched" between two mountains, making it particularly vulnerable to flash floods when natural waterways are blocked by urban development.[37] Experts also emphasized that Baghdad's outdated drainage infrastructure has been overwhelmed by urban expansion, contributing to frequent urban flooding and damaged property.

The MEACAM team used ESRI's land use/land cover time series[38] to analyze urbanization trends in Iraq's capital and Erbil. Figure 1 shows Baghdad's rapid urban growth, with a notable conversion of rangeland (4.44%) and cropland (5.07%) into built-up areas, alongside a smaller contribution from bare ground (0.66%). The Tigris river runs through Baghdad, making the city particularly vulnerable to riverine floods because its flat terrain limits water drainage.

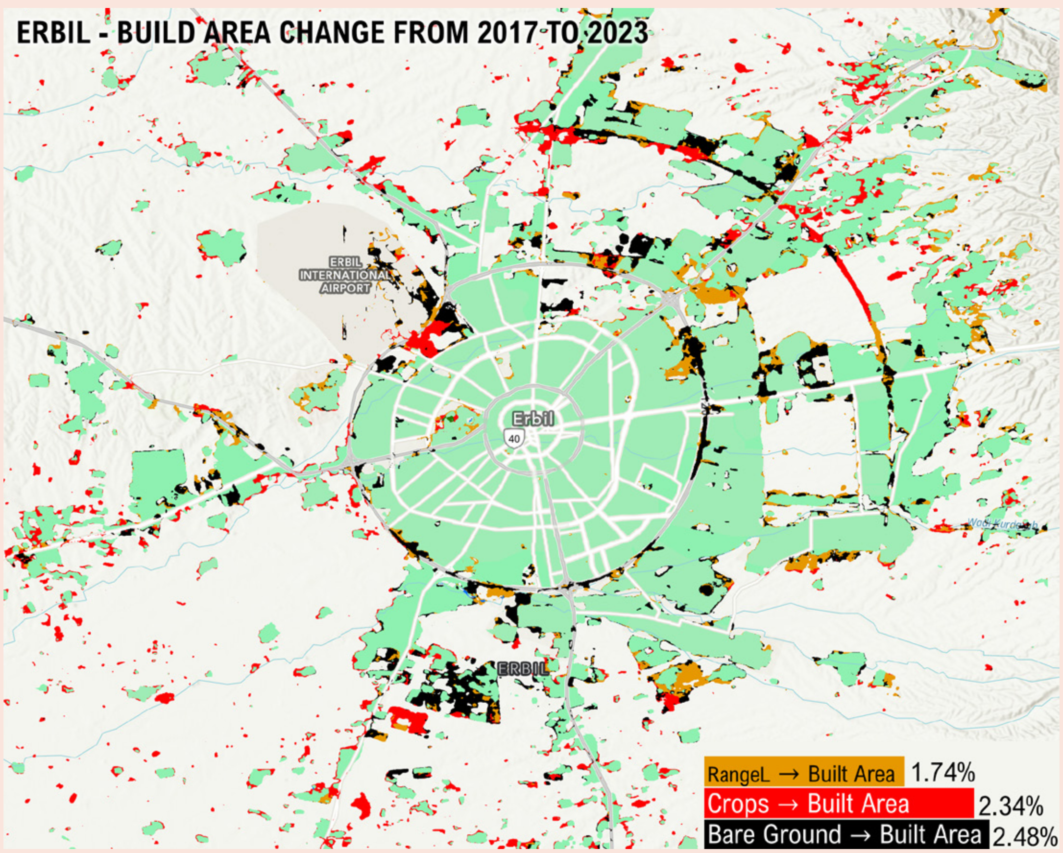

Figure 2: Build-up area expansion in Erbil from 2017 to 2023 based on Sentinel-2 10m Land Use/Land Cover data.

35 KII, engineer at government ministry A, January 2025
36 Rudaw, Severe floods damage vehicles, houses in Erbil March 20, 2024
37 KII, engineer at government ministry A, January 2025
38 Arcgis, Sentinel-2 10m Land Use/Land Cover Time Series (Updated May 28, 2024)

Figure 2 highlights urbanization trends in Erbil, namely the conversion of rangeland (1.74%), cropland (2.34%), and bare ground (2.48%) into built-up areas. The city's drainage system is unable to channel large amounts of rainwater and is often blocked by debris.[39] The urban expansion is also encroaching on the floodplain in the foothills surrounding the city, which heightens the city's vulnerability to high-intensity, short-duration rainfall events. Specifically, earthen barriers have been removed or partially deconstructed in recently expanded areas and houses and roads have been constructed in the path of wadi drainage areas in the periphery.[40]

Not proactive

Drainage system improvements are a primary flood mitigation tool in urban areas. A key informant highlighted that the government in Erbil allocates an emergency budget to clear water catchment areas before the rainy season and remove illegally built structures that obstruct water flow.[41] However, these efforts are reactive rather than preventive, as no specific flood-related policies or regulations are in place to systematically address urban flood risks. Another key informant suggested that requiring flood risk assessments before approving construction projects could help prevent future disasters, but such regulations have not been implemented.[42]

Early warning systems have also been introduced. Key informants said that Erbil's Joint Crisis Center provides some support by issuing rainfall warnings, though these alerts lack detail and are not widely disseminated.[43] At the national level, meteorological reports and monitoring of dam water releases help inform flood warnings, but key informants noted that these systems are not advanced enough to provide communities with sufficient time to take protective measures. Community engagement is another crucial component of flood preparedness. A key informant stressed that citizens need to be more aware of their impact on urban planning and how their actions contribute to flood risks.[44] Public awareness campaigns, educational programs, and local flood response training initiatives would help ensure that communities understand the risks they face and how to respond effectively.

Humanitarian impacts

Flood risks have a particular impact on Iraq's most vulnerable populations, including those living in informal settlements and displaced or impacted by conflict. For example, thousands of families living in IDP camps in the governorates of Salah al-Din and Ninewa needed assistance after floods in November 2018.[45] Key informants said that over 1 million IDPs and refugees have settled in the Kurdistan region, many in flood-prone areas near riverbanks. KIIs with community members from flood-affected areas indicated that the start of the major ISIS offensive in 2014 and ensuing conflict weakened their ability to respond to floods, primarily due to displacement, economic decline, infrastructure destruction, and reduced government support.[46]

One key informant emphasized that before this conflict, flooding was not a major concern, and the community had faced fewer challenges in responding to extreme weather events. However, infrastructure damage, a lack of government support, and weakened coordination among local officials have made flood preparedness and response increasingly difficult.[47]

---

39 SCIRP, Flood Hazards in Erbil City Kurdistan Region Iraq, 2021: A Case Study 2022
40 ibid.
41 KII, engineer at government ministry A, January 2025
42 KII, engineer at government ministry A, January 2025
43 KII, engineer at government ministry A, January 2025
44 KII, engineer at government ministry A, January 2025
45 UN OCHA, Iraq - Floods: Flash Update No. 1 November 25, 2018
46 KII, engineer at government ministry B, January 2025
47 KII, engineer at government ministry B, January 2025

Another key informant highlighted the severe economic impact of the conflict, which has exacerbated flood recovery challenges.[48] The displacement of families depleted household resources, making it harder for individuals to rebuild their homes and livelihoods after floods. Even families who remained in their homes suffered economically, as the market value of agricultural and livestock products declined, reducing their financial ability to cope with disasters. Many were forced to abandon traditional livelihoods – such as farming and raising livestock – and seek alternative sources of income, leaving them with fewer resources to recover from flood-related losses.

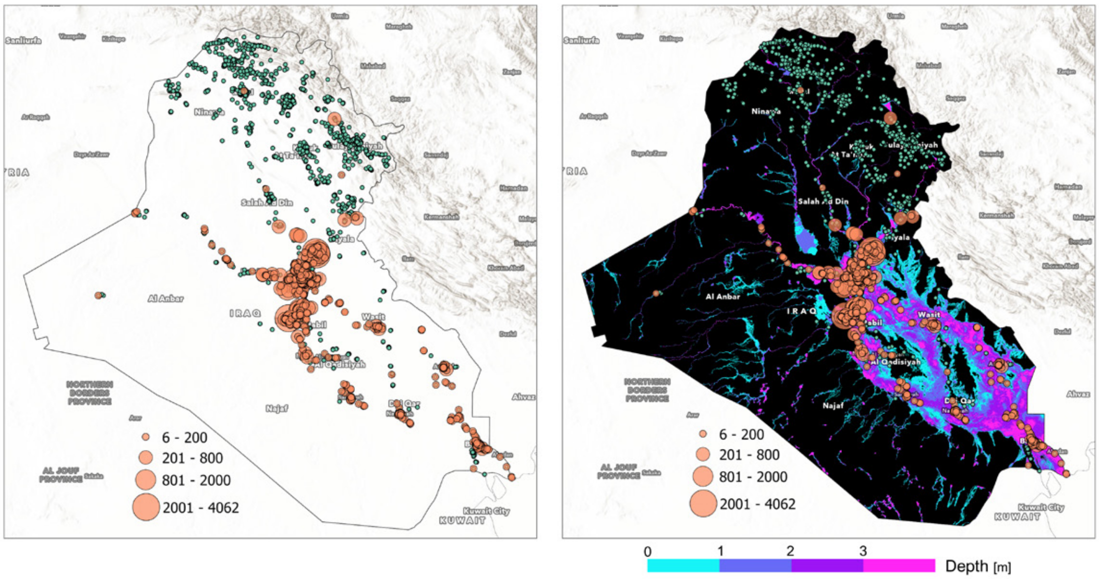

Figure 3: The spatial distribution of IDP camps and their population sizes, for locations with flood depths exceeding 0.5m.

