Modeling in aquatic environment

Lecture 7

Sediment transport models

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Settling velocity (v_f): Stoke's equation

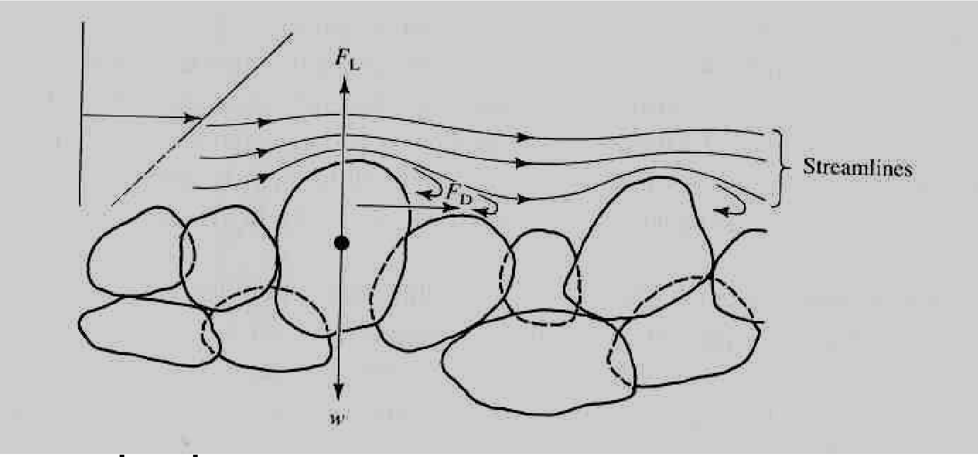
$$w_s = \frac{2(\rho_s - \rho) g r^2}{9\mu} = \frac{(\rho_s - \rho) g d^2}{18\mu}$$

- Assumption: spherical particles
- Gravity force balances drag force
- Particle reaches a constant settling velocity
- This velocity is dependent on: fluid viscosity (μ), density difference between the particle and water (ρ_s-ρ) and finally on particle diameter (d),
- g=gravity constant= 9,81 m/s^2
- Velocity range: From 0.07 m/d (clay, d=1.2 μm) to 710 m/d (sand, d=200μm), density=2.5 gcm^{-3}

Settling speed in natural waters

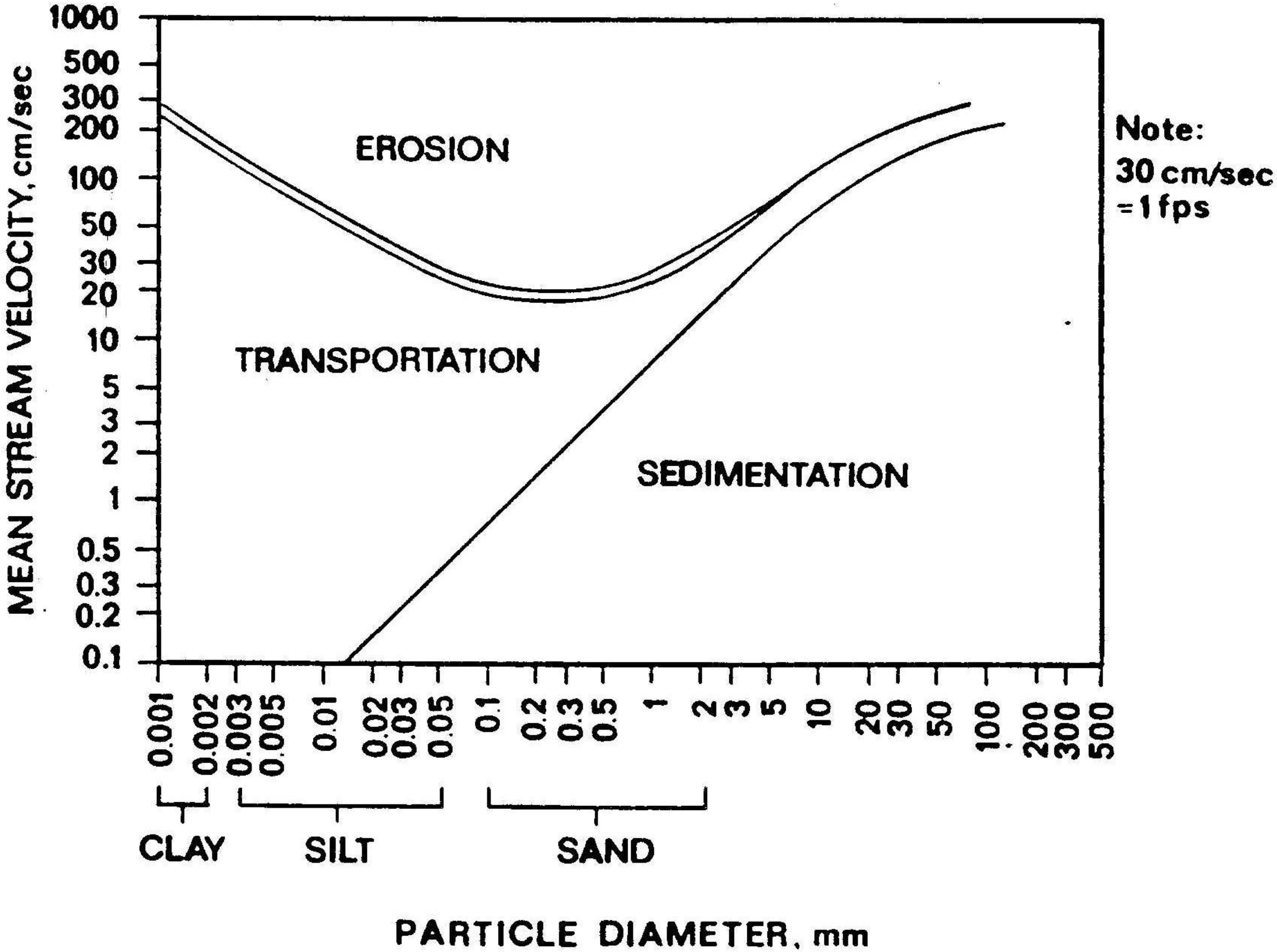
- Particles are seldom spherical: clay particles are like plates
- Aggregation of particles happens due to the electromagnetic forces ➔ cohesive soils (clays, mud…)
- Organic compounds like humic substances have a very fragile structure ➔ structure changes even in water column
- ➔ velocity from Stoke's equation has to be corrected with empirical relations
- Baba& Komar, 1981: w_{real}=0.761w_s
- In sediment transport models w_s is determined on the basis of the median particle size from a surface sediment sample

