InsuResilience Solutions Fund

FLOOD RISK ASSESSMENT

SOUTH UKRAINE

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Conducted by InsuResilience Solutions Fund in partnership with the Ukrainian Climate Office and Lobelia Earth

UKRAINIAN CLIMATE OFFICE

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The Study Collaboration

The Flood Risk Assessment in the Southern Ukraine study is part of the research and climate risk analysis supported by the InsuResilience Solutions Fund (ISF) with the goal of enhancing knowledge in climate risk analysis in the region. The study is prepared jointly by the Frankfurt School of Finance and Management responsible for implementing the ISF since 2019, which is funded by the KfW Development Bank on behalf of the German Ministry for Economic Cooperation and Development (BMZ); the Ukranian Climate Office as part of the Capacities for Climate Acction project implemented by GIZ on behalf of the German Federal Government and cofinanced by European Union; and Lobelia Earth a climate modelling company. The collaboration between these partners combines technical expertise, local knowledge, and innovative modelling tools to produce a comprehensive analysis of flood in southern Ukraine.

On behalf of:
Federal Ministry for the Environment, Climate Action, Nature Conservation and Nuclear Safety
of the Federal Republic of Germany
IKI INTERNATIONAL CLIMATE INITIATIVE
Implemented by:
giz Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH
Lobelia.

LIST OF ACRONYMS

AAI	Average Annual Impact
BCR	Benefit-Cost Ratio
CHIRPS	Climate Hazards Group InfraRed Precipitation with Station
EAD	Expected Annual Damage
EFAS	European Flood Awareness System
EURO-CORDEX	Coordinated Downscaling Experiment - European Domain
GDP	Gross Domestic Product
GRDC	Global Runoff Data Centre
ISF	InsuResilience Solutions Fund
JRC	European Union Joint Research Centre
MDD	Mean Damage Degree
PAA	Proportion of Assets Affected
RBMPS	River Basin Management Plans
RCP	Representative Concentration Pathways
UCO	Ukranian Climate Office
UNFCCC	United Nations Framework Convention on Climate Change
WRI	World Resources Institute

EXECUTIVE SUMMARY

This Climate Risk Assessment (CRA) for the Lower Dnipro Basin in Ukraine provides an analysis of riverine flood risk under current and future climate conditions. By assessing potential impacts of climate related risks, organisations and governments can make analytically informed decisions for risk management strategies and investment planning, e.g. in adaptation measures. The 2023 destruction of the Kakhovka Dam altered local hydrology, increasing uncertainty in river flow and thus flood behaviour pointing to the need for updated, data-driven risk assessments. This study, prepared through a collaboration among Ukranian Climate Office (UCO), Lobelia Earth, and the InsuResilience Solutions Fund (ISF), uses the CLIMADA modelling framework, an open-source climate risk modelling platform developed and maintained by ETH Zurich, to **quantify flood risk and evaluate potential effectiveness of adaptation measures across four southern oblasts—Dnipropetrovsk, Zaporizhzhia, Mykolaiv, and Kherson.**

The assessment focuses on three main **asset categories: buildings, agriculture, and critical infrastructure**. Two hydrological conditions are examined: pre-collapse of the dam, representing the regulated river system prior to June 2023, and post-collapse of the dam, reflecting the new hydrological regime following the collapse of the Kakhovka Dam. For the post-collapse case, new high-resolution (30 m) flood hazard maps for parts of the Dnipro River catchment from Zaporizhzhia to Kherson is used and was developed by Lobelia using the FastFlood simulation framework. Inputs are derived from multiple open access datasets, including the Copernicus digital elevation model, Climate Hazards Group InfraRed Precipitation with Station (CHIRPS) precipitation data, European Flood Awareness System (EFAS) river discharge records, and Coordinated Downscaling Experiment - European Domain (EURO-CORDEX) climate projections under the Representative Concentration Pathways (RCP) 8.5 scenario. Exposure modelling combines satellite-derived building data combined with local expert judgment for agricultural and infrastructure asset valuation. Vulnerability is assessed for each sector individually relating flood depth and asset damage ratio allowing for consistent estimation of economic losses. Hazard, exposure, and vulnerability data are combined to estimate the Average Annual Impact (AAI) of riverine flood risk.

Results indicate that flood risk in the Lower Dnipro Basin is projected to grow significantly by mid-century. In the pre collapse scenario, AAI for buildings increases from about USD 262 million in 2020 to nearly USD 680 million in 2050 (+160% increase), while agricultural losses rise from roughly USD 8 million to USD 22 million (+175% increase), and critical infrastructure losses from around USD 590 million to USD 1.4 billion (+137% increase). The primary driver of this increase is the expansion in exposed asset value, linked to projected economic growth, while the contribution of climate change itself remains limited at basin scale. The post-collapse scenario covers the downstream section between Zaporizhzhia and Kherson and thus a reduced modelling area but the analysis captures greater local detail and shows clearer climate sensitivity due to higher spatial resolution.

Spatial risk mapping highlights the uneven distribution of impacts across the basin. Dnipro city shows the highest concentration of building damages, while Kherson and Mykolaiv oblasts stand out for agricultural exposure. Infrastructure losses are most pronounced near Kryvyi Rih and Nikopol, where key industrial and energy assets are located. The results demonstrate that medium-frequency flood events, those with return periods of 10 to 20 years, are responsible for most economic losses, suggesting that adaptation strategies targeting these levels of flooding would be most effective. In contrast, rare, extreme floods contribute proportionally less to average long-term risk in the pre-collapse condition but become more significant in the post-collapse hydrological system.

A cost–benefit appraisal is conducted to evaluate the effectiveness of selected adaptation measures for the building sector. Five options are tested: detention ponds, drainage rehabilitation, river embankments, flood-proofing of structures, and relocation of highly exposed housing. The analysis finds that detention ponds and drainage rehabilitation deliver the highest economic benefit, with benefits in form of avoided damage exceeding implementation costs for these measures significantly. River embankments, household-level flood-proofing, and relocation show much lower cost-effectiveness, with benefits falling short of implementation costs under current assumptions. These findings underscore the importance of prioritising investments that yield the highest returns in avoided damages.

Overall, the assessment shows that flood risk in the Lower Dnipro Basin is dominated by exposure growth rather than by changes in climate-related hazard. Nevertheless, adaptation remains beneficial, as urban expansion and reconstruction following recent conflicts are likely to increase vulnerability if resilience considerations are not integrated into planning. The comparison between pre-collapse and post-collapse conditions highlights the value of high-resolution modelling for capturing localised flood dynamics and informing site-specific adaptation strategies. The study also identifies areas for assessment improvement, including the need for more detailed exposure datasets, particularly for specific infrastructure and crop types, and enhanced hazard modelling to better represent local variability.

The climate risk assessment provides a quantitative base to support climate-resilient recovery and investment planning in southern Ukraine. Regional authorities, particularly in Kherson and Mykolaiv, may use these findings as a starting point for future urban development and infrastructure reconstruction strategies. The results demonstrate that data-driven risk assessments can guide cost-effective adaptation, strengthen disaster preparedness, and inform sustainable water management in a region undergoing both climatic and geopolitical challenges.

INTRODUCTION

Ukraine is increasingly exposed to the impacts of climate change, with rising temperatures and shifting precipitation patterns driving more frequent and severe hydrometeorological extremes as recognised in Ukraine's First Adaptation Communication to the UNFCCC (UNFCCC, 2024). Riverine flooding is of particular concern in the Dnipro River Basin, where large populations, critical infrastructure, and agricultural production are concentrated. The destruction of the Kakhovka Dam in 2023 significantly altered local hydrology, potentially affecting the level of flood risk, disrupting water supply, and creating long-term environmental and economic challenges. Comprehensive, quantitative flood risk assessments remain limited, constraining the ability of national and municipal authorities to plan for adaptation. This CRA helps to close this gap by analysing riverine flood risk in the Lower Dnipro Basin under current and future climate conditions using the modelling framework CLIMADA and flood maps produced by Lobelia Earth. While the main emphasis of this report is on the assessment of risk, a cost-benefit adaptation analysis for buildings is presented demonstrating the value of risk analytics for disaster risk management.

The Dnipro River, one of Europe's largest rivers at 2,201 km in length, flows for 980km through Ukraine. It runs across nearly half of the country's territory and sustains over 50% of the population living near its banks. The river is divided into five sub-basins: Desna, Pripyat, Middle Dnipro, Upper Dnipro, and Lower Dnipro (European Union Water Initiative, 2020). This assessment focuses on the Lower Dnipro Basin, where a quantitative flood risk assessment is conducted.

The analysis covers four oblasts within the southern region of Ukraine: Dnipropetrovsk, Zaporizhzhia, Mykolaiv, and Kherson which are central to the Lower Dnipro River sub-basin and also the subject of the River Basin Management Plans (RBMPs) for 2025–2030 (EU4Environment, 2025). Each oblast plays a distinct role in Ukraine's economy and infrastructure:

- Dnipropetrovsk is a key hub for trade, industry, and transport, hosting a river port, rail networks, and an airport (Pravda, 2025).
- Zaporizhzhia supports a major metallurgical industry and energy production, and it is home to the Zaporizhzhia Nuclear Power Plant, the largest nuclear facility in Europe (Britannica, 2025).
- Mykolaiv is a centre of shipbuilding and maritime transport with access to the Black Sea (EU4Business, 2025).
- Kherson, strategically located at the mouth of the Dnipro, influences national water supply and economic connectivity with the Black Sea and Crimea (BBC, 2022).

