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Modeling Mine Tailing and Water Dam Failures in Armenia

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Outline

- Types of Studied Dams
- Historical Dam Failure Events
- Dam Failure Modes and Breach Characteristics
- Peak Flow Calculation
- Flood Modeling Basics
- Popular Dam Break Software
- Required Data for Dam Break Analysis/Flood Mapping
- Flood Hazard Index Calculation
- River Maximum Flow Calculation
- Dam Breach Maximum Outflow and Breach Hydrograph Calculation for Studied Dams
- Example of Dam Break Flood Map

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Types of Studied Dams

Water Reservoir Dams (Geghi)

A **water reservoir** is an enclosed area for the storage of water to be used at a later date. It can also serve to catch floods to protect valleys downstream of it, to establish an aquatic environment, or to change the properties of the water.

Tailing Storage Facility (TSF) Dams (Geghanoush)

A **tailings storage facility (TSF)** is a structure made up of one or more dams built for the purposes of storing the uneconomical ore (ground up rock, sand and silt) and water from the milling process.

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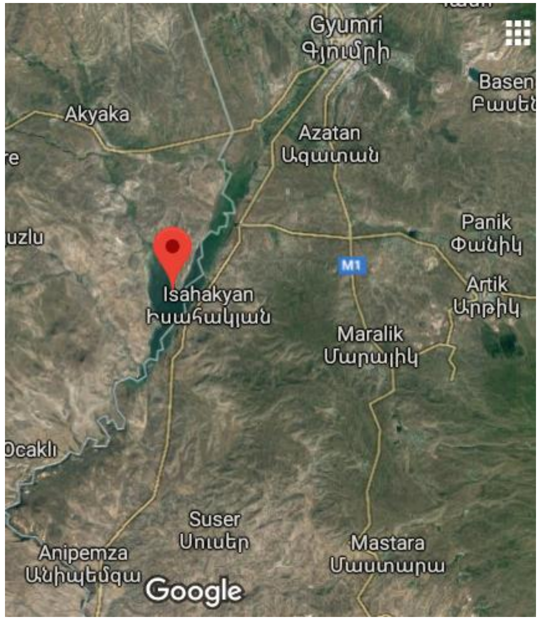
Water Reservoirs in Armenia

- About 80 Water Reservoirs
- Total Volume: ~988 Million m^3
- Largest Reservoir: **Akhuryan**, 525 Million m^3
- Purposes:
  - Irrigation
  - Energetics
  - Flow regulation
  - Fish-farming
  - Recreational



Tailing Storage Facilities in Armenia

23 TSFs (15 operational, 8 closed)

9 TSFs in Syunik Province

Largest TSF: **Artsvanik**, 212 Million m^3/288ha

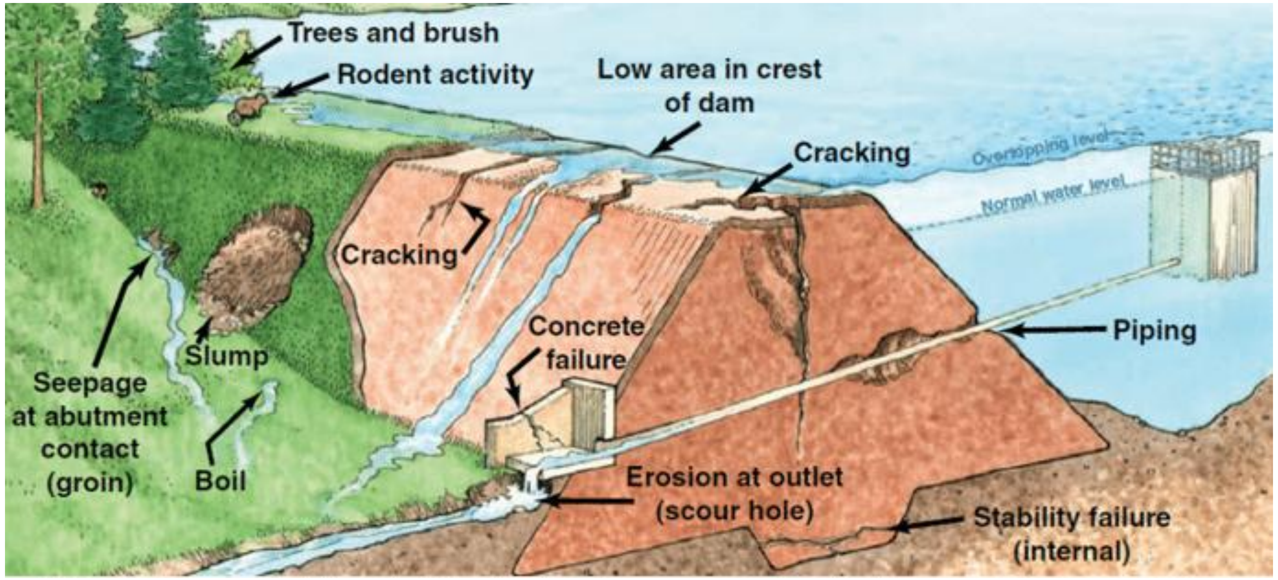
Owner: Zangezur Copper-Molybdenum Combine

Dam Failure (Break)

Catastrophic type of failure characterized by the sudden, rapid, and uncontrolled release of impounded water.

Dam Failure Causes

- Flood event
- Landslide
- Earthquake
- Foundation failure
- Structural failure
- Piping/seepage (internal and underneath the dam)
- Rapid drawdown of pool
- Planned removal
- Terrorism act



Teton Dam Failure, Teton River, Idaho, June 5, 1976

- Type: Earthen dam
- Cause: Piping/seepage
- Deaths: 11 people and 13,000 cattle
- Financial losses: 300 Million USD
- Water volume at the time of dam failure: 310,466,916 m^3
- Maximum outflow: 57,000 m^3/s
- Reservoir emptied in 8 hours

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Malpasset Dam Failure, Frejus, France, December 2, 1959

- Type: Arch dam
- Cause: Flaws in design of the dam (located on tectonic fault)
- Deaths: 423 people
- Financial losses: 480 Million USD
- Water volume at the time of dam failure: 50,000,000 m^3

Fundão TSF Dam Failure, Mariana, Minas Gerais, Brazil, November 5, 2015

- Type: Upstream tailings dam
- Cause: Flaws in design of the dam
- Deaths: 19 people
- Financial losses: 5.3 Billion USD
- Released volume of tailings: 43,000,000 m^3 (80% of total contained volume)
- **Irreversible environmental damage**

Ajka TSF Dam Failure, Ajka, Veszprém County, Hungary, October 4, 2010

- Type: Earthen dam
- Cause: Flaws in design of the dam
- Deaths: 10 people
- Financial losses: 642 Million USD
- Released volume of tailings: 700,000 m^3 (70% of total contained volume)
- **Irreversible environmental damage**

Geghi Dam Failure, May 15, 2010






Geghi-Kavchut – 87.5m^3/s, Voghji-Kapan – 133m^3/s

Dam Failure and Flood Modelling Questions

- What will be the characteristics of the breach?
- How the maximum flow and hydrograph will look like?
- How long will it take for the reservoir to be emptied?
- What will be the extent, area and depth of the flood associated to the dam failure?
- When the flood wave will reach the certain location?

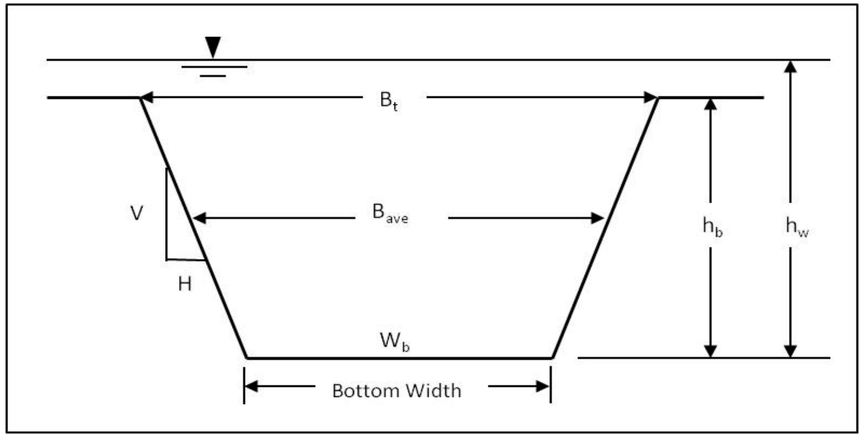
The two primary tasks in the analysis of a potential dam failure are the prediction of the reservoir outflow hydrograph and the routing of that hydrograph through the downstream valley to determine dam failure consequences.

