Case study of possible future impacts of climate change on sediment yield for a semi-arid catchment in South Africa

12TH INTERNATIONAL SEDNET CONFERENCE 2 JULY 2021

Prof Gerrit Basson, Erik Barnardt and Dr Jeanine Vonkeman
Department of Civil Engineering, Stellenbosch University, South Africa

Stellenbosch University Iyunivesithi Universiteit

SedNet

INTRODUCTION

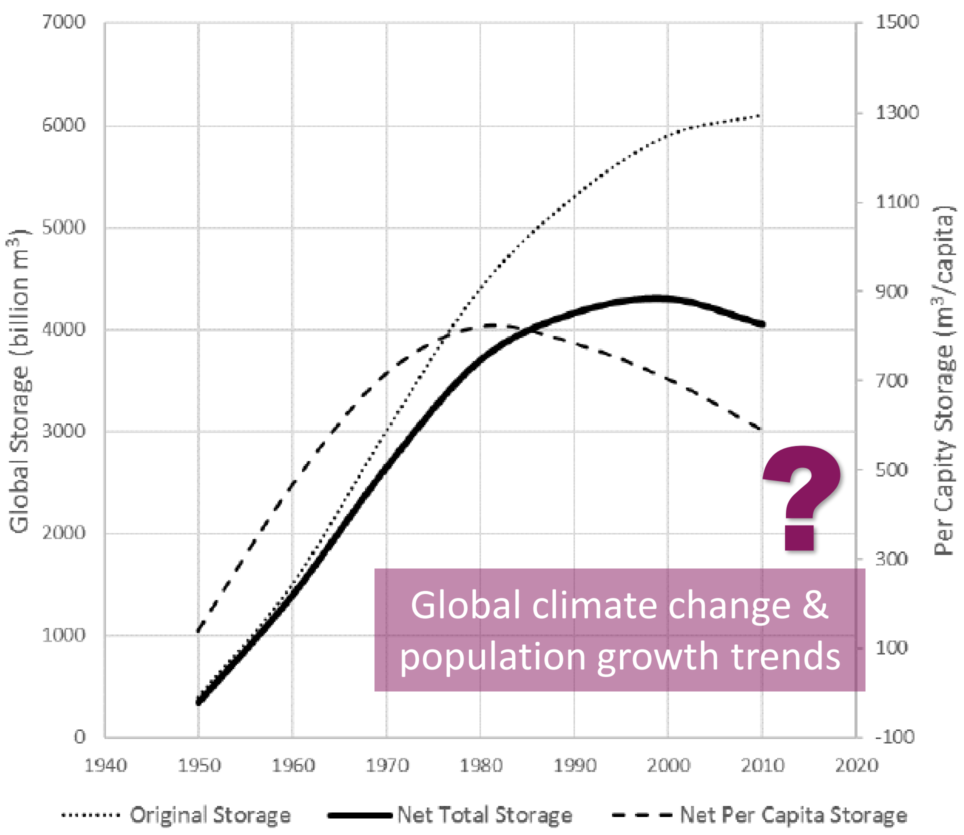
Sedimentation caused by soil erosion and high sediment yields has become a major problem in South Africa, especially in water-scarce regions like the Karoo

- Uncertainties regarding the impact of future climate change

Nqweba Dam
© Reuters 2019

RESERVOIR SEDIMENTATION AS A GLOBAL & LOCAL PROBLEM

- Storage capacities are reducing at a worldwide average annual rate of 0.8% due to reservoir sedimentation
- South Africa (SA) has a 0.37% mean annual loss of storage capacity due to siltation
- Undermines food and water security 98% of available water in SA is already allocated
- Due to landscape & soil conditions, soil erosion is one of SA's leading environmental problems
- SA has variable MAP, rainfall intensities and landscape
- Temp increased by >1.5X global average of 0.65°C over last 5 years & more frequent rainfall



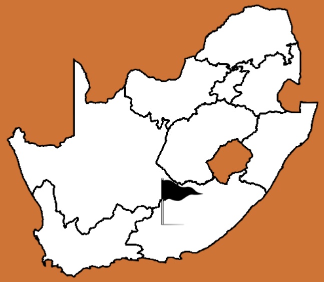
Subsequent issues:

- Water yield
- Food security
- Hydropower
- Flood levels
- Abrasion of turbines
- Clogging of outlets
- Forces on the dam wall
- Disruption of the sediment balance
- Contamination of water quality

SOIL EROSION CONTROL AS A MITIGATION MEASURE

Reduce sediment yield	Reroute sediment	Remove sediment	Adaptive strategies
Catchment practices to reduce erosion	Sluicing suspended sediment	Drawdown or partial flushing	Raise dam
Sediment check dams	Density current venting	Mechanical dry excavation	Address water losses
Off-stream storage	Bypass canal or tunnel	Dredging (mechanical & hydraulic)	Inter-basin transfer
			Construct new dam
			Aquifer recharge
			Modify intakes
			Operational efficiency

<u>Poor catchment practices that can aggravate soil erosion:</u>
Poor land management, overgrazing, road construction, urban development, mining activities, deforestation, etc.