Since 2022, the ongoing geopolitical situation has significantly complicated data collection efforts, particularly in Kherson and Zaporizhzhia

BACKGROUND

The INFORM Risk Index (2025)[1] indicates high disaster risk in Ukraine ranking the country 31st out of 191 countries, with an overall score of 5.6 of 10 (10 being highest risk). The index includes natural and human components. Riverine flooding (score 6.2) and coastal flooding (score 5.0) are identified as the most significant natural hazards, exceeding earthquakes, droughts, cyclones, and other events (Figure 1).

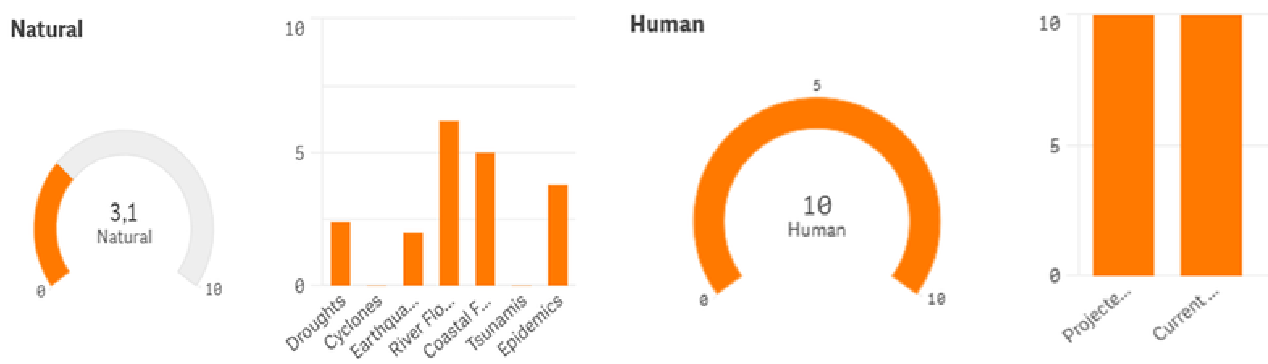

Figure 1. Hazard & Exposure Index (JRC, 2025)) – The figures show Hazard & Exposure for both Natural and Human categories. Natural hazards have a moderate exposure score of 3.1, with coastal flooding posing the greatest risk. In contrast, human-related hazards show a maximum exposure level of 10, indicating significantly higher overall risk from human factors.

Historical data reinforce these findings. Since 2000, 11 major flood disasters have been recorded in Ukraine, with total damages exceeding USD$1.7 billion (EM-DAT). The 2008 floods as the single costliest event led to USD$1.46 billion in damages, primarily in the Prut and Dniestr basins. Several events have affected the Lower Dnipro sub-basin directly, including floods in Crimea (2006), Odessa (2016), and the 2023 Kakhovka Dam collapse (Figure 2).

Year	Country	Disaster	Origin	Total Deaths	Total Affected	Total Damage, Adjusted ('000 USD$)
2001	Ukraine	Riverine flood	Heavy rain	9	300,000	26,574
2003	Ukraine	Riverine flood	Heavy rains, melting snow	-	600	-
2005	Ukraine	Flood (General)		-	8,340	-
2006	Ukraine	Riverine flood		-	-	-
2006	Ukraine	Riverine flood	Heavy rains	2	5,000	37,120

[1] INFORM - Global, open-source risk assessment for humanitarian crises and disasters

Year	Country	Disaster	Origin	Total Deaths	Total Affected	Total Damage, Adjusted ('000 USD$)
2008	Ukraine	Riverine flood	Heavy rains and thunderstorms	38	224,725	1,456,968
2010	Ukraine	Riverine flood	Heavy rains	6	40,059	2,733
2013	Ukraine	Riverine flood		2	2,260	28.278
2016	Ukraine	Flood (General)	Heavy rains	3	200	-
2020	Ukraine	Flood (General)	Heavy rains	3	55,000	186,485
2023	Ukraine	Flood (General)		-	2,850	-
2025	Ukraine	Flood (General)	Heavy rains	9	2,010	-

Table 1. Floods in Ukraine (2000-2025) (EM-DAT, 2025)) -The figure lists major flood events in Ukraine from 2001 to 2025, including both riverine floods and general floods, mostly caused by heavy rain, leading to varying impacts.

The 2008 flood serves as a benchmark for extreme events, inundating 24,000 hectares of farmland, damaging 650 km of roads, and flooding over 9,000 houses. In addition, 38 fatalities were reported (WHO, 2008).

By contrast, the 2023 Kakhovka Dam collapse resulted in far greater human, economic and environmental losses, with water levels rising by 3.5–5.6 m, flooding more than 600,000 hectares of farmland and causing nearly USD$4 billion in total damages. This includes USD$950 million in damages to housing and infrastructure and over USD$2 billion in environmental costs (Djankov, 2023). Beyond its scale, the event marked a turning point in the region's hydrological dynamics, fundamentally altering flow regimes, floodplain morphology, and long-term risk patterns. The former Ministry of Environmental Protection and Natural Resources of Ukraine reported that the maximum flood extent exceeded 630 km² between 6–9 June 2023. Approximately 100,000 residents were directly impacted. Humanitarian aid was provided by the ICRC and the EU Civil Protection Mechanism,

Together, these historical and recent events highlight the urgent need for systematic and forward-looking risk assessment. This report addresses that need by applying the CLIMADA modelling framework to the Lower Dnipro Basin, generating quantitative estimates of flood risks and evaluating the potential effectiveness of adaptation measures to inform regional planning and resilience-building efforts.

METHODOLOGY

Study Area and Scope

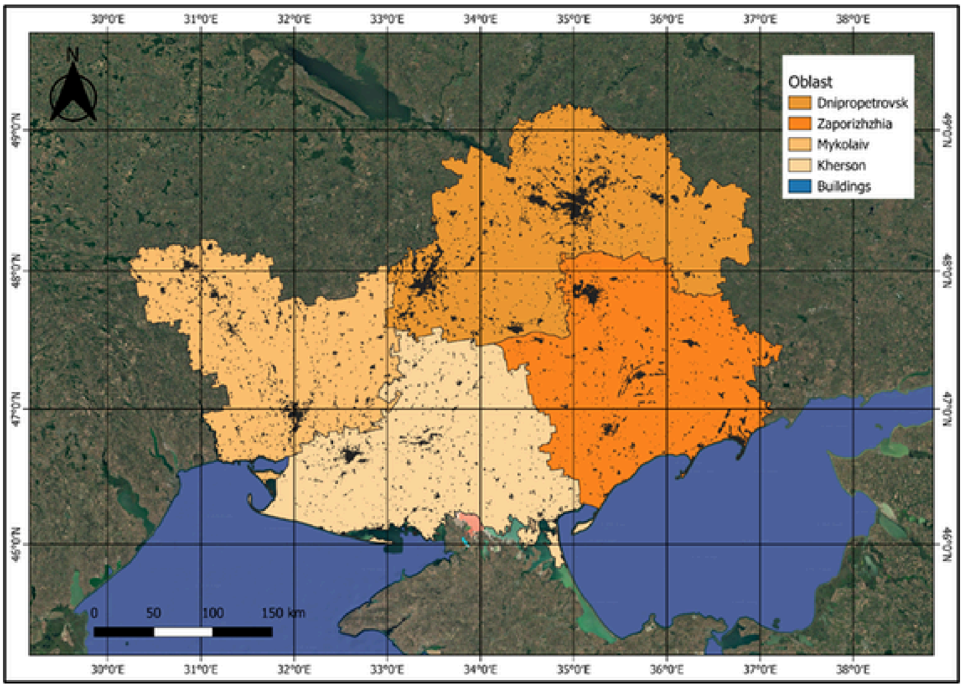

Figure 2. Area of study Southern Ukraine - The figure shows the map of the study area in southern Ukraine, encompassing the Dnipropetrovsk, Zaporizhzhia, Mykolaiv, and Kherson oblasts. These regions are displayed in distinct colors, with black dots representing buildings, indicating populated areas.

In this CRA the regions are selected mainly for two reasons:

- Changing hydrological conditions: The destruction of the Kakhovka Dam in June 2023 fundamentally altered the Dnipro River's flow regime and hydrological profile. This created new uncertainties about flood behaviour across all four oblasts and future water management.
- Post-conflict recovery needs: The conflict is leaving widespread damage to housing, infrastructure, and water systems. As reconstruction starts, integrating updated flood-risk information is essential to ensure that rebuilding efforts are resilient and climate-informed.
- Socioeconomic significance and vulnerability: These regions host a concentration of industrial facilities and large population centres, making them critical for Ukraine's economic recovery while also potentially heightening exposure and vulnerability to hydrological hazards.

The CRA looks only at riverine flooding and estimates:

- Exposed value: the economic value of buildings, agriculture, and selected critical infrastructure located in flood-prone areas.
- AAI: Average Annual Impact, also referred to as Expected Annual Damage (EAD), which combines hazard, exposure, and vulnerability to show the expected long-term average losses from flooding.

