Dam Breach Analysis and Damage Assessment of Nova Kakhovka Dam using Satellite data and 1D and 2D Hydrodynamic Modeling

Piyusha B. Kadam[1], Praveen K. Thakur[1*], Sanjay K Dwivedi[2], Vaibhav Garg[1] and Pankja R Dhote[1]
[1]Indian Institute of Remote Sensing (IIRS) Dehradun, 248001, Uttarakhand, India
[2]Indian Institute of Technology (IIT) Roorkee, 247667, Uttarakhand, India
*corresponding author: praveen@iirs.gov.in

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Abstract:

A dam is a man-made structure that crosses a river or other body of water intending to hold water and create a reservoir. When a dam fails, it results in the loss of lives and economic devastation, which directly depends on factors like water depth, velocity, warning time, and the presence of people in the affected area. Dam failure necessitates the use of dam-break modeling, which evaluates the flood characteristics such as the discharge and timing of flood waves resulting from the dam's breach. This study focuses on examining the two breach scenarios of the Kakhovka dam located in Ukraine. The analysis utilized the HEC-RAS software, a widely recognized tool for hydraulic modeling. Multiple breach parameters, including breach width, breach depth, and breach time, were considered to evaluate their impact on downstream flooding. The model is utilized to assess the potential outcomes of a dam break in downstream areas, including factors such as water level rise, travel time of flood waves, flow velocity, and other parameters. The resulting flood plain was also mapped using GIS tools to show the extent of flooding. Damage assessment for the downstream area was also done by using remote sensing based LULC. The study estimated 35962 m^3/sec of peak discharge from the 300-meter dam breach scenario and the flood extent (823 km^2) from this scenario also matched with the actual situation as observed by remote sensing data. These estimations help in understanding and managing the risks associated with structural failures.

1. Introduction and objectives

1.1 Introduction

Dams are classified in a variety of ways, with the most popular classifications based on their function, structure, and design. (https://www.ussdams.org/types-of-damsv2/). There are several advantages to building dams on rivers, including the provision of drinking and agricultural water, water for urban and industrial requirements, ease of navigation, generation of electricity, and flood protection (Jain et al., 1998). A dam break refers to the failure of a dam, which can be either partial or catastrophic, resulting in the uncontrolled release of water. Dam failures can occur due to various factors such as seepage, piping, insufficient freeboard (Bharti et al., 2020). Dam breach modeling is essential to avoid flood-like situations or provide early services to flood-prone areas after a dam breach, which can be done using different hydrological modeling software (Psomiadis et al., 2021). This estimation helps in planning emergency measures effectively.

HEC-RAS is a computer program that simulates the hydraulic behavior of water flow in rivers and channels. It is specifically designed to calculate 1D and 2D hydraulic scenarios involving natural and man-made channels, floodplain areas, and overbank regions. 1D Saint Venant's equations are used as the fundamental equations in the HEC-RAS software to analyze unsteady flow scenarios (USACE-HEC, 2022). The following equations can be run using the HEC-RAS two-dimensional computational module: 2D Diffusion Wave equations, Shallow Water Equations (SWE-ELM) using an Eulerian-Lagrangian method to solve for advection, or a novel Shallow Water Equation solver (SWE-EM) (USACE-HEC, 2022).

Many studies have been done for dam breach simulation using this software such as, (Bharath et al., 2021) used a one-dimensional hydraulic model called HEC-RAS to investigate the possibility of a dam break at the Hidkal Dam. The HEC-GeoRAS tool is used in conjunction with a digital elevation model (DEM) called Cartosat-1 to collect data on the river's shape and generate maps of the affected areas. They predicted breach characteristics such as breach flood hydrograph, peak flow, and flood arrival time in this study. The breach outflow hydrograph and hydraulic conditions at critical downstream locations were determined using the HEC-RAS tool. Dynamic flood wave routing is also used to simulate the path of the breach outflow.

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1.2 Study objectives

For the present research work, following are the main objectives, 1) Dam breach simulations of Kakhovka Dam in the geospatial environment using 1D and 2D hydrodynamic modeling. 2) Flood inundation mapping using remote sensing and hydrodynamic modeling outputs and damage assessment.