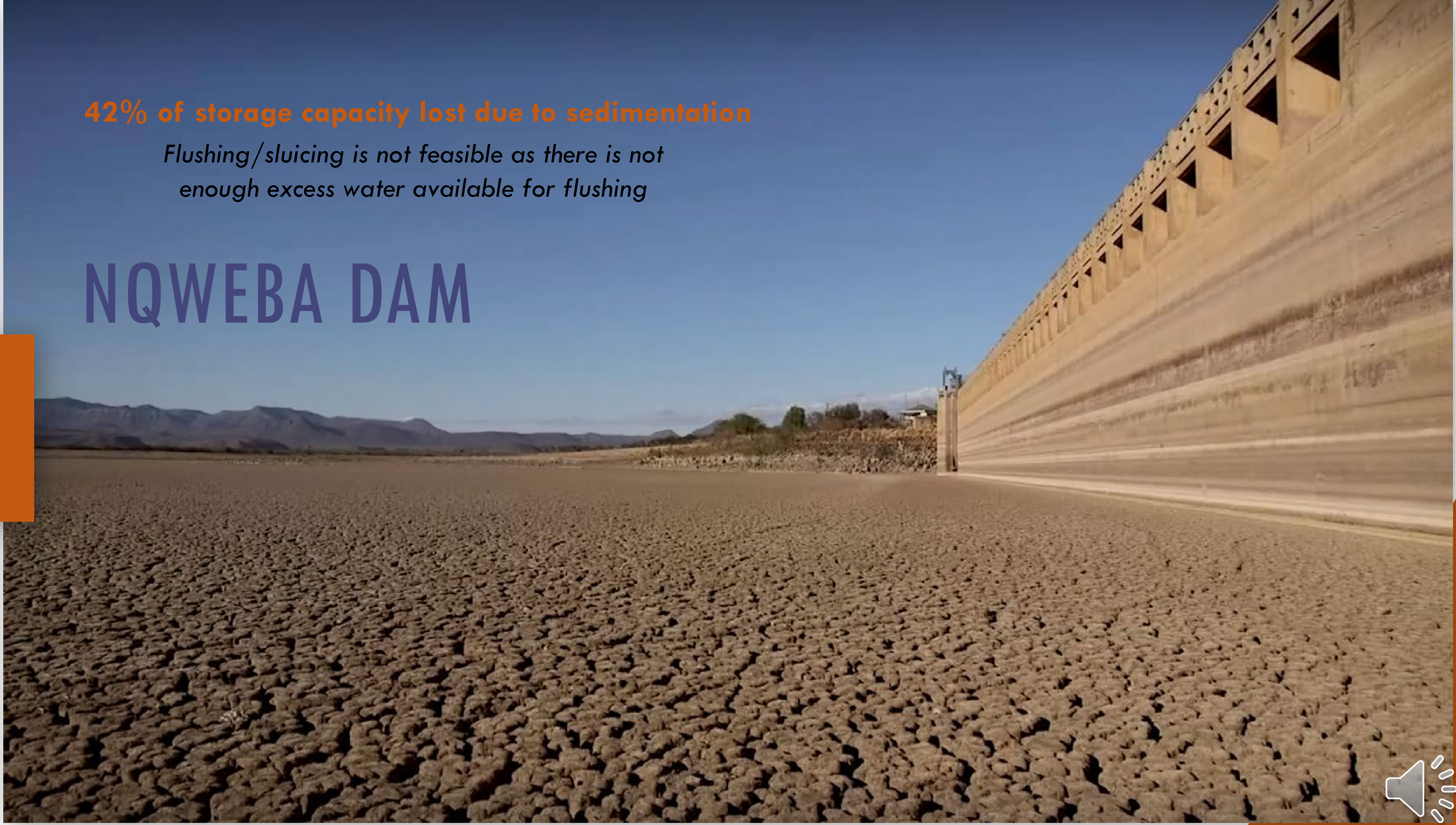
CASE-STUDY

Nqweba Dam catchment on the Sundays River located in the semi-arid region of the Eastern Cape of SA

42% of storage capacity lost due to sedimentation

Flushing/sluicing is not feasible as there is not enough excess water available for flushing

NQWEBA DAM



GRAAFF-REINET WATER REQUIREMENTS

→ CURRENT SUPPLY DEFICIT

AADD ~ 3.3 M m^3/a increasing at 1.8% pa with growing population

42% of storage lost to sedimentation (79 in 1925 to 46 M m^3 in 2020)