Results are provided for both current and future mid-century scenario conditions (2050, RCP8.5), based on different flood return periods (10-, 20-, 50-, 75-, and 100-year events). In addition, a simplified appraisal of adaptation measures is carried out for the building sector. Results are presented as waterfall charts, which illustrate how each measure can reduce expected future damages step by step compared to the baseline.

Exposure Modelling

Exposure refers to the assets, people, and economic activities that could be affected by flooding. In this assessment, exposure is represented by three layers: buildings, agriculture, and selected infrastructure. All exposure datasets are prepared using the most up-to-date data available and the best expert knowledge. However, due to the ongoing situation in Ukraine, asset distributions may have changed since the data were compiled. As a result, the exposure layers may not fully represent the current on-ground conditions.

Buildings:

Following the methodology described in the report by the Global Risk Modelling Alliance and InsuResilience Solutions Fund (2022), the building exposure layer is derived from Humanitarian Data Exchange (HDX) building polygons in asset level. This dataset provides detailed spatial information on the location and geometry of structures. Each footprint is assigned an economic value using the GAR15 database, which provides globally harmonised estimates of reconstruction costs adjusted by region. This allows for a consistent monetary valuation of the built environment across the study area.

Although the HDX dataset provides good spatial coverage, there are uncertainties in classification (e.g., distinguishing between residential and commercial use). For this reason, the building exposure layer is best interpreted as an aggregate estimate of building stock value rather than a detailed cadastral inventory. Additionally, the GAR15 exposure data are likely to be outdated, particularly given recent changes in the region. However, no more recent, comprehensive exposure database is currently available.

Agriculture:

Agricultural exposure is developed through expert consultations with Ukrainian specialists, reflecting the absence of high-resolution open datasets for crop distribution and valuation. A grid with a 10 × 10 km resolution is created, in which each cell contained estimates of dominant crop types, yield levels, and market values. These values are then downscaled proportionally to 100 × 100 m resolution to provide spatially explicit information for integration with hazard maps.

The valuation is based on average production values per hectare, multiplied by expected yields and adjusted with market price data. While this approach ensures coverage across the basin, it inevitably introduces simplifying assumptions about uniformity of crop value within each grid cell. Local heterogeneity (e.g., high-value crops, irrigation practices) is not fully captured, which should be considered when interpreting results.

Selected Infrastructure:

Selected infrastructure assets are identified through local expert knowledge and compiled into an exposure database of approximately 500 individual assets. However, it is important to note that due to the current situation in the region, the database may not reflect the most recent exposure. These include:

- Energy facilities (power plants, substations, transmission nodes);
- Water management systems (pump stations, treatment plants, reservoirs);
- Transport infrastructure (terminal, ports, airports);
- Production facilities: mineral mining, industries, farms, pre-treatment plants, logistics.

Each asset is assigned a proxy economic value based on its type, scale, and replacement costs drawn from regional and international databases. Unlike the agricultural datasets, the infrastructure layer is asset-based, reflecting the discrete and critical nature of these facilities.

Hazard Modelling

Flood hazard modelling in this assessment is divided into two modelling conditions: pre-collapse of the dam conditions, which represent the state of the Dnipro River before the destruction of the Kakhovka Dam in June 2023, and post-collapse of the dam conditions, which reflect the new hydrological reality downstream of the Zaporizhzhia Dam after the collapse. This distinction is essential, as the dam played a regulatory role in the hydrological regime in the Lower Dnipro.

For the pre-collapse scenario, the analysis relies on Lobelia's precomputed hazard maps, which cover the Dnipro basin at 100-metre resolution. These maps combine datasets from the European Union Joint Research Centre (JRC) for historical flood data and the World Resources Institute (WRI) for future projections, downscaled to sub-basin level. They provide a consistent, validated view of flood hazards across the basin under stable dam conditions and are used to represent both historical baselines and mid-century futures (RCP8.5) for a range of return periods.

For the post-collapse scenario, since no hazard datasets existed for the new river conditions after the destruction of the Kakhovka Dam, Lobelia developed a new flood model covering the Dnipro River reach from the Zaporizhzhia Dam to Kherson city, with the following considerations:

Model:

The FastFlood model (Van den Bout et al., 2023) is selected for the simulations. FastFlood is designed for rapid simulation of large riverine flood events. It assumes steady-state flows, which makes it computationally efficient while still able to reproduce maximum flood extents and water levels with sufficient accuracy for risk analysis.

Resolution and Inputs:

The base topography is taken from the Copernicus 30 m DEM, which was further refined by Lobelia using additional methods, including comparisons with satellite imagery and land cover data, as well as empirical approaches to better represent river channel depth and geometry.

Forcing – Precipitation and River Discharge:

- Precipitation: Historical precipitation inputs came from the CHIRPS dataset at 5 km resolution. For climate change projections, data is drawn from the EURO-CORDEX ensemble, which includes 20 models at 11 km resolution for both historical and mid-century futures.
- River Discharge: Historical discharge is taken from the EFAS at 1.4 km resolution and validated against observed records from the Global Runoff Data Centre (GRDC). For future scenarios, discharge projections are based on CORDEX-driven hydrological simulations from the Copernicus Climate Service, available at 5 km resolution from 8 models for both historical and future conditions.

Future Scenarios:

- Post-collapse simulations are repeated for mid-century climate conditions under the RCP8.5 scenario as described above, ensuring robust estimates of future hazard conditions.
- Outputs consist of flood depth and extent maps for return periods of 10, 20, 50, 75, and 100 years, for both historical and future mid-century (2050, RCP8.5) conditions.

Vulnerability Modelling

The vulnerability component describes how exposed assets are expected to respond to flood impacts of varying depth and intensity. In this assessment, vulnerability is represented through depth–damage functions, which express the proportion of asset value lost at different flood depths. Different functions are applied for buildings, agriculture, and selected infrastructure, reflecting the differences in asset type, structure, and data availability.

Buildings and Agriculture:

For both buildings and agriculture, generic depth–damage functions from the Global Flood Depth–Damage Functions Database are applied. The building stock is treated as one category, since no distinction is available between residential, commercial, or other use. Agriculture is also represented in aggregate, with all crops assumed to have the same vulnerability. While this approach introduces uncertainty, it provides a consistent basis for estimating potential damages.

Selected Infrastructure:

For infrastructure, sector-specific functions are applied from the Physical Vulnerability Database for Critical Infrastructure Hazard Risk Assessments. In total, 15 distinct vulnerability curves are used, covering different categories such as energy facilities, water management systems, and transport infrastructure.

Risk Assessment

The risk assessment is carried out using the CLIMADA modelling framework (Aznar-Siguan & Bresch, 2019), which integrates hazard, exposure, and vulnerability data to estimate flood risk. CLIMADA operates using an event-based probabilistic approach, where hazards are represented as a set of discrete events, each associated with an annual probability of occurrence. In the context of flood analysis, each event corresponds to a flood characterised by its depth and spatial extent, together with an associated frequency.

In this study, flood hazard maps are generated for predefined return periods (10, 20, 50, 75, and 100 years). These return periods are converted into event frequencies, and each flood map was treated as an individual flood event within CLIMADA. For each event, CLIMADA combines the flood depth with vulnerability functions to estimate damage ratios, which are then applied to the exposed assets to calculate the economic loss associated with that event.

The losses from all events are then weighted by their respective frequencies and aggregated, resulting in the AAI.

Annual Average Impact

AAI is the main indicator of risk in this assessment. It represents the average annual losses expected from flooding when considering both frequent small events and rare catastrophic ones. In practice, AAI answers the question: "If we average all possible expected floods weighted by their probability, how much economic damage do we expect to occur on average each year?"

In this study, AAI values are calculated separately for buildings, agriculture, and selected infrastructure. Results are reported for both the present baseline (2020) and future mid-century. Comparing these values shows how much flood risk could increase over time due to climate change and changes in exposure.

Impact Frequency Curves

While the Annual Average Impact (AAI) condenses flood risk into a single expected annual value, impact frequency curves provide a more complete picture of how damages scale across events with different probabilities. These curves show economic damages as a function of event likelihood or return period, allowing the contribution of both frequent and rare floods to be examined explicitly.

At the left end of the curve, frequent floods with short return periods (for example 5- or 10-year events) are associated with relatively lower damages/losses. Toward the right end, rarer/less frequent floods with long return periods (such as 50- or 100-year events) produce much larger impacts/losses.

Other Outputs

In addition to AAI and impact frequency curves, the CLIMADA analysis produces several complementary outputs:

- Impact value maps, which show the spatial distribution of estimated damages at the resolution of the exposure data, allowing the identification of areas and assets with higher expected impacts.
- Waterfall plots, which decompose changes in AAI between the baseline and future scenarios into contributions from economic development (changes in exposure) and climate change (changes in hazard intensity).

Because of CLIMADA's event-based design, the modelling is carried out twice: once for the pre-collapse condition (using basin-wide precomputed maps) and once for the post-collapse condition (based on the new modelling downstream of the Zaporizhzhia Dam).