2. Study area, data used and methods

The study was conducted on the Kakhovka dam. The dam is located at 46°46'45.76"N latitude 33°22'13.50"E longitude in Kherson Oblast, Ukraine. The total study area is 332.9 km long, including a 240 km long reservoir and a 92.9 km downstream area of the reservoir (figure 1). Elevation of the area is up to 254 meters. The dam was built on the Dnipro (Dnieper) River, which stretches from the northern reaches of Ukraine into the Black Sea, and with average discharge of 1670 m^3/sec. An earth-fill embankment dam with gravity sections, standing at a height of 30 meters has been built on the Dnipro River during Soviet Union time, with installed hydropower capacity of 357MW.

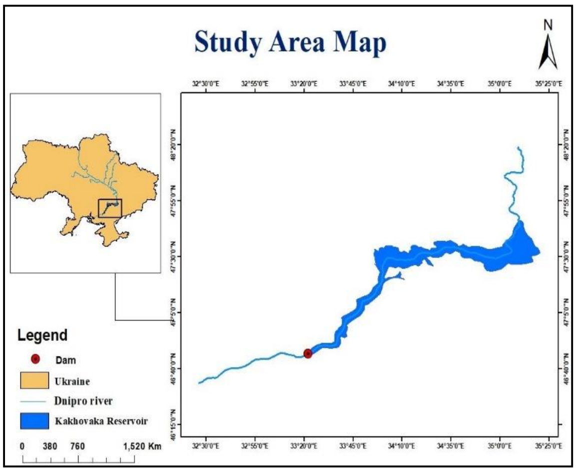

Figure 1. Location map of Nova Kakhovka dam, Ukraine.

The dam's construction was finalized in 1956 and dam break happened on 6 June 2023. The reservoir formed by the dam covers a surface area of 2155 square kilometers (832 sq mi). It is 240 Km long and up to 23 km wide. It has a total capacity of 18.2 cubic kilometers. The depth of the reservoir varies from 3 to 26 m and averages 8.4 meters.

2.2 Data used

The data used in this study is summarized in the table 1. Most of the satellite and geospatial data is freely available and open source hydrodynamic model is for dam break induced flood simulations.

Table 1: Data used summary for the present study

Data Use	Data Source
ALOS 3D DEM (30m × 30m)	open topography (https://opentopography.org/)
Landsat 9 Optical image	USGS Earth Explorer https://earthexplorer.usgs.gov/
Reservoir and Dam parameters	Britishdaily newspaper (https://www.theguardian.com/world/2023/jun/06/nova-kakhovka-dam-everything-you-need-to-know-about-ukraines-strategically-important-reservoir)
River Discharge	Britannica (https://www.britannica.com/place/Dnieper-River/Hydrology)
Country shape file	Diva GIS (https://www.diva-gis.org/gdata)
Land Use land Cover (LULC) tile	ESRI Sentinel 2 (https://www.arcgis.com/apps/instant/media/index.html?appid=fc92d38533d440078f17678ebc20e8e2)

2.3 Methods used and Hydrodynamic model setup

The main flow chart used for this work is shown in figure 2. The software used for this study was HEC-RAS 6.3.1 (Hydraulic Engineering Centre River Analysis System), which is free downloadable software developed by the US Army Corps of Engineers Hydrologic Engineering Centre (USACE-HEC, 2022).

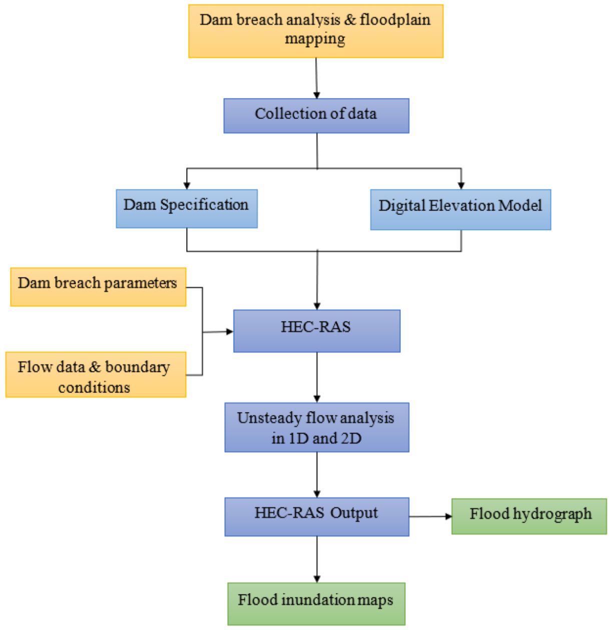

Figure 2. Location map of Nova Kakhovka dam, Ukraine.