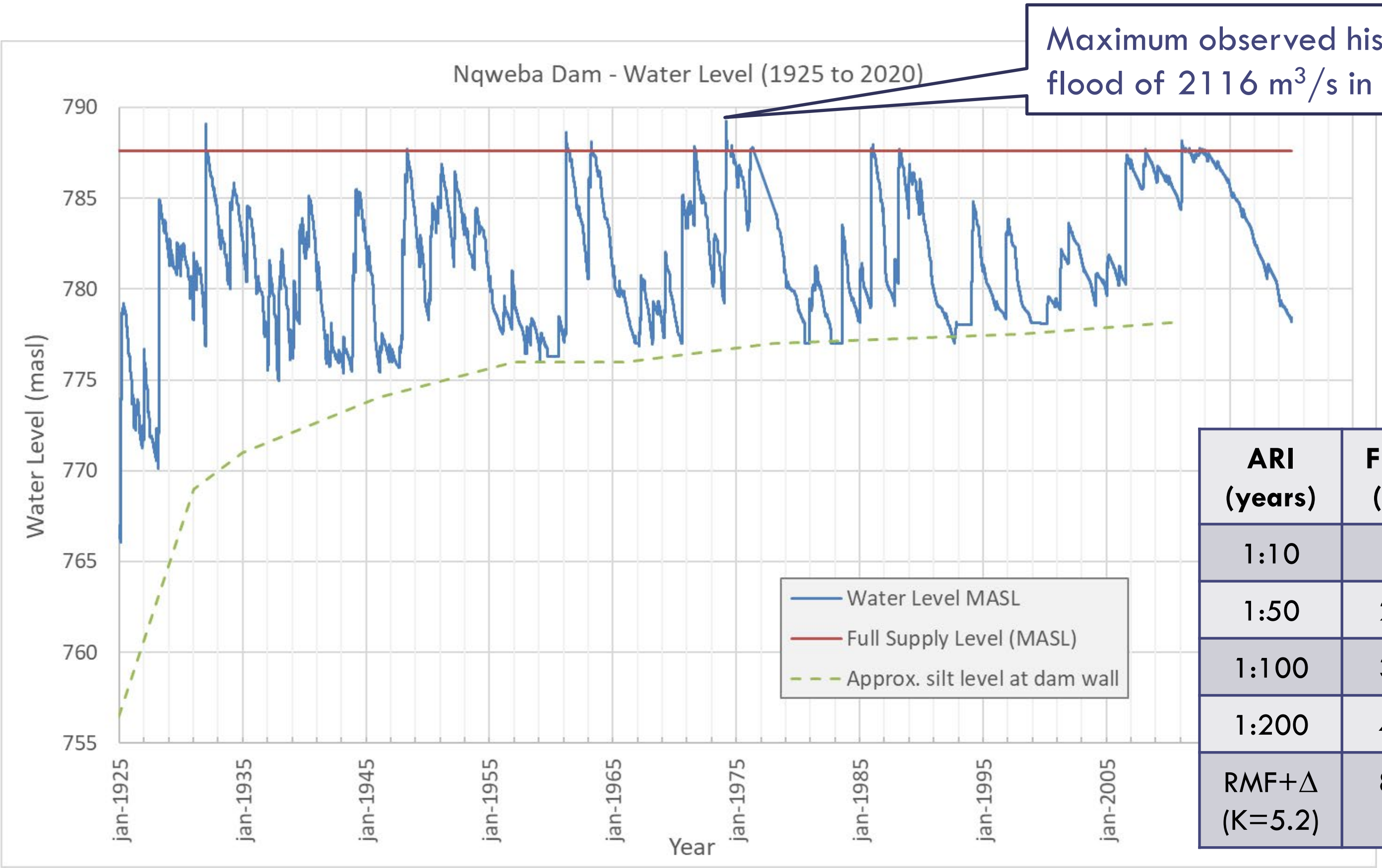
5 M m^3/a historic firm yield in 1925 for irrigation & now potable use

1.9 M m^3/a current firm yield in 2020 (58% of water demand)

38% NRW losses in old distribution network (1.7 M m^3/a)

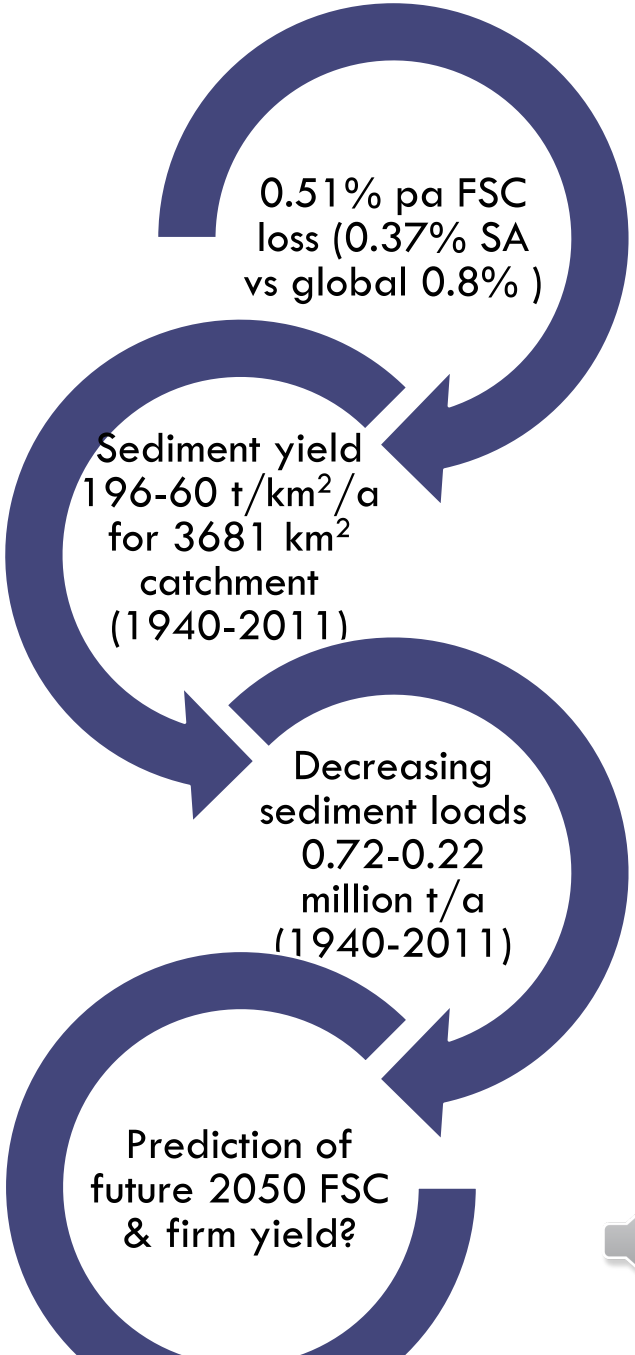
Groundwater resources 1.2 M m^3/a during drought plus 0.3 M m^3/a from planned boreholes

RESERVOIR SEDIMENTATION RATES



ARI (years)	FLOOD (m^3/s)
1:10	720
1:50	2140
1:100	3080
1:200	4260
RMF+Δ (K=5.2)	8560

The Nqweba Dam is characterized by a large surface area with high evaporation rates and a low assurance of supply, having only spilled 8 times and dried up 9 times to date.



