Modeling in aquatic environment

Lecture 5&6

Advection and dispersion models

Timo Huttula

Timo.huttula@environment.fi

http://www.ymparisto.fi/syke/jyvaskyla

Currents

- The observed value of velocity vector at a certain point (x,y,z) at certain time v(t,x,y,z,) is a vector sum of vectors v_i
- $v(t,x,y,z,) = \Sigma v_i(t,x,y,z,)$
- v_i, i=1, n, where most important components are
- v_1= current generated by wind
- v_2= current generated by run off
- v_3= convective currents
- v_4= currents related to periodic oscillations
- v_5
- v_{n-1}
- v_n= currents related to ….

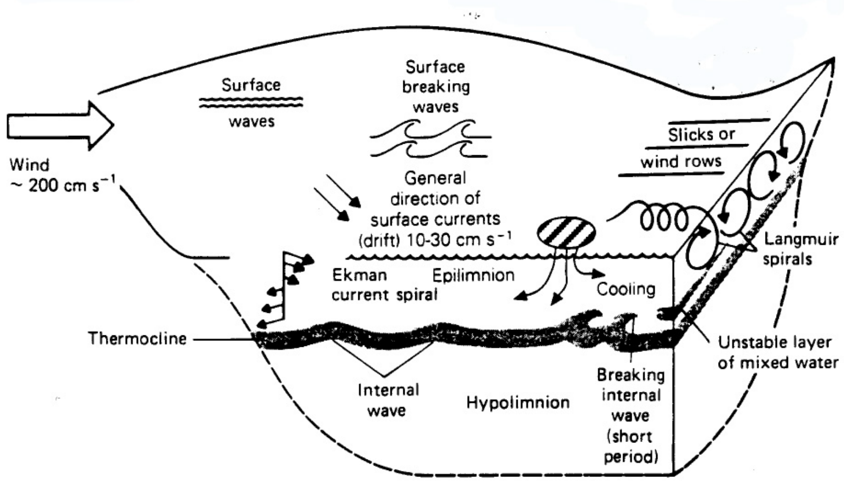


FIGURE 5-1 Forces (wind, gravity, evaporation, and the earth's rotation) and the resultant water currents and waves. Wind moves the water, gravity makes horizontal flow easier than vertical, evaporation cools surface water which then sinks, and the earth's rotation moves surface flows to the right (northern hemisphere) and to the left (southern hemisphere).

TABLE 5-1

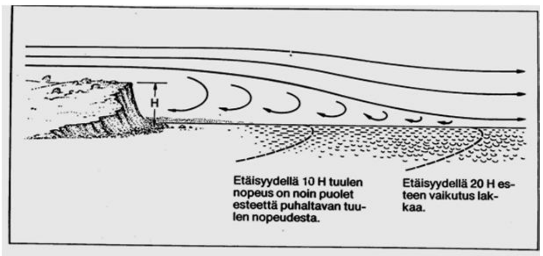
SIZE, FREQUENCY, VELOCITY, AND IMPORTANCE OF WAVES, CURRENTS, AND OTHER LAKE WATER MOTIONS

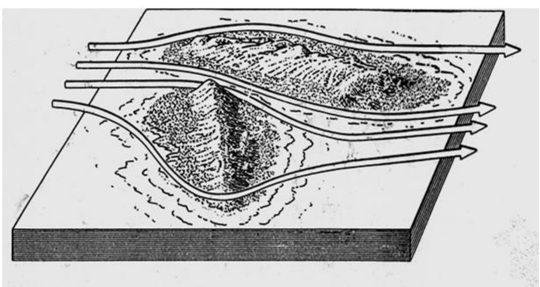
Type of motion	Length scale: Horizontal	Length scale: Vertical	Time Scale	Velocity scale	Importance to kinetic energy spectrum	Importance for plankton (P_t) or nutrient recycling (R)
Horizontal						
Surface systems						
Wind-driven surface gravity waves	1–10 m	1 m	1 s	10 m s^{-1}	Small	P_t, R: small
Standing surface gravity waves (surface seiches)	1 km–100 km	10 cm	2–10 h	2 cm s^{-1}	Small	P_t, R: small
Surface wind drift and whole-lake gyres	1 km up	1–25 m	Days	1–30 cm s^{-1}	Large	P_t, R: large
Deep-water systems						
Short freely propagating internal waves	100 m	2–10 m	2–10 min	2 cm s^{-1}	Major mixing energy at the thermocline	R: summer moderate
Long freely propagating internal waves steered by lake shape (including internal seiches)	to 10 km	2–20 m	1 day	50 cm s^{-1}	Major source of motion in hypolimnion of large lakes	P_t, R: moderate
Vertical (in epilimnion)						
Random flows						
Vertical diffusion of momentum	1 cm–100 cm	1 cm–10 m	1 min	1 cm s^{-1}	A major vertical force	P_t, R: important
Breaking waves	1 m	1 m	Mins	50–500 cm s^{-1}	Moderate to small	P_t: moderate
Organized flows, Langmuir spirals	50 m–100 m	2–20 m	5 min	0–8 cm s^{-1}	Moderate to small	P_t: important
Hypolimnial	1 km up	Up to 200 m	long	0.5 cm s^{-1}	Small	P_t: important in clear lakes; R: small

Modified from Boyce (1974).