For setting up the model in HEC RAS, first the DEM was imported into the RAS mapper, and the terrain was created and overlain Google Satellite in HEC-RAS as shown in Figure 3. Using the geometric data tool of HEC-RAS, the storage area, its downstream area, and dam structure were drawn in RAS Mapper as in Figure 3. The Manning roughness coefficient value is assumed to be 0.025 for bare ground, 0.08 for trees, 0.04 for water, 0.05 Figure 4.1: Geometry Used in Simulation for crops, 0.03 for urban, 0.05 for wet, and 0.035 for no data. Also, the percent impervious is assigned 0 for trees, bare ground, crops, and no data land cover, and 100 for both water and urban.20 for wetland.

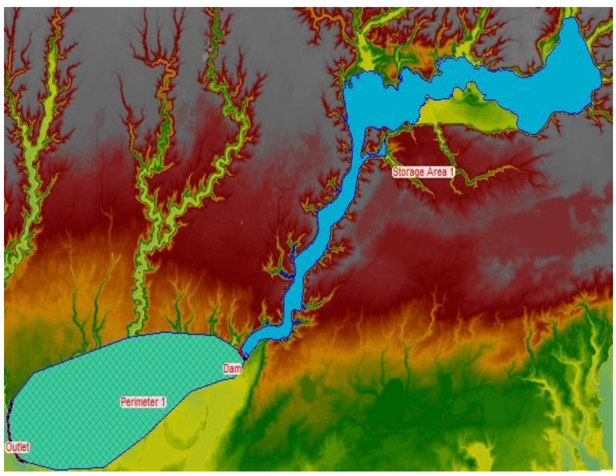

Figure 3. Location map of Nova Kakhovka dam with upstream and downstream, Ukraine, as imported in RAS mapper.

Parameters for geometries were added in the edit geometry tool, the mesh having a 50 x 50 mesh size is forced for the downstream area. The elevation volume curve was generated using elevation data and the maximum storage capacity of the reservoir. Also, the structure was added between the downstream perimeter area and storage area. dam parameters such as dam width and dam station elevation were set shown in figures 4 and 5. Breaching parameters for dam breach such as breach width, breach elevation, and breaching time were set in breach (plan data) (Leoul et al., 2019). In this analysis scenarios with two different breach widths as 300 meters and 600 meters were considered as shown in figures 5 and 5 respectively.

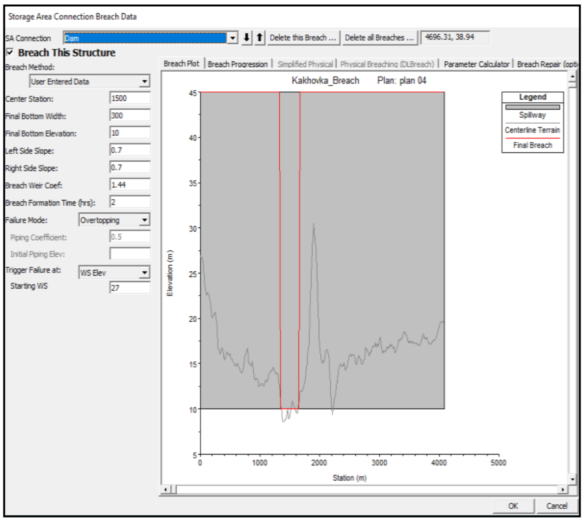

Figure 4: Dam breaching parameters having a breach width of 300 meters in RAS geometry editor

The unsteady flow analysis is done by using boundary conditions as 0.01 normal depth for the outlet and. Model were run by using unsteady flow. Computation was done for 1-minute time step and 1- hour mapping interval. For the period from 6 June 2023 to 20 June 2023. A flood plain was get generated in the RAS mapper.