METHODOLOGY

Hydrological and sediment yield modelling

SHETRAN: physically-based and spatially-distributed 3D finite-difference model

Model calibration and validation

Observed streamflow and sediment data for the current catchment and climate conditions

Climate change data

- 11 climate models for 2 possible future emission scenarios
- Determine average monthly climate change signals for future periods
- Applied to the current data to represent possible future climate conditions

CLIMATE CHANGE

influences spatial patterns of hydro-climatic systems

GCMs (General Recirculation Models) simulate dif emission scenarios or **RCPs** (Representative Concentration Pathways)

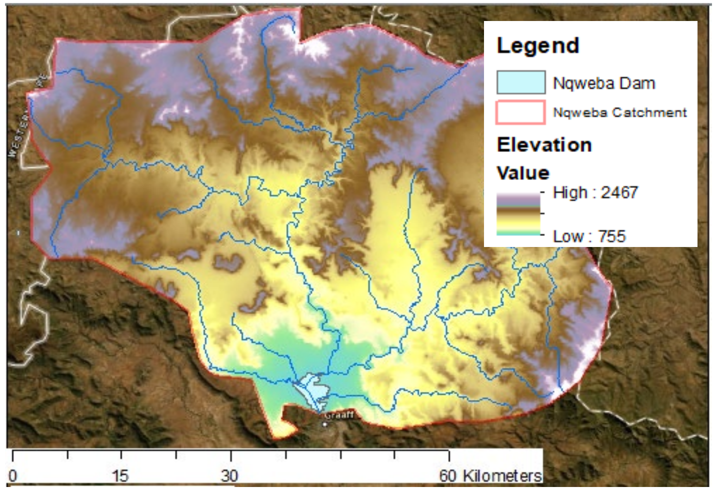
Regional downscaling of 11 GCMs by UCT & CSAG to characterize impacts on a local scale for 2 RCP's in accord with the CMIP5 i.e. RCP4.5 & RCP8.5

SHERAN modelling of rainfall & temp to simulate hydrological consequences of climate change within a catchment

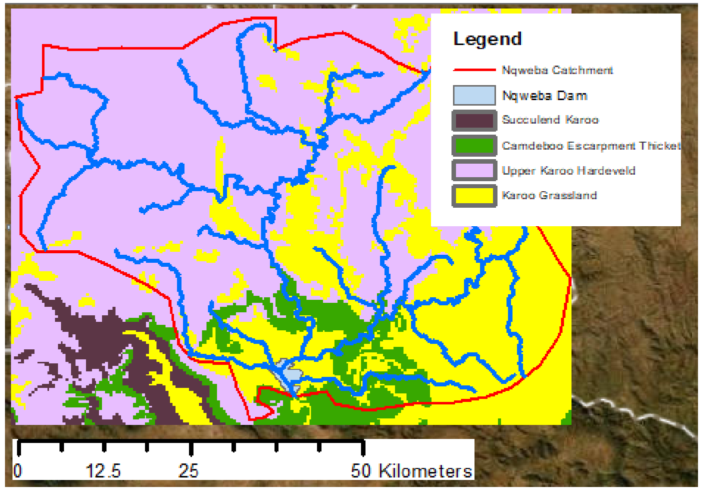
WHY SHETRAN?

- Physically based with initial and boundary conditions
- Spatial distribution of topography, soil properties, land cover and land use (basin scale)
- Modify to represent changes within catchment or climate data
- Daily time step to model subsurface flow, sediment transport and erosion
- Only model developed for raindrop impact and different types of erosion
- Recommended in literature for climate change studies

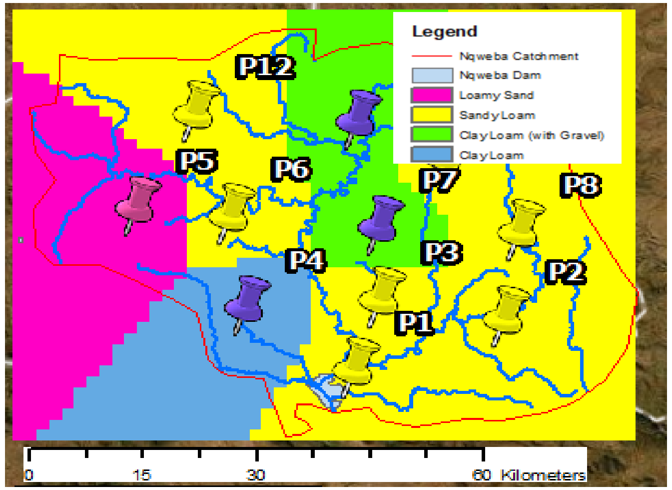
CATCHMENT CHARACTERISTICS



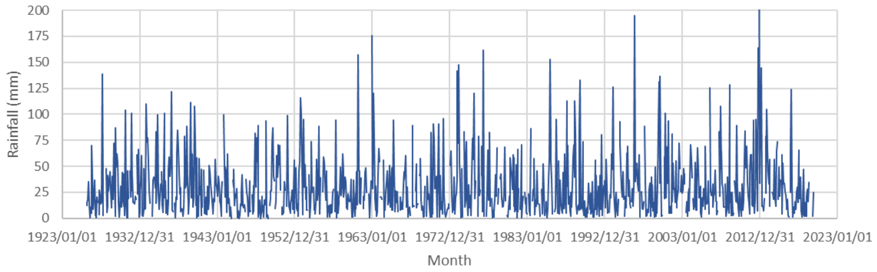
Digital Elevation Model (DEM) from USGS (2020)