Cost–Benefit Analysis

A simplified cost–benefit analysis is carried out to explore how some flood protection measures could reduce damages in the building sector of the Lower Dnipro Basin. The adaptation measures considered are rehabilitation of drainage systems, river embankments, construction of detention ponds, flood-proofing of buildings, and relocation of highly exposed housing. The analysis is restricted to buildings for two main reasons. First, there are no reliable data sources on crop-specific flood adaptation measures that could be applied to agriculture at basin scale. Second, for critical infrastructure, adaptation measures are highly asset-specific (e.g., protection of an individual power plant). Since CLIMADA does not simulate adaptation on a facility-by-facility basis, infrastructure is excluded from this analysis.

In CLIMADA, adaptation measures are represented in a parametric way rather than as detailed physical interventions. The model assumes that measures reduce either the damage assets suffer at a given hazard intensity or the intensity of the hazard that reaches the assets. The latter is applied here. This is done by adjusting the underlying functions that link hazard intensity to damage, namely the vulnerability function, defined by the mean damage degree (MDD) and the proportion of assets affected (PAA), and, where relevant, the hazard intensity itself.

The MDD represents the average proportion of an asset's value that is lost at a given flood depth, while the PAA describes the share of assets that sustain any damage during an event. Together, these two parameters define how vulnerable an exposure is to flooding.

To assign a cost and an expected hazard intensity reduction to each measure, two sources are used. Costs are taken either from measures listed in the Dnipro RBMP[2], which already outlines a portfolio of actions for the Lower Dnipro sub-basins, or from unit cost values reported in the European study Cost-effective Adaptation Strategies to Rising River Flood Risk in Europe. Assumptions about impact reduction are based on earlier project experience and cross-checked against the same European study to maintain consistency with international benchmarks.

[2] davr.gov.ua

Drainage rehabilitation and detention ponds

RBMP serves as the starting point, since both measures are already included in the basin planning framework. The planned investments provided an indicative scale of costs, while previous projects offer reference values for their likely effectiveness in reducing flood intensity.

River embankments

The analysis identifies stretches of the Dnipro where exposed settlements would require additional protection. Drawing on the example of embankment construction in Dnipro City, the approximate length of embankments is estimated and multiplied by a cost per kilometre from the European reference study. This provides both a cost estimate and a benchmark for the expected reduction in flood levels.

Flood-proofing

Hazard maps for lower return periods are overlaid with the exposure dataset to identify locations where flooding is frequent but not catastrophic. These areas are considered suitable for household-level protection measures. The corresponding surface area of houses is calculated and multiplied by a cost per square metre from the European study, with damage reduction rates taken from earlier project evidence.

Relocation

Hazard maps are used to locate areas of consistently high and recurrent flooding where structural protection or flood-proofing would not be viable. In these zones, relocation is treated as the only realistic adaptation option. The total surface area of housing stock is derived and multiplied by a relocation cost per square metre from the European benchmark, with the measure assumed to remove almost all damage in the affected locations.

It should be noted that the cost benefit analysis is conducted only for the pre collapse scenario. The post dam modelling covers a smaller downstream area below the Zaporizhzhia Dam and represents the newly established hydrological conditions after the collapse of the Kakhovka Dam. At present, the level of information is insufficient to apply the same adaptation measures consistently at this more local scale. Since the measures considered such as drainage rehabilitation, embankments, detention ponds, flood proofing and relocation are defined for a broader basin scale context, the adaptation appraisal was therefore limited to the pre collapse conditions.

RESULTS AND DISCUSSION

Exposed value

The exposure layers developed for the Lower Dnipro Basin quantify the economic value of buildings, agriculture, and critical infrastructure in the study area for both the baseline year 2020 and the mid-century projection for 2050. Across all three sectors, results indicate an increase in total asset value between 2020 and 2050 due the GDP growth.

- Buildings: Exposed value is estimated at USD$ 52.57 billion in 2020 and increases to USD$ 136.88 billion in 2050. Concentrations are highest in urban centres across the basin, including Dnipropetrovsk, Zaporizhzhia, Kherson, Mykolaiv, Kryvyi Rih, and Nikopol, as well as other large settlements along the Dnipro River corridor.
- Agriculture: Exposed value rises from USD$ 1.34 billion in 2020 to USD$ 3.52 billion in 2050. Agricultural fields are widely distributed across the basin and cover extensive areas of all four oblasts. While crop types are not distinguished at the local scale, the aggregated results show substantial growth in agricultural value by mid-century, particularly in the downstream oblasts of Kherson and Mykolaiv, where GDP increases are projected.
- Selected Infrastructure: Exposed value is USD$ 103.05 billion in 2020 and grows to USD$ 255.69 billion in 2050. Notable concentrations of infrastructure value are found near Kryvyi Rih and Nikopol, which are key industrial and energy hubs within the basin.

For each sector, three sets of spatial maps are produced:

- 2020 baseline distribution, showing the location and value of assets.
- 2050 distribution, showing projected asset values under the RCP8.5 scenario.
- Difference maps (2050–2020), identifying areas with the largest changes in asset value.

Only the building sector maps are presented in this report, while equivalent maps are generated for agriculture and infrastructure.

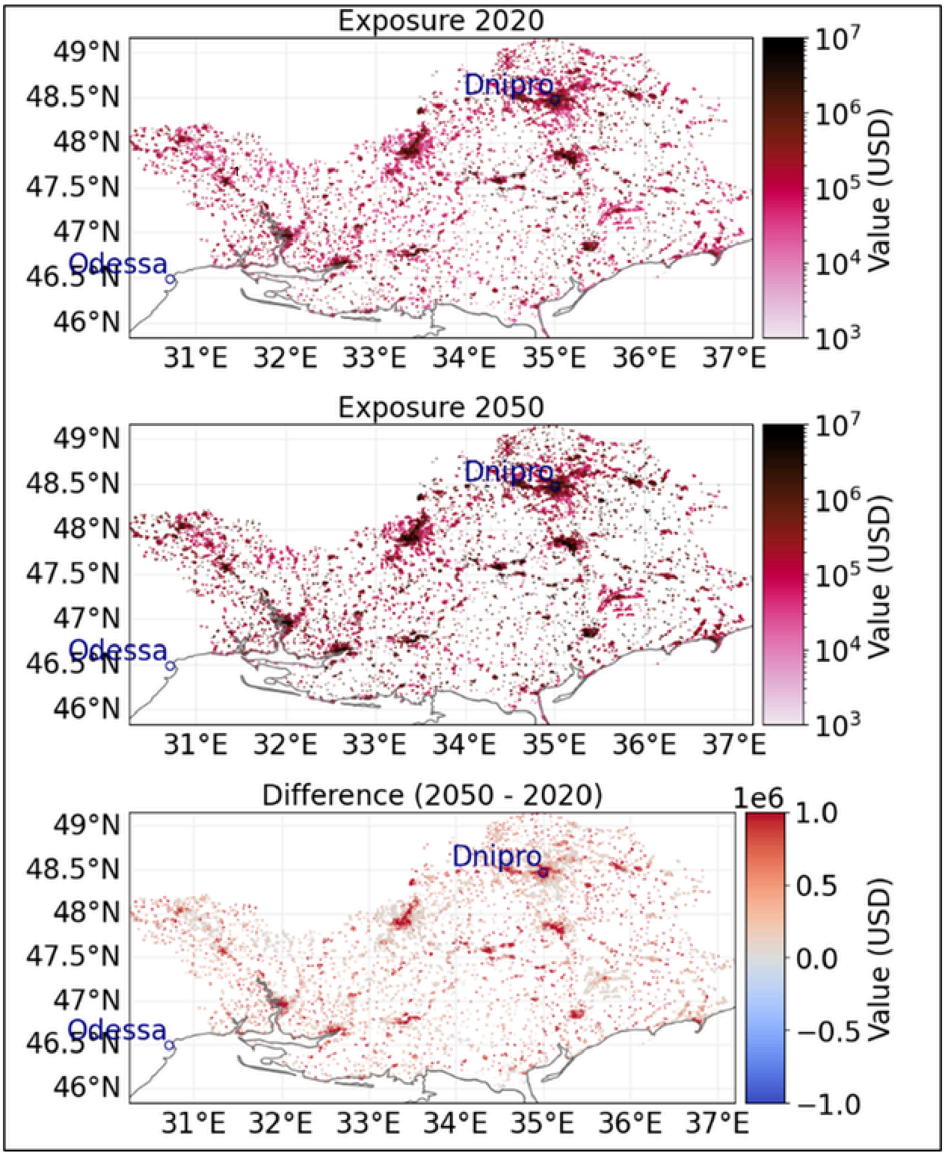

Figure 3. Building exposure maps - The figure shows three different maps. The first map presents the building portfolio and its exposed value exposure in southern Ukraine for 2020, while the second map shows the exposed value for and 2050. The third maps presents the projected change between these the first and second map, it shows an increase in value of the exposure portfolio of buildings. Exposure values, expressed in USD, show higher concentrations around Dnipro and coastal regions near Odesa.

Hazard maps

Using CLIMADA's event-based hazard representation, a composite map is produced showing the maximum intensity at each point in the study area. In this context, maximum intensity refers to the maximum flood depth and the extent reached, combining the results of all return-period events into a single layer.

