MODELLING LOSSES OF RESERVOIR STORAGE CAPACITY FROM SEDIMENTATION IN DIFFERENT LANDSCAPES

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Motivation

- **Over time, reservoir storage capacity is lost due to incoming sediments which settle and accumulate within the reservoir**
- **Reservoir sedimentation has wide-ranging impacts on[1]:**
  - Water Supply Reliability
  - Environment
  - Hydropower
  - Recreation
  - Flood Management
  - Infrastructure
  - Economy
- **Climate change impacts on reservoirs[2]:**
  - Changes in flow regimes
  - Increasing incoming sediment and nutrient loads
  - Increasing summer water temperatures

Completely silted Denadai Dam in Eritrea (De Vito, n.d.)

[1]Annandale, 2006; [2]Yasarer & Sturm, 2016

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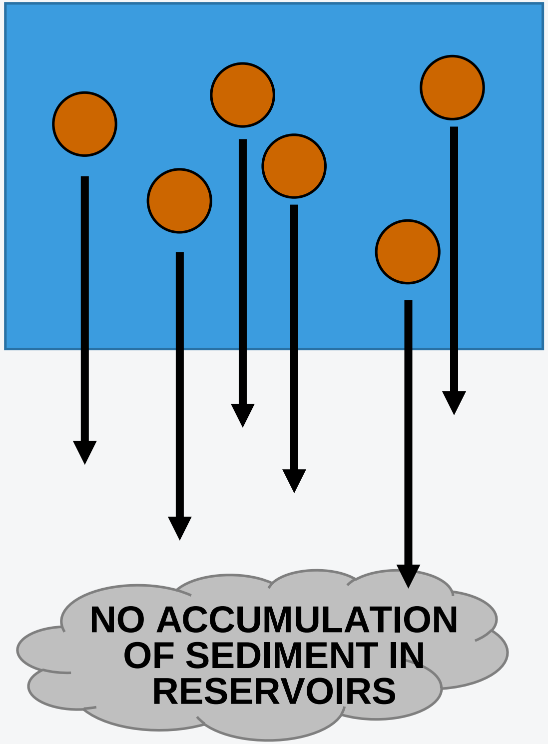
HYPE Model Overview

- **Hydrological Predictions for the Environment (HYPE) Model**
  - **Developer:** Swedish Meteorological and Hydrological Institute (SMHI)
  - **Spatial Representation:** Semi-Distributed (Catchment)
  - **Modeling Scale:** Catchment, Country, Continent, Global
  - **Time Step:** Daily
  - **Website:** https://hypeweb.smhi.se/

- **Original HYPE Reservoir Sedimentation Scheme**
  - Sedimentation occurs, but settled sediments are lost from the system and have no effect on hydrology or reservoir storage capacity
  - Sedimentation rate (*sed*) is calculated as a function of settling velocity (*v*), concentration of sediment in lake water (*conc*), and lake area (*area*)

$$sed = v \times conc \times area$$



Simulating Reservoir Sedimentation

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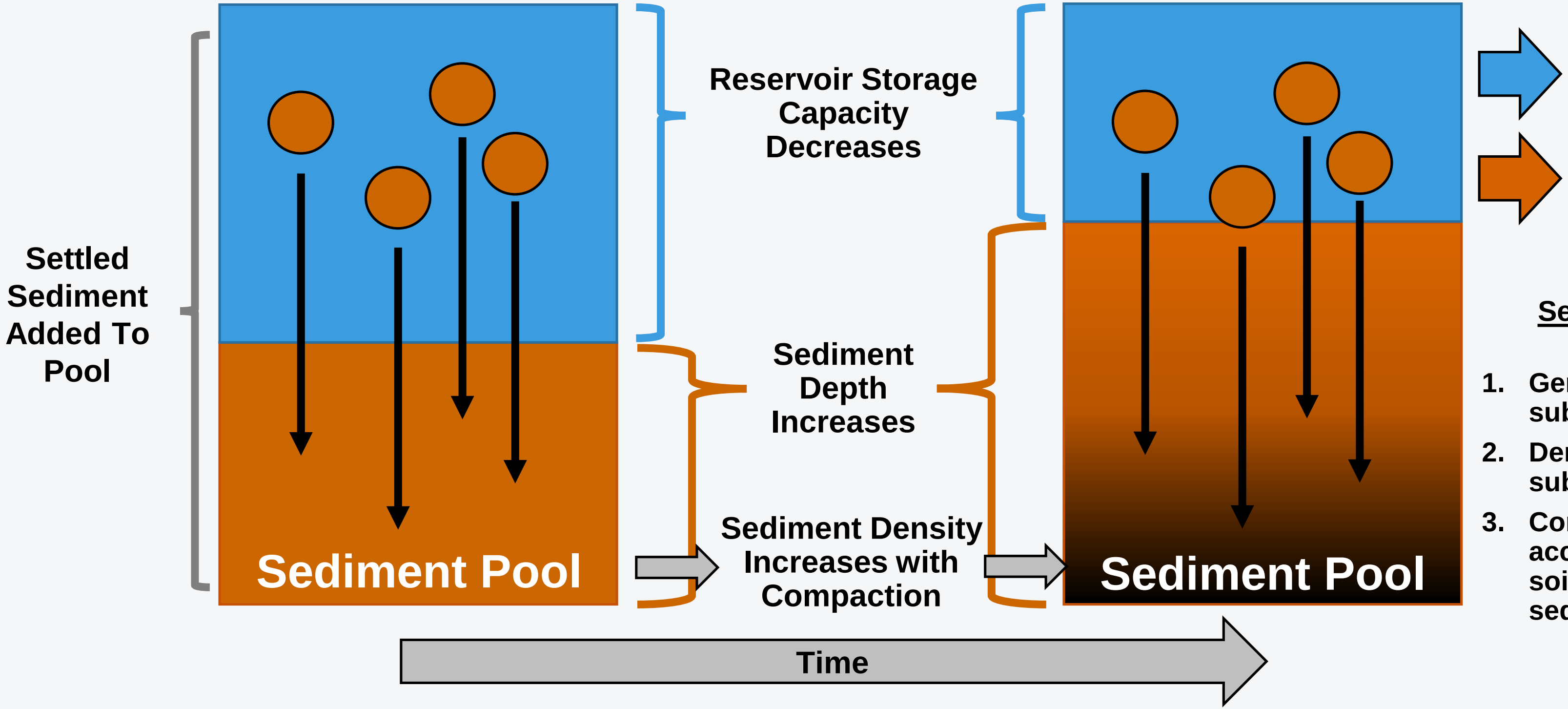
New HYPE Sedimentation Scheme