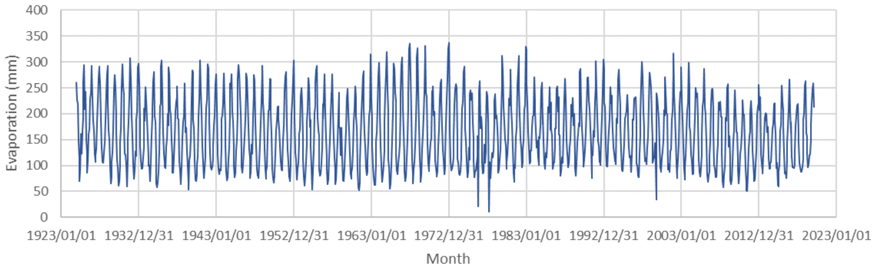


Spatial land cover distribution from SANBI (2012)



Sampling for soil properties & grading





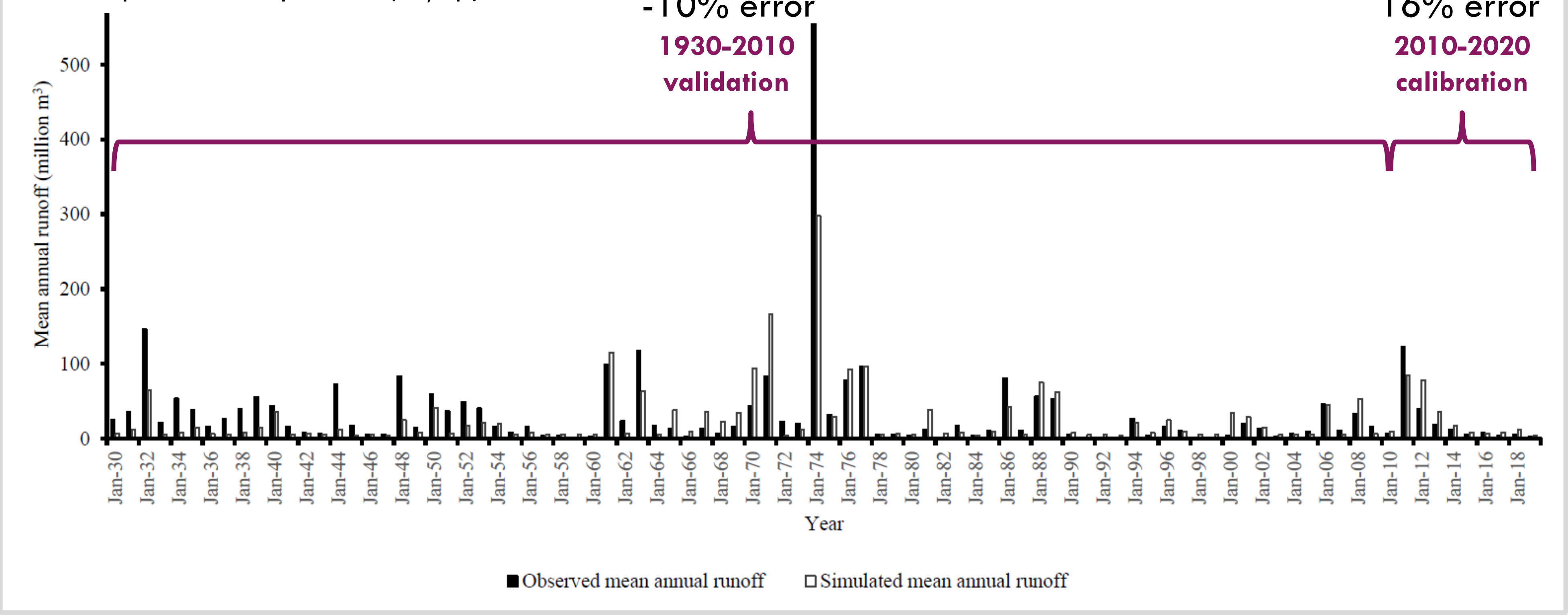
Historic rainfall and evaporation data from DWS (2011) applied spatially using Thiessen polygon of 4 stations