Erosion or resuspension from bottom



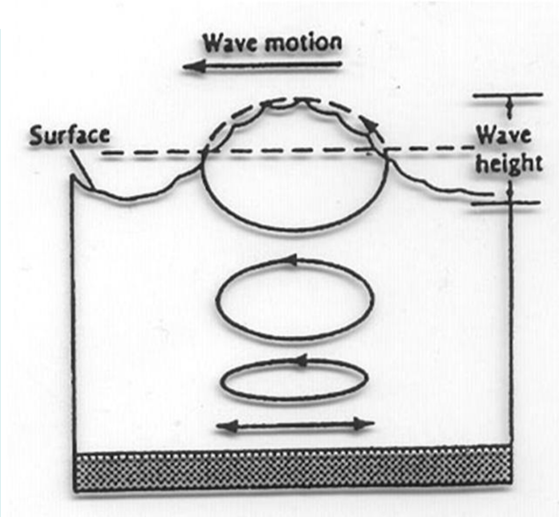
- Acting forces on a particle laying on the bottom
  1. difference between gravity and buoyancy
  2. drag force by the current
  3. lifting force due to the pressure differences as caused by water flowing between particles
  4. electromagnetic forces causing aggregation
- Term 1. $\propto$ (‘is related to’) density difference and particle $(\text{diameter})^3$
- Terms 2 and 3. $\propto$ shear force caused by current and particle $(\text{diameter})^2$
- Shields’s empirical curve for erosion used much in designing of structures
- A simplified erosion curve by Hjulström (erosion vs. current velocity)
- In models we use most often the critical shear concept

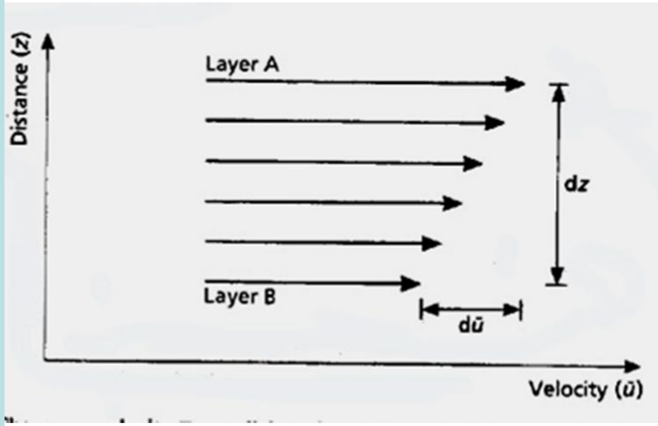
Hjulström's curve for erosion



Critical shear

- Total shear (τ) on the lake bottom has two components:
  - 1) shear caused by orbital movements of waves = f(wind fetch over lake, lake mean depth, wind velocity and duration)Lake Pyhäjärvi example
  - 2) shear caused by currents
- τ > critical shear (τ_{cr}) : erosion happens with a rate $\propto$ a*(excess shear)^b
- τ_{cr}, a and b are experimental values, which we calibrate during model application
- values for τ_{cr}: 0.008…1 Nm^{-2}, b=1..3, a = depends on sediment
- In this formulation there are no consolidation effects and bottom morphology is not included





Institute, SYKE

Calculation of sediment transport

- Simple screening tools can be found from www: http://www.wes.army.mil/el/dots/doer/tools.html or http://www.coastal.udel.edu/faculty/rad/
- Using numerical flow models for predicting the horizontal current field
- Suspended solids concentration is calculated with concentration equation
- Following terms in concentration equation:
  - horizontal advection with settling speed in vertical dimension
  - turbulence
  - mass flow from tributaries and to out flowing river
  - settling and deposition to bottom
  - erosion or resuspension from bottom