Possible Failure Modes for Various Dam Types

Failure Mode	Earthen/ Embankment	Concrete Gravity	Concrete Arch	Concrete Buttress	Concrete Multi-Arch
Overtopping	X	X	X	X	X
Piping/Seepage	X	X	X	X	X
Foundation Defects	X	X	X	X	X
Sliding	X	X		X	
Overturning		X	X		
Cracking	X	X	X	X	X
Equipment failure	X	X	X	X	X

Possible Values for Breach Characteristics
(US Federal Agency Guidelines)

Dam Type	Average Breach Width (B_{ave})	Horizontal Component of Breach Side Slope (H) (H:V)	Failure Time, t_f (hours)	Agency
Earthen/Rockfill	(0.5 to 3.0) x HD	0 to 1.0	0.5 to 4.0	USACE 1980
	(1.0 to 5.0) x HD	0 to 1.0	0.1 to 1.0	FERC
	(2.0 to 5.0) x HD	0 to 1.0 (slightly larger)	0.1 to 1.0	NWS
	(0.5 to 5.0) x HD*	0 to 1.0	0.1 to 4.0*	USACE 2007
Concrete Gravity	Multiple Monoliths	Vertical	0.1 to 0.5	USACE 1980
	Usually ≤ 0.5 L	Vertical	0.1 to 0.3	FERC
	Usually ≤ 0.5 L	Vertical	0.1 to 0.2	NWS
	Multiple Monoliths	Vertical	0.1 to 0.5	USACE 2007
Concrete Arch	Entire Dam	Valley wall slope	≤ 0.1	USACE 1980
	Entire Dam	0 to valley walls	≤ 0.1	FERC
	(0.8 x L) to L	0 to valley walls	≤ 0.1	NWS
	(0.8 x L) to L	0 to valley walls	≤ 0.1	USACE 2007
Slag/Refuse	(0.8 x L) to L	1.0 to 2.0	0.1 to 0.3	FERC
	(0.8 x L) to L		≤ 0.1	NWS



Dams that have very large volumes of water, and have long dam crest lengths, will continue to erode for long durations (i.e., as long as a significant amount of water is flowing through the breach), and may therefore have longer breach widths and times than what is shown in Table. HD = height of the dam; L = length of the dam crest; FERC - Federal Energy Regulatory Commission; NWS - National Weather Service

Regression Equations for the Breach Characteristics

- Froehlich (1995a)
- Froehlich (2008)
- MacDonald and Langridge-Monopolis (1984)
- Von Thun and Gillette (1990)
- Xu and Zhang (2009)

$$B_{ave} = 0.1803 K_0 V_w^{0.32} h_b^{0.19} \qquad t_f = 0.00254 V_w^{0.53} h_b^{-0.90}$$

$$B_{ave} = 0.27 K_0 V_w^{0.32} h_b^{0.04} \qquad t_f = 63.2\sqrt{\frac{V_w}{g h_b^2}}$$

$$V_{eroded} = 0.0261 (V_{out} \times h_w)^{0.769} \qquad t_f = 0.0179 (V_{eroded})^{0.364}$$

$$B_{ave} = 2.5 h_w + C_b \qquad t_f = 0.02 h_w + 0.25$$

$$\frac{B_{ave}}{h_b} = 0.787 \left(\frac{h_d}{h_r}\right)^{0.133} \left(\frac{V_w^{1/3}}{h_w}\right)^{0.652} e^{B_3}$$

B_{ave} = average breach width (meters)
t_f = breach formation time
V_w = reservoir volume at time of failure (cubic meters)
h_b = height of the final breach (meters)
h_d = height of the Dam (meters)
h_r = fifteen meters, is considered to be a reference height for distinguishing large dams from small dams

h_w = height of the water above the breach bottom elevation at time of breach (meters)
V_{eroded} = volume of material eroded from the dam embankment (cubic meters)
V_{out} = volume of water that passes through the breach (cubic meters)
K_o = constant (1.4 for overtopping failures, 1.0 for piping)
C_b = coefficient, which is a function of reservoir size
B_3 = coefficient that is a function of dam properties

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Physically-Based Embankment Dam Breach Computer Models

Model and Year	Sediment Transport	Breach Morphology	Parameters	Other Features
Cristofano (1965)	Empirical formula	Constant breach width	Angle of repose, others	
Harris and Wagner (1967) **BRDAM (Brown and Rogers, 1977)**	Schoklitsch formula	Parabolic breach shape	Breach dimensions, sediments	
Lou (1981); **Ponce and Tsivoglou (1981)**	Meyer-Peter and Müller formula	Regime type relation	Critical shear stress, sediment	Tailwater effects
BREACH (Fread, 1988)	Meyer-Peter and Müller modified by Smart	Rectangular, triangular, or trapezoidal	Critical shear, sediment	Tailwater effects, dry slope stability
BEED (Singh and Scarlatos, 1985)	Einstein Brown formula	Rectangular or trapezoidal	Sediments, others	Tailwater effects, saturated slope stability
FLOW SIM 1 and FLOW SIM 2 (Bodine, undated)	Linear predetermined erosion; Schoklitsch formula option	Rectangular, triangular, or trapezoidal	Breach dimensions, sediments	

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Peak Flow Calculation

- **USBR (1982):** $Q = 19.1(h_w)^{1.85}$
- **MacDonald and Langridge-Monopolis (1984):** $Q = 3.85(V_w h_w)^{0.411}$
- **Froehlich (1995b):** $Q = 0.607{V_w}^{0.295}{h_w}^{1.24}$
- **Xu and Zhang (2009):** $\frac{Q}{\sqrt{g{V_w}^{5/3}}} = 0.175\left(\frac{h_d}{h_r}\right)^{0.199}\left(\frac{{V_w}^{1/3}}{h_w}\right)^{-1.274} e^{B_4}$
- **Kirkpatrick (1977):** $Q = 1.268(h_w + 0.3)^{1.24}$
- **Soil Conservation Service (SCS,1981):** $Q = 16.6(h_w)^{1.85}$
- **Hagen (1982):** $Q = 0.54(h_d)^{0.5}$
- **Singh & Snorrason (1984):** $Q = 13.4(h_d)^{1.89}$; $Q = 1.776(S)^{0.47}$
- **Costa (1985)**: $Q = 2.634(S\, h_d)^{0.44}$
- **Evans (1986):** $Q = 0.72(V_w)^{0.53}$

Q = peak breach outflow (cubic meters per second)
h_w = depth of water above the breach invert at time of breach (meters)
V_w = volume of water above breach invert at time of failure (cubic meters)
S = reservoir storage for water surface elevation at breach time (cubic meters)
h_d = height of dam (meters)
h_r = fifteen meters, which is considered to be a reference height for distinguishing large dams from small dams
B_4 = $b_3+b_4+b_5$ coefficients that are a function of dam properties
b_3 = -0.503, -0.591, and -0.649 for dams with corewalls, concrete faced dams, and homogeneous/zoned-fill dams, respectively
b_4 = -0.705 and -1.039 for overtopping and seepage/piping, respectively
b_5 = -0.007, -0.375, and -1.362 for high, medium, and low dam erodibility, respectively.

Tailing Dam Breach Outflow Calculation

$\log(V_F) = -0.477 + 0.954\log(V_T)$ or $V_F = 0.332 \times {V_T}^{0.95}$ $R^2 = 0.887$; standard error: 0.315

$\log(D_{max}) = 0.484 + 0.545\log(H_f)$ or $D_{max} = 3.04 \times {H_f}^{0.545}$ Residual standard error= 0.658

V_F - volume of tailings that could potentially be released, Million m^3
D_{max} - distance to which the material may travel in a downstream channel (run-out distance), km
V_T- total impounded volume in TSF, Million m^3

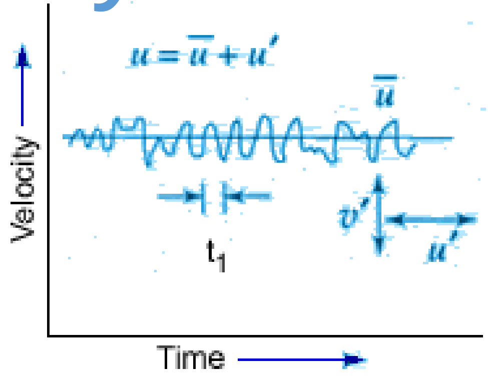
H_F – predictor. $H_F = H \times \left(\frac{V_F}{V_T}\right) \times V_F$

*Method is based on the statistical analysis of 28 TSF dam failure events

Fluid Dynamics: Steady and Unsteady Flow

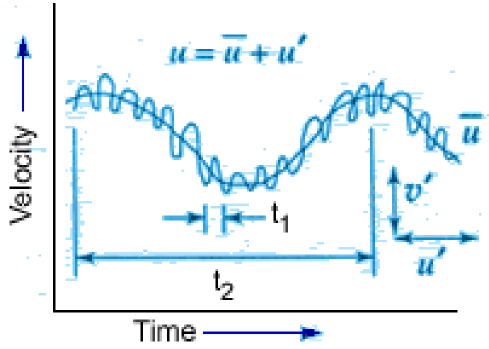
- Steady flow means the fluid characteristics* at any point in the flow field does not change with respect to time.

$$\frac{\partial P}{\partial T} = 0, \frac{\partial V}{\partial T} = 0, \frac{\partial \rho}{\partial T} = 0$$



- If the fluid characteristics at a point change over time, then the flow is unsteady.