Currents generated by wind

- **Wind is the dominating factor** causing lake currents during open water period
- Wind field over the lake is seldom uniform
  - Sheltering effects ==> the shelter effects to a distance, which is 20*the height of the sheltering e object
  - Trees 20 m ==> shelter effect at maximum to 400 m
  - Considering all wind directions ==> lake with 1 km open area is affected directly with wind,
  - On smaller lakes wind affects only indirectly
  - Air stratification affects to the sheltering
- Channelling effects due to the topography





Wind driven currents: magnitude

- Air flow causes a shear (τ_s) onto the lake surface:

$$\tau_s = C_d \rho_{air} U^2$$

  - where, C_d = drag coefficient, about 0.001, ρ_{air} = density of air f(air pressure, humidity and temperature) about 1 kgm^{-3} , U= wind velocity (ms^{-1})
- In practice surface **current speed is about 2-3 % from the wind speed**
- Typical current speed: 5 cm/s = 180 m/h = 4320 m/d = 30 km/week
- Mean wind speed in Finland is about 3.2 ms^{-1} ==> typical current velocity is about 6-9 cms^{-1}

Wind driven currents: direction 1(3)

- Theoretically on an open deep lake in Northern Hemisphere the direction of surface current is 45 º to right form the wind speed
- when going down in water column the current direction is turning further right and decaying (Ekman-spiral)
- D_E= depth of Ekman layer

$$D_E = 4.3W/(\sin\theta)^{0.5}$$

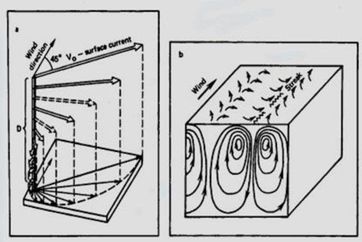
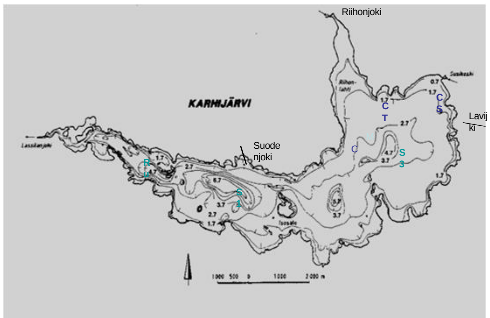


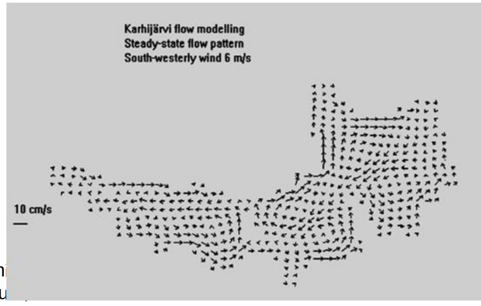
Fig. 1.64: Structure of water movement induced by wind
a–theoretical Ekman spiral of steady-state nondivergent wind-driven current;
b–Langmuir's circulation

Latitude	Wind m/s	D_e m
4	5	81
4	10	162
60	5	23
60	10	46

Wind driven currents: direction 2(3)

- In practice the bottom morphology determines the current direction in a lake
  - in shallow lakes (polymicitic , non stratified)
    - the current follows wind on shallow regions
    - compensation (=return) current is found on deepest areas or on wind sheltered areas





Wind driven currents: direction 3(3)

- Stratified lakes
  - the same structure is found in epilimnion as in shallow lakes, currents are highest there, when compared to metalimnetic and hypolimnetic currents
  - in metalimnion the currents are sporadic due to the indirect effects of epilimnetic currents and periodical oscillations
  - in upper part of hypolimnion the currents are slowly following the currents in epilimnion and metalimnion
  - current pattern is responding to the changes of wind with a typical lag of one to three hours in our lakes
- The highest current speeds are found at steepest slopes and in narrow straights

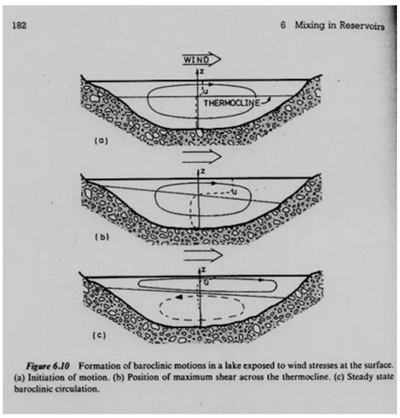
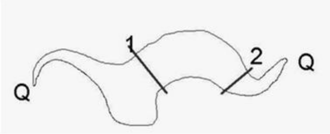


Figure 6.10 Formation of baroclinic motions in a lake exposed to wind stresses at the surface. (a) Initiation of motion. (b) Position of maximum shear across the thermocline. (c) Steady state baroclinic circulation.

Run off generated currents



- called also as hydrological currents
- tributary waters flowing through the lake (ΣQ)
- important during ice covered period and in shallow lakes with high amount of river water
- currents are calculated with continuity equation
- steady as compared to the wind generated currents
- important during winter, when lake is not affected by wind, also always in lakes with a short retention time

$$\sum Q = v_1 A_1 = v_2 A_2$$

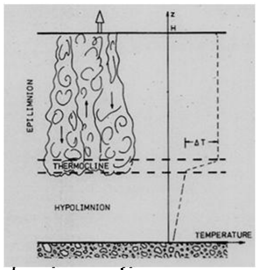
v_i =mean velocity in the cross section i

A_i =area of the cross section i

Example from Saimaa

- Annual mean outflow of Lake Saimaa (ΣQ) at Tainionkoski is about 500 m^3s^{-1}.
- What is the mean run off generated current in a straight with 5 m depth and 1000 m width?
- v= ΣQ/A = 500 m^3 s^{-1}/(5 m * 1000 m) = 500/5000 ms^{-1} = 10.0 cms^{-1}

Convective currents 1(2)