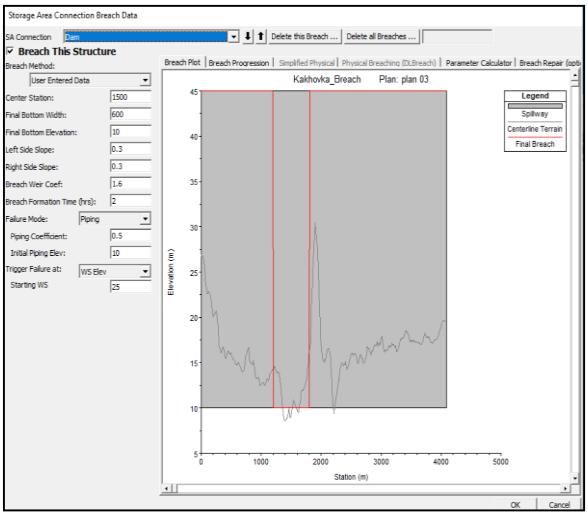

Figure 5: Dam breaching parameters having a breach width of 600 meters in RAS geometry editor

For 1-D hydrodynamic (HD) simulations, the geometry was created in the RAS mapper. The river, bank line, food plan, and cross sections were generated in the RAS mapper shown in Figure 6. For the boundary conditions, an inflow breach hydrograph (figure 7) was applied for the first cross-section, and normal depth is applied for an outlet. The inflow hydrograph was generated by considering a peak of 30000 m^3/sec which is having an area under the curve approximately equal to the capacity of the total reservoir. As the reservoir gets fully empty up to 20 June the breach hydrograph was generated from 5 June to 20 June having a 1-hour time step and, the simulation was run from 5-20 June 2023, having a computational interval of 1 minute and a mapping interval of 1 Hour.

Figure 6: Geometry for 1D simulation in HECRAS

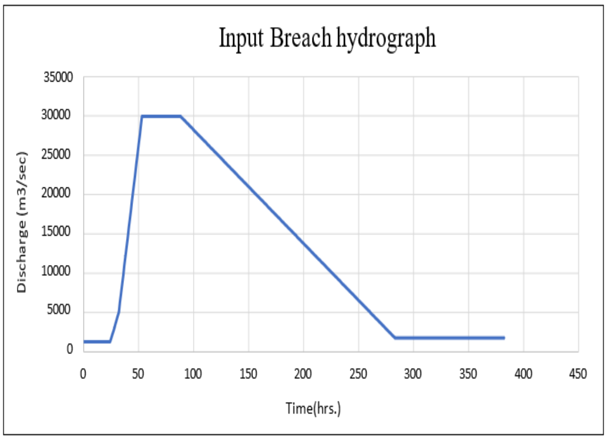

Figure 7: Input boundary inflow hydrograph

The floodplain results from the RAS mapper were exported as a raster layer and imported into ARC GIS. By using these raster layers' floodplain maps were generated as given in methodology flowchart (figure 2).

3. Results and Discussions

This section provides the main results and discussions for 1-D and 2-D hydrodynamic simulations due to dam breach, as well as damage assessment due to floods and as observed by satellite datasets.

3.1 Dam Break hydrodynamic simulations

The main results of 2-D unsteady flood simulations are shown in the figure 8 with the breaching hydrograph when the breaching width is 300 meters. For this breach width, the peak discharge of 35962 m^3/sec was observed. The peak discharge occurred on 6 June 2023. Figure 9 shows the flood inundation area during the maximum inundation. With this breach width, the total area of this flood inundation was 823 Sq. Km. This inundation was validated from post-flood satellite imagery.

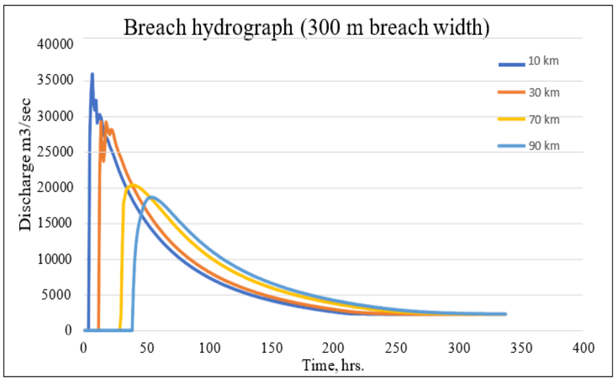

Figure 8: Outflow breach hydrograph at different downstream locations from dam breach for the period of 5-20 June 2023.