The MEACAM team analyzed data on internally displaced persons (IDP) camps in Iraq in relation to future flood hazards, which are mapped in Figure 3 (see Annex: IDP flood risk analysis methodology). The spatial analysis found that IDP camps in southern and central Iraq, particularly in Babil, Wasit, and Maysan, are disproportionately exposed to riverine flood risk.[49] The analysis simulates fluvial flooding and does not account for the risk of flash flooding, particularly in small, steep river basins in the northeast.[50]

Figure 4 shows the extent of potential pluvial flooding in Iraq using the JRC Global Flood Hazard map.[51] When overlayed with 2025 Global Human Settlement population estimates,[52] the MEACAM team forecasts (see Annex: Displacement analysis methodology) that approximately 1.4 million people are at risk of being displaced by significant pluvial (river) flooding per-year in Iraq and that approximately 2 million people could be exposed to lower-depth floods. Figure 5 shows the number of people displaced by flooding in Iraq from 2008 to 2021 and illustrates how the country's high population density along rivers contributes to the large number of people displaced by pluvial flooding.[53,54]

48 KII, engineer at government ministry C, January 2025
49 The analysis has certain limitations, such as not accounting for floodwater control infrastructure, including levees and drainage systems.
50 For an analysis of flash flooding in Iraq focusing on daily maximum precipitation, see Annex: Daily Maximum Precipitation.
51 ibid.
52 Joint Research Centre, Global Human Settlement Layer: Population (1975-2030)
53 FloodList, Iraq and Syria – Floods Cause Deaths and Damage in Several Provinces
54 FloodList, Iraq – Flash Floods Leave Thousands Displaced and 21 Dead

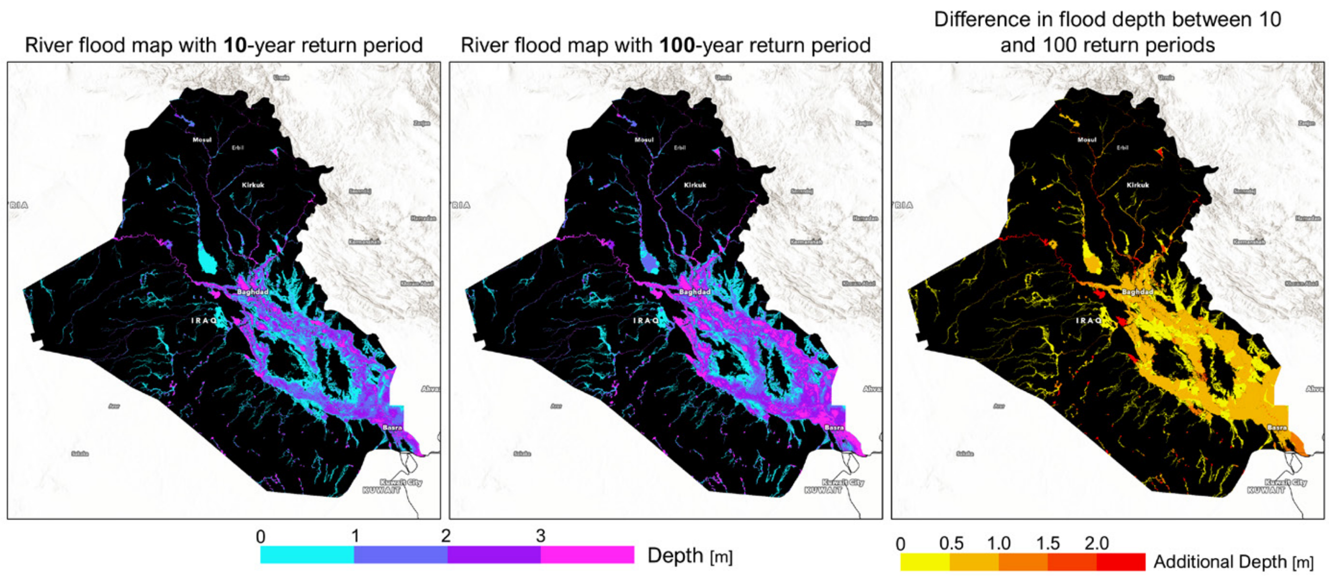

Figure 4: Flood hazard maps for Iraq illustrating flood depths for a 10-year return period (left), 100-year return period (center), and the difference in flood depths between the two return periods (right). These maps are derived from JRC Global River Flood Hazard Maps Version 1.[55]

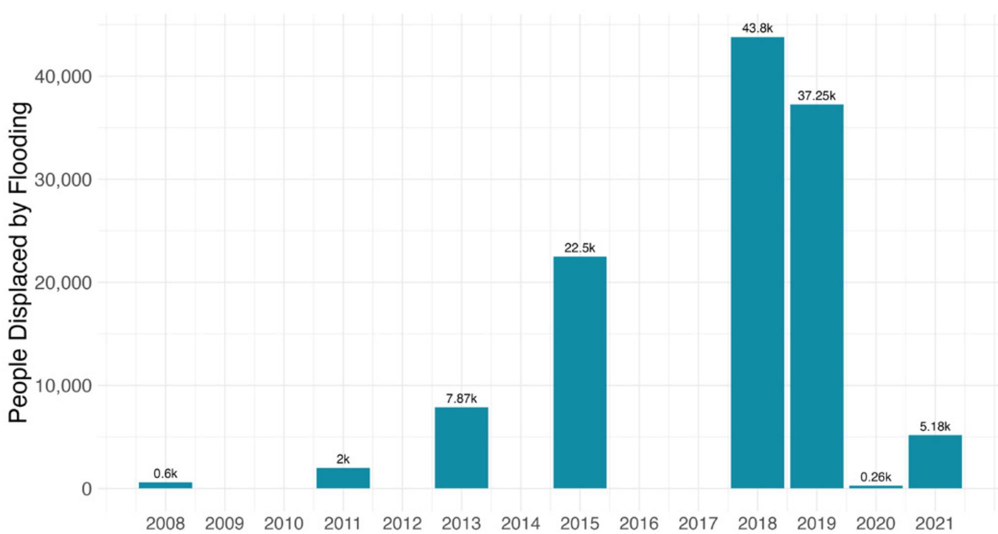

Figure 5: The number of people displaced by flooding in Iraq from 2008 to 2021. Data obtained from IDMC (nternal Displacement Monitoring Centre, IDP Data for Iraq) is updated through 2023 but no displacement from floods was reported in 2022 and 2023.

Mitigation and response efforts

Mitigating the impacts of flooding in Iraq requires a multifaceted approach. Upgrading and maintaining critical infrastructure, such as dams and urban drainage systems, is essential to reducing vulnerabilities. Improved governance of transboundary water resources, coupled with sustainable water management policies, can alleviate some of the stress on the Tigris and Euphrates systems.[56] Investing in hydrological monitoring systems

55 Joint Research Centre, Global River Flood Hazard Maps Version 1

56 Baskin, A., The perils of modernization: the uncertain benefits of the Turkish GAP project and downstream Iraqi farmland University of Pittsburgh, December 14, 2023;Yaseen, Z. et al., Enhancing Long-Term Streamflow Forecasting and Predicting using Periodicity Data Component: Application of Artificial Intelligence Water Resources Management, July 6, 2016

and predictive modeling can also enhance early warning mechanisms, enabling communities to better prepare for extreme weather events.[57] The integration of climate-resilient infrastructure and coordinated disaster response plans will be critical for Iraq to account for and be resilient against future flooding.

Experts interviewed by the MEACAM team said that local-level officials in Iraq lack the technical and financial resources to mitigate and respond to floods. Key informants described a lack of cooperation between agencies involved in flood risk management, leading to inefficiencies and delays in response. Experts emphasized the importance of international cooperation for technical and financial support, as Iraq requires significant investment in infrastructure and flood management capacity building. Key informants also indicated that conflict has significantly damaged Iraq's flood prevention infrastructure, leaving many areas vulnerable to extreme weather events. Dams, drainage systems, bridges, and other critical flood mitigation structures have been either weakened or destroyed, with limited financial resources available for repair and maintenance.[58] Key informants said that while there are some early warning mechanisms in Iraq, including through the Water Resources Directorate and meteorological agencies, these systems are not comprehensive. Experts noted that warnings are primarily issued through social media, television, and radio. While they have helped save lives, warnings often come too late to prevent economic losses, especially in agriculture. Farmers and residents lack the necessary lead time to take preventive action, and there is no structured dissemination system to ensure that flood alerts reach all vulnerable populations.[59]

Yemen

Trends and Geography

Yemen's topography features coastal plains, uplands, highlands, and desert regions. Seasonal weather patterns, particularly during the monsoon period, contribute to heavy rainfall in some areas.[60] Intense, short-duration rains often lead to flash floods, especially in wadis (dry riverbeds). Yemen is prone to flash flooding, particularly during the rainy season, typically between March and April. However, flash floods can occur unexpectedly throughout the year, especially in areas with steep slopes and arid landscapes, such as in the highlands of Sana'a and Saada.[61] Coastal cities like Aden and Hodeida are also vulnerable to flooding caused by heavy rainfall and storm surges. Even desert areas in Hadramout and Al-Mahara can experience flash floods brought on by intense rainfall over a short period.[62] Climate change is expected to worsen flood hazards in Yemen – including increasingly intense and frequent flash floods – that are already the most common natural disaster in the country.[63]