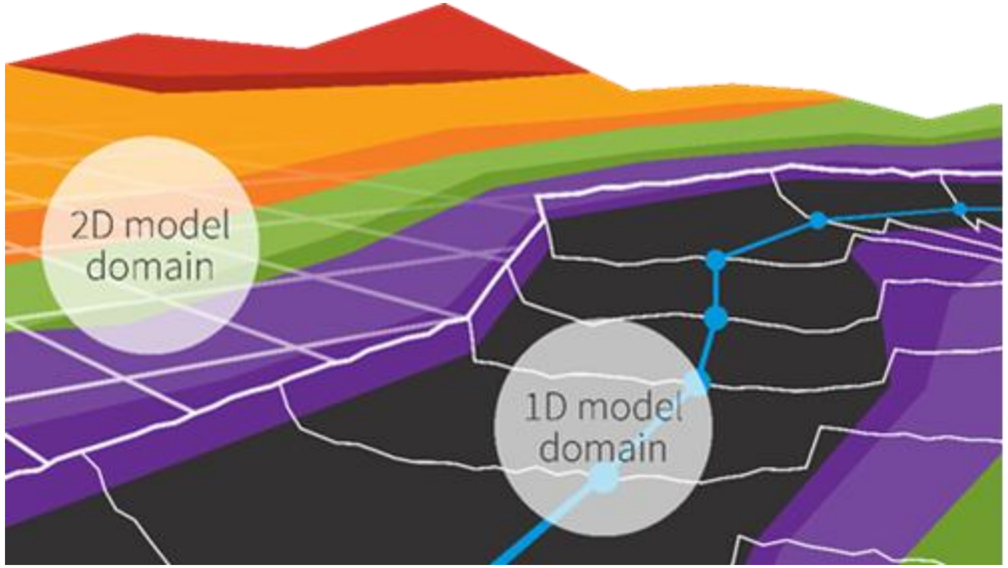
$$\frac{\partial P}{\partial T} \neq 0, \frac{\partial V}{\partial T} \neq 0, \frac{\partial \rho}{\partial T} \neq 0$$



*Fluid characteristics: pressure; velocity; density

1D and 2D Flood Modeling

One-dimensional	Two-dimensional
Flow velocity perpendicular to the cross section considers	Speed in different directions are considered
Ability to model the flow is permanent and non-permanent	Ability to model the flow is turbulent
Only the channel cross sections are defined	Model in computational mesh is divided into small pieces
Average speed in cross-section considers	Flow rate can vary



Manning Equation and N Values

- Roughness coefficients represent the resistance to flow in channels and floodplains.
- Roughness is usually presented in the form of a Manning's *n* value in dam break software.
- The actual selection of *n* values to be used for each dam assessment will require judgment by the engineer responsible for hydraulic model development.
- Significant turbulence, sediment load and debris should be expected for the immediate reach downstream of a failed dam.
- Manning's roughness coefficient of the main channel (compiled by Dr. Jarret c using ross sectional shape, flow rates, and water surface elevations at 21 locations for a total of 75 events:

$$n = 0.39\, S^{0.38}\, R^{-0.16}$$

where:

n = Manning's roughness coefficient of the main channel
S = energy slope (slope of the energy grade line, feet/feet)
R = hydraulic radius of the main channel (feet).

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Comparison of Dam Break Software (1)

Software	Developer	Dimension	Fluid Dynamics	Model Input	Model Output	Price, USD
BOSS-DAMBRK (FLDWAV)	BOSS International (now part of Autodesk)	1D	Unsteady State	Typical breach parameters or hydrograph; Cross-section data; Bridge/culvert geometry or rating curves	High water profiles; Flood arrival times; Hydrographs at selected locations	1495
DSS-WISE = "The Decision Support System for Water Infrastructural Security"	Funded by DHS, developed by the NCCHE at Ole Miss	2D	Steady/unsteady state	Typical breach parameters (for partial breach scenario); Automatically utilizes NED, NBI, NID, & NLCD	Inundation area; Arrival time shapefile; Max Depth shapefile; Summary report	Freeware
HEC-RAS 1D	US Army Corps of Engineers	1D	Steady/unsteady state	Cross section geometry, reach lengths, Mannings n Discharge: peak flow (steady-state), hydrograph (unsteady-state) Breach parameters or breach hydrograph	Water surface elevation average velocity, and other variables for each cross section Depth grids, velocity grids using RASMAPPER	Freeware
HEC-RAS 1D	US Army Corps of Engineers	1D/2D	Steady/unsteady state	Typical HEC-RAS setup, plus elevation data to define 2D area	Typical HEC-RAS output (1D); Gridded Depths; WSELs; Velocities at max and at time-steps	Freeware

Comparison of Dam Break Software (2)

Software	Developer	Dimension	Fluid Dynamics	Model Input	Model Output	Price, USD
FLO-2D	FLO-2D Software, Inc.	1D/2D	Steady/Unsteady state	Typical breach parameters, physical breach parameters (NWS-BREACH) or imported hydrograph; Elevation dataset; Roughness parameters	Grid and/or shaded contour plots of depth, velocity, impact force; Animation of data; Numerous plots, tables that can be constructed for individual cells; Volume monitoring	Basic – Freeware; Pro -995$/year
MIKE 11/21/FLOOD	DHI	1D/2D	Steady/unsteady state	Breach parameters; Cross-section and/or elevation data; Roughness parameters, etc.	Gridded Depths, velocities at max and at time-steps; Animation of data; Timesteps	Requested
Volna	«Titan-Optima» Ltd.	1D	Steady/unsteady state	Dam and breach parameters; Downstream elevation data; Cross-section data.	Maximum discharges and velocities in cross-sections; Timesteps.	285 USD (older version is freeware)

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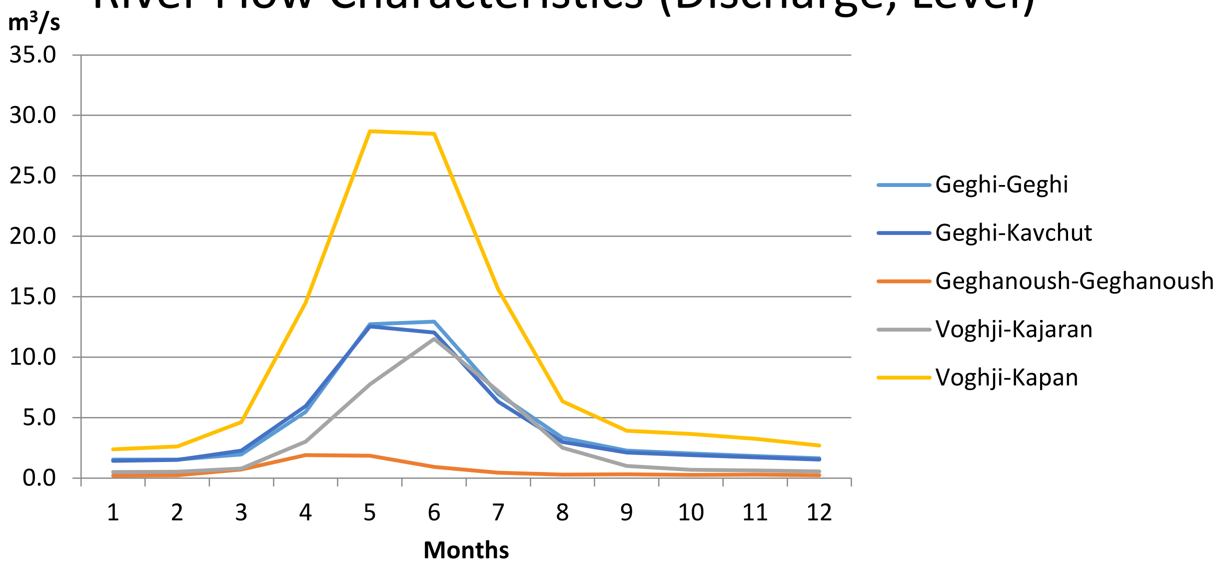
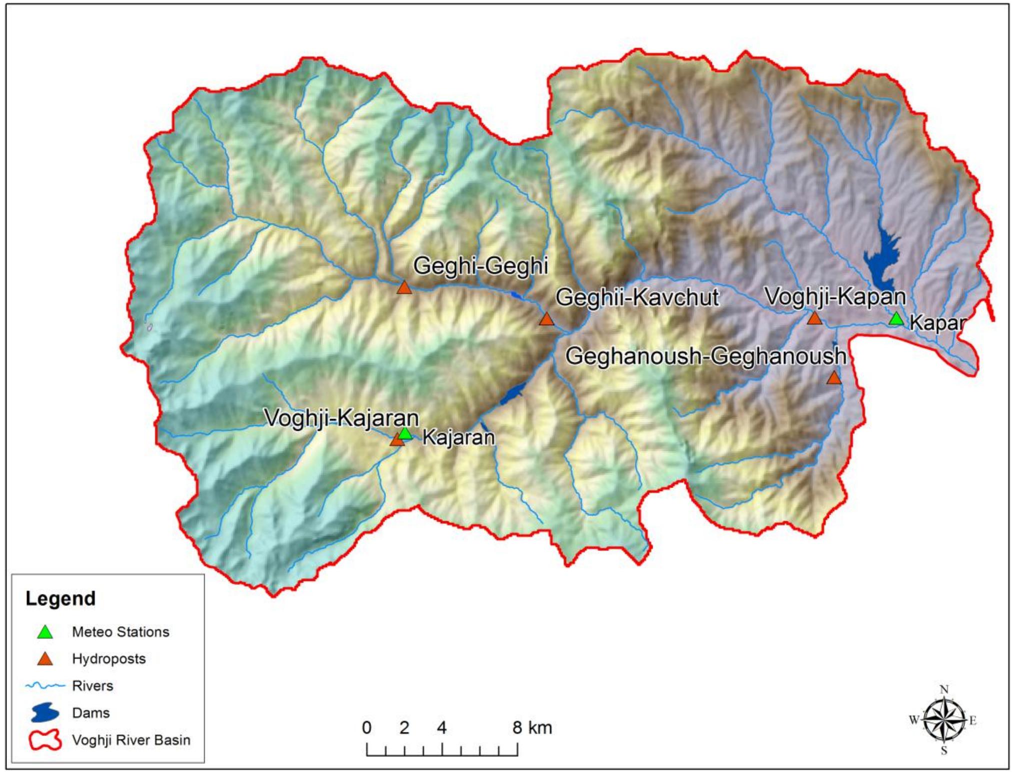
Required Data for Dam Break(ch) Analysis and Mapping