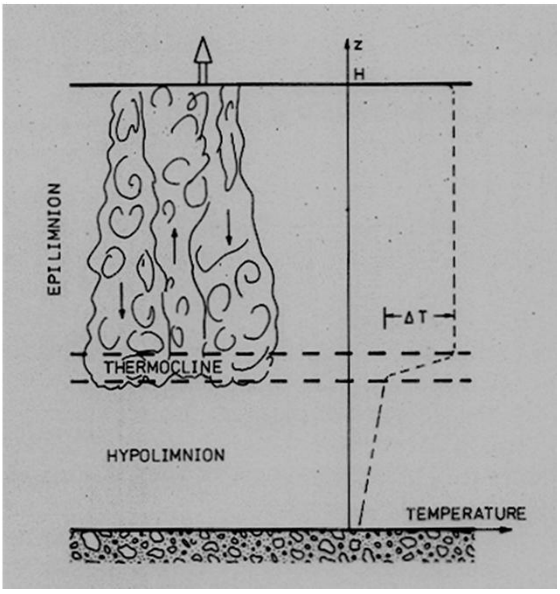


- Caused by density differences in water
- In summer time vertical mixing in night as surface water is cooling down during the night, density is thus increased and water sinks, typically down to the metalimnion
- In summer time in shallow bays water temperature will increase to a higher level than that in deep waters, also cooling of the waters in shallow bays happens quicker that on deep waters ==> this leads to horizontal currents as the cooled dense water seeks water layer with equivalent density and travels to the deep areas of the lake

Convective currents 2(2)

- Sewage water can be warmer as ambient water ==> sinks to the bottom or to the equal density layer ==> flows slowly in thin concentrated layer long distances
- Convective currents are important during ice covered period
- Their typical speed is 1 cms^{-1} ==> during 160 days (= normal ice cover period) the travel distance could be 138 km !! In practice threshold at bottom will stop the flow and accumulation to deep basins will happen

Convection cells during summer night



Currents are damped by internal friction

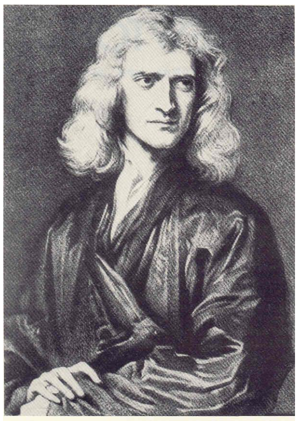
- Effects immediately and all the time as the are currents are generated
- The kinetic energy of currents is turned to the heat by turbulence
- The turbulent stage of the water effects to the state of internal friction
- And internal friction is function of water density and kinematic viscosity
- Floating vegetation increases the turbulence and thus internal friction

Currents are also damped by bottom friction

- Also always present
- Reduces the water movement always and immediately as the moment is generated
- Is a function of bottom type, eq. rocky bottom causes high bottom friction, bottom vegetation increases also
- In deep areas the effect in the total water column negligible

Basic laws for solving the flow field

- Conservation of momentum = II Law by Newton
- Conservation of mass = continuity equation
- Conservation energy



Isaac Newton (1642 – 1727).
Godfrey Kneller maalasi muotokuvan 46-vuotiaasta Newtonista kaksi vuotta Principian ilmestymisen jälkeen.

Momentum equation

- Newton II = m(du/dt) = Σ F_i
- Volume element ΔV= Δx Δy Δz
- Divide NII with ΔV and note that ρ = m/ ΔV
- In fixed coordinates system (Euler) we follow the particels from a fixed point in space ➔ we have to apply total derivation to NII with an operator D/Dt

$$\frac{Du}{Dt} = \frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial v}{\partial y} + w\frac{\partial w}{\partial z} = \frac{\partial u}{\partial t} + (u \cdot \nabla)u$$

$$local \quad advection$$

Forces affecting: gravity, rotation and internal forces

- Gravity: we take g as constant directed towards Earths center
- Rotation as Coriolis-force = 2Ω×u, Ω= angular velocity vector of Earth
- Internal forces:
  - Hydrostatic pressure force ∇ p
  - Internal friction F_k
- NII in new form:

$$F_g = -\rho \Delta V g \Rightarrow F_g = g$$

$$\frac{\partial u}{\partial t} + (u \cdot \nabla)u + 2\Omega \times u = -g + \rho^{-1}\left[-\nabla p + F_k\right]$$

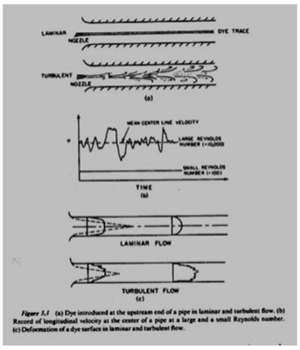
$$adv. \quad rotation \quad gravity \quad pressure \quad \text{int}.friction$$

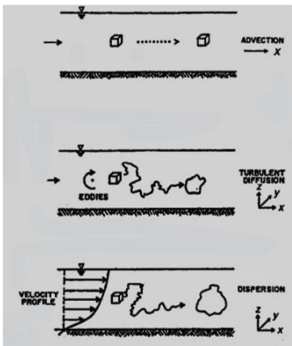
Boundary conditions

- Note that we have taken only gravity as an external force, which effects to whole water body
- Boundary conditions
  - Surface: wind
  - Sides: river discharges
  - Bottom: friction …
  - Can be given
    - Fixed values, velocity=0 at bottom
    - Fluxes
    - Velocities
    - Sliding condtions (frictionless boundary), velocity on the side same as in the lake

Turbulence

- Turbulence smoothens the velocity differences (compare heat conductivity or Fickian diffusion)





$$\frac{\partial u}{\partial t} + (u \cdot \nabla)u + 2\Omega \times u = -g + \rho^{-1}\nabla p + \nu\nabla^2 u + A_H \nabla_H^2 u + A_V \partial^2 u / \partial z^2$$

adv. rotation gravity press. int. frict. turbulence terms

Other equations

- Continuity equation for incompressible fluid = law for mass conservation
- Equation of state = density function, most often it is f(T,S)
  - Most of the Chen and Millero or UNESCO-equations are used
- Conservation of heat and salt

$$\nabla \cdot \bar{u} = 0 \Leftrightarrow \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0$$

$$\rho = \rho_0 + \alpha (T - T_0) + \beta (S - S_0)$$

$$\frac{DT}{Dt} = \frac{\partial T}{\partial t} + (u \cdot \nabla) T = k \nabla^2 T + q_s$$

$$Dif\ .Si./So.$$

Solutions

- Common solution in analytical form is impossible
- Using scale analysis we can leave unimportant terms away and solve