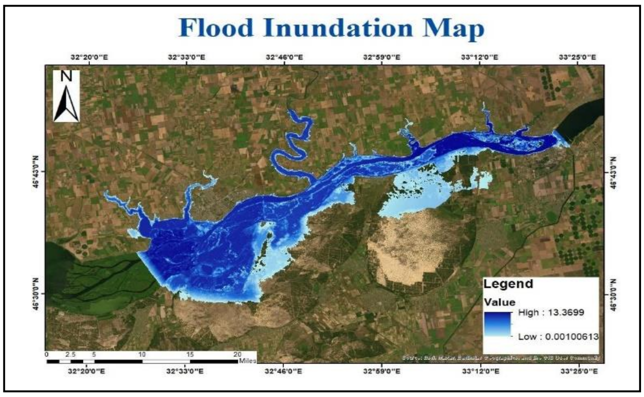

Figure 9: Flood inundation when breach width is 300 meters.

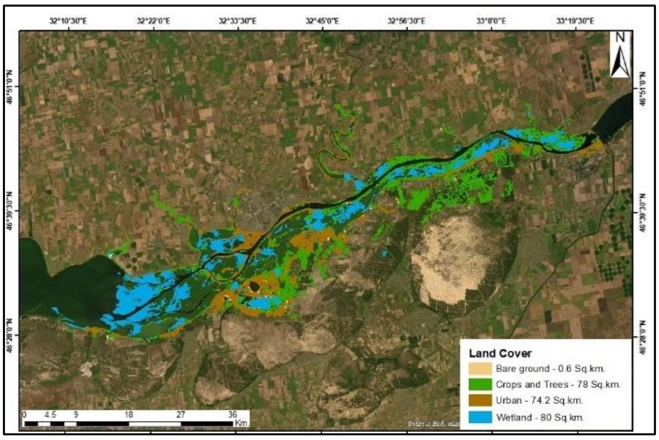

Figure 10: Damage assessment map (300-meter breach).

The flood damaged area is estimated by overlaying the simulated flood inundation map with existing LULC map. The figure 10 shows the flood damaged LULC classes with area in km^2.

Similarly, results of 2-D unsteady flood simulations with breaching hydrograph with breach width of 600 meters are shown in the figure 11 and figure 12. For this breach width, the peak discharge of 48466 m^3/sec was get observed. The peak discharge occurred on 6 June 2023. Figure 12 shows the total flood inundation area during the maximum inundation, which is 873.60 Sq. km. The figure 13 shows the flood damaged LULC classes with area in km^2 for the 600m breach width with 2D HD simulations.

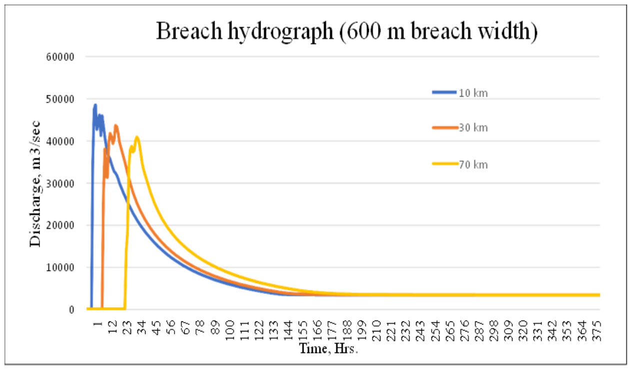

Figure 11: Outflow breach hydrograph at different downstream locations from dam breach for the period of 5-20 June 2023