Adjusted Reservoir Outflow & Sediment Concentration

Sediment Density Options:

1. General density for all subbasins
2. Density according to subbasin soil fractions
3. Compacted density according to subbasin soil fractions & age of sediment pool

$$\text{Sediment Depth (m)} = \frac{\text{Sediment Pool}\left(\text{kg/m}^2\right)}{\text{Sediment Density}\left(\text{kg/m}^3\right)}$$

Initial Sediment Density

- **Lara & Pemberton (1965)**
  - Developed expression for initial sediment bulk density (at t=0)

$$\rho_{bulk} = \rho_{clay}\rho_{clay} + \rho_{silt}\rho_{silt} + \rho_{sand}\rho_{sand}$$

Where:

- p=percentages of clay/silt/sand of incoming sediment
- ρ= density from tables below – dependent on operation mode

Operation	Reservoir operation
1	Sediment always submerged or nearly submerged
2	Normally moderate to considerable reservoir drawdown
3	Reservoir normally empty
4	Riverbed sediments

Operation	Initial weight (initial mass) in lb/ft^3 (Kg/m^3)		
	W_c	W_m	W_s
1	26 (416)	70 (1120)	97 (1550)
2	35 (561)	71 (1140)	97 (1550)
3	40 (641)	72 (1150)	97 (1550)
4	60 (961)	73 (1170)	97 (1550)

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Sediment Density After Compaction

- **Lane & Koelzer (1943)**
  - Developed expression for bulk density of 1st year's deposition after T years of compaction due to later deposits (on top of 1st year's deposit)

$$\rho_{bulk} = \rho_{initial} + K * log(T)$$

Where:

- $\rho_{initial}$ = Initial bulk density, K = Coefficient, T = Time (years)

- **Miller (1953)**
  - Developed expression for average density of total sediment deposited from 1-T years

$$\rho_{bulk} = \rho_{initial} + 0.4343K\left[\left(\frac{T}{T-1}\right)\ln(T) - 1\right]$$

Operation	Reservoir operation
1	Sediment always submerged or nearly submerged
2	Normally moderate to considerable reservoir drawdown
3	Reservoir normally empty
4	Riverbed sediments

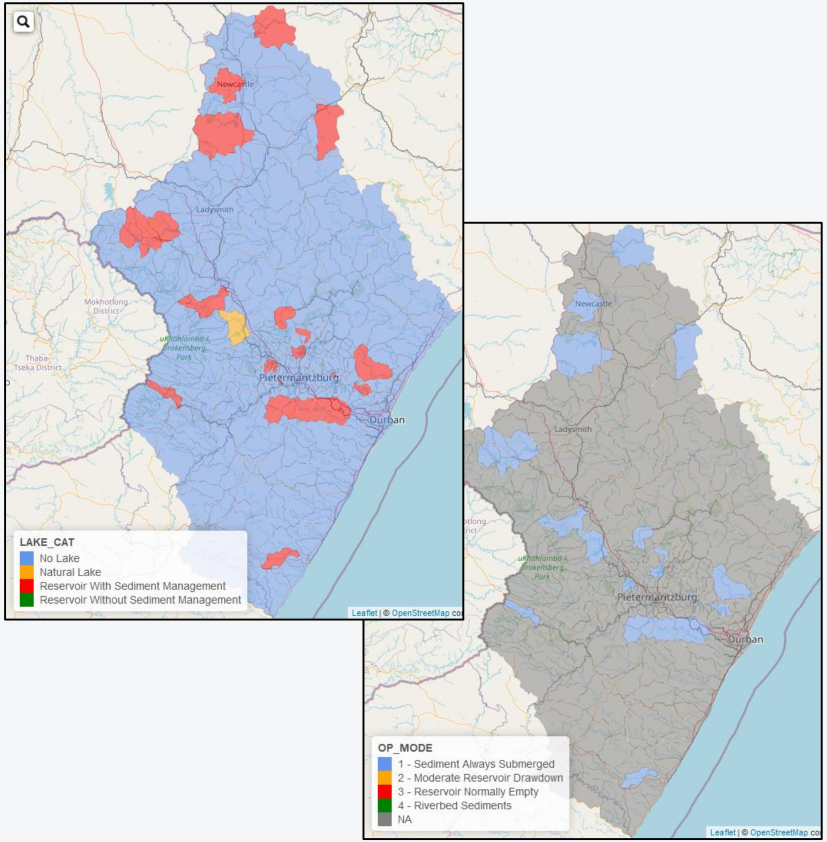
Reservoir operation	K for inch-pound units (metric units)		
	Sand	Silt	Clay
1	0	5.7 (91)	16 (256)
2	0	1.8 (29)	8.4 (135)
3	0	0 (0)	0 (0)

Note that greatest compaction occurs for reservoir operation mode 1 and that no compaction occurs (K=0) for reservoir operation modes 3 and 4!