Example: inertial flow on sea when wind is ceasing down

$$\frac{d\mathrm{u}}{dt} = fk \times \mathrm{u} \qquad \mathrm{u}(t=0) = \mathrm{u}_0$$

$$\mathrm{u} = \mathrm{u}_0 \exp(-ift) = \mathrm{u}_0 [\cos(ft) - i \sin(ft)]$$

Numerical solution

- Aproximative solution , which are based on Taylor series
- Space derivatives ➔ space discretation
- Time derivatives ➔ time step discretations
- Solution in grid system
- 1D, 2D or 3D solutions

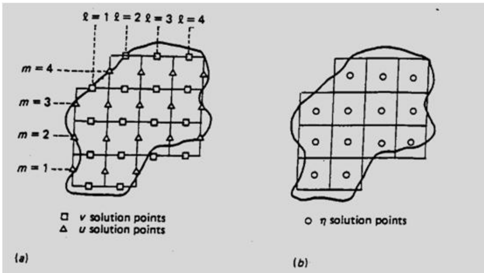
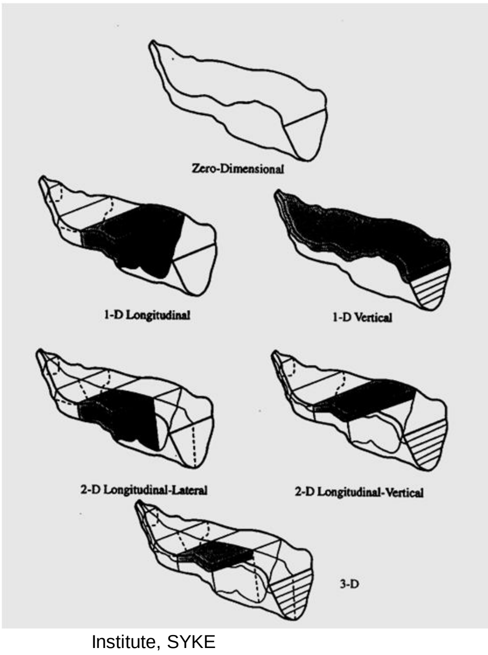
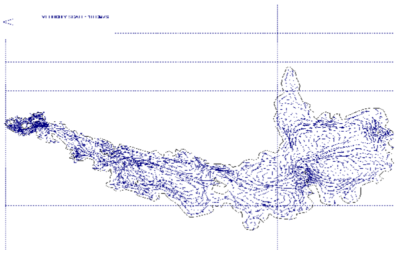


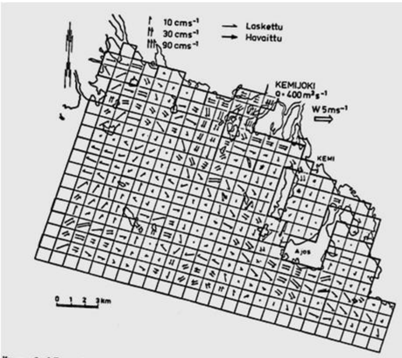
Figure 9.19. Finite-difference solution procedure. (a) Full time steps, solution for velocity; (b) half time steps, solution for water surface elevation.

Different grid types

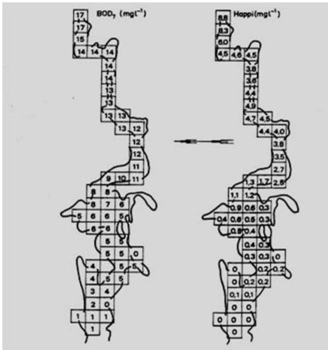


2D horisontal grids

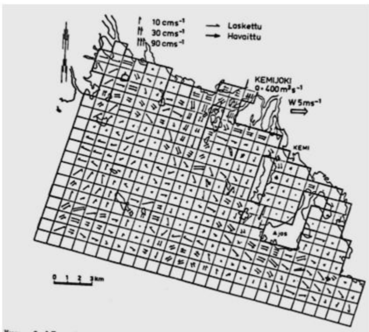




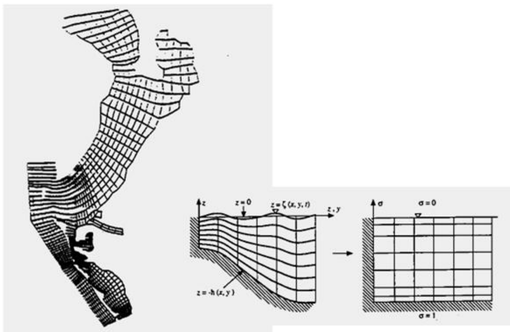
Kuva 3.17. Kemin edustan virtauskenttä länsituulella.

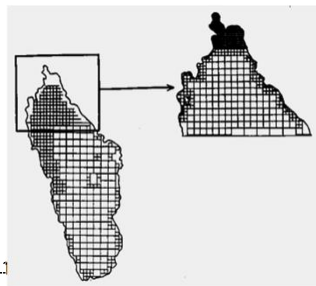


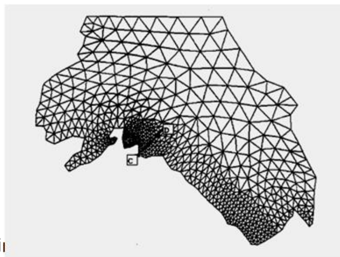
Kuva 3.15. BOD₇:n ja hapen horisontaaliset jakaumat keskivirtaamalla, kun kuormitus on 20 BOD₇td⁻¹.