- Hydro-Meteorological Observation Data
- Digital Elevation Model
- Land Use/Land Cover Dataset
- Other Spatial Datasets
- Hydro-technical Survey Data

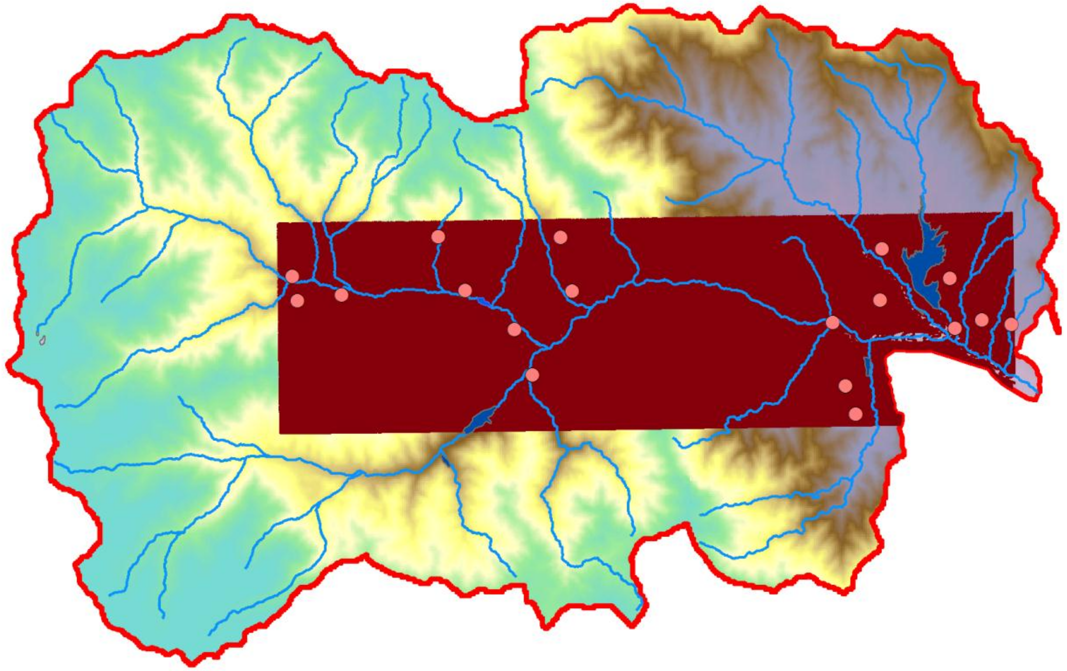
Hydro-Meteorological Observation Data

- Air Temperature
- Precipitation
- Evaporation
- River Flow Characteristics (Discharge, Level)





Elevation Data



SRTM 30m Global DEM

Isolines (vector linear format, 1:10,000, Georisk)

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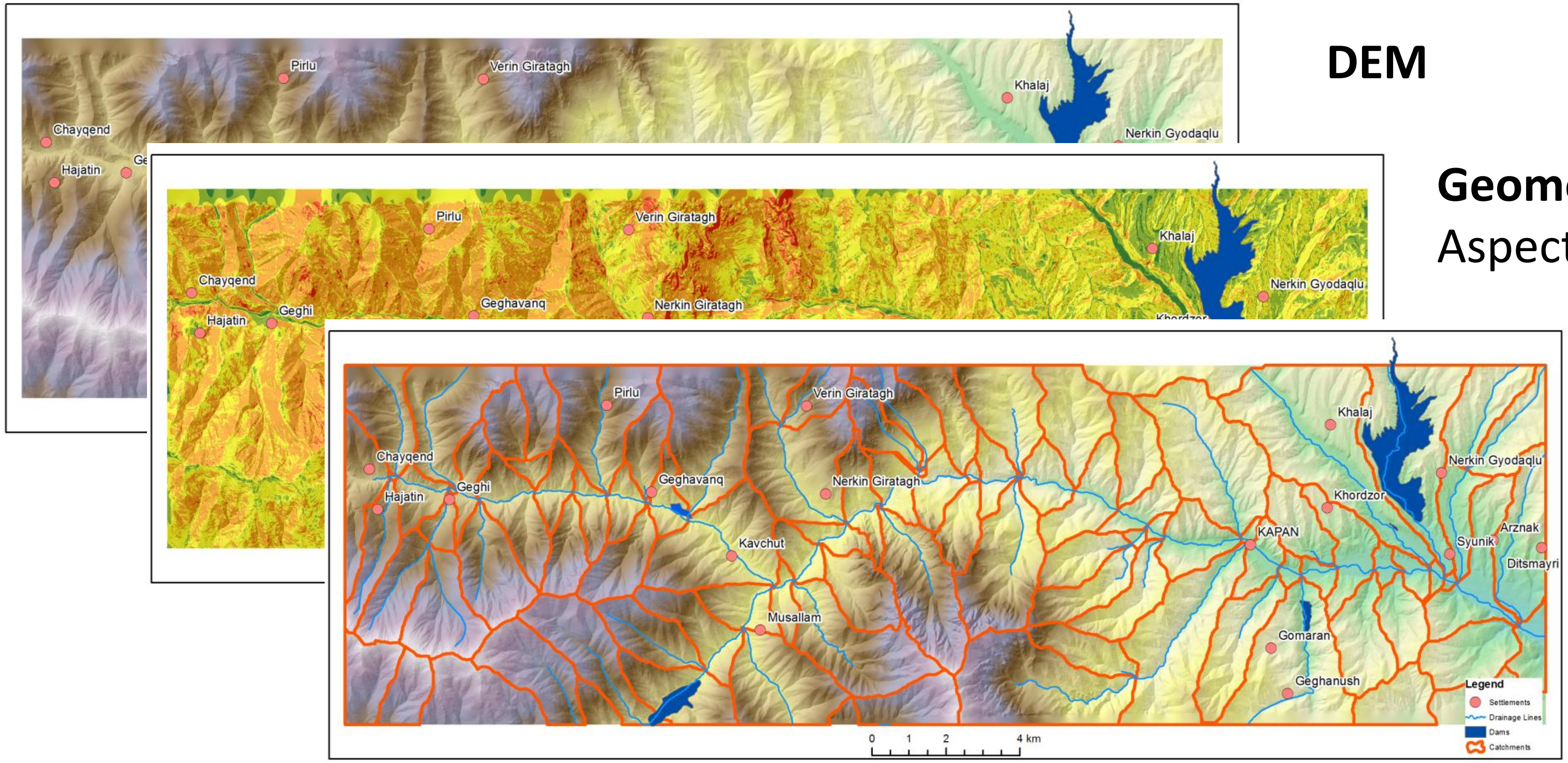
Digital Elevation Model