Example from Mänttä

2DH flow model with BOD7 water quality compartment

Sediment was light organic fibre

Short term regulation at hydropower plant

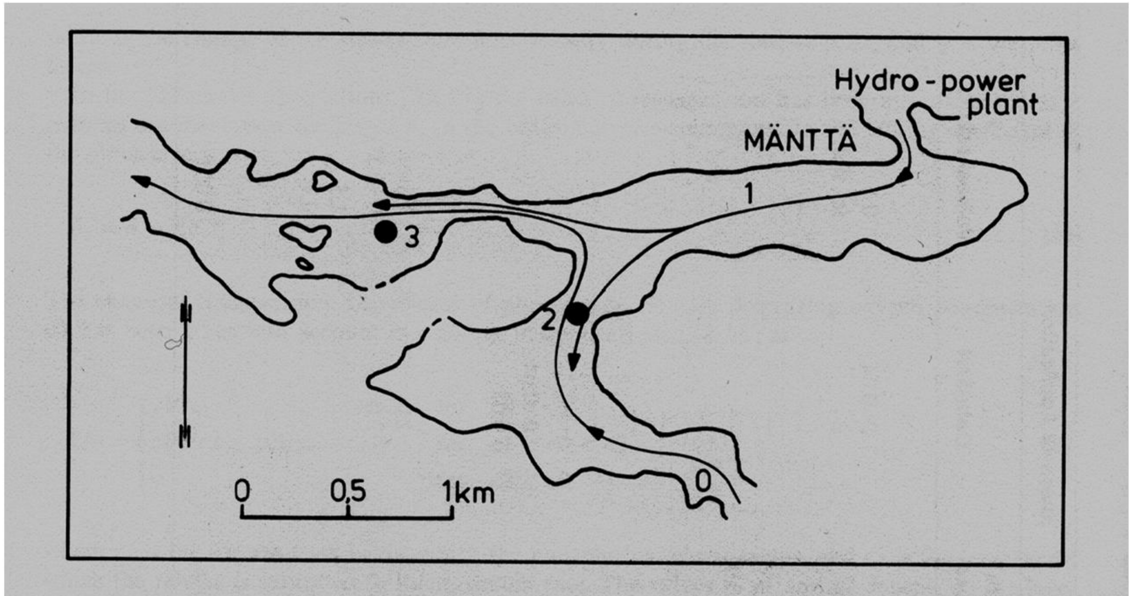
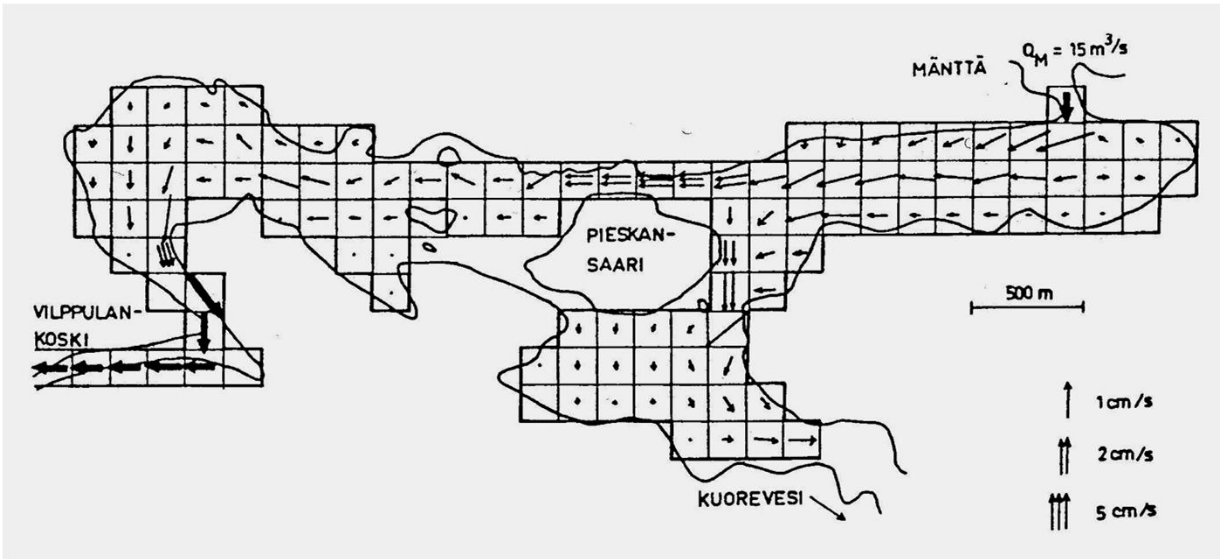


Figure 27. The research area downstream of the hydropower plant and the pulp and paper mill in Mänttä, Central Finland (29). 0 = the natural throughflow, 1 = flow induced by the discharge through the hydropower plant, 2 = the main place of the flow measurements (e.g., Figure 11), 3 = the main place of the concentration sampling (e.g., Figure 29).