Under the pre-collapse condition, both the historical baseline and the mid-century projection are analysed. Differences between the two scenarios are minimal, with the maps showing small to no change in flood extent or depth. In both time horizons, extensive flooding is visible along the floodplains, particularly in the northern part of the Lower Dnipro Basin around Pavlohrad and Kamianske. Areas of higher intensity are also observed downstream of the city of Dnipro and near the former Kakhovka reservoir.

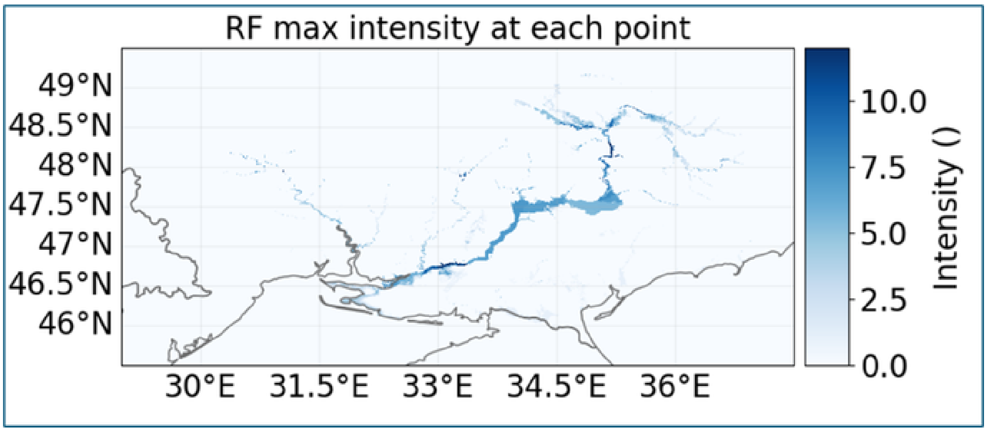

Figure 4. Hazard map pre-collapse scenario 2050 - The figure shows the maximum river flood (RF) intensity at each point across southern Ukraine for the pre dam 2050 projection scenario. Higher intensities (shown in dark blue) are concentrated along the Dnipro River and its tributaries.

Under the post-collapse condition, on the localised section of the river at higher resolution, comparisons between the baseline and the mid-century projection show a slight increase in flood extent and depth. The newly mapped flooded areas correspond to floodplains created after the emptying of the Kakhovka reservoir following the dam's destruction.

Comparing the pre-collapse and post-collapse present-day conditions (2020 vs. 2023–2025) illustrates the shift to a new hydrological regime downstream of the Zaporizhzhia Dam. Where the Kakhovka reservoir once stored water, the maps now depict the re-emergence of a river channel and floodplain system closer to its natural configuration prior to reservoir construction.

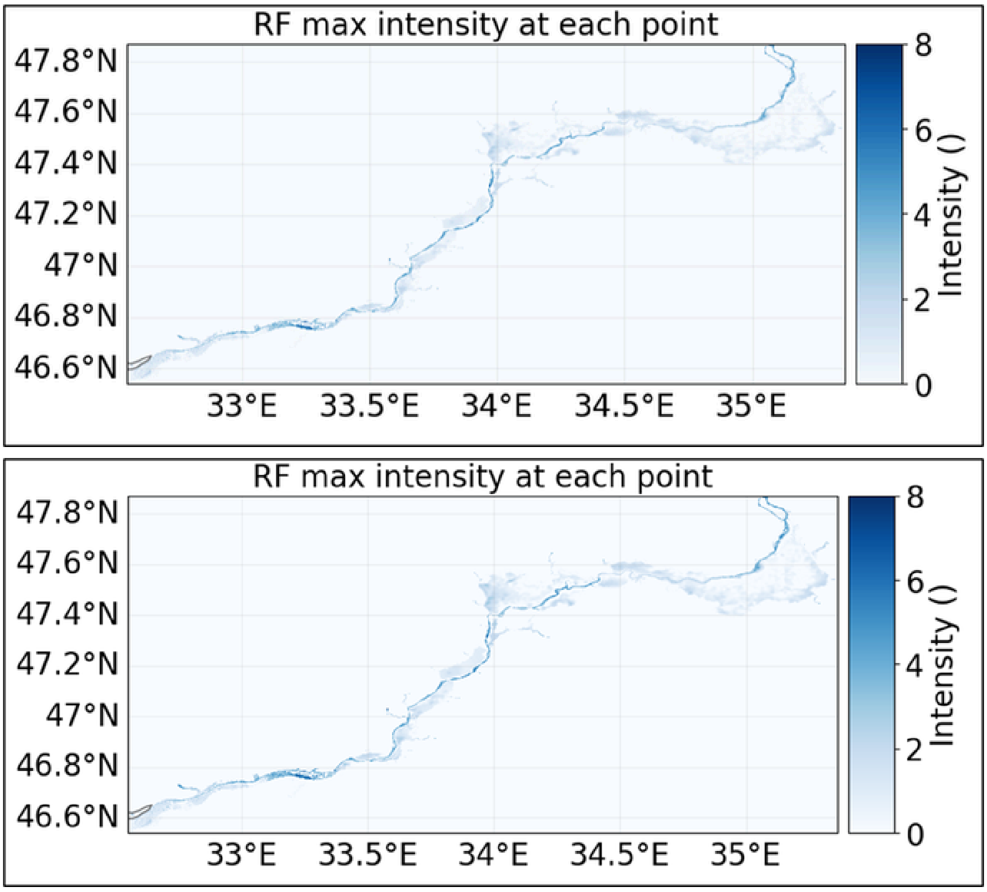

Figure 5. The figure shows two hazard maps for the post-collapse scenario. The first map shows the maximum river flood (RF) intensity at each point after the Zaporizhian dam for the baseline or the current conditions. The second figure presents also maximum RF intensity but for the 2050 projection. Slightly higher intensities can be seen in the 2050 scenario.

Risk Assessment

AAI

In the pre-collapse condition for the Lower Dnipro Basin, the AAI for buildings is estimated at USD$ 261.66 million in 2020, rising to USD$ 678.55 million in 2050 (+160% increase), which represents about 0.36% of Ukraine's GDP (USD$ 190 billion in 2024). For agriculture, the AAI is USD 8.47 million in 2020 and increases to USD$ 22.34 million in 2050 (+164% increase), equal to roughly 0.01% of GDP. The highest values are observed for critical infrastructure, with an AAI of USD$ 590.60 million in 2020 and USD$ 1.40 billion in 2050 (+137% increase), corresponding to around 0.74% of GDP.

In the post-collapse condition for the section of the Lower Dnipro downstream of Zaporizhzhia, the AAI for buildings is estimated at USD$ 2.94 million in 2020, increasing to USD$ 7.32 million in 2050 (+149% increase). For agriculture, the AAI rises from USD$ 1.27 million in 2020 to USD$ 3.39 million in 2050 (+167% increase). The highest values are observed for critical infrastructure, with an AAI of USD$ 16.10 million in 2020 and USD$ 38.08 million in 2050 (+137% increase).

The pre-collapse and post-collapse results should be interpreted separately. While both use the same CLIMADA framework, the pre-collapse condition covers the entire Lower Dnipro Basin at 100 m resolution, whereas the post-collapse condition focuses on the downstream reach from Zaporizhzhia to Kherson at 30 m resolution. These differences in spatial scope and resolution explain the differences in absolute AAI values. The pre-collapse model includes all major cities, extensive cropland, and a large number of building assets, which leads to higher total AAI values. By contrast, the post-collapse model covers a smaller area with fewer assets, resulting in lower overall numbers. In addition, the lower resolution of the pre-collapse maps tends to produce higher flood depths, which also contributes to larger AAI values when compared to the more detailed post-collapse modelling.

With that in mind, a further exploratory comparison is made by aligning the historic pre-collapse computation with the baseline post-collapse model over the same spatial scope. This allows a first indication of the role of the Kakhovka Dam in flood dynamics. The results show notably higher AAI values in the pre-collapse case compared to the post-collapse baseline. For example, for buildings, the AAI decreases from USD 43.49 million (pre-collapse) to USD 2.07 million (post-collapse baseline). Similar differences are observed for infrastructure and agriculture.

These differences should be interpreted with caution, as they depend strongly on the modelling setup and data resolution. However, they suggest that the presence of the Kakhovka reservoir in the pre-collapse condition led to higher modelled flood depths and consequently larger AAI values, while the post-collapse condition reflects a narrower river channel and newly formed floodplains with lower overall impact values.

Frequency Curves

Six frequency curves are generated, covering the three sectors (buildings, agriculture, and critical infrastructure) under both pre-collapse and post-collapse conditions. For illustration, the curve for buildings under the pre-collapse baseline (2020) is shown in the figure.

It indicates that for a 10-year return period the expected impact is about USD$ 1.3 billion, for a 20-year return period it rises to around USD$ 1.6 billion, and for a 100-year return period it reaches approximately USD$ 1.8 billion. While the absolute values vary by sector and scenario, the pattern is consistent: there is a notable increase in damages between 10- and 20-year events, whereas the change from 20-year to 100-year events is smaller. This suggests that, although impacts continue to rise with more extreme floods, the difference between medium- and high-return period events is less pronounced than the jump from more frequent to medium-sized events. In contrast, the post-collapse curves show a slightly different behaviour. Here, damages continue to increase across all return periods, without the flattening seen in the pre-collapse case. This indicates that in the post-collapse configuration, rare and extreme floods contribute more strongly to overall damages, and the damage curve grows more evenly across the probability spectrum.