Humanitarian Impacts

In recent years, Yemen has suffered from flash floods that have resulted in displacement and severe infrastructure damage. For example, flooding between April and August 2024 across 19 governorates caused an estimated

57 Awchi, T., River Discharges Forecasting In Northern Iraq Using Different ANN Techniques Water Resources Management, 2014
58 KIIs, engineers at government ministry (B & C), January 2025
59 ibid.
60 World Bank, Yemen Country Profile
61 Food and Agriculture Organization, FAOSTAT: Yemen; Al-Awad, T., et al. "Flash Flood Hazards in the Yemeni Highlands: A Case Study of Sana'a Basin." Arabian Journal of Geosciences, 12(24), 2019
62 UNDP, The Impact of Climate Change on Human Development in Yemen
63 Climate Centre, Yemen Climate Fact Sheet June 29, 2024; IOM, Desk Review: Report on Migration, Environment, and Climate Change in Yemen April 3, 2024; World Bank – Climate Change Knowledge Platform, Risk – Historical Natural Hazards March 12, 2025 The World Bank's Climate Change Knowledge Platform reports that an average of 56.67% of Yemen's natural disasters per year from 1980 through 2020 were floods.

725 casualties while destroying approximately 17,000 shelters and homes, forcing the displacement of thousands of people. These floods also damaged or destroyed 22 schools and disrupted operations at 74 health centers and two major hospitals.[64] Flash floods in Yemen have also significantly harmed agriculture, which employs approximately half the country's population.[65] Floods have inundated agricultural land, damaged irrigation infrastructure[66] and contributed to the erosion of cropland, which was reduced from 1.6 million hectares in 2010 to 1.2 million hectares in 2020.[67] Flooding in Yemen has also contributed to water contamination and the increased risk of the spread of waterborne diseases such as cholera[68] and vector-borne diseases like malaria and dengue fever via mosquitos that rapidly multiply in stagnant water left behind by floods.[69] Conflict, poverty, and weak infrastructure exacerbate the impact of these disasters, compounding challenges faced by affected communities as they recover.[70]

Figure 6 shows the extent of potential pluvial flooding in Yemen using the JRC Global Flood Hazard map.[71] When overlayed with 2025 Global Human Settlement population estimates,[72] the MEACAM team forecasts (see Annex: Displacement analysis methodology) that approximately 28,000 people are at risk of being displaced by pluvial (river) flooding per year in Yemen. Approximately 76,000 people could be exposed to such floods. Figure 7 shows the number of people displaced by flooding in Yemen in 2023 and that flooding affects populations across the country, especially in the governorates of Hajjah (52,206), Taiz (23,635), and Hodeidah (22,750).

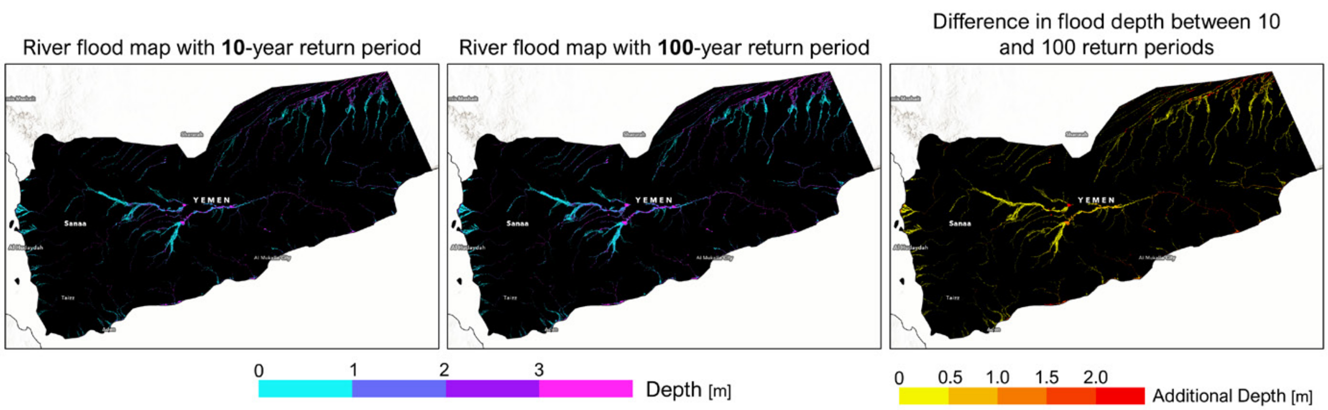

Figure 6: Flood hazard maps for Yemen illustrating flood depths for a 10-year return period (left), 100-year return period (center), and the difference in flood depths between the two return periods (right). These maps were derived from JRC Global River Flood Hazard Maps Version 1.[73]

Yemen also experienced severe flooding, first in Hadramawt in April 2024 and then in Hodeida and the Tihama plain from June to August 2024, displacing 10,000 people and killing over 100.[74] Seasonal deviations from

64 IFRC, 2024 Yemen Floods Disaster Brief September 2, 2024
65 FAO, Family Farming Knowledge Platform – Yemen March 12, 2025
66 FAO, Rapid Assessment of Flood Impacts on Yemeni Agriculture - August 2024 September 11, 2024
67 Yemen Family Care Association, Climate Change Impacts on Yemen and Adaptation Strategies September 23, 2023
68 IOM, Desk Review: Report on Migration, Environment, and Climate Change in Yemen April 3, 2024; WHO, Yemen: when the rain hits hard August 26, 2024
69 ReliefWeb, Severe Flooding Hits Yemen's Hodeida Governorate August 2024
70 FEWS NET, Middle East and Asia Food Security Outlook, June 2024
71 Joint Research Centre, Global River Flood Hazard Maps Version 1
72 Joint Research Centre, GHSL: Global Population Surfaces 1975-2030 (P2023A)
73 Joint Research Centre, Global River Flood Hazard Maps Version 1
74 ReliefWeb, Yemen: Floods - Apr 2024 April 2024

typical weather patterns produced rainfall levels not seen in 20 years in Hodeida governorate, causing major flooding, and in the governorates of Hajjah and Taiz. In August 2024, floods killed at least 15 people, displaced at least 10,000 people, buried at least 80 wells, swept away crops, houses and infrastructure in western Taiz. In August 2024, intense rainfall broke existing water barriers and caused a landslide in the town of Al Mahwit, about 100km west of Sana'a city, which killed at least 33 people and destroyed at least 28 homes.[75]

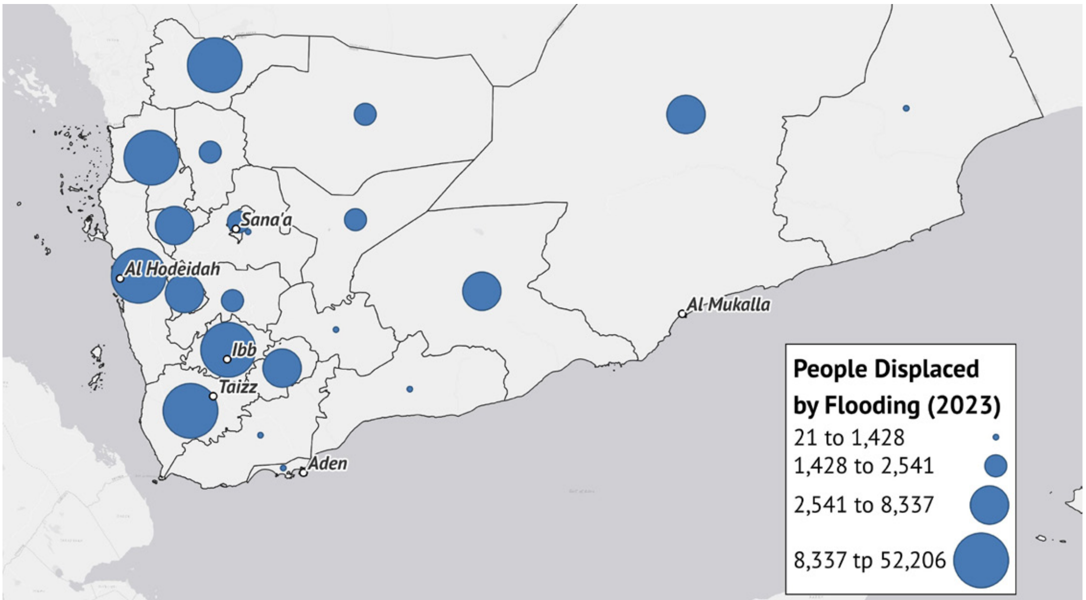

Figure 7: The number of people displaced by flooding in Yemen by governorate 2023. Data obtained from IDMC.No flood-induced displacement was observed in 2023 in Socotra.