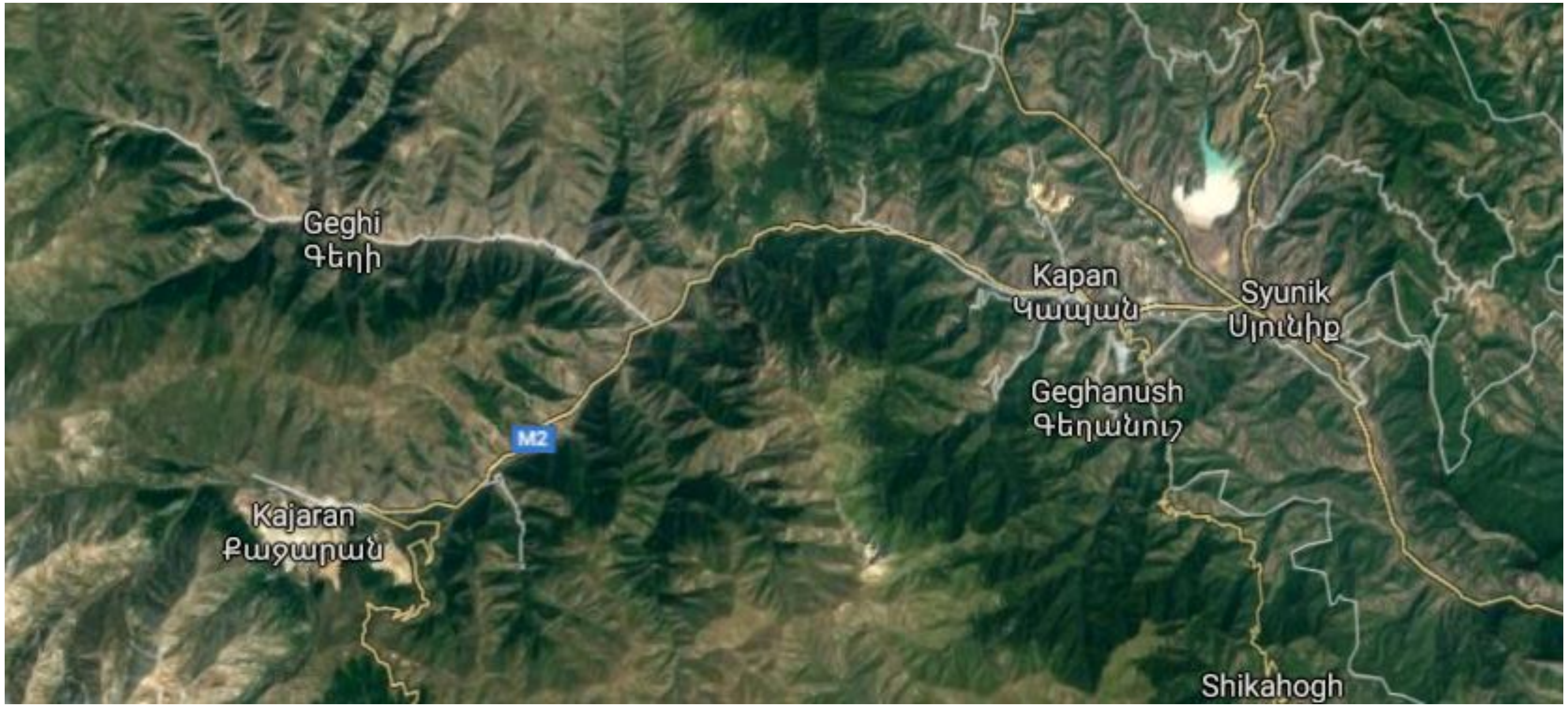
DEM

Geomorphometry (Slope, Aspect, Hillshade)

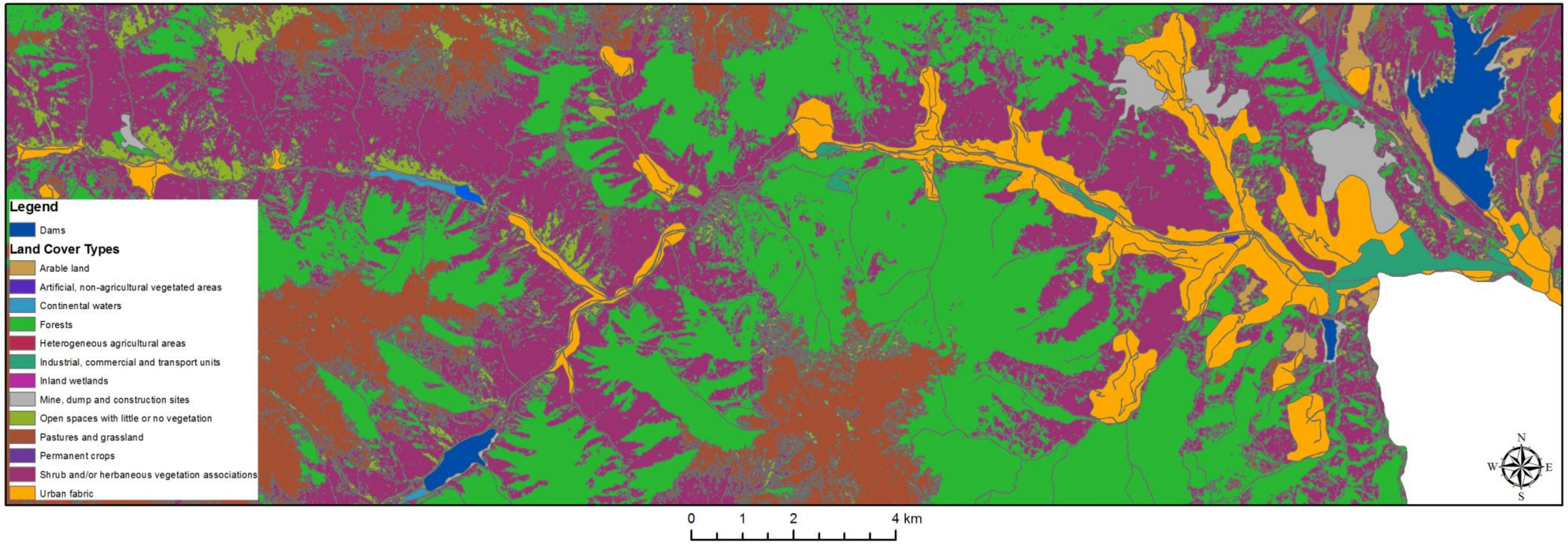
Hydrology

- Hydrologically-correct DEM Generation
- Flow Direction and Accumulation
- Stream Definition and Segmentation
- Catchment and Drainage Line Generation

Satellite Imagery



Land Cover



RapidEye (5m), USAID CEW Project

Sentinel (20m), AUA Acopian Centre

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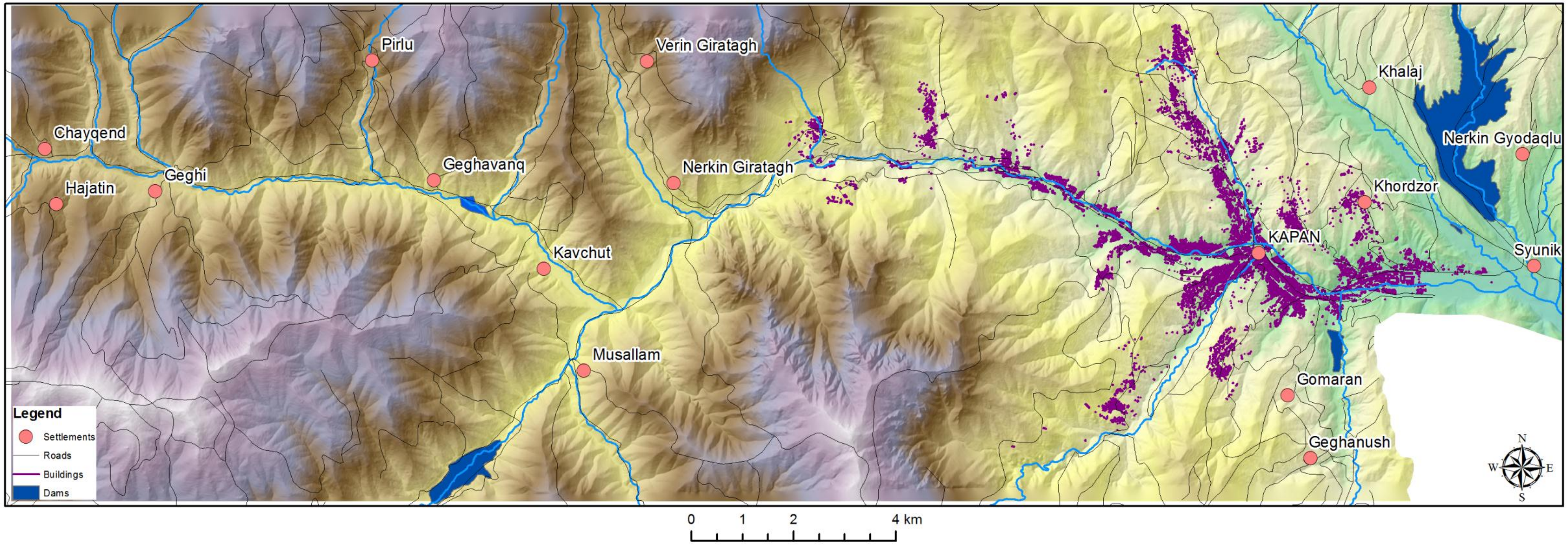
Other Spatial Datasets