Evaluating Sedimentation Methods

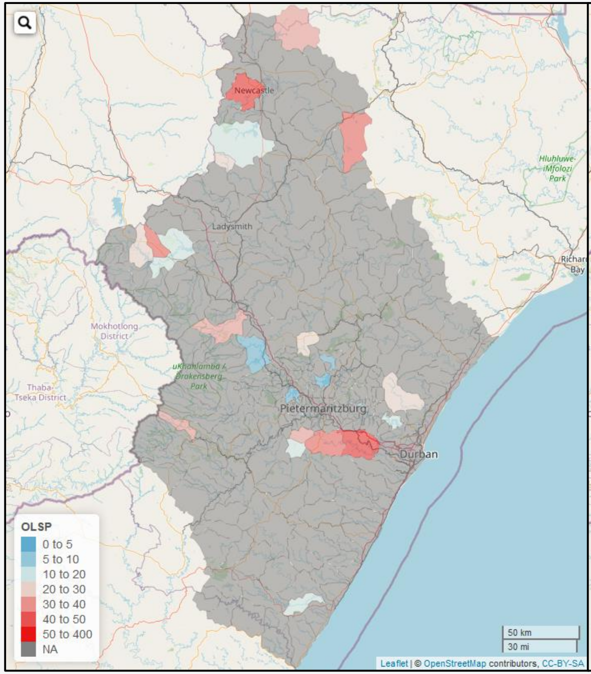
GuM-HYPE Model

- **Sediment density methods were compared using the HYPE model of the Greater uMngeni River Basin (GuM-HYPE) in South Africa**
  1. General Density (Used 1200 kg/m^3 for all subbasins)
  2. Density from Soil Fractions
  3. Density from Soil Fractions + Compaction
- **Soil Fraction Data from Regridded Harmonized World Soil Database v1.2 (Wieder et al., 2014)**
- **25 lakes/reservoirs within model**
  - Did not simulate any sediment management
  - All lakes/reservoirs had Reservoir Operation Mode 1 (Sediment Always Submerged); compaction occurs in density method 3
- **Model simulations performed for 1985 – 2013**

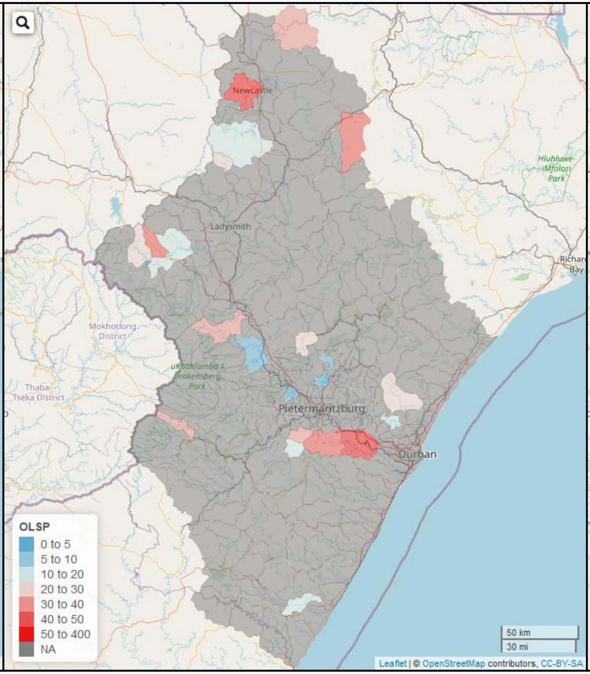


Sediment Pool (kg/m²)

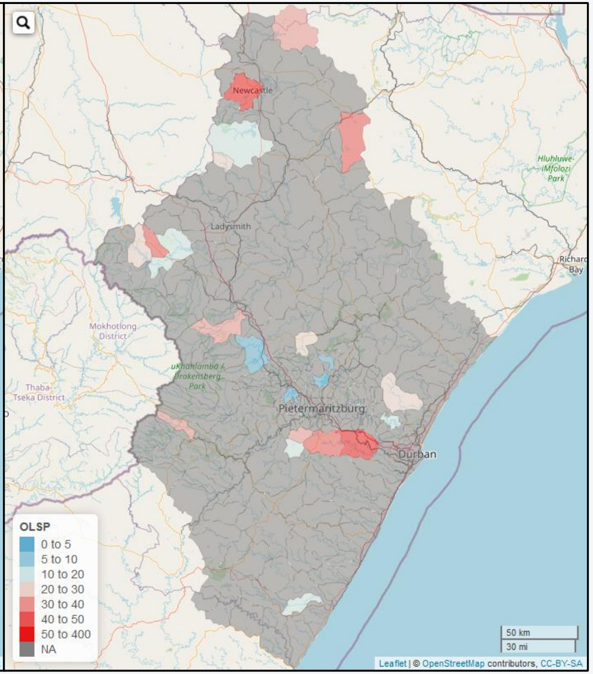
- **Amount of accumulated sediment in reservoir, normalized by reservoir surface area**
- **Essentially no differences between the three density methods (small variations because sedimentation affects reservoir outflows which affect sediment transport)**