Mitigation and response efforts

Divided by conflict and suffering from economic collapse and lack of resources, Yemen lacks adequate state-level resources for natural disaster mitigation, such as early warning systems.[76] At the local level, the conflict has led to the weakening of governance structures. Yemen was the second-most-fragile state in the world as of 2023, ahead of only Somalia, moving from 7th place in 2015 and 15th place before 2010.[77] International organizations and aid actors, coordinating with local authorities, play a key role in mitigating flood hazards and responding to these disasters. The International Organization for Migration and International Federation of Red Cross and Red Crescent Societies (IFRC) issued funding appeals to provide humanitarian assistance to victims of the devastating flash floods in Yemen in August 2024,[78] and the IFRC issued a funding appeal for future flood relief efforts. However, a lack of humanitarian funding poses a key obstacle. For example, the IFRC flood assistance appeal has so far secured 8% of needed funds.[79] Governance in flood-prone areas has become less effective since the beginning of the conflict, significantly hindering both national and international efforts to prevent and mitigate the impacts of flooding across much of the country.

---

75 NOS, Tientallen doden door noodweer en aardverschuivingen in Jemen August 2024

76 IOM, Desk Review: Report on Migration, Environment, and Climate Change in Yemen April 3, 2024; Sana'a Center, Extreme Weather and the Role of Early Warning Systems in Yemen: Al-Mahra as a Case Study August 3, 2023

77 Fragile State Index, Download Data in Excel Format March 13, 2025

78 IOM, IOM Appeals for USD 13.3 Million to Help Hundreds of Thousands Affected by Yemen Floods September 5, 2024; IFRC, Yemen: Floods March 13, 2025

79 IFRC, Yemen: Floods March 13, 2025

Hodeida flooding under the lens

Torrential rains in July and August 2024 triggered devastating flash floods in and around the coastal city of Hodeida.[80] The MEACAM team's interviews with a local NGO volunteer and residents, ranging from neighborhood leaders to heads of households, offer a case study of the challenges of mitigating and responding to floods in Yemen.

Key informants said that urban sprawl in Hodeida, limited coverage of dedicated drainage systems, and waste blocking the few existing ditches heightened flood risks in the area. Meanwhile, dirt roads in the area – dried out by arid conditions – could not absorb precipitation when especially heavy rainfalls hit in the summer of 2024. According to a key informant, water flowed into areas not previously affected by floods. The flooding destroyed residences built from mud and straw while blocking the Kilo 16 road, a key motorway connecting the area to the rest of the country. No advanced flood warnings were issued, either by government agencies or NGOs.[81]

The same key informant highlighted the importance of flood awareness programs, upgrading infrastructure – such as sealed drainage systems – and protecting natural waterways. Outdated urban infrastructure, which relies on open ditches and unsealed canals, led to sewage contamination following the floods.[82]

Syria

Trends and Geography

Syria's topography stretches from a narrow coastal plain along the Mediterranean to mountains, then steppes to the northeast, and desert to the southeast, with 60% of the country characterized by arid conditions with little rainfall.[83] While climate change is expected to decrease precipitation in Syria in the coming decades,[84] the country will be at increased risk of flash floods.[85] Experts and officials said that flood patterns in Syria have changed significantly over the past decade, attributing increased flash flooding to heightened climate variability and conflict-induced damage to drainage infrastructure. Experts warned in interviews that flooding is expected to be more severe in the future due to deforestation and unregulated urbanization.[86] Life-threatening floods triggered by intense rainfall episodes are anticipated every decade in the northwestern governorates of Aleppo and Hama, as well as the governorates of Deir-ez-Zour and Ar-Raqqa to the east.[87]

In recent years, Syria has been battered by significant and life-threatening flash floods in the governorates of Idlib and Aleppo, including in the winter months of 2018,[88] 2021,[89] 2023,[90] and 2024.[91] Following dry summers in the

---

80 AP, Flooding in Yemen has left 30 people dead and hundreds displaced, official says August 8, 2024; WHO, Severe flooding hits Yemen's Hodeida governorate August 8, 2024;
81 KII, local NGO worker, Hodeideh, March 2025
82 ibid.
83 Naaouf N. et al., Climate of Syria Based on Cordex Simulations: Present and Future, Earth Systems and Environment September 11, 2023; Climate Centre, Syria Climate Fact Sheet June 29, 2024
84 Climate Centre, Syria Climate Fact Sheet June 29, 2024
85 Richardson, K. et al., Climate Risk Report for the Middle East and North Africa (MENA) Region 2021; Climate Centre, Syria Climate Fact Sheet June 29, 2024
86 KII, technical specialist at government ministry, March 2025
87 Climate Centre, Syria Climate Fact Sheet June 29, 2024
88 REACH, North-west Syria: Inter-Sector Rapid Needs Assessment - Flood Impact, January 2019 January 31, 2019
89 ReliefWeb, Syria: Floods - Jan 2021 March 12, 2025
90 OCHA, Syrian Arab Republic: Earthquakes - Syria situational updates No. 6 April 6, 2023
91 ECHO, ECHO Daily Flash of January 19, 2024

region, heavy rains in December create conditions for flash floods.[92] In northeastern Syria, flash floods usually recur in March and April,[93] such as those in 2019 in Al-Hasakeh governorate that were the worst in the region in a decade.[94] Elsewhere, dilapidated infrastructure, including clogged storm drains, have led to urban flooding in Latakia during winter storms, including in January 2024.[95] In December 2024, heavy rains led to rivers overflowing in Tartus governorate.[96]

Humanitarian Impacts

Flash floods in Syria have severely impacted populations whose livelihoods are already threatened by conflict and economic deprivation and shortages of essential goods.[97] In northwest Syria, IDPs reside in densely populated areas susceptible to flash flooding, such as embankments in the Orontes River valley.[98] IDP camps suffer from a lack of drainage systems and unpaved roads, heightening the risk of flooding.[99] Recurring winter floods in Idlib and Aleppo governorates have caused heavy damage to IDP settlements, destroying residences and damaging infrastructure. For example, January 2021 flash floods in the region "badly affected" 121,000 people according to the UN Office for the Coordination of Humanitarian Affairs, destroying 21,700 tents while washing away already low stocks of food and household goods.[100] In northeast Syria, flash floods in 2019 forced the relocation of an IDP camp in the town of Areesheh.[101] Beyond loss of life and property, flooding in IDP camps can exacerbate poor sanitation conditions and exacerbate health hazards.[102]

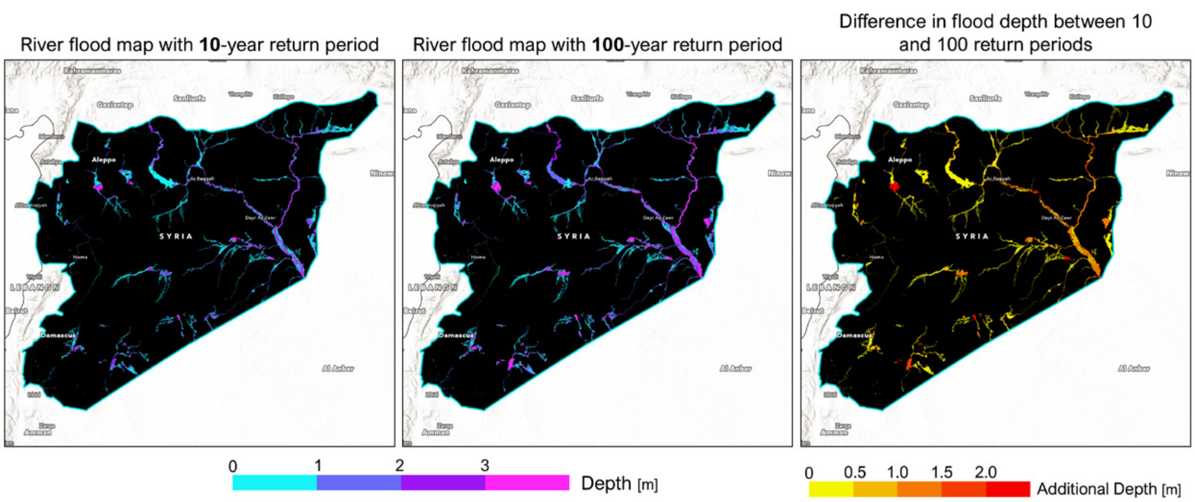

Figure 8: Flood hazard maps for Syria illustrating flood depths for a 10-year return period (left), 100-year return period (center), and the difference in flood depths between the two return periods (right). These maps were derived from JRC Global River Flood Hazard Maps Version 1.

92 Relief International, Dealing with the Winter Weather in Syria February 2, 2022
93 REACH, Research Terms of Reference: Flood Impact on Agriculture in Northeast Syria April 6, 2021
94 IFRC, Syria: Heaviest flooding in decade worsens humanitarian crisis in Al Hasakeh region April 17, 2019
95 KII, technical specialist at government ministry, March 2025; Enab Baladi, Poor roads burden Latakia residents January 22, 2024
96 KII, technical specialist at government ministry, March 2025
97 KII, technical specialist at government ministry, March 2025
98 CCCM Cluster et al, Idleb: IDP Camps and Informal Sites Flood Susceptibility and Flood Hazard Assessment (November 2020) November 9, 2020; PAX, Thirst for peace November 6, 2024
99 KII, technical specialist at government ministry, March 2025
100 UNOCHA, Syria floods: Humanitarians working 'round the clock' to provide urgent relief January 29, 2021
101 IFRC, Emergency Appeal Final Report - Syria: Floods April 8, 2020
102 CCCM Cluster et al., Idleb: IDP Camps and Informal Sites Flood Susceptibility and Flood Hazard Assessment (November 2020) November 9, 2020

Figure 8 shows the extent of potential pluvial flooding in Syria using the JRC Global Flood Hazard map.[103] When overlayed with 2025 Global Human Settlement population estimates,[104] the MEACAM team forecasts (see Annex: Displacement analysis methodology) that approximately 91,000 people are at risk of being displaced by pluvial flooding[105] per-year in Syria. Approximately 147,000 people could be exposed to such floods. Figure 9 shows the number of people displaced by flooding in Syria from 2014 to 2023 and highlights that flood-induced displacement is concentrated in the country's northwest (Aleppo and Idlib) relative to the northeast, though thousands have been displaced by flooding in the northeast over the past decade.