Kuva 3.17. Kemin edustan virtauskenttä länsituulella.







Applicability of grids

Model Classification and Effective Transport Processes

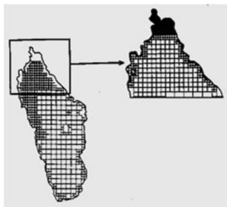
Transport Process	One-Dimensional	Two-Dimensional: Horizontal Plane	Two-Dimensional: Vertical Plane Homogeneous	Two-Dimensional: Vertical Plane Stratified	Three-Dimensional Homogeneous	Three-Dimensional Stratified
Wind stress	X	X	X	X	X	X
Far-field forcing (coastal currents and storm surges)	X	X	X	X	X	X
Tidal activity	some models	many models	X	X	X	X
Local turbulence				some models	X	X
Residual circulation	X	X	P	X	X	X
River inflow	X	X	X	X	X	X
Surface slope (set up)	X	X	X	X	X	X
Sea level		X	X	X	X	X
Velocities						
a. Tidal	some models	many models	X	X	X	X
b. Residual	X	X	X	X	X	X
c. Turbulent				some models	X	X
Salinity intrusion	some models	some models			X	X
Internal waves				P		P
Topographic waves		X			X	X
Coastal jets		X			X	X
Upwelling					X	
Thermal stratification				X		X
Vertical shear			X	X	X	X
Inertial motions		X			X	X

Definitions: H = homogeneous, S = stratified; P = partially resolved; 1-D = one dimensional model; 2-D = two dimensional models; 3-D = three dimensional model.
Modified from Bedford 1985.

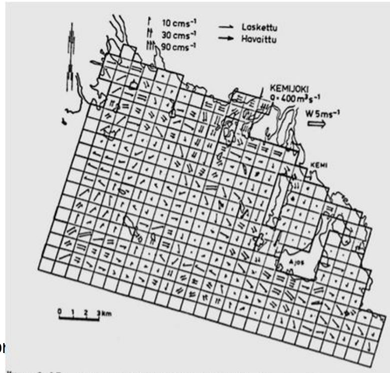
Data collection

- Existing publications
- Existing data
  - Bathymetry, river discharges, water levels, wind data, temperature data (if baroclinic model = takes into account the density differences), water currents
- New measurements often
  - Water currents (Eulerian and Lagrangian)
  - Bathymetry (echo sounding)
  - Winds on the lake
- Interviews of people, who know the lake (fishermen, sailors,…)

Defining the geographical area of application



- Dominant cross sections
- Scaling down on hot spot areas
- Open boundaries
  - Measurements, output of large scale models, artificial boundary
- 2D or 3D solution ???
  - Bathymetry and variables to be calculated determine

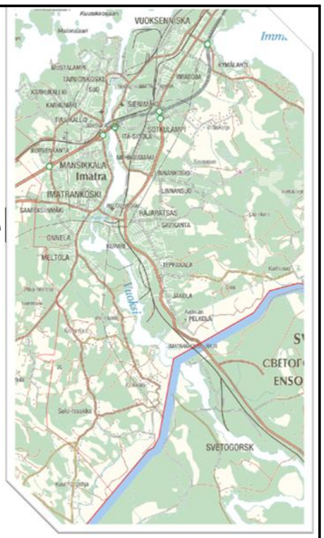


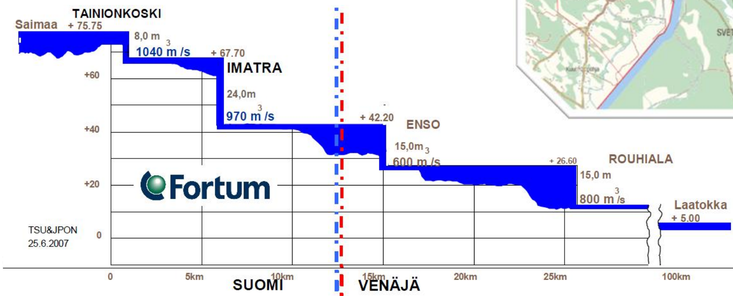
Kuva 3.17. Kemin edustan virtauskenttä länsituulella.

Calibration of flow model

- Simulations in different wind and water level/discharge situations
- Compare observed and calculated
  - Water levels
  - Water currents
  - Discharges in straights and other cross sections
- Calibration
  - Friction and eddy diffusivity parameters
  - Grid corrections
- Materials\Flow_and_WQ_Models_Sarkkula.pdf

3. River mode





First models for flowing waters

$$\frac{dC}{dt} = K_2(C_s - C) = K_2 D$$

$$-\frac{dL}{dt} = K_1 L$$

$$C = C_s - \frac{K_1 L_0}{K_2 - K_1}((e^{-K_1 t} - e^{-K_2 t}) + (C_s - C_0)e^{-K_2 t})$$

- Oxygen model by Streeter-Phelps (1925)
- Oxygen = f(advection by river waters, aeration and decomposition by bacteria), steady state
- In equation:
  - C=oxygen concentration (mg/l), C_0 =initial oxygen concentration in waters, C_s=saturation concentration of oxygen, D=oxygen deficit, K_2 = aeration coefficient (like 0,15 1/d), L=BOD value (mg(l), L_0= BOD- initial value , K_1 = decay coefficient of BOD (like 0,25 1/d), T=time (days)

Using Streeter-Phelps

- Water temperature and oxygen saturation concentration in that temperature have to be known.
- K_1 is temperature dependent. K_2 only slightly
- Several temperature correction equations available. Frisk and Nyholm (1980) mostly used in Finland
- Flow time has to be calculated for each river reach. In this way advection is taken into account