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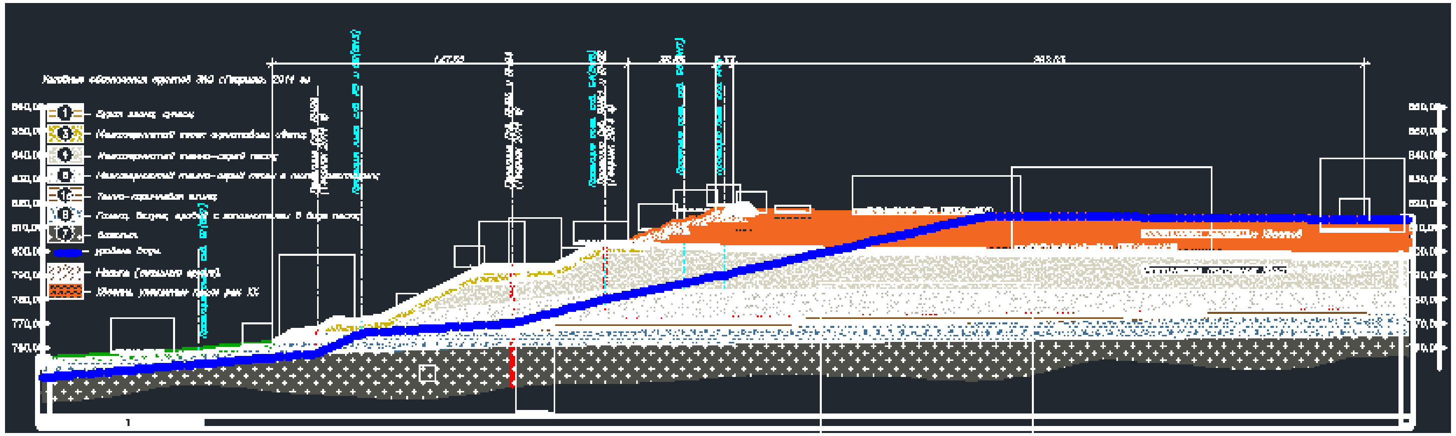
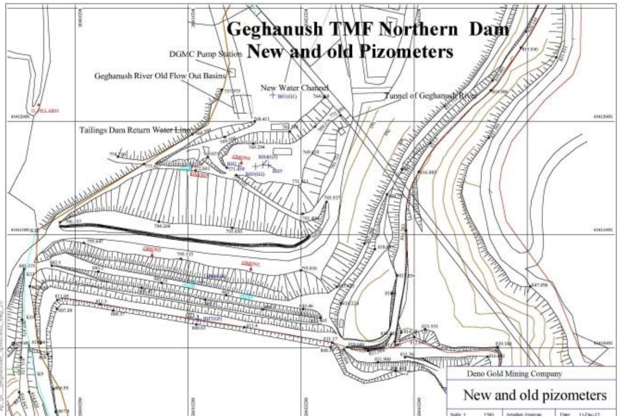
Survey Data





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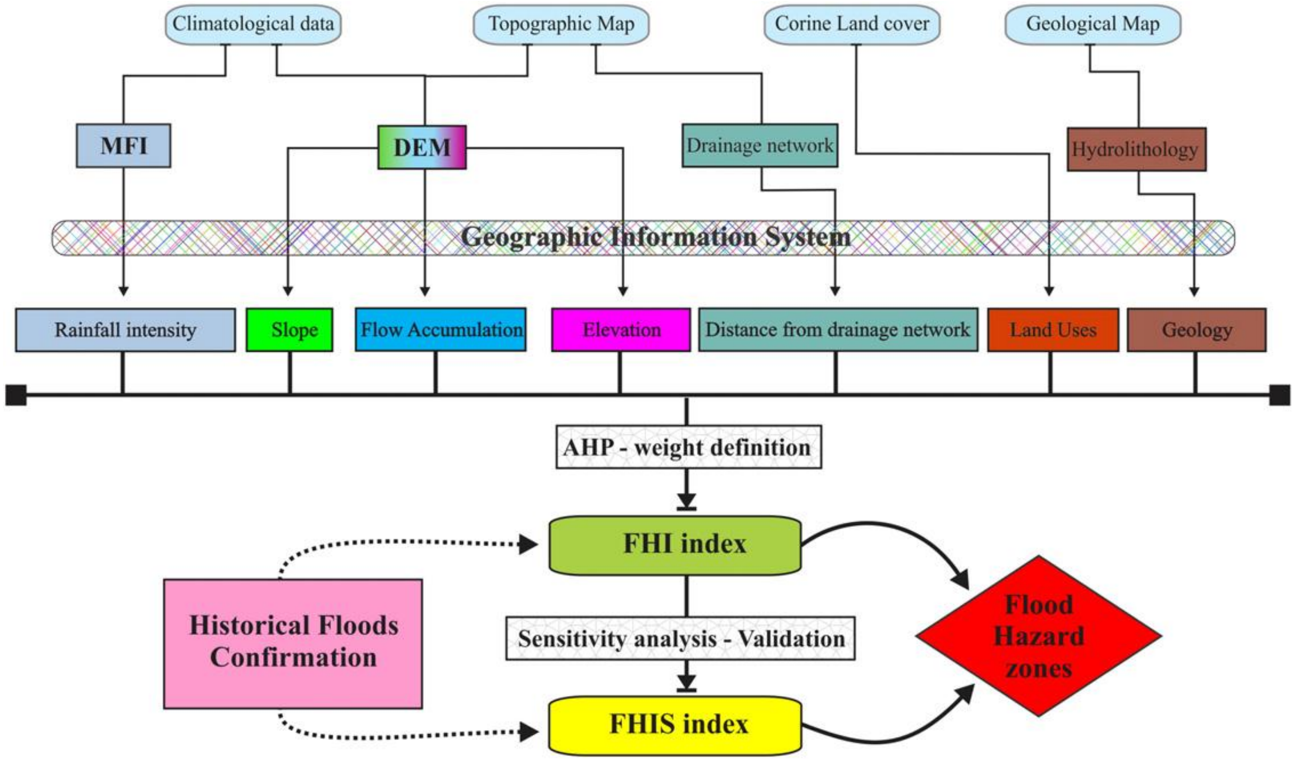
Flood Hazard Index Calculation



Parameters	Flow acc.	Drain. dist.	Elev.	Land use	Rainf. inten.	Slope	Geol.
Flow acc.	1	2	2	3	3	5	7
Drainage distance	1/2	1	1	3	3	4	6
Elevation	1/2	1	1	3	3	4	6
Land use	1/3	1/3	1/3	1	2	4	5
Rainfall intensity	1/3	1/3	1/3	1/2	1	4	5
Slope	1/5	1/4	1/4	1/4	1/4	1	3
Geology	1/7	1/6	1/6	1/5	1/5	1/3	1