Floods have also disrupted agriculture, the main source of income for residents of northeastern Syria.[106] In 2019, 194,000 acres of agricultural land were flooded in the region, leading to the destruction of wheat, barley, and lentil crops and the deaths of livestock.[107] Flooding in northeastern Syria has also contaminated agricultural land with crude oil, leading to lost harvests.[108] Flash floods in the Orontes river basin in northwestern Syria – where flood protection infrastructure has deteriorated due to conflict – have damaged agriculture, including floods caused by a dam collapse after the February 6, 2023 Turkey-Syria earthquake.[109]

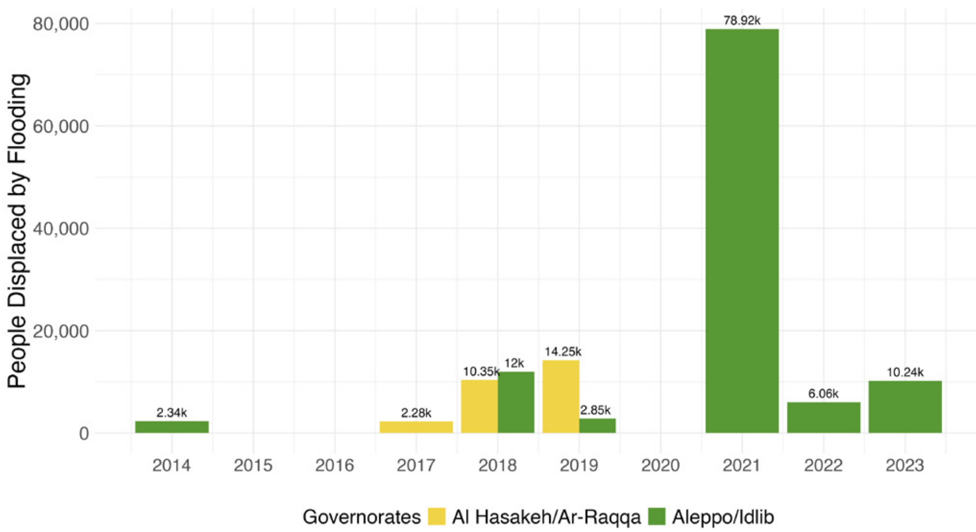

Figure 9: Number of people displaced by flooding in Syria by region from 2014 to 2023. Data obtained from IDMC.

Mitigation and response efforts

Since 2011, flood mitigation and response efforts in Syria have been significantly degraded by conflict, namely due to economic collapse and the division of the country across multiple lines of control. Limited resources, inadequate maintenance, and damage from armed conflict have contributed to a deterioration of flood control infrastructure, including dams, bridges, drainage systems, and levees along rivers.[110] For example, flow measurement stations set up in 2008 as part of a Turkish-Syrian initiative for early flood warning in the Orontes

103 ibid.
104 Joint Research Centre, Global Human Settlement Layer: Population (1975-2030)
105 For an analysis of flash flooding in Syria, focusing on daily maximum precipitation, see Annex: Daily Maximum Precipitation.
106 REACH, Research Terms of Reference: Flood Impact on Agriculture in Northeast Syria April 6, 2021
107 IFRC, Emergency Appeal Final Report - Syria: Floods April 8, 2020
108 PAX, A River of Death November 29, 2020
109 PAX, Thirst for peace November 6, 2024; Middle East Eye, Syria earthquake: Flooding wipes out vital farmland after dam bursts its banks February 13, 2023; Syria Direct, Flooded soil, cracked earth: Farmers face earthquake damage along the Orontes River April 19, 2023
110 KII, technical specialist at government ministry, March 2025

River basin have not been operational since 2011.[111] Early warning systems are either nonexistent or ineffective, according to experts interviewed by the MEACAM team. Meanwhile, emergency evacuation plans and flood response teams are underdeveloped. The lack of coordination among officials in different areas of control in Syria have also led to ineffective responses to natural disasters.[112]

Experts assert that the lack of investment in flood control infrastructure has turned the Orontes River into a significant hazard in Idlib's opposition-held areas. The river's flow has become increasingly unpredictable due to a lack of maintenance on diversion channels and existing dams, leading to severe flooding in western Idlib. In northeast Syria, the Autonomous Administration of North and East Syria set up drainage systems, including in IDP camps in Manbij, according to individuals interviewed by the MEACAM team. In 2020, heavy rains caused a bridge to collapse in rural Al-Hasakeh, cutting off villages and limiting access to essential services.[113]

Experts stated that humanitarian programs for flood victims remain limited and primarily focused on short-term relief efforts.[114] Limited funding and resources have negatively impacted such programming. For example, following winter floods in Idlib in 2018, local activists asserted that aid from the UN and other international organizations was not reaching the region.[115] UN OCHA has administered humanitarian programming for flood response in northwestern Syria, with its 2024-2025 plan securing only 20% of needed funding as of the end of 2024.[116] Political instability and ongoing conflict have complicated coordination between aid agencies, while access to flood-affected areas has been restricted due to security concerns and infrastructure damage. Despite these systemic challenges, flood mitigation initiatives have been fully implemented. For example, the White Helmets volunteer emergency response group has been conducting a campaign to boost community resilience to flooding, including paving roads and open spaces with gravel in 104 villages and 58 IDP camps in northwestern Syria, installing 413 stormwater drainage points, and excavating and expanding 12 kilometers of drainage networks in 58 villages and 24 camps to improve floodwater management.[117]

Flood resilience

Flash floods in northwest Syria in January 2021 provide examples of the impact that natural disasters have had across two IDP camps. The MEACAM team's interviews with experts and residents highlight the difference in flood preparedness efforts and response capabilities across lines of control in the two communities.

The Um Jurn IDP camp in rural northern Idlib was heavily affected by flash flooding in January 2021, which according to key informants, affected 403 displacement camps in the region, destroying 2,358 tents and affecting 123,493 people.[118] Families lost mattresses, blankets, and essential supplies due to flooding, leaving them exposed to extreme cold. Due to limited resources, displaced persons in the camp had set up their makeshift housing in flood-prone areas, including clay-rich areas that turn into mud during heavy rains and low-lying zones near rivers and drainage routes. Even well-established housing suffered significant damage, including concrete tent foundations that collapsed due to prolonged water exposure. Key informants stated that humanitarian

111 PAX, Thirst for peace November 6, 2024
112 KII, technical specialist at government ministry, March 2025
113 KII, technical specialist at government ministry, March 2025
114 KII, technical specialist at government ministry, March 2025
115 Middle East Monitor, Syria refugees appeal for aid after Idlib camps flooded December 27, 2018
116 UN OCHA, Northwest Syria: Winterization and Flood Response Monitoring 2024 - 2025 Season (as of 31 December, 2024) January 30, 2025
117 KII, technical specialist at government ministry, March 2025
118 Syria Direct, شمال غرب سوريا: الفجوة بين الاحتياجات والاستجابة تحول شتاء النازحين إلى "كابوس" متجدد February 2, 2021

assistance was delayed, with aid organizations providing only a limited number of tents and blankets in response to the crisis.[119]

The Dair Ballout IDP camp in the Afrin area of northern Aleppo demonstrated a higher level of flood resilience. This camp is managed by Turkish authorities and relief organizations, which implemented several flood mitigation measures. These included a rainwater drainage system constructed by the Turkish Disaster and Emergency Management Authority, the replacement of traditional tents with brick housing units – significantly reducing exposure to flooding – and the graveling and elevating of ground surfaces to prevent water accumulation. According to camp residents interviewed by the MEACAM team, these improvements greatly reduced flood damage compared to other camps in northwestern Syria.[120]

Key informants highlighted that land ownership is one of the key challenges in implementing similar measures in other IDP camps. Private landowners often refuse to allow infrastructure upgrades, either due to financial demands or concerns about losing farmland. Despite receiving rental payments from humanitarian organizations and displaced families, landowners often prohibit the construction of permanent structures.[121]

Using MEACAM to predict flood risks and population displacement

Methodology

The MEACAM platform provides flood hazard predictions for Iraq, Syria, and Yemen at different time intervals, making it useful for forecasting flash, pluvial, and fluvial flooding. Furthermore, the platform measures the total population and number of communities and IDP camps[122] impacted by projected flooding. MEACAM provides flood predictions stretching 3, 6, 12, 24, 48, 72, and 96 hours into the future.[123] The shorter-term prediction windows (3 to 12 hours) enable rapid-response actions to mitigate immediate risks, the medium-term prediction windows (12 to 72 hours) can facilitate a potential early action response for slower-onset floods, and the long-term prediction window (96 hours) can inform strategic planning and proactive risk reduction. The flood predictions are generated from a classical linear regression model[124] as follows:

$$VV_t = PR_t + PR_{t13\text{-}24} + OR_{t\,24\text{-}48} + OR_{t\,48\text{-}96} + HAND + UpStrm + VV_{lag} + LC_t$$

Where VVt is the observed backscatter intensity[125] recorded at time t, PRt is the total rainfall forecasted 12 hours before t;[126] PR13-24 is the total rainfall forecasted 13 to 24 hours before t, OR24-48 is the observed total rainfall

119 KIIs, Um Jurn camp residents, Idlib, March 2025
120 KIIs, Dair Ballout camp residents, Aleppo, March 2025
121 ibid.
122 The location of IDP camps in Yemen are currently unavailable for public use.
123 MEACAM will launch with a minimum of 1-day prediction window but will add the intra-day predictions in the following months after its initial release.
124 MEACAM selected a classical linear regression model for its computational efficiency and its ability to run natively within Google Earth Engine.
125 VV polarization; descending orbit
126 MEACAM used the forecasted – and not observed – total rainfall values 12 hours before the Sentinel-1 image observation so the resultant regression coefficient could be used to predict the backscatter value 12 hours into the future using the 12-hour rainfall predictions at time t.