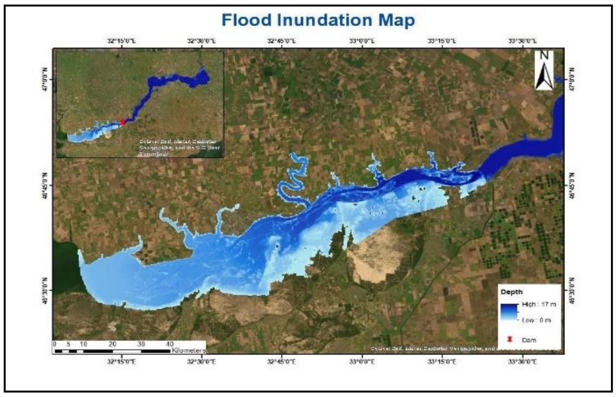

Figure 12: Flood inundation when breach width is 600m

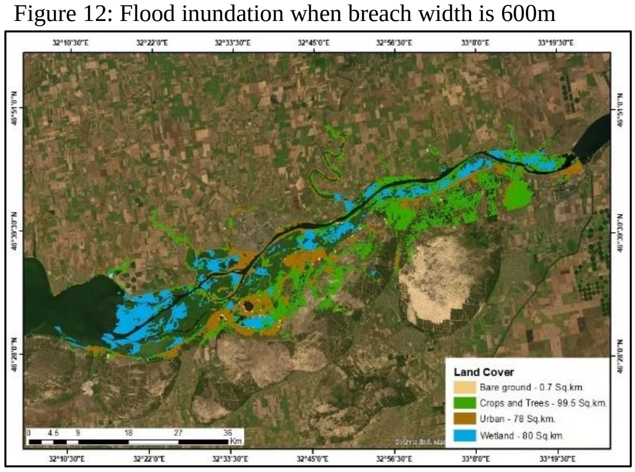

Figure 13: Damage assessment map (600-meter breach).

The main results of 1-D unsteady flood simulations are shown in the figure 14, 15 and 16. Figure 14 shows the downstream hydrographs at different location from dam breach site, the graph shows as the distance from dam increases the peak also get shifted to right. The peak discharge got from this 1D unsteady simulation is estimated as 29994 m^3/Sec. which was observed on 8 June 2023 16:00 hours. The figure 15 map shows the total inundation area of the downstream side of the Kakhovka dam. After this 1D unsteady analysis, we got the depth of the water ranges from 0.001 to 13.36 m. Total flood inundation area is estimated as 681 km^2 when the flood depth is maximum. The water depth in the Kherson city ranges from 2 to 5 meters. Also, according to this simulation, the 109.611 Sq. km of urban area got affected.

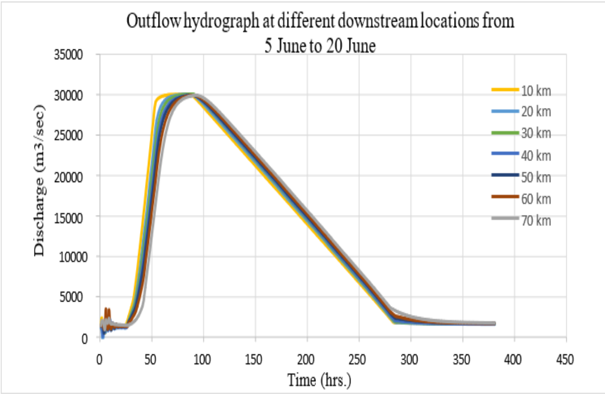

Figure 14: Outflow breach hydrograph at different downstream locations from dam breach for the period of 5-20 June 2023.

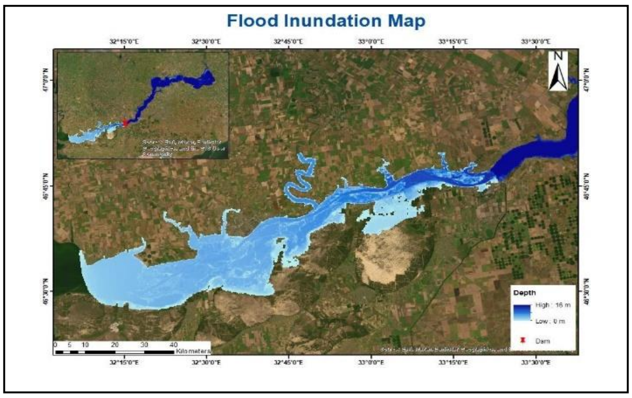

Figure 15: Flood inundations 1D HD simulations (300m breach)

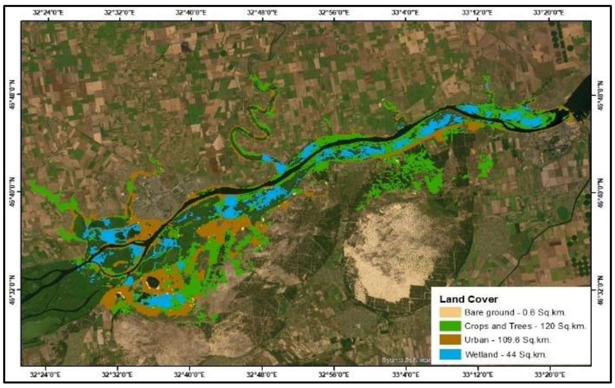

Figure 16: Damage assessment map (1D HD simulations).