Mänttä: Transport model result

Sediment: fibrous material

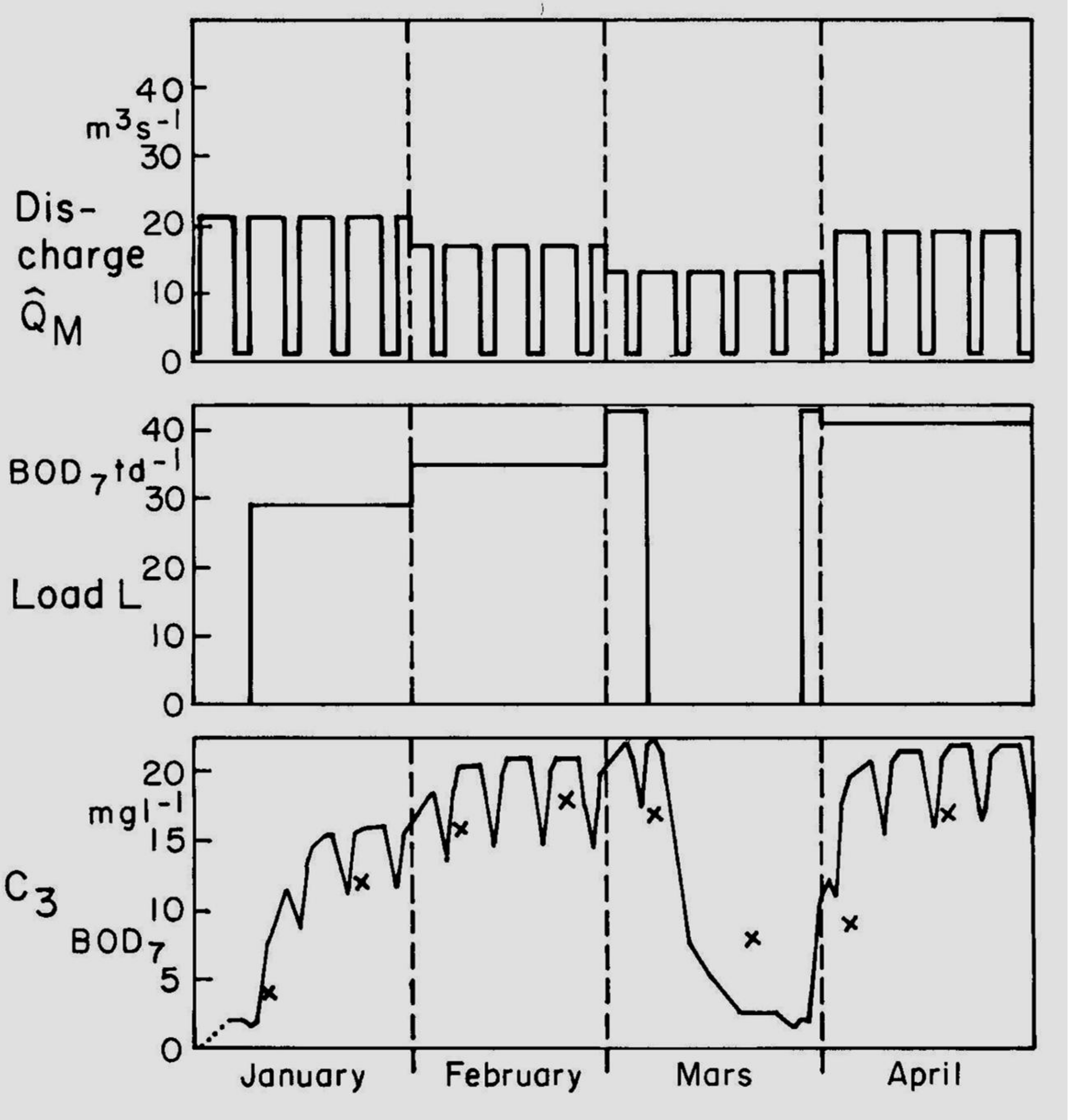


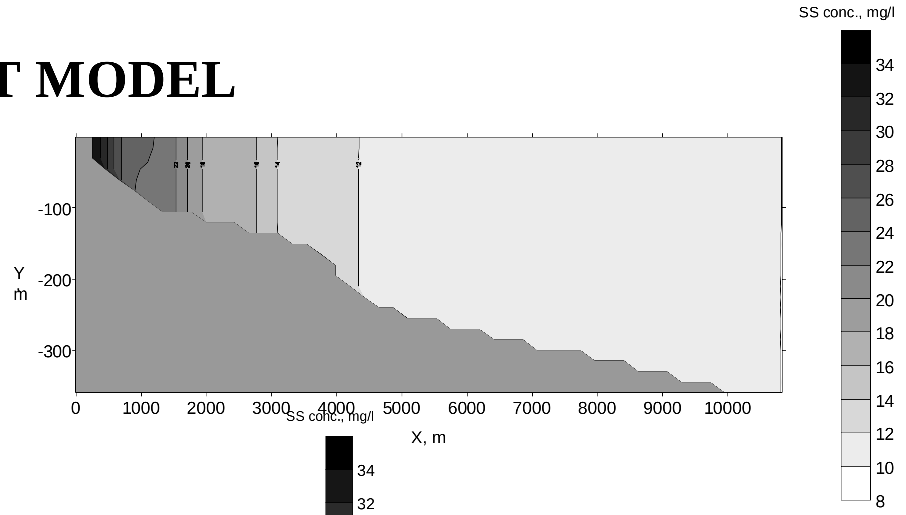
Figure 29. The discharge through the hydropower plant (Q_M, above), the loading from the pulp and parer mill (BOD_7, middle), and their concentration effect (C_3, below) at the sampling point 3 (Figure 27) downstream of Mänttä in winter 1978 as modeled (line) and measured (crosses).