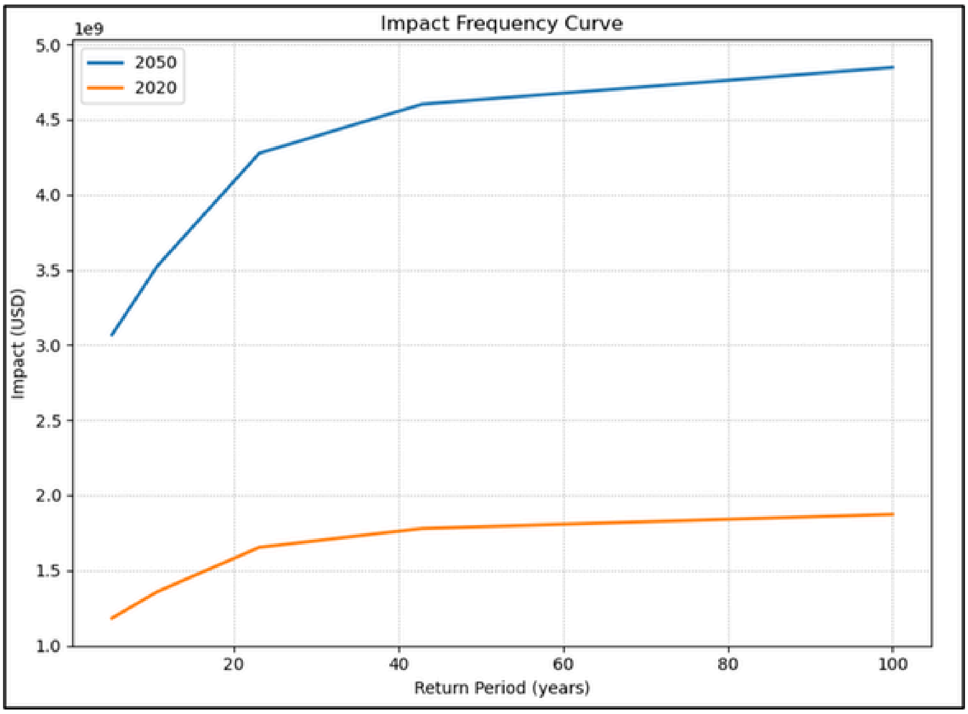

Figure 6. Frequency curve for buildings, pre-collapse scenario - The figure shows the Impact Frequency Curve for the pre-collapse scenario, comparing estimated flood impacts for 2020 and 2050. The curve rises sharply with return period, with 2050 impacts much higher than 2020, showing a increase in future flood risk.

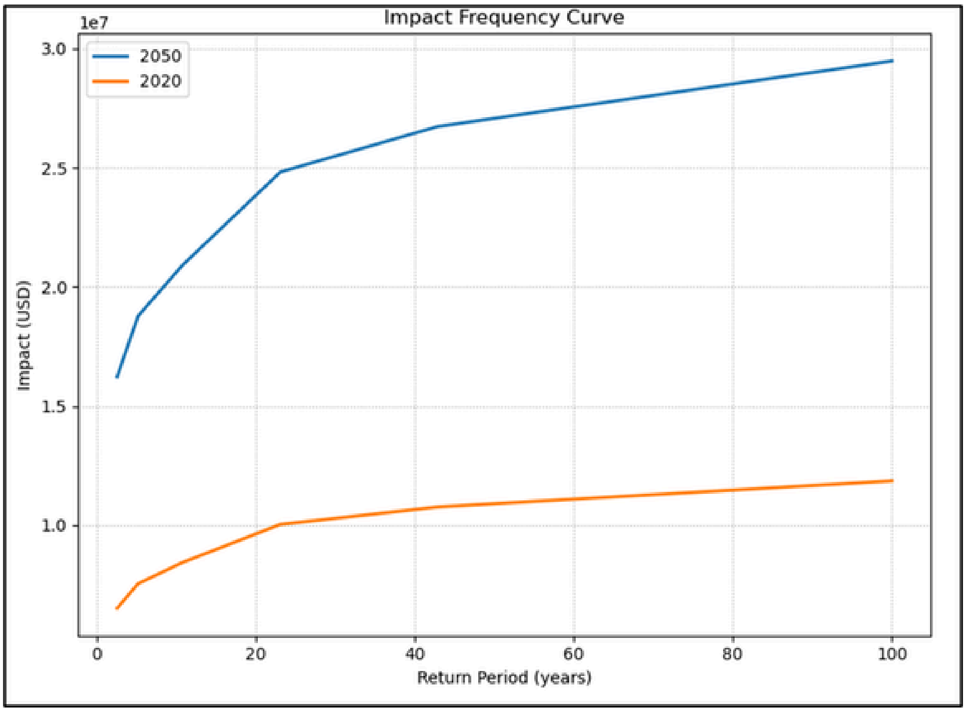

Figure 7. Frequency curve for buildings, post-collapse scenario - The figure shows the Impact Frequency Curve for the post-collapse scenario, comparing estimated flood impacts for 2020 and 2050. The curve also increases with return period, but overall, it has a more continued growth in risk.

AAI Maps

Spatial maps are produced to visualise the AAI with different approaches applied to each sector depending on the nature of the assets.

For buildings, two types of maps are developed. The first is based on hexagon aggregation, which highlights clusters of higher annual impacts across the basin. The second shows asset-level centroids, allowing individual buildings with higher expected damages to be identified. These two views complement each other: hexagons provide a regional overview, while centroids highlight localised hotspots.

For agriculture, only the hexagon aggregation is applied, since cropland is represented in grids rather than as individual assets. This allows the distribution of agricultural impacts to be seen across different river valleys and floodplain areas.

For critical infrastructure, only the asset-level representation is used. This reflects the fact that infrastructure is modelled as an individually identified assets, making centroid-level mapping the most meaningful way to show results.

When comparing these maps with the original exposure value maps, several patterns emerge. For buildings, it is clear that the largest cities along the Dnipro show concentrations of impacts, while not all areas within each city are equally affected. For example, Dnipro city stands out as having the largest number of impacted building assets.

For agriculture, the maps show a more even distribution of impacts across multiple river valleys, reflecting the wide spatial extent of cropland. Infrastructure maps highlight specific facilities with high annual damages rather than broad clusters.

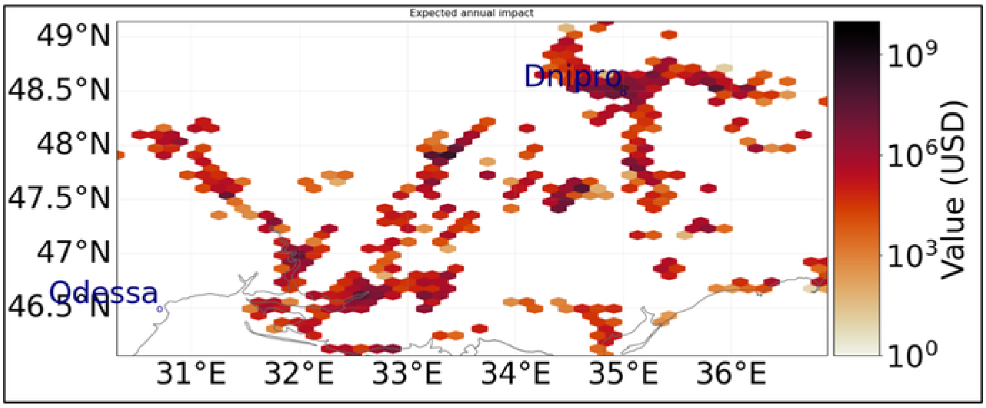

Figure 8. Building AAI map hexagons - The figure shows the AAI for buildings, aggregated using hexagonal grids. Higher AAI values (dark red to black) are concentrated around Dnipro and along major river corridors.