Dynamic flow models for rivers

$$Q = \frac{WY^{3/5}}{n}\left(S_0 - \frac{\partial Y}{\partial x} - \frac{V}{g}\frac{\partial V}{\partial x} - \frac{1}{g}\frac{\partial V}{\partial t}\right)^{1/2}$$

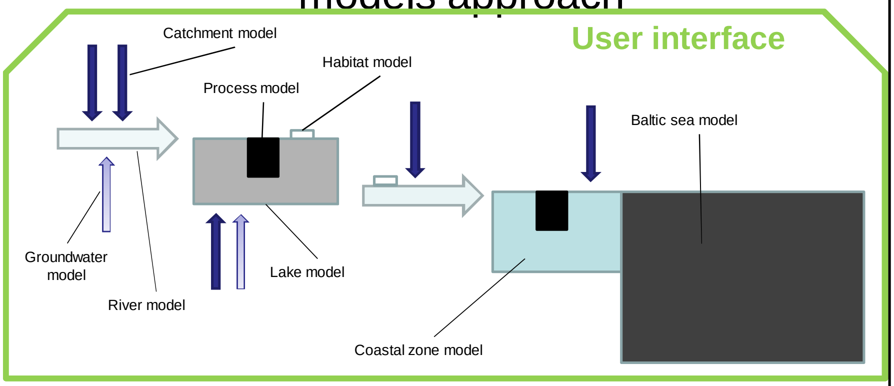
1 2 3 4 5

- St. Venant (1848) for river dynamics
- In equation
  - 1=discharge, 2=pressure gradient=bottom sloping term, 3=pressure gradient due to the surface slope, 4=advection due to the river flow, 5=local acceleration term
- For WQ -simulations
  - Streeter-Phelps type equation
  - Suspended solids like we look later in 3D models
  - Nutrients also similarly
- Presently we use SOBEK model from Deltares and HEC-RAS from US/EPA

7. Some visions and lessons

WETS151 Huttula Lecture Set 1 V2 37

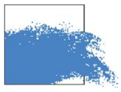
Modelling philosophy: the chain of models approach



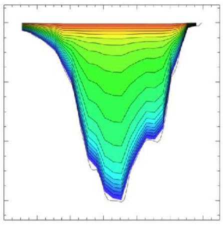
- Water flows through the different models and tracers flow along with the water. Process models can act on the tracers, or calculate small scale flow, and e.g. habitat models depend on the other models
- **Catchment model**: WSFS-Vemala, INCA, SWAT, SOBEK
- **River model**: SOBEK, River2D, COHERENS
- **Habitat model**: Delft HABITAT, River2D
- **Lake model**: COHERENS, MyLake
- **Process models**: biological models, sediment models, Elmer
- **Coastal zone model**: COHERENS
- **Baltic sea model**: COHERENS

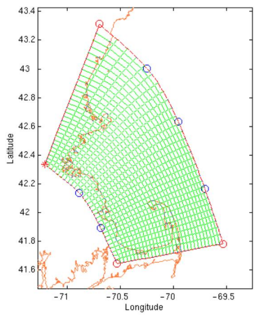
38

COHERENS modelling tool



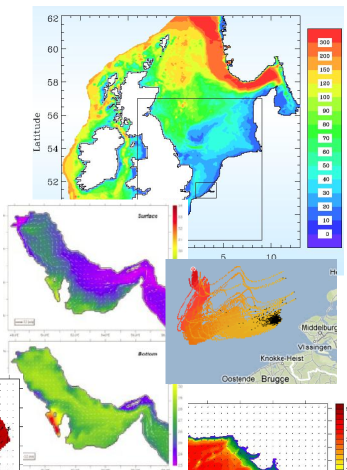
- **CO**upled **H**ydrodynamical **E**cological model for **RE**gio**N**al **S**helf seas, RBINS-MUMM, Belgium
- 3D finite difference, s-layer, multi-purpose numerical model designed for application in coastal and shelf seas, estuaries, lakes and reservoirs
- Open source, available to the public since 2000
- Multi-platform, extremely good documentation (1500+ pages)
- Modular design
  - Physical core
    - selectable simulation modes, dimensions, numerical schemes
  - Flexible and expandable
    - Biological/ecological module
    - Sedimentation module
    - Wave modules
    - Tracers
    - Processes
- Actively developed , constantly evolving (latest version V2.5.1 available since August/2013)

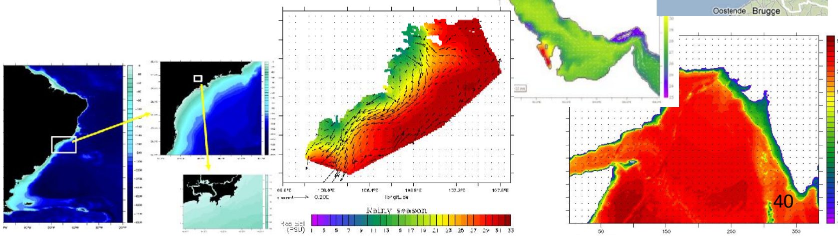




COHERENS around the world

- North Sea, operational currents and speeds for navigational assistance, www.mumm.ac.be
- Oil Spill Evaluation and Response Integrated Tool (OSERIT), oserit.mumm.ac.be
- Persian Gulf, seasonal circulation, Kämpf and Sadrinasab, JGR, 2006
- Arabian Sea, tidal and surge model, P. Saheed, NIO, Goa, India, December 2010
- Brazil coast – South Brazil Bight – Santos Estuary, Carlos França, Univ. Sao Paulo
- Halong Bay and Red River delta, Vietnam, physical-biological model and climate change, Katrijn Baetens, MUMM