SHETRAN RUNOFF CALIBRATION

Calibrated against streamflow data based on historic Nqweba Dam water levels

Parameters for calibration

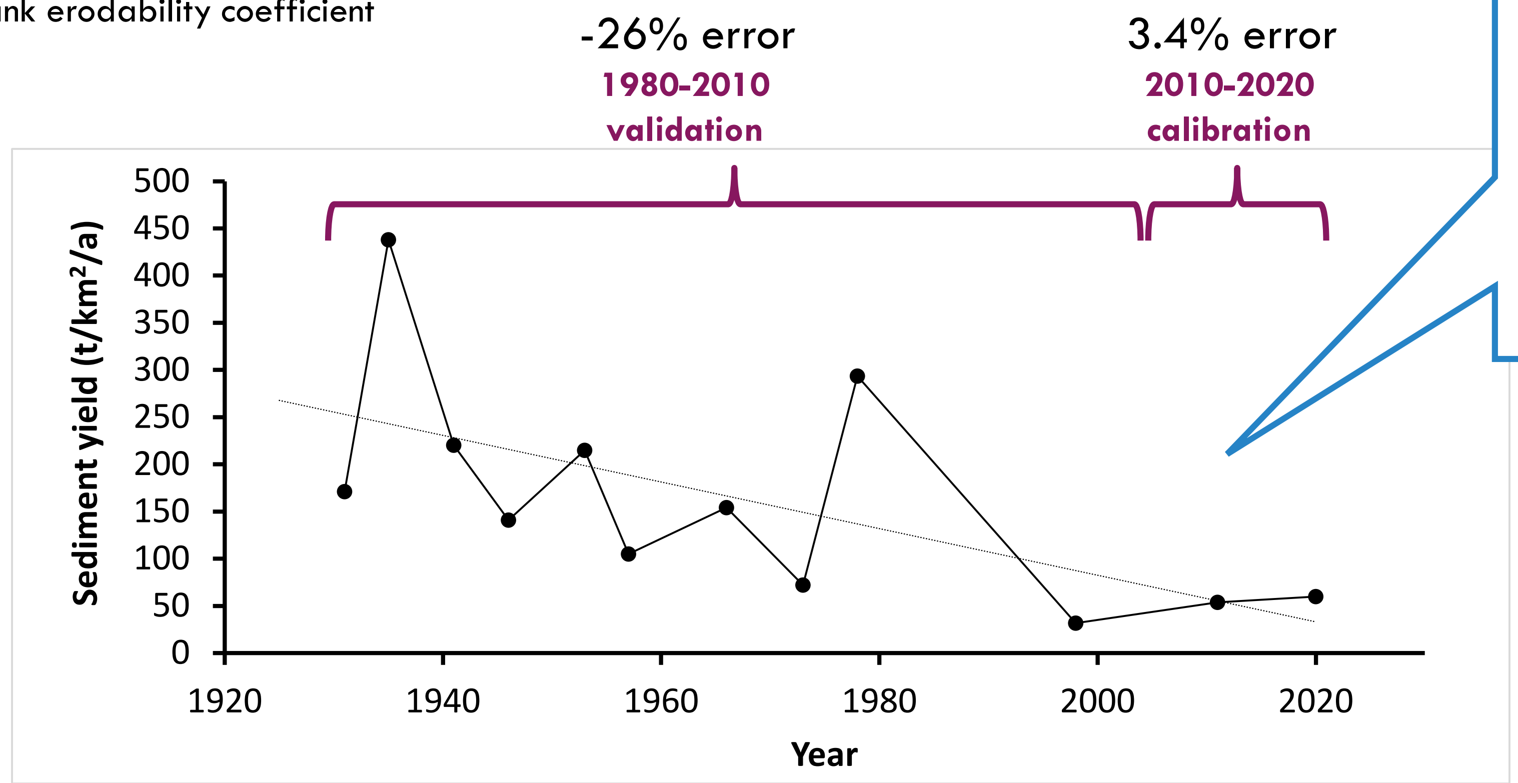
- Saturated hydraulic conductivity (Ks)
- Soil hydraulic property parameters (van Genuchhten α and η)
- Overland flow resistance coefficient (1/Manning n)
- Ratio of actual and potential evaporation (Ea/Ep)

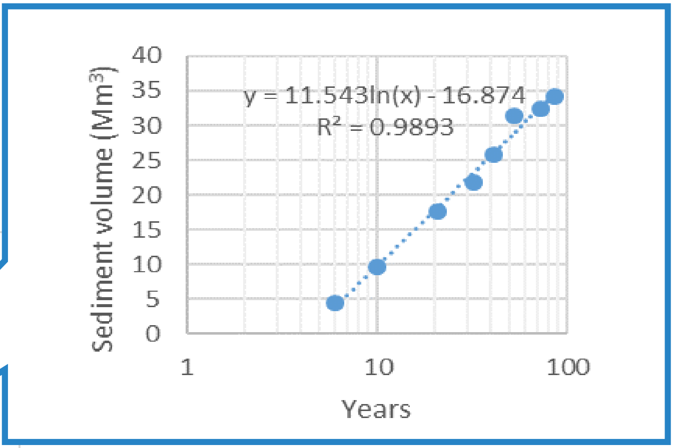


SHETRAN SEDIMENT YIELD CALIBRATION

Calibrated against sediment yield data based on historic Nqweba Dam storage capacity (traps 97% of sediment)

Parameters for calibration
- Raindrop erodability coefficient
- Overland flow erodability coefficient
- Channel bank erodability coefficient





Nqweba Dam sediment density is variable over years & calibrated for consolidation 813-1215 kg/m^3

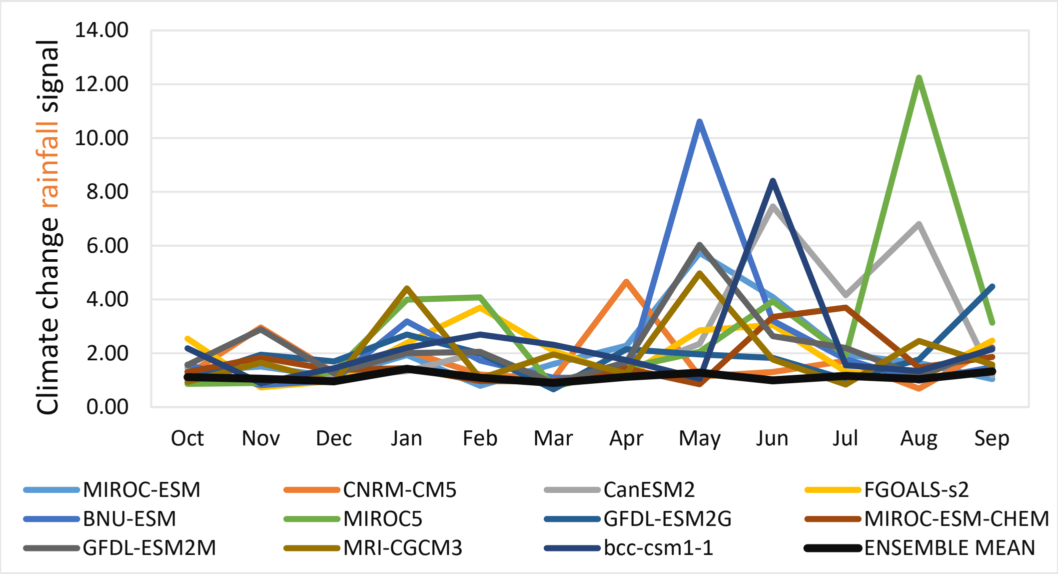
$$S_y = \frac{\rho_T * V_T - \rho_{T-n} * V_{T-n}}{n * A_e}$$