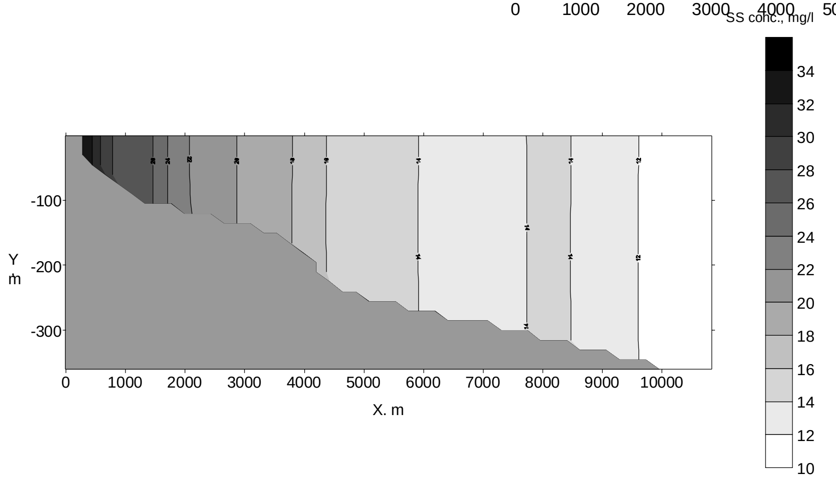
Sediment transport in Tanganyika

- Model simulation
  - lake wide circulation model ➔boundary values (current velocity) for high resolution model at river mouths
  - flow model and suspended sediment (SS) transport models
  - SS input was estimated from historical data
  - real winds from atmospheric model HIRLAM (this model was used first time in tropics)

3D SEDIMENT TRANSPORT MODEL

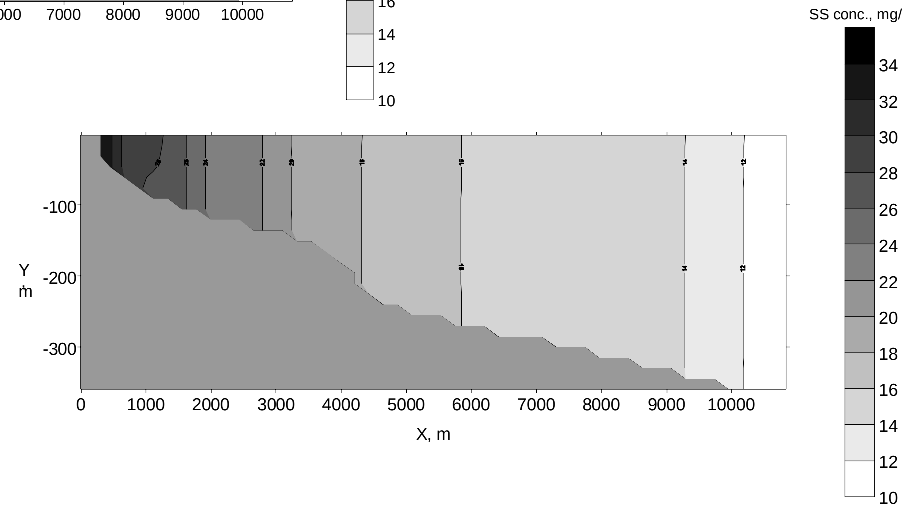
(A), 12:00 24.08.97





(B) 0:00 28.08.97

(C) after 22, 82 and 166 hours after the simulation start respectively.



Example from Karhijärvi

- Three different models were tested 2DH, 2DV and 3D model
- Models were tested in an runoff case in Oct 1992, when heavy rains caused erosion from watershed and a heavy suspended solids load to lake
- Data: winds on the lake, water current observations, turbidity observations
- ➔ 3D model gave best results

Sediment transport in Coherens: 1

Sediment transport in Coherens: 2

Sediment concentrations can be represented either as a volumetric concentration c in units of m^3/m^3 or as a mass concentration c_{mass} in kg/m^3.The two forms are related by

$$c_{mass} = \rho_s c \tag{7.25}$$

The volumetric form is taken in COHERENS, which is considered as more physically meanigfull, especially in processes as hindered settling.

A dimensional analysis by Yalin (1977) shows that the sediment transport can be expressed by a number of dimensionless parameters:

$$Re_* = \frac{u_* d}{\nu} \tag{7.26}$$

$$\theta = \frac{\rho u_*^2}{(\rho_s - \rho) g d} \tag{7.27}$$

$$s = \frac{\rho_s}{\rho} \tag{7.28}$$

$$d_* = d \left[(s-1) \frac{g}{\nu^2} \right]^{1/3} \tag{7.29}$$

$$\Phi = \frac{q}{\sqrt{(s-1) g d^3}} \tag{7.30}$$

where d is the particle diameter, Re_* the particle Reynolds number, θ the dimensionless shear stress or Shields parameter (Shields, 1936), s the relative density, d_* the dimensionless particle diameter and q the sediment load per unit width (in m^2/s).