1 - GENERAL DENSITY



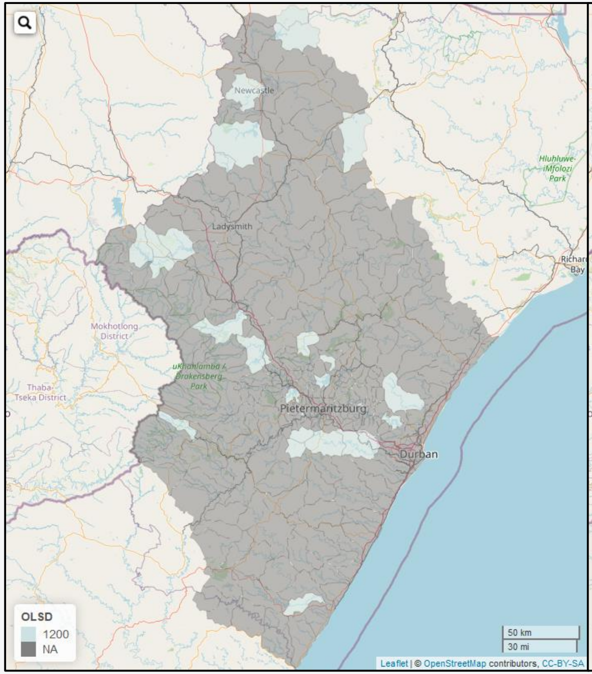
2 - SOIL FRACTIONS



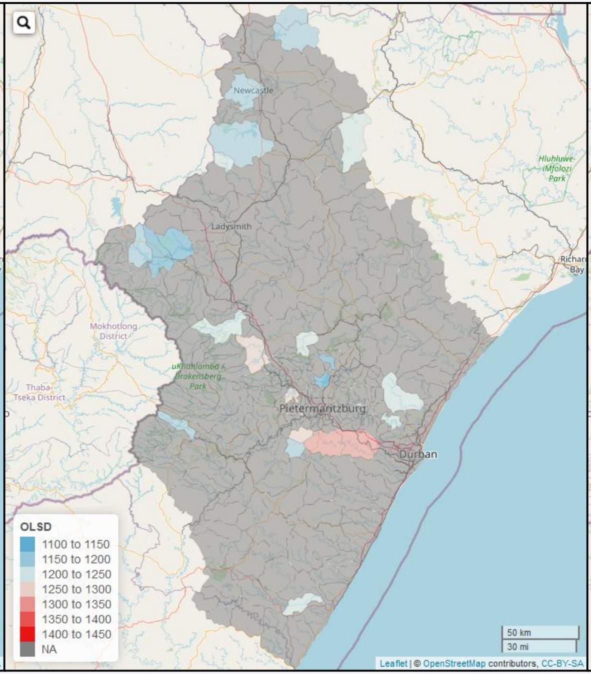
3 - SOIL FRACTIONS + COMPACTION

Sediment Density (kg/m^3)

- **For method 3, compaction occured in all subbasins (sediment always submerged)**
- **Density used for "General Density" was 1200 kg/m^3**
- **Including compaction increased densities by 3.8-9.8% over the ~30 year modeling period**



1 - GENERAL DENSITY



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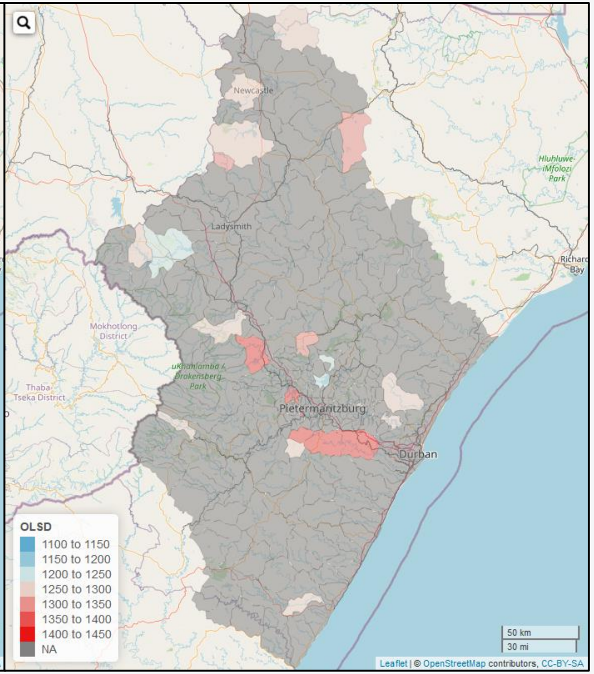

3 - SOIL FRACTIONS + COMPACTION

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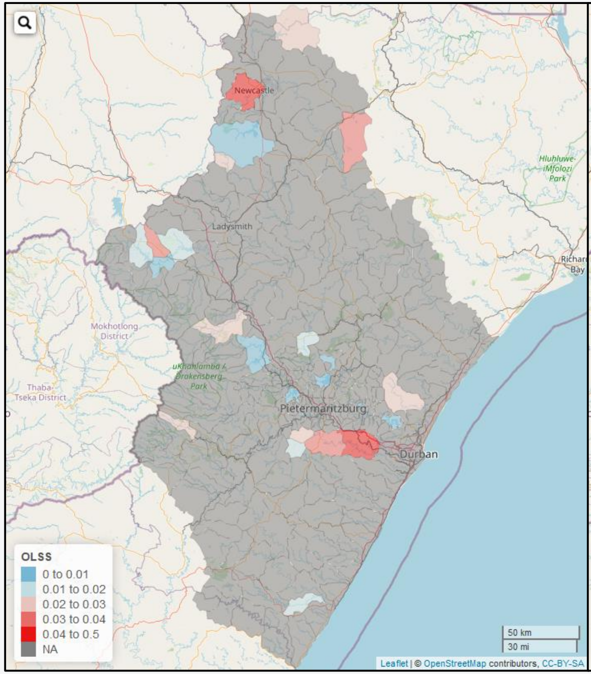
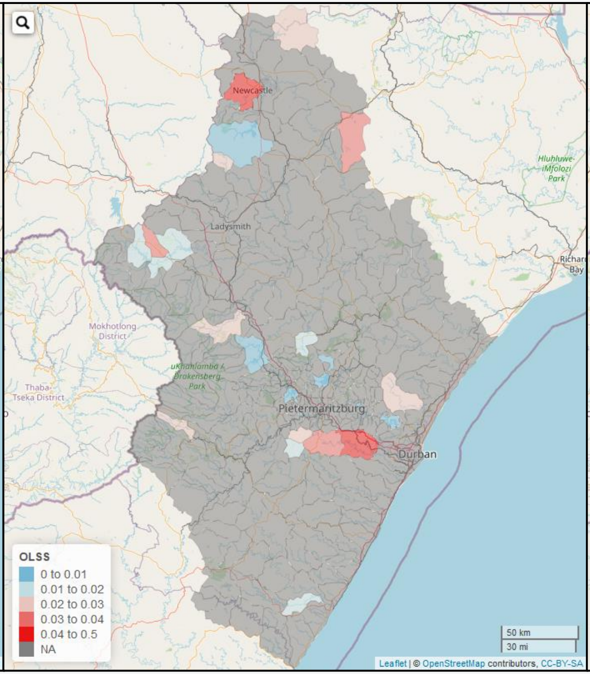
Reservoir Sediment Depth (m)