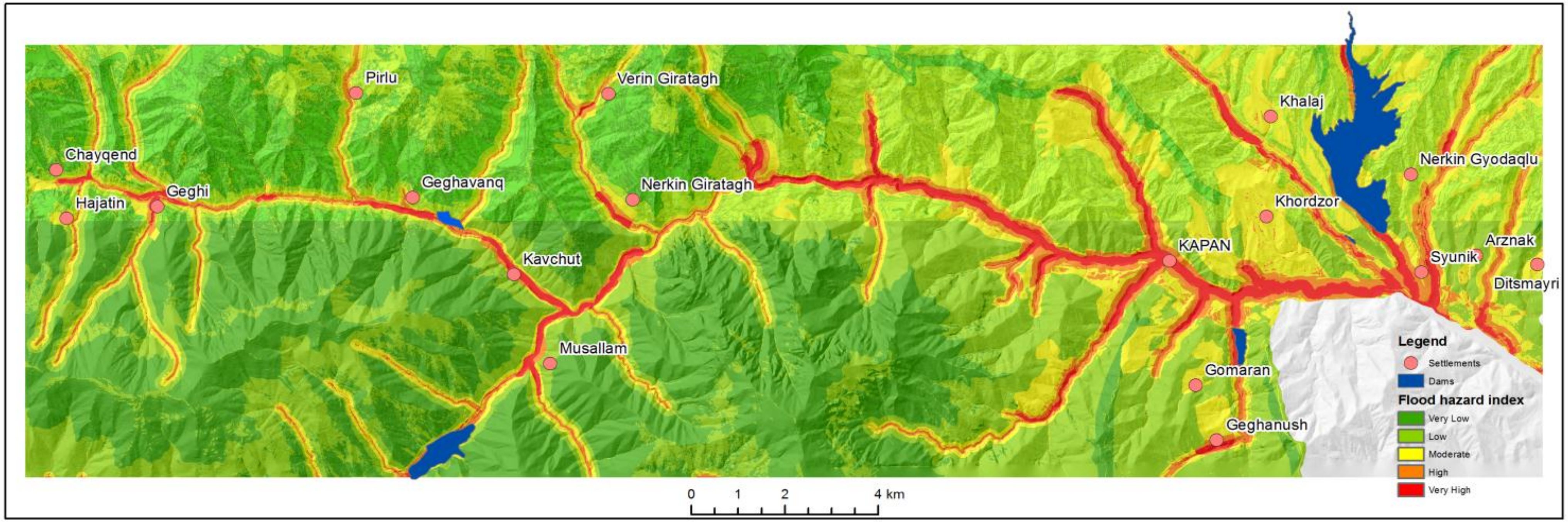
Flowchart for FHI Assessment Method (N. Kazakis et al. / Science of the Total Environment 538 (2015) 555–563)

Classes, Rating and Weights of FHI Assessment Parameters

Parameter	Class	Rating	Weight
Flow Accumulation (cells)	0-5000	10	3
	5000-20000	8	
	20000-100000	6	
	100000-1000000	4	
	1000000-11000000	2	
Distance from Drainage Network, m	0-25	10	2.1
	25-50	8	
	50-75	6	
	75-100	4	
	>100	2	
Elevation, m	<1000	10	2.1
	1000-1500	8	
	1500-2000	6	
	2000-2500	4	
	>2500	2	
Land Cover	Urban; industrial; water objects	10	1.2
	Arable land	8	
	Pastures and grassland; permanent crops	6	
	Open Spaces with little or no vegetation	4	
	Forests and shrubs	2	

Parameter	Class	Rating	Weight
Rainfall Intensity (MFI)	63-68	6	1
	59-63	4	
	<59	2	
Slope (degree)	0-5	10	0.5
	5-15	8	
	15-30	6	
	30-45	4	
	>45	2	
Geology	Alluvial deposits	10	0.3
	Slope deposits	8	
	Volcanogenic and volcanogenic-sedimentary rocks	6	
	Moraines	4	
	Eluvial, eluvial-deluvial deposits in watershed zones	2	

Flood Hazard Index Map of Studied Area



FHI = 3.0 x FAC + 2.1 x DIST + 2.1 X ELEV + 1.2 X LC + 1.0 X MFI + 0.5 X SLOPE + 0.3 X GEOLOGY

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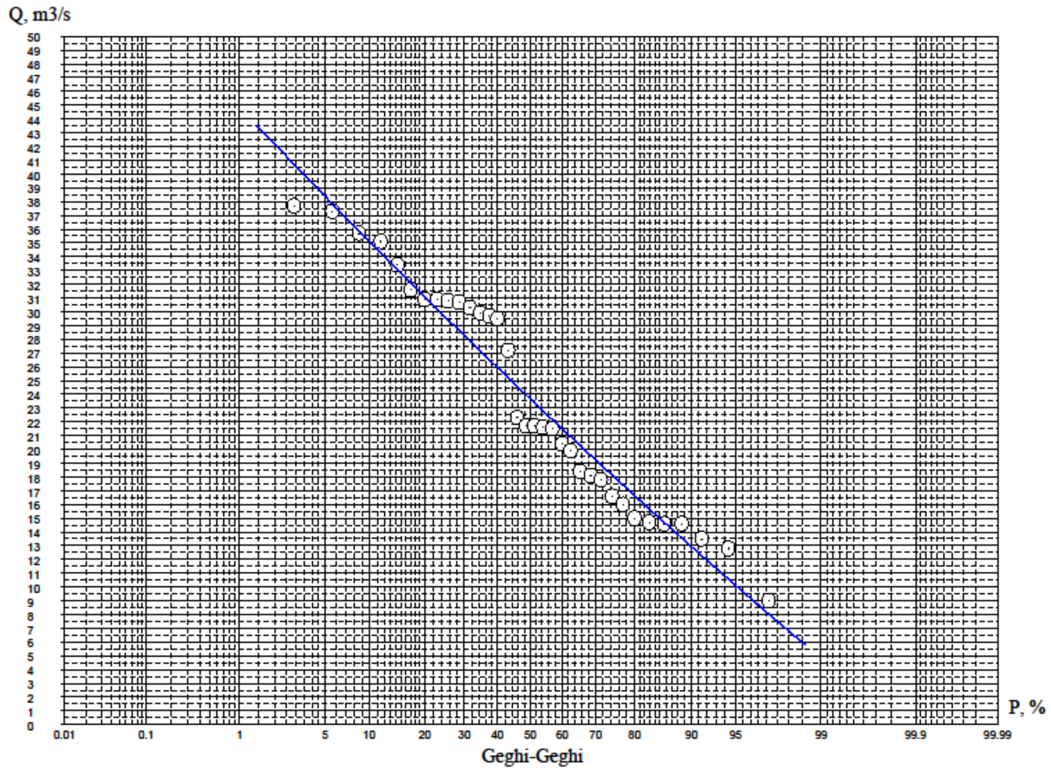
River Maximum Flow Calculation

N	Year	Max. m^3/s	Observation Date	Max. m^3/s, descending	Probability, (m/(n+1))x100
1	1959	21.5	27/05	37.7	2.9
2	1960	33.4	29 - 31.05	37.3	5.7
3	1961	9.00	06,07.05	35.7	8.6
4	1962	13.5	22/05	35.1	11.4
5	1963	30.7	02.06	33.4	14.3
6	…	….	…	…	…



Q_0 (time-series average value) = 23.85;

C_v (variation coefficient) = 0.336;

C_s (asymmetry or skewness coefficient) = 0.159;

C_s/C_v = 0.47

P	0.01	0.1	1	2	5	10	25	50	95	99
Φ	4.05	3.31	2.44	2.13	1.68	1.3	0.66	-0.02	-1.6	-2.2
$Φ*C_v$	1.36	1.11	0.82	0.72	0.56	0.44	0.22	-0.01	-0.54	-0.75
$K_h=1+Φ*C_v$	2.36	2.11	1.82	1.72	1.56	1.44	1.22	0.99	0.46	0.25
$Q_h=K_h*Q_0$	56.31	50.38	43.40	40.92	37.31	34.27	29.14	23.69	11.03	6.06

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Dam Breach Maximum Outflow and Breach Hydrograph Calculation

Elevations		
Top of Dam	4,609.6	Ft* msl
Water Surface@Breach	4,599.8	Ft msl
Average Valley Floor	4,379.9	Ft msl
Wave Berm	4,489.9	Ft msl
Stability Berm	4,489.9	Ft msl
Length of Dam@Breach Elev	886	Ft
Storage Volume@Breach Elev	12,161	Ac Ft
Top Width	32.8	Ft
Upstream Slope Above Berm	2.5	:1
Upstream Slope Below Berm	2	:1
Downstream Slope Above Berm	2.5	:1
Downstream Slope Below Berm	2	:1
US Wave Berm Width	50	Ft
DS Stability Berm Width	50	Ft

Theoretical breach width

$T = 65(H_w^{0.35})/0.416 = 1{,}032$ ft or 314 m

$Q_{max} = 65(H_w^{1.85}) = 1{,}400{,}000$cfs or 39,643 m^3/s

Timesteps	Breach Outflow, m³/s		
	Worst Case	Average Case	Best Case
0 min	56.31*	56.31*	56.31*
6 min	39700.6	13895	3970
12 min	5968.7	12936.2	7576.6
18 min	2339.6	10081.2	8771.1
24 min	938.1	6099.2	8084.2
30 min	396.8	2977.4	6721.1
36 min	187.8	1478.1	5368.7
42 min	107.1	881.3	3680.2
48 min	75.9	592.0	2219.8
54 min	63.9	270.3	1493.1
60 min	59.2	239.9	773.8
66 min	57.4	186.5	593.4
72 min	56.7	160.0	378.3
78 min	56.5	133.9	235.1
84 min	56.4	108.0	163.6
90 min	56.3	82.1	92.1

TR-60 and TR-66 simplified dam breach outflow and routing models developed by the Engineering division of Soil Conservation Service of US Department of Agriculture