Sediment transport in Coherens: 3

- Number of sediment fractions is not limited, but in practice the most important are d50 (median particle size) and some decadal values like, d10 and d90
- Hindered settling when SS-concentration large, like 3 g/l. In F. in natural waters it about 1-10 mg/l.
- Surface waves are not included in main code. Still the effect of waves is included in bottom stresses
- Wave height, wave period and wave direction as input from external data

Sediment transport in Coherens: 4

- At bottom boundary the critical shear stress approach is used
- Several options are available
  - Modification of Shields non-dimensional shear stress to become dependent only on d_* as Brownlie (1981)
  - Or as Soulsby&Whitehouse (1997) provided a new form
  - Or constant value of critical shear stress 0.03 as proposed by Wu et al. (2000)
  - User can set a value (note: has to be the kinematic one)

Sediment transport in Coherens 5

- Bed load is active in the near bed layer with thickness taken often as zsb ≈ 2d. Very thin layer ➔ Seldom used by us.

Sediment transport in Coherens 6

- By us mostly the suspended sediment transport calculation

Sediment transport in Coherens 7

Sediment transport in Coherens 8

7.6.3.1 Erosion and deposition of sand in 3-D

The following equation is used as the boundary condition near the bed for the suspended sediment transport equation (taken at a reference height a above the bed)

$$-D_V(a)\frac{\partial c_n}{\partial z}(a) - w_{s,in}(a)c_n(a) = E_n - D_n \qquad (7.120)$$

Here, E_n is the erosion of sediment fraction n, D_n the deposition, c_n the volumetric sediment concentration, and $w_{s,n}$ the settling velocity of fraction n. Note that because the volume concentrations are used in COHERENS, the dimensions of the erosion and deposition are m/s.

The deposition flux is given as

$$D_n = w_{s,n}(a)c_n(a) \qquad (7.121)$$

Using this expression, the bottom boundary conditions reduces to the following Neumann boundary condition:

$$-D_V(a)\frac{\partial c_n}{\partial z}\Big|_a = E_n \qquad (7.122)$$

MoMa-project

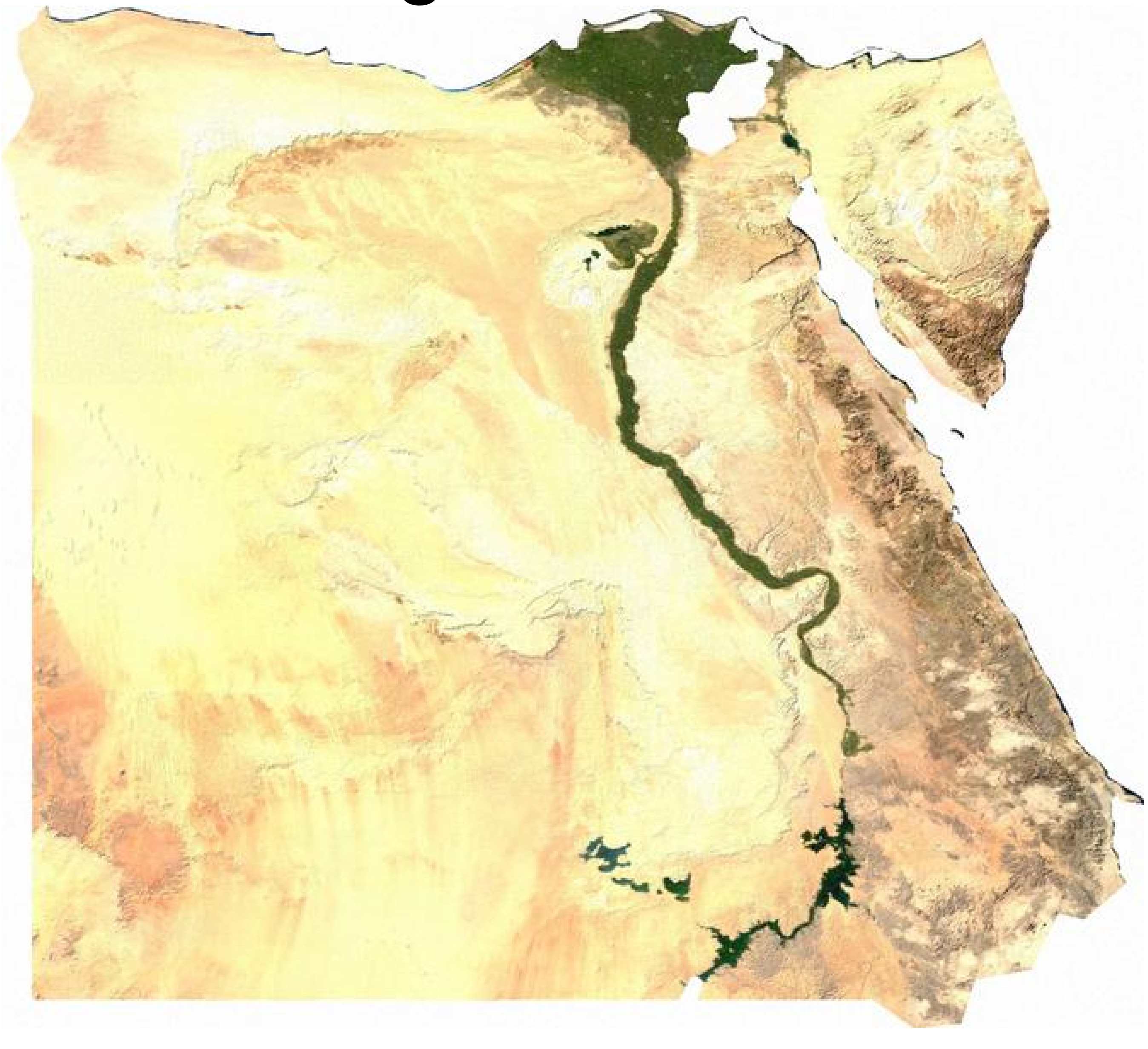
- MoMa – MONITORING MASTER
- Full name: AQUATIC MONITORING FOR SUSTAINABLE DREDGING IN NORTHERN LAKES OF EGYPT
- Funded by the Ministry of Foreign Affairs Finland
- Project duration 2017-2018, possible extension to 2019
- Partners: Finnish Environment Institute (SYKE) and General Authority for Fish Resources Development (GAFRD) in Egypt