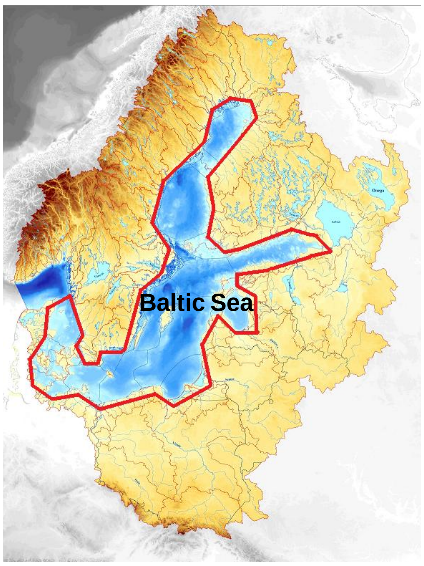


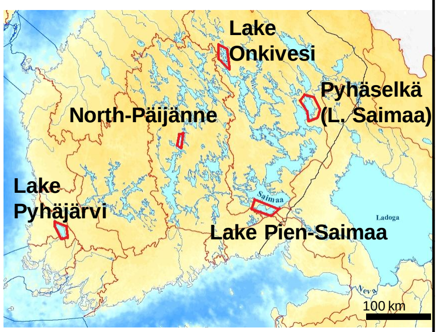
COHERENS at SYKE

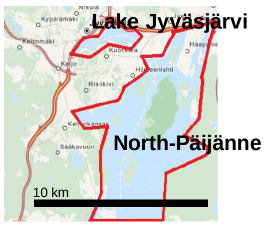
- COHERENS was selected as SYKE's marine and lake modelling tool of choice
  - Performance as multi-purpose modelling tool – adaptability to both lake and marine environment
  - Open source code & excellent documentation
  - Modularity
  - Active development
- COHERENS performed well in model inter-comparison study in the Gulf of Finland (Myrberg et al, 2010)
- Development resources can be concentrated to improving a single modelling tool
  - The goal of module development work at SYKE is to improve the applicability of the COHERENS model in low-salinity Baltic region applications for multi-year (incl. winter) simulations
  - Modules have been developed for eg. tracers, sediments and ice formation/melting
- V1 code used since 2006, from 2012 all new projects use V2

41

Scales of COHERENS models



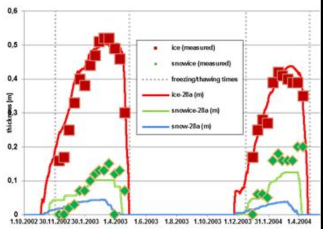




42

Ongoing, near-future and proposed COHERENS developments at SYKE 1/4

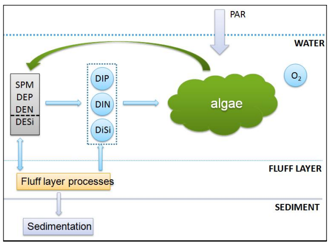
- Adapting model heat balance to boreal lake environment
  - Shallow lake thermodynamics not completely correctly modelled
- Ice and snow model
  - Important for multi-year simulations and climate change scenarios
  - Measurements
  - Calibrate and validate the developed code
  - Add simple advection
- Fully utilise the advances in COHERENS V2 code
  - Nesting
  - Sediment model
  - Flooding and drying schemes
  - etc
- Coupling COHERENS to other models
  - River models, catchment models, WSFS-VEMALA, groundwater flows
  - "Chain of models"



43

Ongoing, near-future and proposed COHERENS developments 2/4

- Increase understanding of shallow area flows
  - Fetch
  - Local wind effects on the same horisontal scale as lake model itself
  - Hydraulic effects of bottom macrophytes
- Wave modelling
  - Coupling to external models
- Ecological/nutrient model with particle-bound nutrient transport
- Transport and evolution of harmful substances
  - Organic tin compounds (TbTs)
  - Bacteria, viruses
  - Artifical sweeteners, medicines
- Coupling to external biological models
  - BFM
  - PyWQM

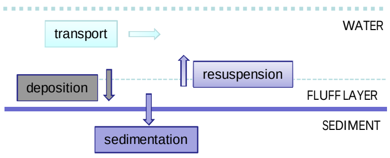


Ongoing, near-future and proposed COHERENS developments 3/4

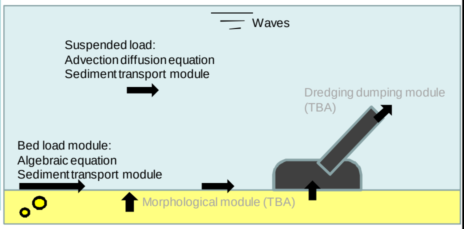
- Age tracers and automatic fraction calculations (2013-2014)
- Automatic sanity checking mid-simulation
- Improving data output usability
    - Looking at results while simulation is running
    - Importing/exporting NetCDF to other software
    - Visualisation improvements
- Seto inland sea, Japan (Okayama U.)
    - Complex morphology
    - Tidal interactions
    - Power generation
- Data assimilation and automatic calibration (collaboration with Okayama U.)
    - Initial values and loads from satellite imagery
    - Particle filtering method
    - Ensemble Kalman filtering

COHERENS sediment models

- COHERENS V1
    - Very simple model
    - Single fraction
    - Simple wave-current interaction
    - Temporary deposition in 'fluff layer', resuspension and permanent sedimentation
    - Based on Jones et al. (1995)[1]
    - Area of applicability on ocean floors



- COHERENS V2.5
    - State-of-the-art model
    - Cohesive and non-cohesive sediment
        - Multiple fractions
        - Hiding effects and flocculation
    - Multiple ways to calculate bed-current-wave interactions
    - Two-way coupled with hydrodynamics
        - Density driven sediment flows
        - Turbulence damping
    - Bed slope effects
    - Developed at IMDC & RBINS[2]