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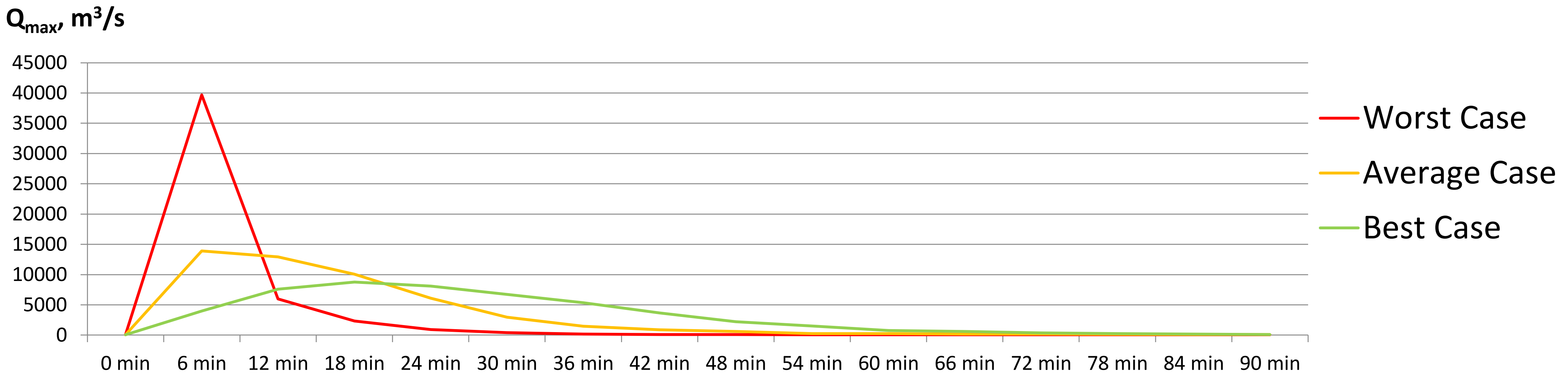
Geghi Reservoir Dam Breach Hydrograph



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Geghanoush TSF Breach Outflow and Tailing Distance Travel Calculation

V_T = 4.6 million m^3 — V_T=total capacity of TSF

$V_F = 0.332 \times V_T^{0.95}$ — V_F=released volume

$D_{max} = 3.04 \times H_f^{0.545}$ — D_{max}=Distance travelled by tailings

$H_f = H \times (V_F/V_T) \times V_F$ — H_f=predictor

V_F = 1.4 million m^3 **$H_f = 19.6$** **D_{max} = 15.4 km**

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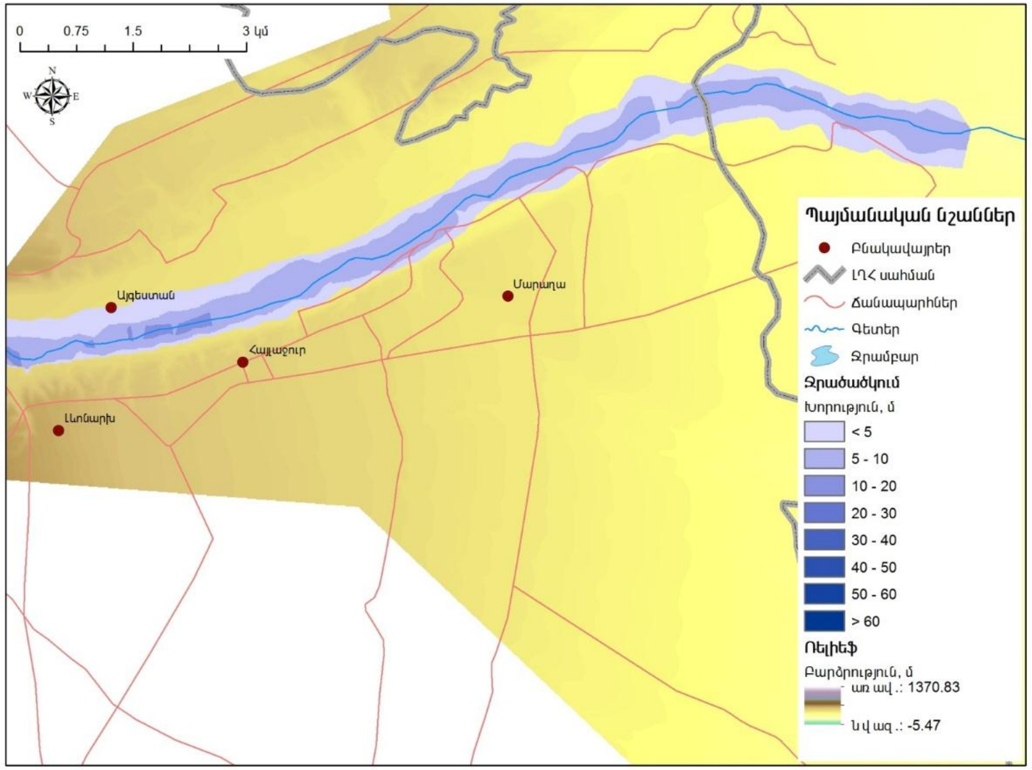
Dam Break Flood Map for Sarsang Reservoir



Cross-Section №	Distanc from Dam, km	Maximum Discharge, $1000m^3/s$	Maximum Altitude of Inundation, m	Wave Arrival Time, minutes
1	0,4	230,58	664,5	38
2	1,6	198,24	656	44,2
3	2,6	176,64	653	49,6
4	3,6	159,39	634	55
5	5,6	133,77	614	65,5
6	7,9	113,23	559	77,4
7	10,6	95,23	528	92
8	12,6	85,71	507	102,2
9	14,6	77,97	487	112,4
10	16,6	71,5	455	122,6
11	18,6	66,03	444	132,7
12	20,8	61,9	408	141,6
13	23,6	57,24	379	153,1
14	27,5	52,11	343	168,2
15	29,5	50,28	323,5	174,3
16	32,1	48,24	298	181,7
17	34,8	46,28	273	189,4
18	36,8	44,49	250	197
19	39,8	43,02	220	203,8

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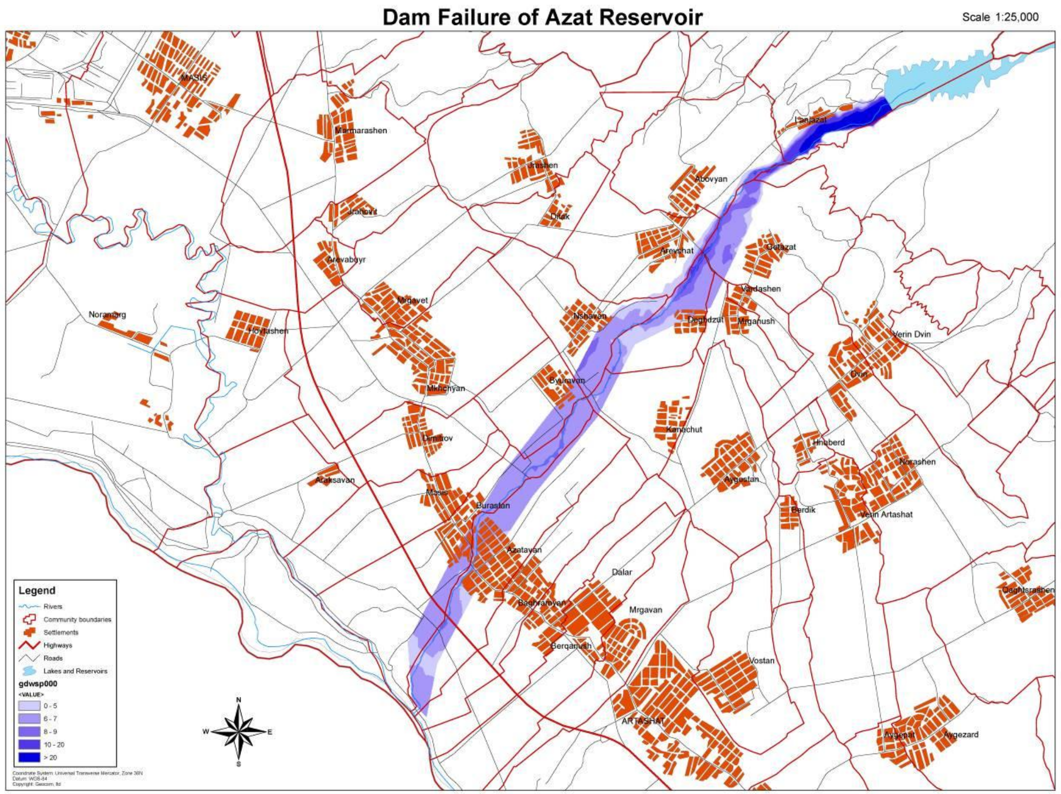
Dam Break Flood Map for Azat Reservoir



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Thanks for your Attention!

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