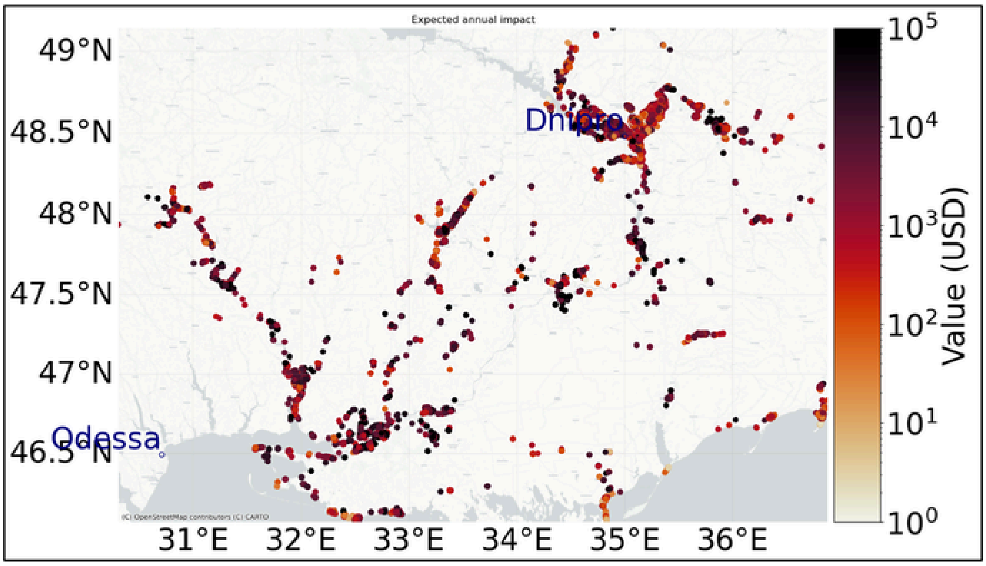

Figure 9. Building AAI map hexagons - The figure shows the AAI for individual buildings. Higher Each point represents a single building, with color indicating the annual flood-related loss value (USD)

AAI Waterfall Plot

To better understand the drivers of change in AAI between 2020 and 2050, a waterfall plot is developed. This figure shows total AAI at the baseline and in the mid-century projection, and decomposes the increase into two components:

- Economic development (exposure growth): the effect of higher asset values in buildings, agriculture, and infrastructure by 2050.
- Climate change (hazard intensity increase): the effect of projected changes in flood hazard under RCP8.5.

For the pre-collapse scenario, the increase in AAI is explained entirely by exposure growth projected with GDP, which can be seen in Figure 10 in orange colour, while the contribution from climate change is negligible or even slightly negative, noted in Figure 11 in green colour. This aligns with the hazard maps, which show almost no change between historical and mid-century conditions across the full Lower Dnipro Basin. A likely explanation is the coarser resolution of the pre-collapse hazard maps (100 m), which smooths out local variations and limits the ability to detect subtle climate-driven changes in flood depth and extent.

In the post-collapse condition, both exposure growth and climate change contribute to the AAI. Which is represented in Figure 11, economic development as reference to exposure growth in orange colour and now a noticeable green colour corresponding with the effect of climate change. This may be due to the higher-resolution modelling, which is more sensitive to projected changes in rainfall and discharge and can capture smaller shifts in flood behaviour. It may also reflect the altered river system after the collapse of the Kakhovka reservoir. The presence of a large reservoir and river regulation in the pre-collapse setup may dampen the climate signal, limiting how much projected changes in precipitation and discharge translate into increased flood hazard. In addition, newly formed floodplains downstream respond differently to future climate forcings.

The same attribution pattern is found for agriculture and infrastructure for both scenarios.

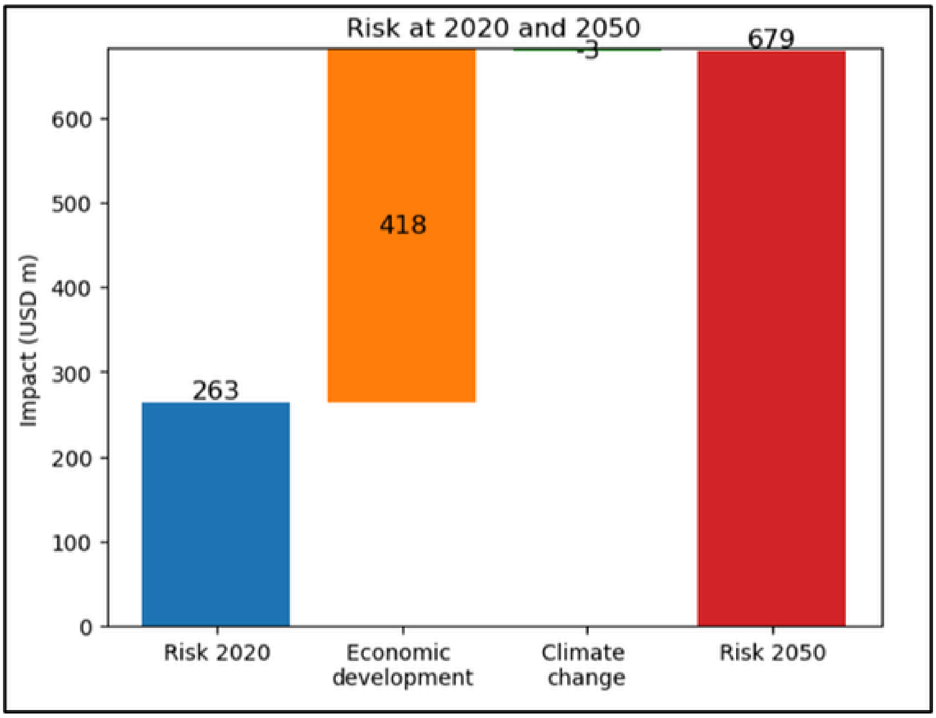

Figure 10. AAI Waterfall plot for buildings - The Figure shows the components of future flood risk drivers. A clear increase in flood risk from 2020 to 2050 in the pre-collapse scenario. The rise is mainly driven by economic development, while the effect of climate change is comparatively minor.

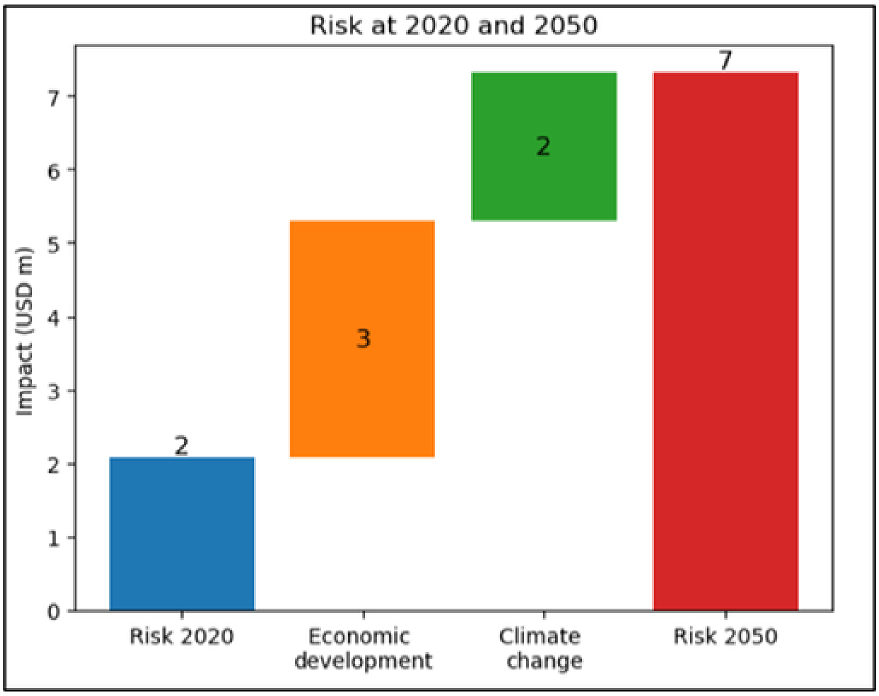

Figure 11. AAI Waterfall plot for buildings - The figure shows the components of future flood risk drivers. It shows a clear increase in flood risk from 2020 to 2050 in the post-collapse scenario. The rise is mainly driven by the economic development, and the effect of climate change.

Adaptation appraisal

The five adaptation measures are evaluated for their ability to reduce the AAI by 2050. Results show that not all interventions deliver the same cost–benefit performance.

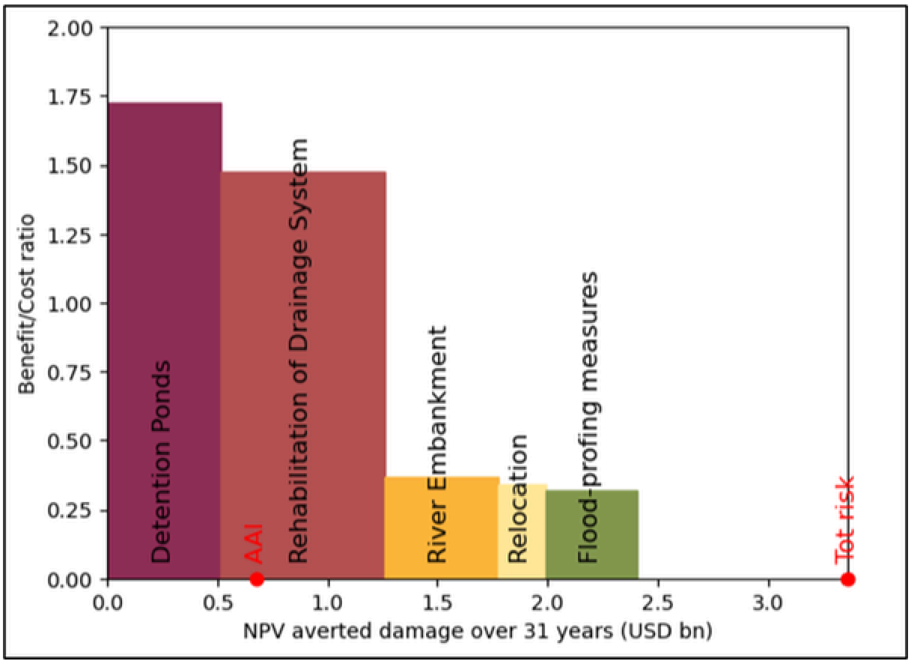

Figure 12. AAI waterfall plot with adaptation measures for buildings. The chart compares different flood risk reduction measures based on their benefit–cost ratios. It shows that detention ponds and rehabilitation of drainage systems provide the highest cost-effectiveness, offering greater benefits relative to their costs. In addition to a representation of the total risk that could be cover by the adaptation measures.