24 to 48 hours (1 to 2 days) before t, OR48-96 is the observed total rainfall[127] 48 to 96 hours (2 to 4 days) before t; HAND is the height above nearest drainage;[128] UpStrm is the upstream drainage area;[129] VVlag is the backscatter intensity observation 12 days before t; and LC is the predominant land cover[130] of the Sentinel-1 pixel. The regression includes all pixels[131] identified as covered by land with a HAND less than 15m.

The backscatter predictions are related to thresholds that determine whether a pixel is flooded or not. The thresholding approach compares the statistical distributions of backscatter values observed when the Modified Normalized Difference Water Index[132] (MNDWI) does and does not indicate the presence of floodwater (MNDWI ≥0.30).[133] The statistical distribution of backscatter values observed under flood and non-flood conditions[134] are used to calculate the Bayesian probability[135] of flooding, which allows users to understand the risk level associated with the flood prediction.[136] maximize the applicability of the predictions, the MEACAM platform visualizes floods consisting of eight or more connected pixels predicted to be flooded.

Figure 10 shows the result of the flood identification process applied to a pixel in a farm field in Tloul, Syria. The graph shows how backscatter values relate to optical floodwater satellite indicators. Specifically, the dotted vertical lines indicate Sentinel-1 backscatter observations with a ≥80% probability of flooding and the color gradient corresponds to the estimated floodwater probabilities, ranging from lower (green) to higher (dark blue). In this example, the thresholding approach produced an 8% false-negative rate[137] with no false positives. The flooding events identified using this approach coincided with flood events recalled by MEACAM team members working in the area.

MEACAM then predicts population exposure and displacement caused by flood risks using the WorldPop[138] 2020 dataset, a global population grid providing estimates at a 100m2 spatial resolution. MEACAM uses WorldPop's age and gender disaggregation to categorize population exposure by demographic, and calculates how much of the population is exposed by summing the total population contained in WorldPop pixels that intersect with pixels predicted to be flooded.

---

127 UCSB Climate Hazards Group, CHIRPS Daily: Climate Hazards Group Precipitation Observed rainfall obtained from CHIRPS Daily: Climate Hazards Center InfraRed Precipitation With Station Data (Version 2.0 Final).

128 University of Tokyo, MERIT Hydro: Global Hydrography Datasets. The elevation difference between a given point on the terrain and the nearest drainage point, measured in meters and obtained from the MERIT Hydro Global Hydrography Datasets.

129 The total area or volume of water that flows into a given point within a watershed or hydrological network, measured in square kilometers and obtained from the MERIT Hydro Global Hydrography Datasets.

130 Google, Dynamic World: Near Real-Time Land Cover Data Six land cover classes were included in the model; specifically, trees, flooded vegetation, crops, shrub and scrub, built, and bare land cover identified by Dynamic World V1. The predominant landcover is defined as the landcover that had the highest aggregate probability in the past 12 months and is calculated for each Sentinel-1 pixel on a rolling basis. Pixels where "snow and ice" or "water" was the predominant land cover were removed.

131 University of Tokyo, MERIT Hydro: Global Hydrography Datasets. Using the "wat" band from the MERIT Hydro Global Hydrography Datasets.

132 The MDNWI was used in the MEACAM's flood identification approach instead of similar indicators like the Normalized Difference Water Index (NDWI) because the MNDWI can discern water and non-water surfaces in semi-arid and arid landscapes and urban areas.

133 European Union/ESA/Copernicus, Sentinel-2 Surface Reflectance Harmonized. MEACAM used Sentinel-2 to measure MNDWI, and observations are considered corresponding if the Sentinel-1 and Sentinel-2 images were taken less than 48 hours of one another.

134 Flood conditions are determined if MNDWI ≥ 0.3.

135 Bayes' Theorem is applied to determine the probability of a flood given a specific VV value (P(Flood|Backscatter)) based on the distributions of backscatter observed during flood conditions (P(Backscatter |Flood)) and non-flood conditions (P(Backscatter |No Flood)), and the prior probability of flooding (P(Flood). The prior distribution was defined by the percentage of observed Sentinel-1 images with corresponding MNDMI ≥0.30 from April 2017 to the present.

136 If a pixel has less than five observations with MNDWI ≥0.30, then the average threshold value of pixels with the same landcover and HAND category is applied. HAND is categorized as 0m to 5m, 5m to 10m, and 10m to 15m.

137 Only 1 out of 11 Sentinel-1 images observed during a flood produced a flood probability less than 80%.

138 WorldPop, Global Project Population Data: Estimated Age and Sex Structures of Residential Population per 100x100m Grid Square

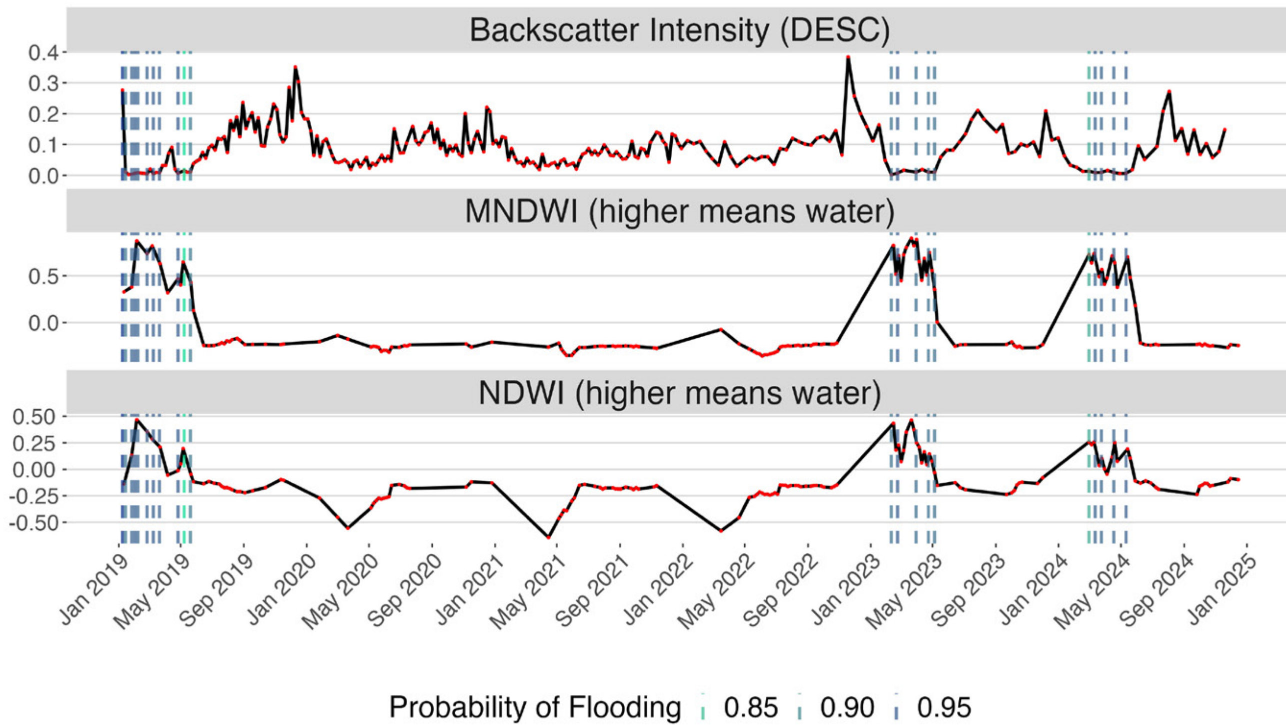

Figure 10. Flood probabilities assigned to backscatter, MNDWI, and NDWI values observed in a farm field in Tloul, Syria from January 1, 2019 to December 31, 2024. The vertical dotted lines indicate backscatter values with an 80% or greater probability of flooding, with colors representing the estimated probabilities.

Several limitations should be considered when using or analyzing MEACAM's flood predictions, most of which can be rectified with additional dedicated research and analysis.

First, the model does not yet account for the presence of flood protection infrastructure such as levees and dams that may mitigate the human impact of flooding. This could be addressed with additional spatial data on the presence and attributes of water control infrastructure. However, such data is currently not publicly available and likely must be obtained at the local level.