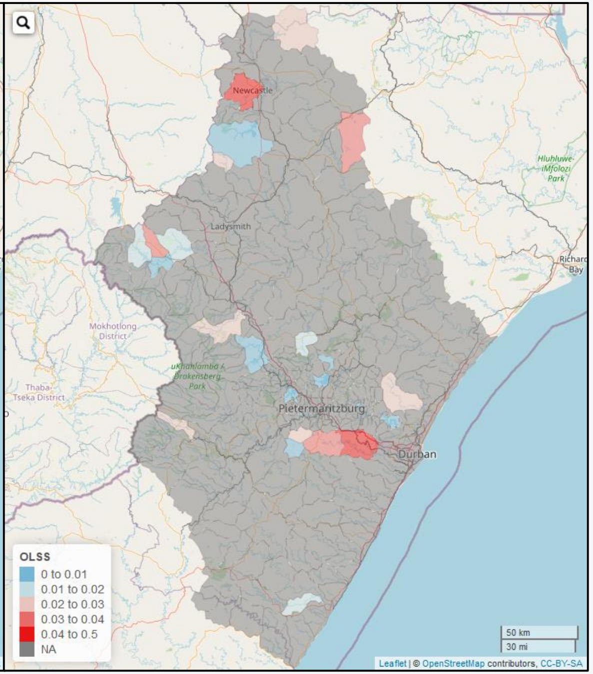
- **Average sedimentation rate ranged from 0.00 – 0.95 cm/year (General Density), 0.00 – 0.98 cm/year (Soil Fractions), and 0.00 – 0.90 cm/year (Soil Fractions + Compaction)**
- **Sediment depth is not sensitive to density method: Greatest difference between methods was 0.022 m**



1 - GENERAL DENSITY



2 - SOIL FRACTIONS



3 - SOIL FRACTIONS + COMPACTION

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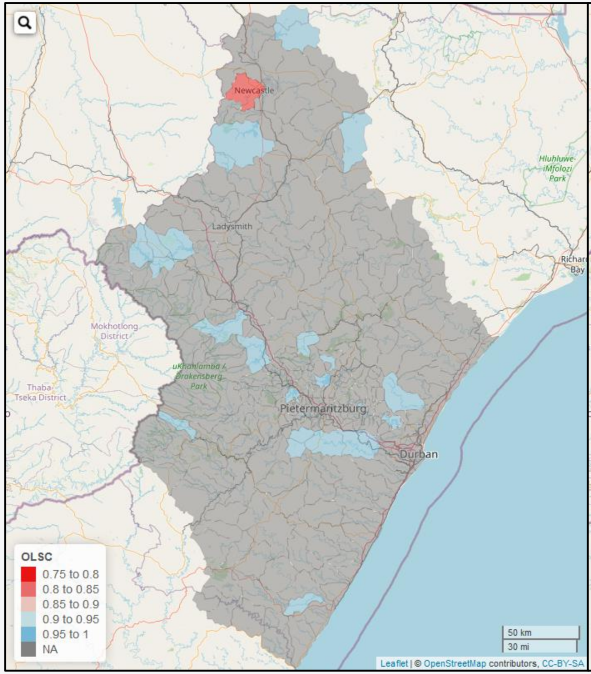
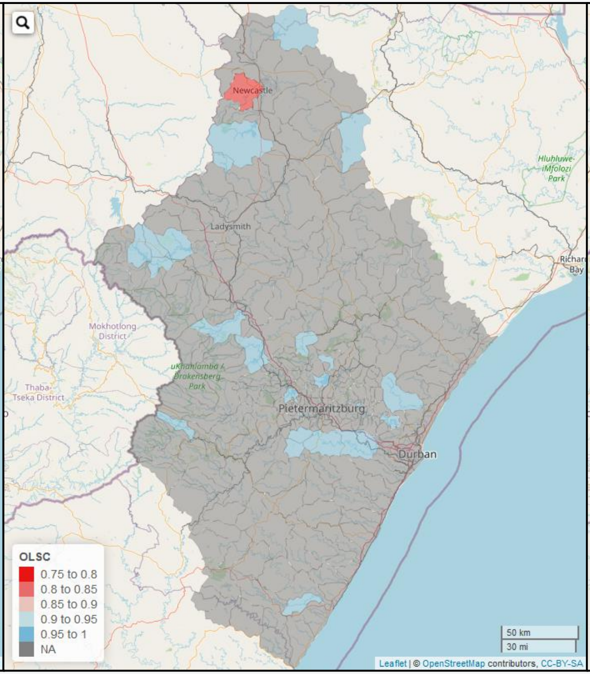
Available Storage Capacity (Fraction)

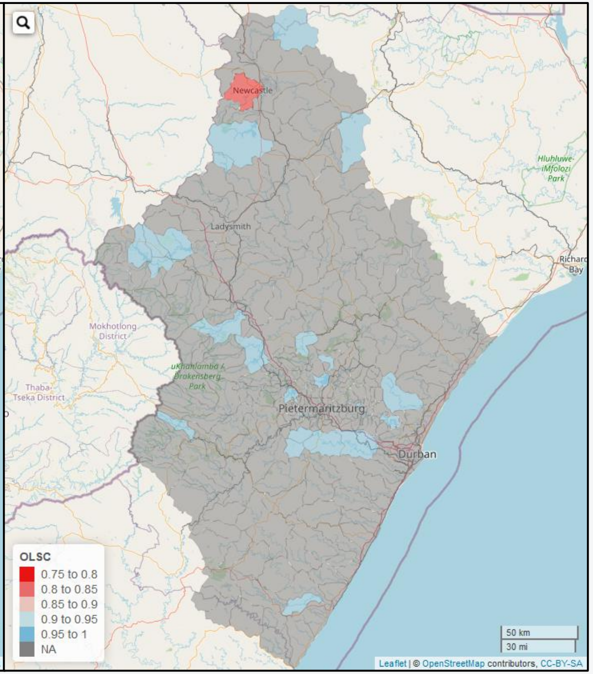
- **Fractions at end of model simulation ranged from 0.79 – 1.0 (General Density), 0.78 – 1.0 (Soil Fractions), and 0.80 – 1.0 (Soil Fractions + Compaction)**
- **Storage Capacity is not sensitive to density method: Greatest difference between methods was 0.016**