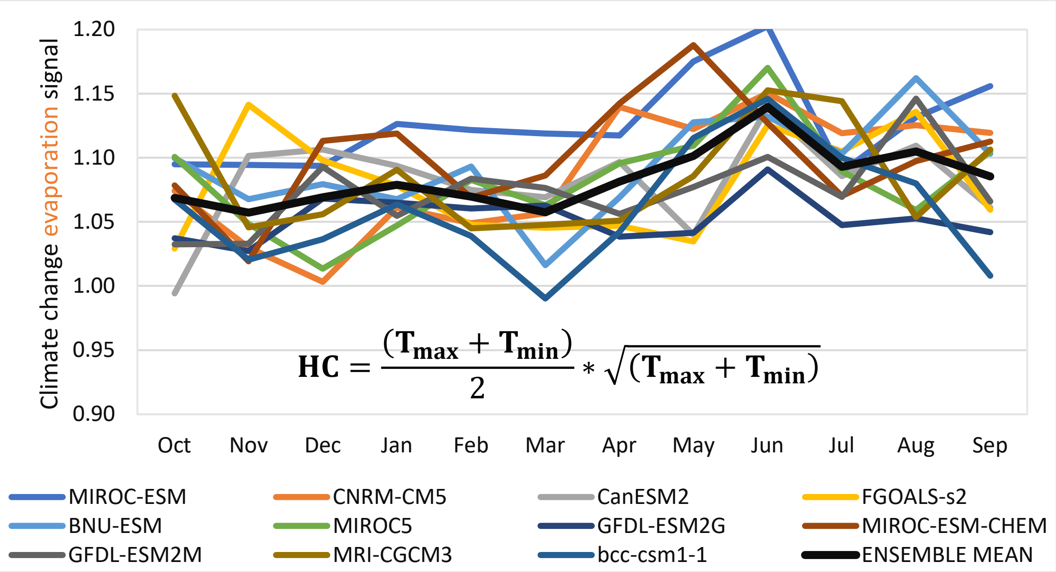
$$\rho_T = \rho_0 + 0.4343 K_0 \left[\frac{T}{T-1}(\ln T) - 1\right]$$

HISTORY OF LAND-USE PRACTICES

- **1877-1886 gold rush damage to Karoo landscape and vegetation**
- **1950-1953 Korean War large wool demand, overstocking of sheep, overgrazing & land degradation**
- **1950s compulsory stock reduction scheme & subsidy**
- **1960s conservation efforts to mitigate soil erosion e.g. Agave American planted for soil retention**
- **Subsequent shift from livestock to game farming**
- **Construction of 100s of farm dams with significant impact on sediment retention**

CLIMATE CHANGE SIGNALS FOR 4 FUTURE PERIODS & 2 RCP'S





Example calculation:

Date (YYYY-MM)	Avg projected Rainfall (mm)	Date (YYYY-MM)	Avg projected Rainfall (mm	Climate change signal
2010-01	41.238	2030-01	28.086	0.68
2010-02	77.668	2030-02	32.318	0.42
2010-03	48.662	2030-03	27.351	0.56

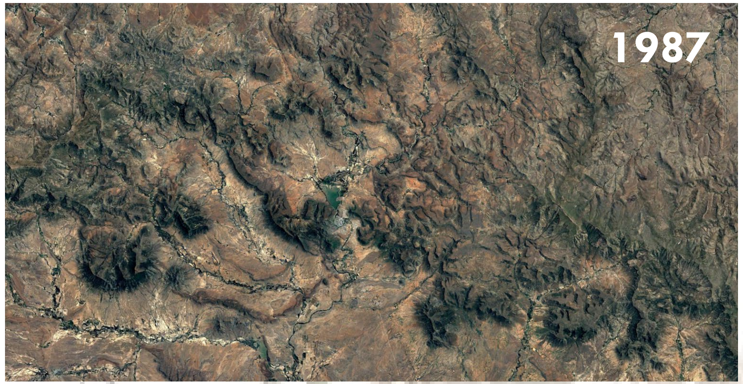
Rain current / Rain future = CC signal

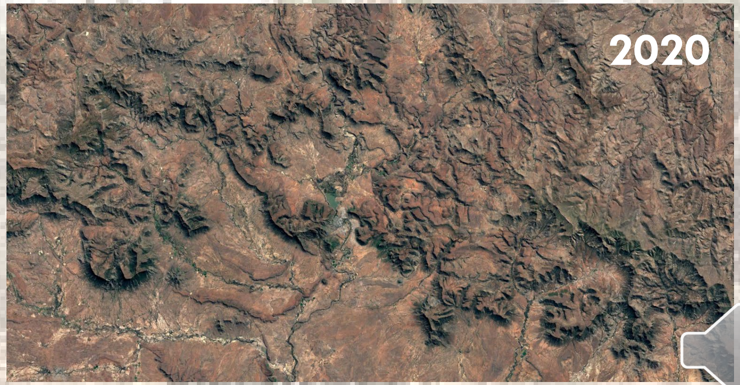
→ **Average of 11 climate change models**

Period	Average Rainfall signal		Average Evaporation signal	
	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
2010-2020	1.00	1.00	1.00	1.00
2030-2040	1.22	1.17	1.04	1.05
2050-2060	1.11	1.12	1.05	1.09
2070-2080	1.13	1.19	1.08	1.15
2090-2100	1.24	1.29	1.09	1.21

SHETRAN SIMULATIONS – CURRENT VEGETATION

Period	Mean annual runoff (million m^3)		Sediment yield (t/km^2/a)	
	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
2010-2020	26	26	60	60
2030-2040	166	122	191	162
2050-2060	86	59	109	105
2070-2080	70	95	122	135
2090-2100	136	110	199	140