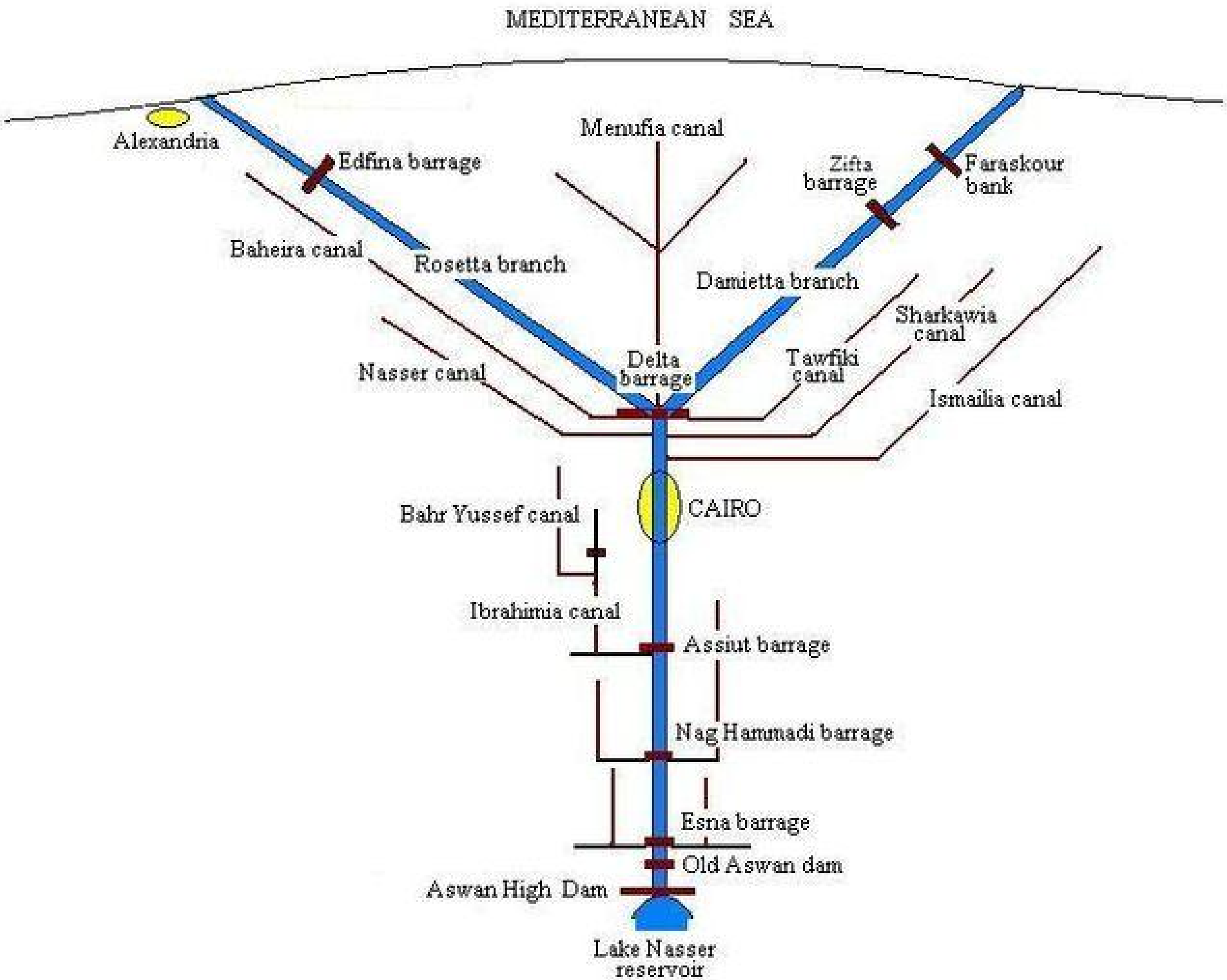
Goals

- To strengthen the monitoring and prediction capacity of GAFRD
- To assess the environmental impacts of dredging
- To evaluate improvement of water exchange (sea water intrusion)
- To define consequent impacts on fish population and determinate the follow-up of possible release of hazardous substances accumulated in the sediments
- The aim of these assignments is to improve the environmental status of the lakes in an environmentally and socially sustainable manner