1 - GENERAL DENSITY



2 - SOIL FRACTIONS



3 - SOIL FRACTIONS + COMPACTION

Simulating Sediment Management

HYPE Sediment Management Options

Management Option:	Start Trigger:		Result:
NO SEDIMENT REMOVAL	NONE	SET SEDIMENT LOAD OUT EQUAL TO LOAD IN WHEN RESERVOIR BECOMES COMPLETELY FILLED	RESERVOIR SEDIMENT POOL IN EQUILIBRIUM
REMOVAL ACCORDING TO RESERVOIR CAPACITY	RESERVOIR CAPACITY REDUCED TO SPECIFIED THRESHOLD	SPECIFY TARGET RESERVOIR CAPACITY & NUMBER OF TIMESTEPS OF REMOVAL	RESERVOIR CAPACITY RESTORED TO THRESHOLD
REMOVAL ACCORDING TO SEDIMENT "AGE"	SEDIMENT ACCUMULATED FOR SPECIFIED NUMBER OF TIMESTEPS	SPECIFY TIMESTEP TO STOP REMOVAL & FRACTION OF CAPACITY TO RESTORE	RESERVOIR CAPACITY INCREASED BY SPECIFIED FRACTION

Removed sediment can be transported downstream or removed from the system (e.g. for dredging)

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HYPE Sediment Management Options

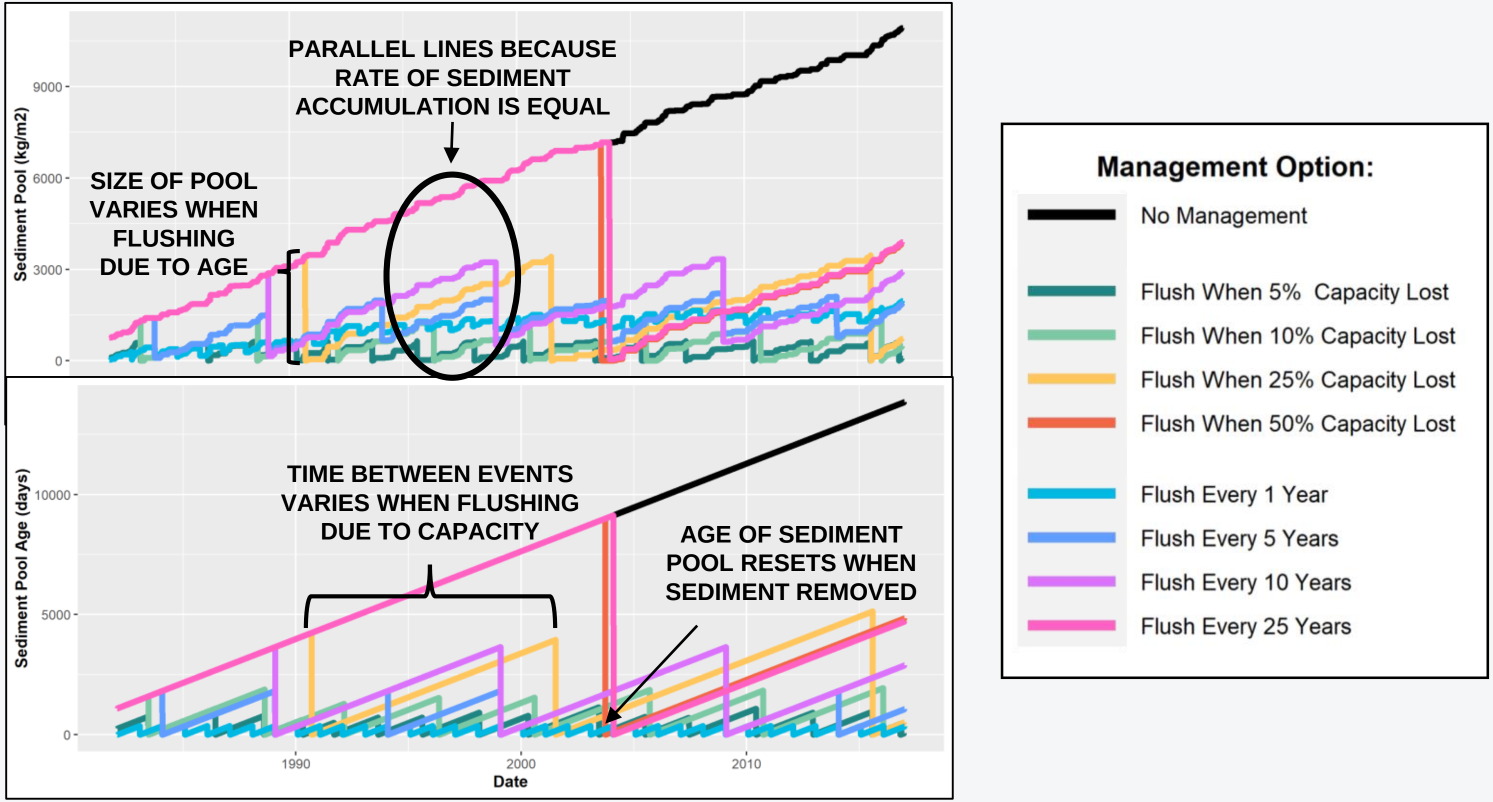
Classified lakes into four types:

1. **No lake**
   - No lake landuse class within subbasin
   - Reservoir Operation Mode: Riverbed sediments
   - **No sediment management**
2. **Natural lake**
   - Lake landuse class within subbasin, but not listed as a dam/reservoir
   - Reservoir Operation Mode: Sediment always submerged or nearly submerged
   - **No sediment management**
3. **Reservoir with sediment management**
   - Lake landuse class within subbasin, listed as a regulated dam/reservoir
   - Reservoir Operation Mode: Sediment always submerged or nearly submerged
   - **Simulate sediment management**
4. **Reservoir without sediment management**
   - Lake landuse class within subbasin, listed as unregulated dam/reservoir
   - Reservoir Operation Mode: Sediment always submerged or nearly submerged
   - **No sediment management**

World-Wide HYPE

- **Model simulations performed for 1979 – 2016**
- **Simulated Management Options:**
  - No Management
  - Flush According to Capacity
    - Remove all sediment when 5, 10, 25, and 50% capacity lost
  - Flush According to Age
    - 1 Year: Restore 2% Capacity
    - 5 Years: Restore 10% Capacity
    - 10 Years: Restore 20% Capacity
    - 25 Years: Restore 50% Capacity
- **Selected a reservoir in China with one of the highest simulated losses in reservoir storage capacity**
  - Reservoir Area: 13.3 km^2
  - Initial Reservoir Depth: 13.2 m
  - Storage Capacity Lost During Simulation: 75.2%

Sediment Pool (kg/m²) & Age (days)



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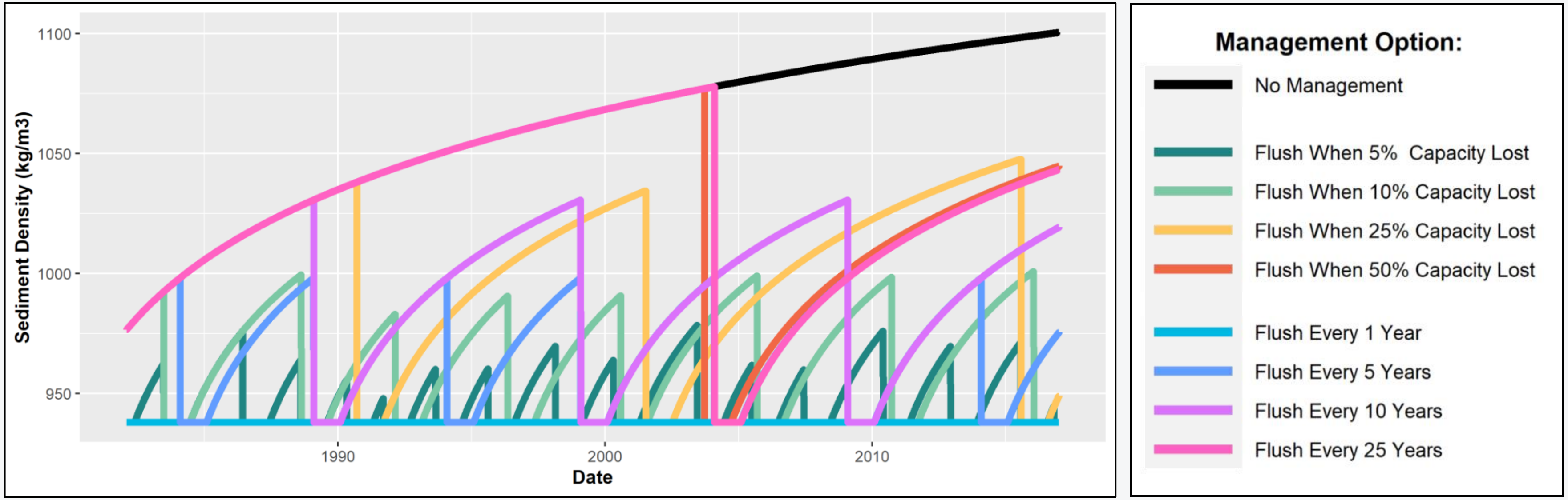
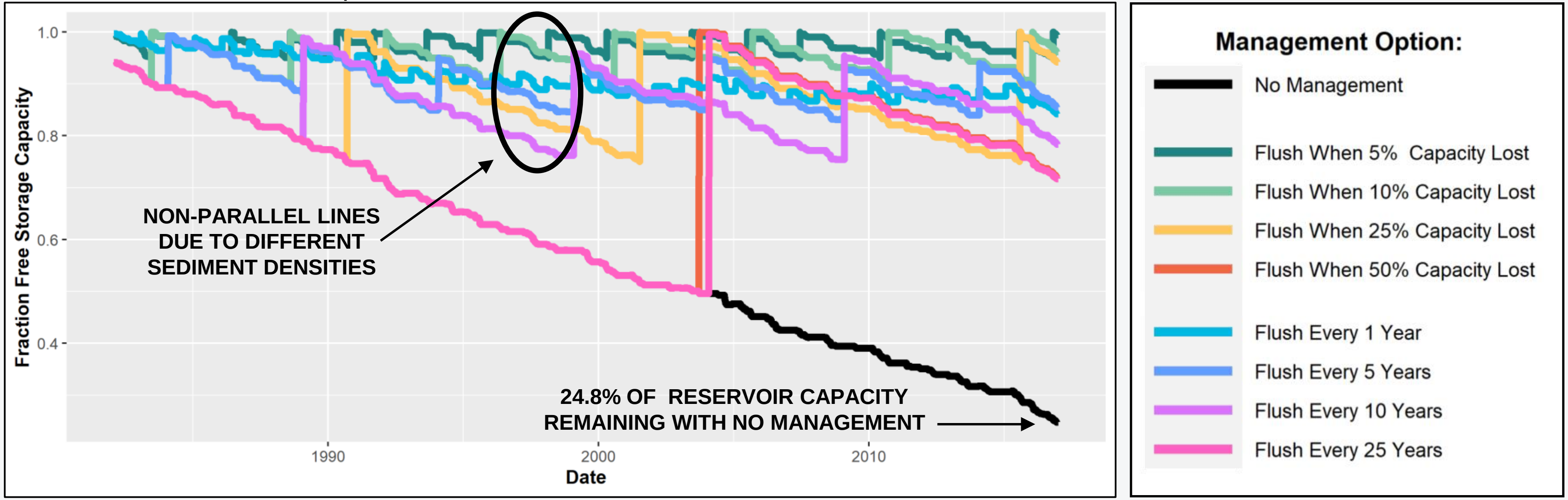
Sediment Density (kg/m³)