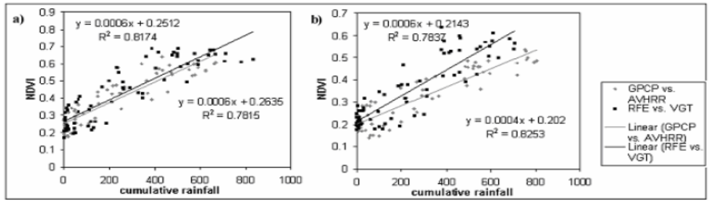
SHETRAN SIMULATIONS – VEGETATION CHANGE

Stickler overland flow coefficient
Canopy storage capacity
Leaf Area Index

Period	Mean annual runoff (million m^3)		Sediment yield ($t/km^2/a$)	
	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
2010-2020	26	26	60	60
2030-2040	159	118	182	155
2050-2060	79	52	101	94
2070-2080	60	83	106	121
2090-2100	122	95	174	133

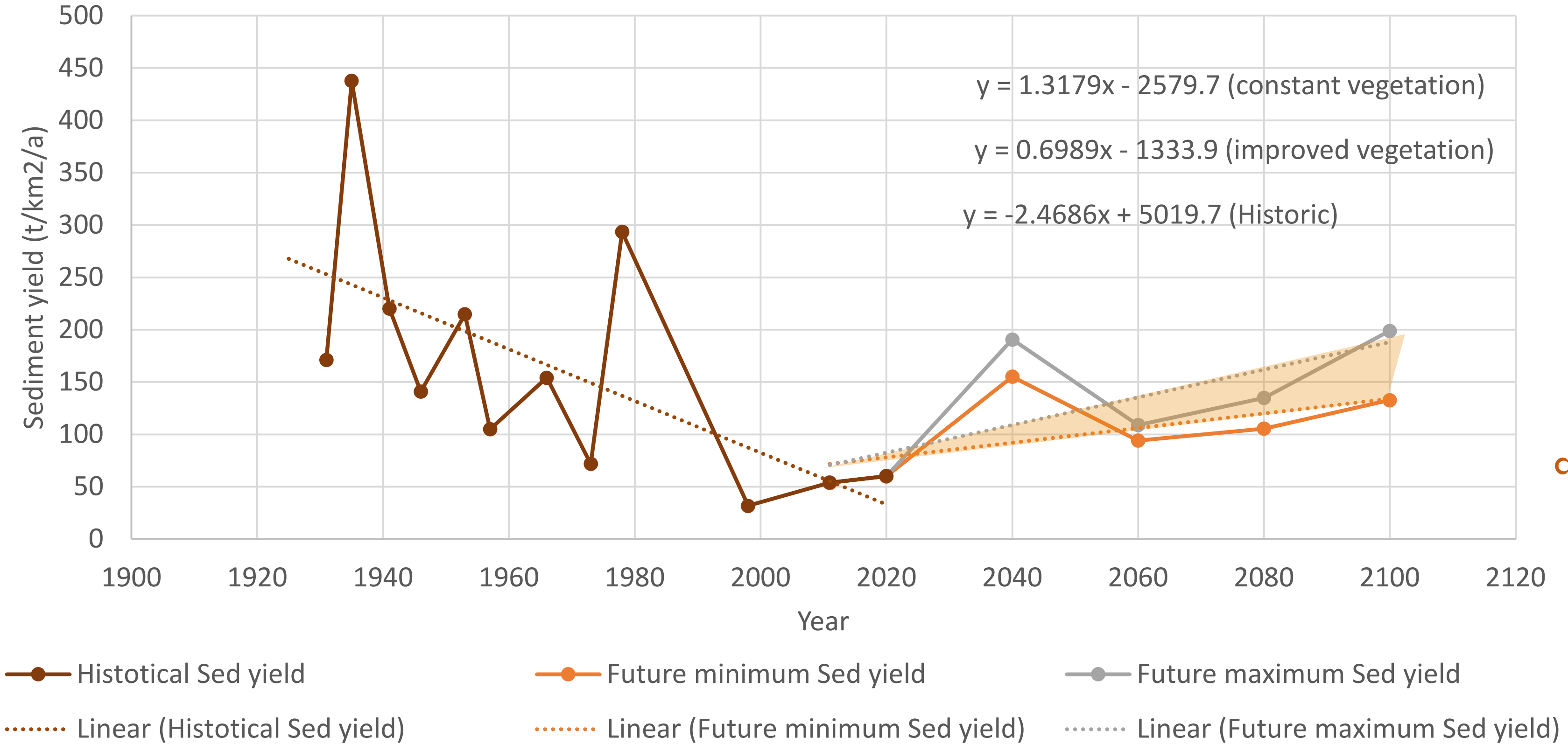
Year	Cumulative Rainfall (mm)		Normalized Difference Vegetation Index (NDVI)		Vegetation change signal	
	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
2020	356	356	0.200	0.200	1.000	1.000
2040	790	772	0.274	0.270	1.370	1.352
2060	1185	1170	0.353	0.350	1.765	1.750
2080	1587	1593	0.433	0.435	2.167	2.173
2100	2028	2052	0.540	0.600	2.700	3.000

Linear regression NDVI = 0.0002R + 0.116
**based on Hermann et al. (2005) approach for West African Sahel*



CONCLUSIONS

Increase in future sedimentation relative to baseline period



Envelope for prediction based on different emission and vegetation scenarios

THANK YOU

Stellenbosch University, South Africa
Department of Civil Engineering
Prof GR Basson
grbasson@sun.ac.za
+27 82 920 6511