4. Conclusions

The downstream impact of the Kakhovka dam break has been simulated in terms of flood hydrograph, flood duration, water elevation, and flood map. For 300 meters of dam breach width peak discharge is 35962 m^3/sec and the total inundated area is 823 km^2. For 600 meters of dam breach width peak discharge is 48466 m^3/sec and the total inundated area is 874 km^2. Results for the floodplain from 300 meters of dam breach width appear to be similar to the actual floodplain after the dam breach at the dam’s downstream side. The peak discharge estimated from this 1D unsteady simulation is 29994.31 m^3/Sec. which is observed on 8 June at 16:00 and the total inundated area is equal to 680.8 km^2. Also, in both 1D and 2D results we got the water depth in Kherson city as 5 meters on 8 June 2023, which is similar to the actual water depth on 8 June 2023. The satellite data of pre and post flood also matches with the HD simulations. Further, using the actual elevation volume curve for the dam, as well as better DEM data, more accurate results can be obtained from such HD modelling. Daily to sub-daily remote sensing data from commercial platforms such as Planet labs can also be used to validate the actual flood inundation scenarios.

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Supplementary data

The following figure shows the pre and post Kakhova dam break (during 1, 9 June 2023) river and flood flows scenarios using Landsat 8 and 9 satellite datasets.

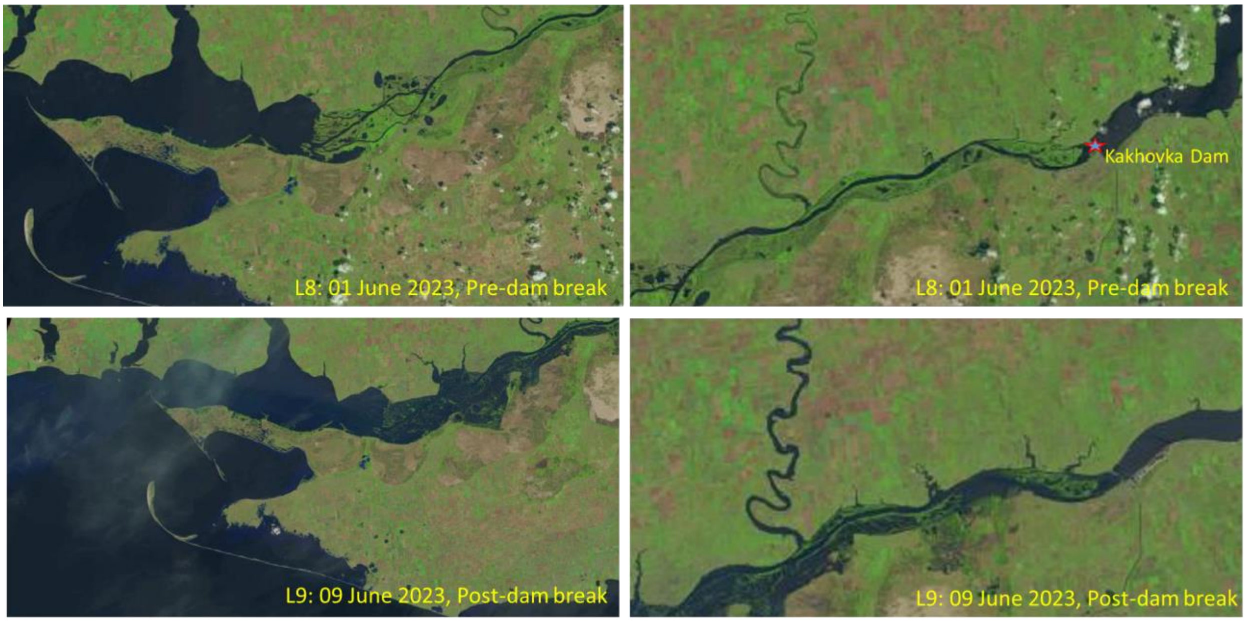

Figure S1: Pre and post satellite images form Landsat 8/ 9 datasets