Second, the flood prediction approach identifies flooding but does not explicitly measure flood depth. Predicting exact flood depths (i.e., meters) is feasible if detailed training data from previous floods can be obtained. However, such data is challenging to acquire at a geographically precise resolution in Iraq, Syria, and Yemen.

Third, Sentinel-1's images contain several distortions[139] that limit MEACAM's current approach to identifying flooding in urban areas with tall buildings, and mountainous or heavily forested regions. Combining predictions

139 Specifically, foreshortening, layover, and shadowing. Foreshortening occurs when the terrain or buildings (mountain slopes; tall buildings) are compressed because the SAR instrument emits and receives signals at an angle (side-looking geometry) rather than capturing image directly downward at nadir. This causes slopes or tall buildings facing the SAR instrument to appear compressed because the radar "sees" them all at once from an angle. Shadowing occurs in Sentinel-1 imagery because the radar signal's side-looking geometry obscures parts of the terrain from the radar signal; for example, narrow streets or areas behind tall buildings may be obscured and appear as shadows in the image. Layover occurs when radar signals reach the top of a steep object, like a mountain or tall building, and return to the SAR instrument before signals from the base of the object, which results in a distortion where the feature is "laid over" toward the radar sensor. For example, a radar signal reaches the top of the slope before the base, causing the slope to appear distorted or flipped.

and flood identification using Sentinel-1 data obtained from different polarizations[140] and both descending and ascending orbit directions would likely increase the accuracy of the flood identification approach in urban and mountainous areas.

Lastly, the spatial resolution of the NOAA rainfall forecasts is relatively coarse (27.83km2), meaning that rainfall forecasts are not as localized as the Sentinel-1 backscatter observations. Therefore, the model measures heterogeneous localized effects of broad-scale weather patterns, meaning model estimates are less precise than if the rainfall forecasts were available at the same spatial resolution as the backscatter data. However, there is no alternative publicly available source for more geographically precise weather forecasts.

Conclusion

Flooding is a major natural hazard in Iraq, Syria, and Yemen, where its effects are amplified by unplanned urban expansion, the establishment of IDP camps, and the use of water drainage infrastructure that is often poorly maintained. As a result, communities and IDP camps are flooded every year in all three countries, creating emergency shelter needs and precipitating physical and economic harm. In addition to water drainage infrastructure rehabilitation and expansion, early warnings for floods can help mitigate the damage continually caused by flooding by allowing a community to react effectively before the flood occurs and inform early action interventions by aid actors.

MEACAM offers an immediate solution to the need for an early warning system for flooding in Iraq, Syria, and Yemen, as it is designed to be a collaborative platform where other organizations and government bodies can house and publicly present their data. MEACAM's ability to predict flooding according to different time windows allows users to anticipate rapidly developing flash floods as well as slower-developing surface water and river flooding. The MEACAM platform was designed with collaboration in mind as it features a flexible back-end infrastructure that can incorporate static (hazard vulnerability) or dynamic (hazard predictions) data produced by other actors, and can therefore serve as a "hub" for hazard prediction and monitoring efforts. Furthermore, collaboration among actors working in the hazard prediction space is needed to jointly agree on common thresholds to activate early action resources and early warning communications, whether by using MEACAM's flood predictions, flood predictions from other actors, or a combination of both.

140 Sentinel-1 polarizations include Vertical-Vertical (VV Vertical-Horizontal (VH), Horizontal-Vertical (HV), and Horizontal-Horizontal (HH). MEACAM used VV polarization for the current MEACAM flood prediction model because it is most often used and widely regarded as the most effective for flood detection in other scientific research on the topic using Sentinel-1 data.

Annex

IDP flood risk analysis methodology

To create Figure 3, the MEACAM team overlayed the location of IDP camps across Iraq[141] in relation to flood hazard zones, offering insights into the vulnerability of these populations to riverine flood events. The map illustrates the spatial distribution of IDP camps, distinguishing camps by flood exposure. In the left panel, camps represented by proportional orange circles indicate locations where flood depths exceed 0.5 meters with circle sizes reflecting the camp populations. Green circles denote camps located in areas where flood depths are zero or below the 0.5-meter threshold. The right panel overlays the camp locations on the JRC Global Flood Hazard dataset's 100-year flood hazard map, visualizing flood depth distribution across the country, and identifies camps where the 100-year flood depths exceed 0.5 meters (orange circles) and where the flood depths are less than 0.5 meters (green circles).

Displacement analysis methodology

The expected annual population exposed (EAPE) and the expected annual population displaced (EAPD) were estimated by integrating the population exposed across the flood extents for return periods of 1, 10, 50, 75, 100, 200, and 500 years, weighted by the annual probabilities of these flood events. Specifically, the EAPE calculation considers population exposure across all flood extents, regardless of depth, while the EAPD calculation is restricted to areas where flood depth exceeds 1 meter.

Daily maximum precipitation

Rainfall intensity is a key factor in flash floods; therefore, the maximum 1-day precipitation, known as RX1, is useful for a basic understanding of where flash floods are likely to occur.[142] The spatial distribution of maximum 1-day precipitation (RX1) in Iraq, Syria, and Yemen[143] are shown in the top-left map of Figures A1, A2, and A3 and reveal distinct regional variations in rainfall intensity. In Iraq, the highest RX1 values (over 40 mm/day) are found in northern Iraq, particularly in the mountainous northern Erbil governorate and Sulaymaniyah governorate. In Syria, the coastal governorates of Lattakia and Tartous and northwest Idlib and Aleppo governorates receive the highest RX1, with a maximum rainfall of over 40 mm/day. RX1 values are comparatively lower in Yemen, with a maximum of 30 mm/day. However, the highest RX1 values are clearly concentrated in western Taiz and southern Hodeidah governorates.

The maps found in the top right of Figures A1, A2, and A3 highlight temporal changes in RX1 values from 1950 to 2016. In Iraq, central and northeast regions such as Kirkuk and Baghdad show a pronounced increase in RX1

---

141 International Organization for Migration, Iraq — IDPs Master Lists — Round 134 February 2025

142 Other critical factors should also be considered, particularly steep slopes, soil permeability, and saturation levels, and the presence of vegetation cover or impermeable surfaces.

143 Contractor, S., et al. Rainfall Estimates on a Gridded Network (REGEN) – a global land-based gridded dataset of daily precipitation from 1950 to 2016 Hydrology and Earth System Sciences, 2020 The REGEN dataset, as described in Contractor et al., 2020, is a global land-based gridded product that interpolates daily precipitation using long-term station data at a 1°x1° spatial resolution. This interpolation inherently smooths localized variations in precipitation extremes, and the observed trends and annual maxima might underrepresent localized extremes within each grid cell, especially in regions with high spatial variability in precipitation. Moreover, the quality of the REGEN dataset is influenced by the density and distribution of weather stations used for interpolation. The dataset relies on long-term stations with at least 40 years of complete data; however, the number of stations available for Iraq, Syria, and Yemen is relatively sparse. This likely introduces uncertainties in the gridded precipitation values, especially in areas with complex topography, such as the mountainous regions. Localized precipitation events, such as those caused by convective storms, may not be adequately captured in grid cells with low station densities. Consequently, the gridded RX1 day values for the three countries may underrepresent the precipitation extremes observed at individual locations and therefore should be analyzed alongside higher-resolution datasets to inform more precise flood risk assessments.

trends (0.3–0.4 mm/day/year), which indicates a rising frequency of extreme precipitation events. In Syria, rainfall maximums are increasing in regions with already high RX1, including coastal Lattakia and Tartous, and around Damascus and the Qalamoun Mountains. RX1 is decreasing in the northwest governorates of Aleppo and Idlib, where rainfall maximums are above 0.4 mm/day. RX1 is did not increase above 0.1 mm/day anywhere in Yemen aside from eastern Socotra, which highlights the significant role of low soil permeability and mountainous terrain on flood risk in the country.

The bottom panel of Figure A1, A2, and A3 provides an area-weighted average of RX1 values across Iraq, Syria, and Yemen from 1950 to 2016. Peaks in RX1 correspond to notable years of extreme high precipitation events and the 11-point tail running mean filter (blue line) illustrates the overall RX1 trend during the study period. Iraq has experienced a gradual upward trend in RX1 over the study period, reinforcing concerns of increasing precipitation extremes in the country. In Syria, the overall trend is relatively stable due to a counterbalancing between several extended drought seasons and years with high RX1, most recently 2013 and 2016. Notably, rainfall levels in 2019 were high but not recorded in the REGEN dataset. In Yemen, the overall RX1 trend is also relatively stable but similarly determined by the fluctuation between very low and very high rainfall years. Tropical storms and cyclones contribute to the latter, with notable examples being Cyclone Chapala in 2015, as well as Cyclones Mekunu and Luban in 2018, and Cyclone Tej in 2023, which occurred after the REGEN dataset.