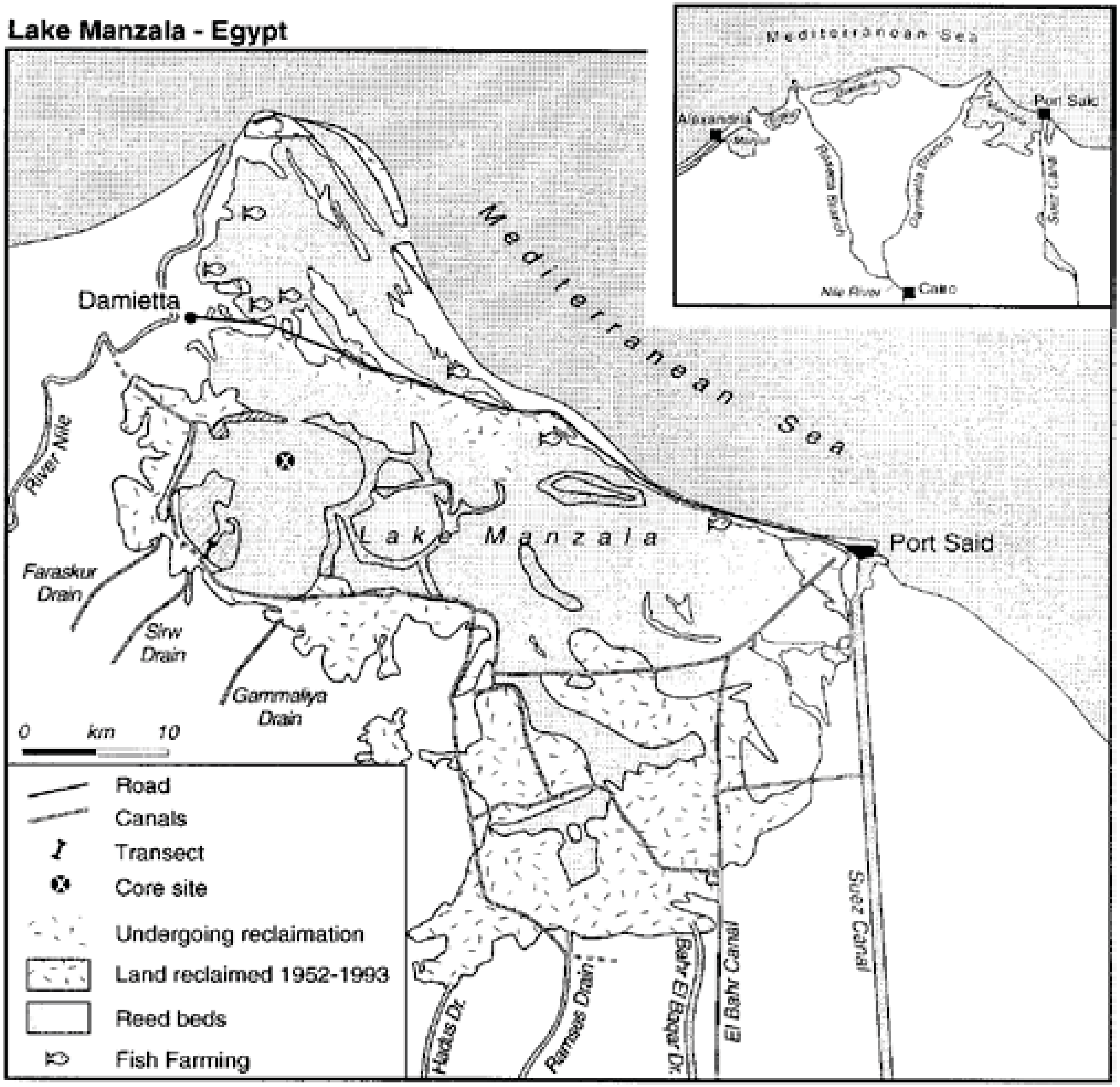

Mediterranean Sea
Dead Sea
Sallum
Alexandria
Port Said
Matruh
ISRAEL
CAIRO
GIZA
Suez
JORDAN
Nile River
MT. SINAI
SAUDI ARABIA
BENI HASAN
Sharm el Sheikh
TUNA EL GABAL
TEL EL AMARNA
Asyut
Hurghada
LIBYA
Sohag
Qena
KARNAK
Red Sea
Luxor
EGYPT
Aswan High Dam
Aswan
Lake Nasser
SUDAN

Irrigated land





Sketch of the system of barrages and main canals along the Nile.
Not to scale



Lake Manzala - Egypt
Mediterranean Sea
Alexandria
Port Said
Cairo
Nile River
Rosetta Branch
Damietta Branch
Suez Canal
Damietta
River Nile
Lake Manzala
Port Said
Faraskur Drain
Sirw Drain
Gammaliya Drain
0 km 10
Road
Canals
Transect
Core site
Undergoing reclaimation
Land reclaimed 1952-1993
Reed beds
Fish Farming
Hadus Dr.
Ramses Drain
Bahr El Baqar Dr.
El Bahr Canal
Suez Canal

- MoMa-project is closely related to an investment project, where Finland supports GARFD to purchase WaterMaster dredgers by Aquamec
- Wbesite: http://www.watermaster.fi/

Key questions for finding optimal solution in dredging

- Balance between
  - Improving water exchange, water quality and space for fish production
  - Effective use of labor time and machinery
  - Harmful effects for aquatic life during the operation and in long time perspective
- Optimal timing: season, time of day
- Sites: where to operate
- Way of operation: all dredgers in same area or they are distributed??
- Solution: Monitoring and modelling
- Model used for planning the dredging activities
- Monitoring used for data collection and validating the model