- **Sediment density increases due to compaction after 1st year of accumulation**
  - Density is constant for "Flush Every 1 Year" scenario because age of sediment pool never exceeds 1 year
  - Rate of compaction decreases as age of sediment pool increases



Fraction Free Storage Capacity

- **Reservoir Storage Capacity decreases as sediment accumulates and increases as sediment is removed**
- **Rate of capacity loss varies among the scenarios (Lines are not always parallel) due to differences in the ages of the sediment pools**
  - Differences in ages results in different sediment densities
  - Mass of sediment added to pool is the same for each scenario, but different densities result in different sediment depths



Highlights & Requested Feedback

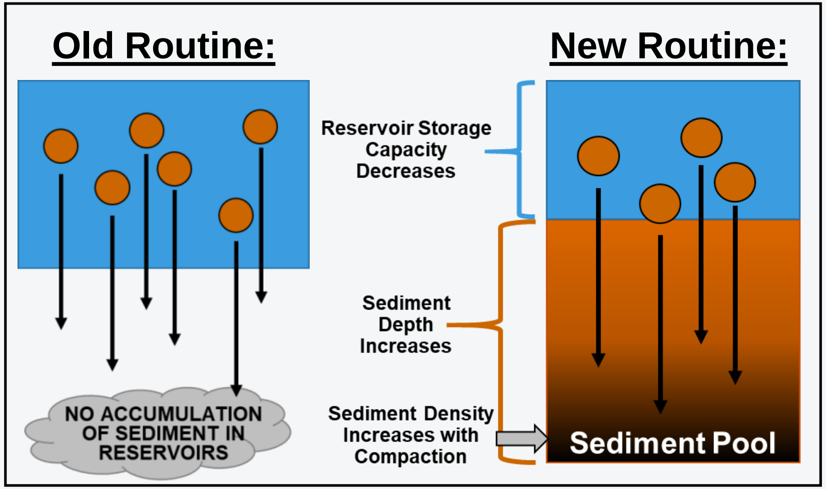
Modelling losses of reservoir storage capacity from sedimentation in different landscapes using HYPE:

Climate change affects reservoirs through:

- Changes in flow regimes
- Increases in incoming sediment and nutrients

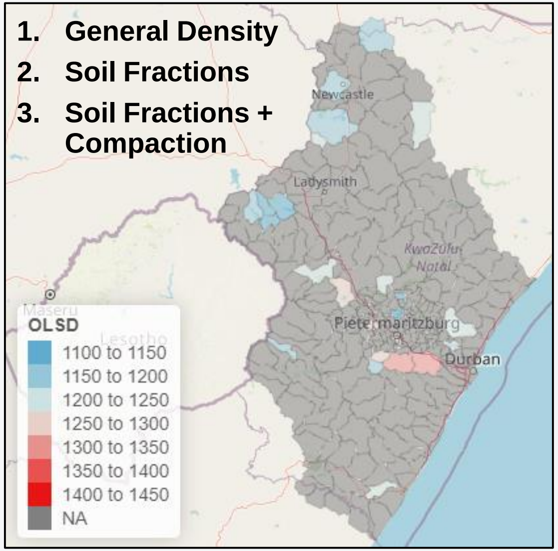
Reservoir storage capacity losses affect:

- Water Supply Reliability
- Hydropower Production
- Flood Management

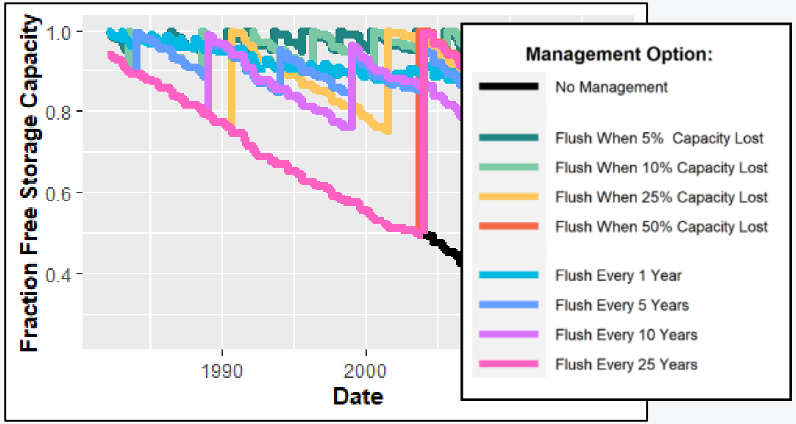


Sediment Density Methods:

1. General Density
2. Soil Fractions
3. Soil Fractions + Compaction



Sediment Management Options:



Findings:

- Simulated reservoir storage capacity losses were not sensitive to choice of sediment density method
- The simulated rate of reservoir storage capacity loss decreased over time as sediments filled the reservoir

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Requested Feedback

- **How can one decide if a reservoir is likely to have sediment management?**
  - Do any global datasets exist?

- **How do reservoir operators decide when to remove sediment?**
  - Is there a standard time interval between flushing/removal events?
  - Is there a standard reservoir capacity to restore during flushing/removal events?

- **How do reservoir operators decide on the rate of sediments to flush?**
  - Is there a standard allowable outflow sediment concentration?
  - Is there a standard length of time over which to remove sediments?

- **What important lake/reservoir sediment parameters should be included in model outputs?**
  - Amount of sediment removed from reservoir during flushing/removal events?

Open Position:
Professor of Hydrology at SMHI

Main focus: development and applications in hydrological modelling

Within one or more (ALL?) scientific fields:

- ✓ Large-Scale Hydrological Modelling
- ✓ Small-Scale Hydrological Modelling
- ✓ Water and Climate Services
- ✓ Hydroclimatology
- ✓ Water Quality Modelling

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