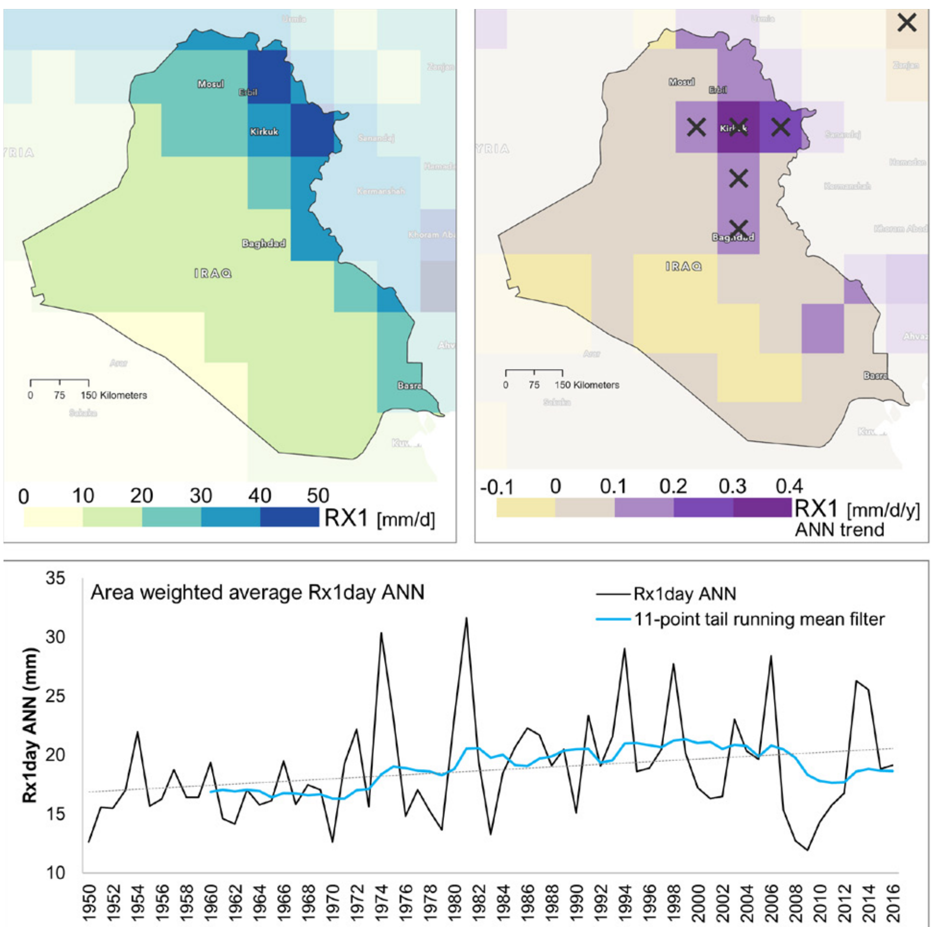

Figure A1: Spatial distribution of maximum 1-day precipitation (RX1, mm/day) and its annual trends (mm/day/year) over Iraq (1950–2016) using the RX1 REGEN LONG V1 dataset.[144] The left panel shows the annual RX1 averages, while the right panel illustrates the RX1 annual trends. The bottom panel presents the area-weighted average RX1 over Iraq, with a 11-point tail running mean filter applied to show long-term precipitation variability.

144 Contractor, S., et al. Rainfall Estimates on a Gridded Network (REGEN) – a global land-based gridded dataset of daily precipitation from 1950 to 2016 Hydrology and Earth System Sciences, 2020

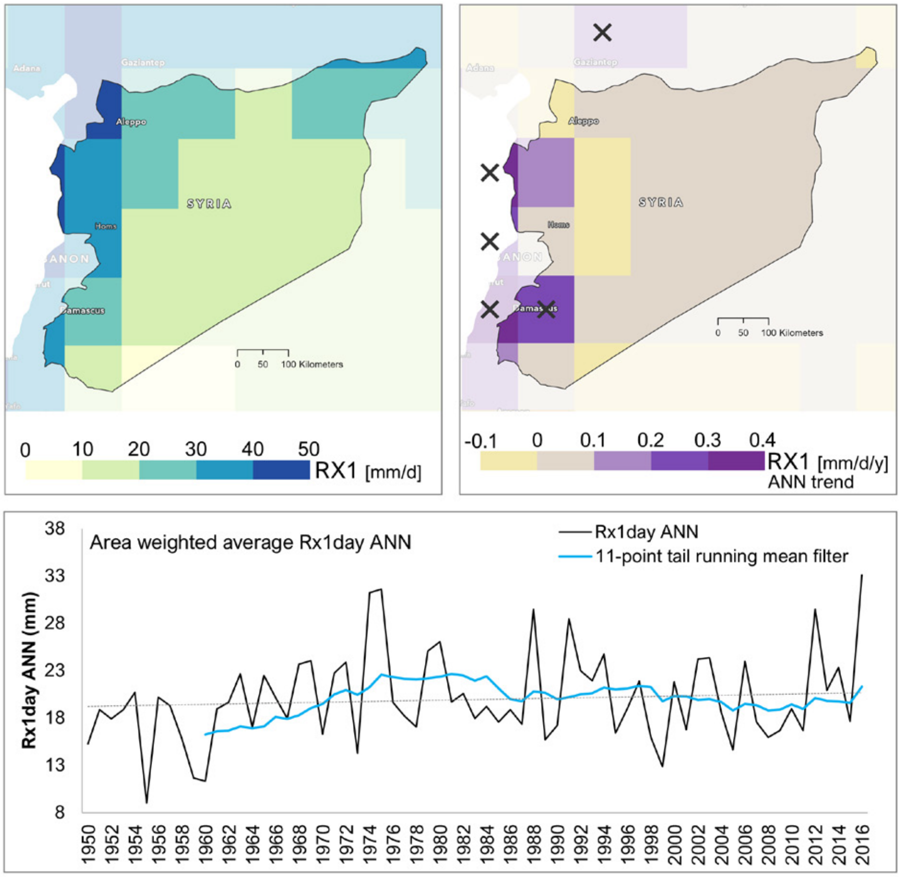

Figure A2: Spatial distribution of maximum 1-day precipitation (RX1, mm/day) and its annual trends (mm/day/year) over Iraq (1950–2016) using the RX1 REGEN LONG V1 dataset. The left panel shows the annual RX1 averages, while the right panel illustrates the RX1 annual trends. The bottom panel presents the area-weighted average RX1 over Syria, with a 11-point tail running mean filter applied to show long-term precipitation variability.

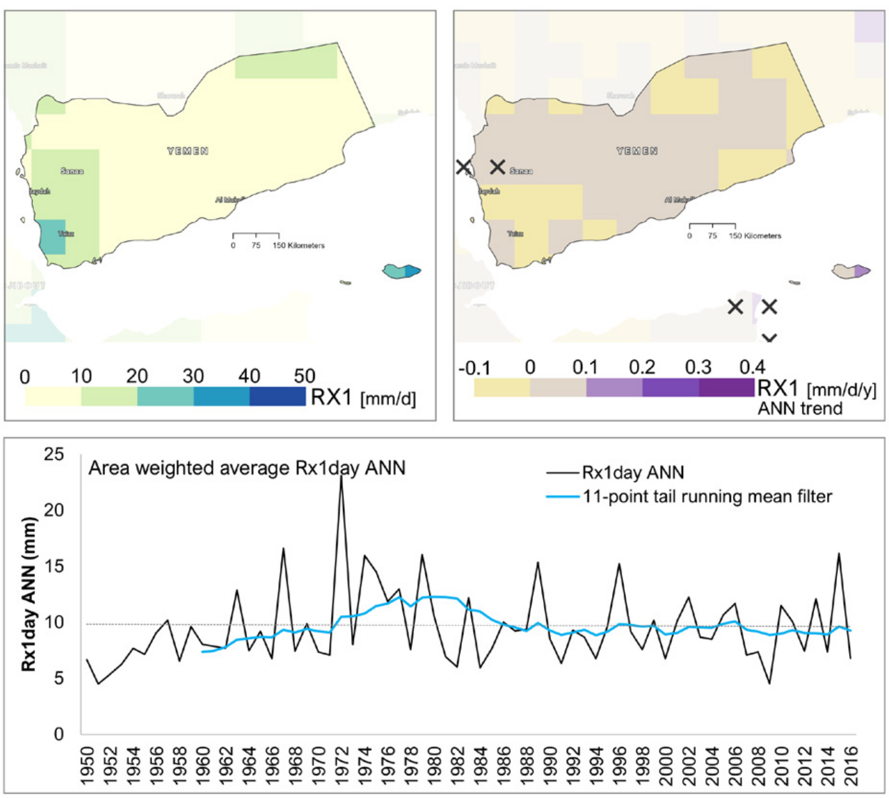

Figure A3: Spatial distribution of maximum 1-day precipitation (RX1, mm/day) and its annual trends (mm/day/year) over Iraq (1950–2016) using the RX1 REGEN LONG V1 dataset. The left panel shows the annual RX1 averages, while the right panel illustrates the RX1 annual trends. The bottom panel presents the area-weighted average RX1 over Yemen, with a 11-point tail running mean filter applied to show long-term precipitation variability.

CONTACT

Michael Chohaney
Regional Quantitative Analysis Specialist | MENA & Europe
mchohaney@mercycorps.org

About Mercy Corps
Mercy Corps is a leading global organization powered by the belief that a better world is possible. In disaster, in hardship, in more than 40 countries around the world, we partner to put bold solutions into action — helping people triumph over adversity and build stronger communities from within. Now, and for the future.

45 SW Ankeny Street
Portland, Oregon 97204
888.842.0842

mercycorps.org