- Detention ponds perform best, with a benefit–cost ratio (BCR) of 1.73, meaning that every USD invested yields almost 1.7 USD in avoided damages.
- Rehabilitation of drainage systems also performs well, with a BCR of 1.48.
- By contrast, river embankments (BCR 0.37), flood-proofing measures (BCR 0.32), and relocation (BCR 0.34) all have benefit–cost ratios well below 1, meaning their costs exceed their benefits under the assumptions used here.

When all measures are combined, the total climate risk for 2050 is estimated at USD$ 3.36 billion, with an average annual risk of USD$ 678.6 million. After applying the selected measures, a residual risk of USD$ 956.5 million remains. These results suggest that, while some interventions can significantly reduce risk in a cost-effective manner, others may be less suitable under current conditions. The appraisal provides an initial indication of where resources could be prioritised, though the analysis remains simplified and would benefit from more detailed, locally specific cost and performance data.

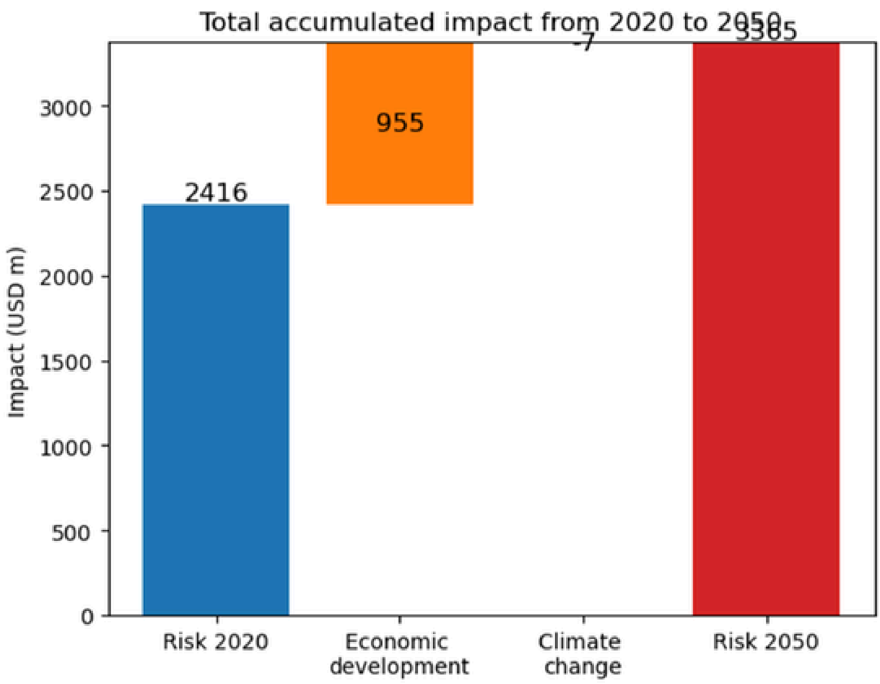

Figure 13. Waterfall plot showing the total accumulated flood impact from 2020 to 2050 and its attribution for the pre-collapse condition. The increase in risk from USD 2,416 million in 2020 to USD 3,385 million in 2050 is driven almost entirely by economic development, while the contribution from climate change is negligible under the assumptions of this scenario.

Uncertainty and validation

Uncertainty in the results comes mainly from climate projections, model resolution, exposure creation, and vulnerability assumptions. The hazard maps are based on results from many different climate models developed within the EURO-CORDEX and Copernicus initiatives. Each model provides a slightly different picture of future conditions. To account for this uncertainty, the assessment does not rely on a single model. Instead, the results are combined to show an average estimate, together with a range of values that reflects most of the model outcomes.

Model resolution also plays a role, with differences between the pre-collapse and post-collapse approaches. Assumptions made during the creation of exposure layers and the assignment of vulnerability functions add further uncertainty.

Validation is carried out by comparing the modelled hazard with local observations and satellite images of river behaviour, and by cross-checking impact estimates against historic flood loss data. These comparisons show that the model reproduces the main patterns of flooding and the order of magnitude of observed impacts reasonably well. While exact matches are not expected given data limitations, the results are found to be consistent with historical evidence, providing confidence that the modelling captures the dominant flood processes and impact levels.

CONCLUSION

The climate risk assessment provides a systematic picture of potential impacts of riverine floods in the Lower Dnipro Basin across the four southern oblasts: Dnipropetrovsk, Zaporizhzhia, Mykolaiv, and Kherson. Results show that critical infrastructure accounts for the largest share of expected annual damages, followed by buildings, with agriculture contributing a smaller portion.

Sector	AAI (2020, Pre-Collapse)	AAI (2050, Pre-Collapse)
Buildings	USD$ 261.7 million	USD$ 678.6 million
Agriculture	USD$ 8.5 million	USD$ 22.3 million
Infrastructure	USD$ 590.6 million	USD$ 1.40 billion

Table 2. AAI by sector for the pre-collapse scenario, comparing baseline conditions in 2020 with mid-century projections (2050)

Within the basin, Dnipro city emerges as the urban centre with the highest number of impacted buildings, while Kherson and Mykolaiv oblasts show significant agricultural exposure, and affected infrastructure is concentrated near Kryvyi Rih and Nikopol. While all sectors are affected, the distribution of impacts differs by region, which has implications for local adaptation priorities.

The post-collapse assessment, taking the destruction of the Kakhovka Dam into account, provides a more detailed view of flood hazard and risk in the downstream section between Zaporizhzhia and Kherson. Although absolute AAI values are lower due to the smaller modelling domain, the finer resolution (30 m) captures localised impacts and reveals a clearer climate change signal than in the pre-collapse assessment. This makes the resolution of the model particularly relevant for reconstruction planning in downstream communities, where asset-level information is crucial for prioritising protective measures.

Frequency curves in the pre-collapse analysis show the increase in damages is most pronounced between 10- and 20-year return period floods, with much smaller changes between 20- and 100-year events. This suggests that medium-frequency events drive most of the risk, and that adaptation measures designed for these levels of flooding will capture the bulk of expected damages. It also implies that such measures are likely to remain effective with continuous climate change since losses of extreme tail events with return periods beyond 20 years are less affected. In the post-collapse case, however, damages continue to grow across the full range of return periods, highlighting the importance of accounting for rare extremes in the downstream reach.

The importance of high-resolution hazard modelling is evident in the comparison between the two scenarios. While the pre-collapse maps at 100 m provided consistent results at basin scale, the 30 m post-collapse model is able to represent finer spatial patterns of hazard and impact, including newly formed floodplains. This demonstrates that investing in higher-resolution data and modelling improves the accuracy and usefulness of risk assessments, especially when results are needed to guide decisions at local or asset level.

Under the exploratory analysis comparing the two modelled conditions, it can be noted that the presence of the Kakhovka Dam altered the natural flow of the Dnipro River, submerging and masking pre-existing floodplains that once provided natural water retention and attenuation capacity. Without the dam, the river has partially returned to a more natural flow regime, reconnecting with these floodplains and redistributing water more evenly across a wider area. This change appears to result in lower modelled flood intensities and a reduction in flood risk within the analysed catchment, although this outcome should be interpreted cautiously given the differences in model resolution and data availability.

The adaptation appraisal shows flood risk protection measures to be cost beneficial because of expected exposure growth as the dominant driver of risk. Climate change alone does not strongly alter flood impacts at basin scale. Among the measures tested, detention ponds (BCR 1.73) and rehabilitation of drainage systems (BCR 1.48) stand out as cost-effective interventions, while river embankments, relocation, and flood-proofing measures show costs exceeding benefits. This highlights the value of cost–benefit analysis in identifying priority measures, ensuring that limited resources are directed towards interventions that provide the greatest return in reduced damages. Beyond these specific results, the methodology applied here could also allow to the test the efficiency of adaptation measures under different cost assumptions. This makes it possible to explore at what cost levels and under which conditions a given measure becomes economically viable. Such flexibility is particularly useful for adaptation planning and project development, where costs can vary depending on design, scale, and implementation context, and supports more informed prioritisation of investments.

Finally, this assessment points to clear opportunities for improvement in future work. The reliability and usefulness of climate risk assessments in Ukraine can be strengthened by developing more detailed exposure datasets under current and future conditions, together with improving hazard models with higher spatial resolution. Together, these steps would enhance the reliability of flood risk assessments and provide even stronger evidence for targeted adaptation and investment planning in the Lower Dnipro Basin.

The results will inform regional investment strategies, recovery planning, and the prioritisation of adaptation projects. Local authorities in Kherson and Mykolaiv could particularly consider integrating these findings into urban and infrastructure planning.

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