1) Jones S.E., Jago C.F. and Simpson J.H., 1995. Modelling suspended sediment dynamics in tidally mixed and periodically stratified waters : progress and pitfalls. In : C.B. Pattiaratchi (Editor), Mixing Processes in Estuaries and Coastal Seas. Coastal and Estuarine Studies, Vol. 41, American Geophysical Union, 315–338.
2) Breugem, W.A., Decrop, B., Frederix, K., Delecluyse, K., v .Holland, G., Luyten, P., Hyde, P., Development of a sediment transport model in Coherens, Fifth International Conference on Advanced COmputational Methods in ENgineering (ACOMEN 2011)

46

Ongoing, near-future and proposed COHERENS developments 4/4

- Archipelago Sea model
  - Commission from the Ministry of Environment
  - The goal is to produce an intuitive graphical tool to help decision-making in controlling loading to the Archipelago Sea area
  - Nested marine model on the Baltic, coupled to WQ models
    - Full Baltic Sea coarse resolution + fine resolution archipelago sea model
    - River/agricultural loading (WSFS-VEMALA)
    - Eutrophication & water quality (PyWQM/SEABED project)
  - Joint project with SYKE's Freshwater and Marine Centers with partners from FMI, regional authorities, Åbo Akademi, KTH (Sweden)

COHERENS applicability

- From large sea areas with high salinity down to small lakes (~ 1 km^2) with zero salinity
- Physical modelling in three dimensions
  - Currents, temperature, salinity
  - Tidal effects
  - Flooding
  - Morphology changes
- Ecological modelling
  - Nutrient fluxes, biology, sedimentation, resuspension
- Fate of substances
  - Transport, drifting, spreading, diffusion
  - Process modelling
- Climate change scenarios
  - Multi-year modelling

48

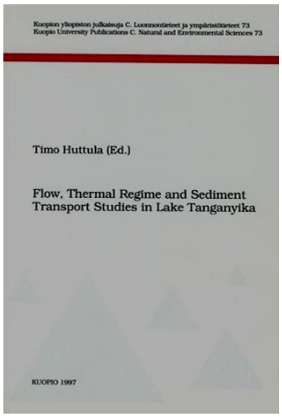
HYDRODYNAMICS AND THERMAL REGIME OF LAKE TANGANYIKA

Timo Huttula, Olli Huttunen, Victor Podsetchine, Anu Peltonen, Pekka Kotilainen, Hannu Mölsä

www.fao.org/fi/ltr/

Contents

- Lake characteristics
- Projects conducted
- Data collection
- Models applied
- Results
  - meteorology
  - thermal regime
  - hydrodynamics
  - optics
- Summary

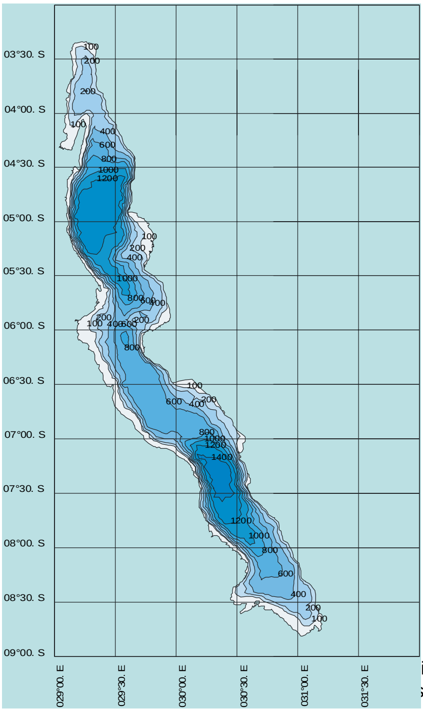


Kuopion yliopiston julkaisuja C. Luonnontieteet ja ympäristötieteet 73
Kuopio University Publications C. Natural and Environmental Sciences 73

Timo Huttula (Ed.)

Flow, Thermal Regime and Sediment Transport Studies in Lake Tanganyika

KUOPIO 1997



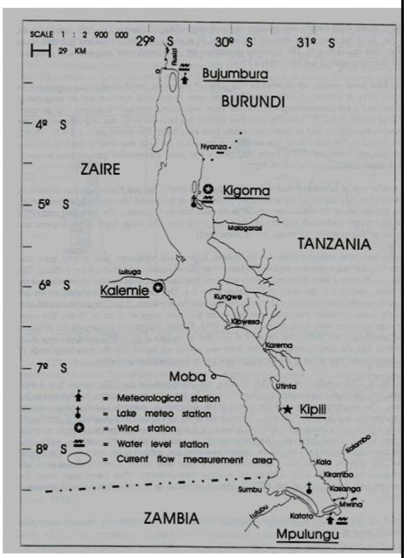
in
stit

Lake Tanganyika

- Surface area=32 900 km^2, mean depth=572 m, maximum depth=1472 m,
- Watershed area= 263 000 km^2
- Meromictic, surface temperature about 26…28 ^oC, hypolimnetic temperature 23.25 ^oC, thermocline depth around 50…120 m,
- Two main seasons: dry May-Sept and wet
- Very clear water
- Highly productive lake, important protein source for more than 10 Mill. people

---

- Lake Tanganyika Research for Fisheries (LTR) by FAO in 1992-1996. Hydro and thermodynamics:
  - understand the upwelling phenomena of the nutrient rich deep waters and their effects to biological production
  - develop flow and upwelling model for predictions
- Lake Tanganyika Biodiversity Project/LTBP by UNDP/GEF. Hydro and thermodynamics in 1996-97:
  - develop lake wide circulation model
  - determine the transport and mixing river waters and suspended solid load
- Field courses in tropical limnology 2000 and 2001, joint effort by Universities of Kuopio, Turku, Jyväskylä and Helsinki

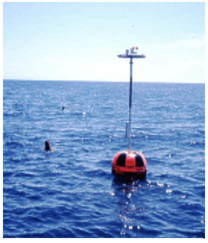


nment

52

INSTRUMENTS

Wind station in Kigoma

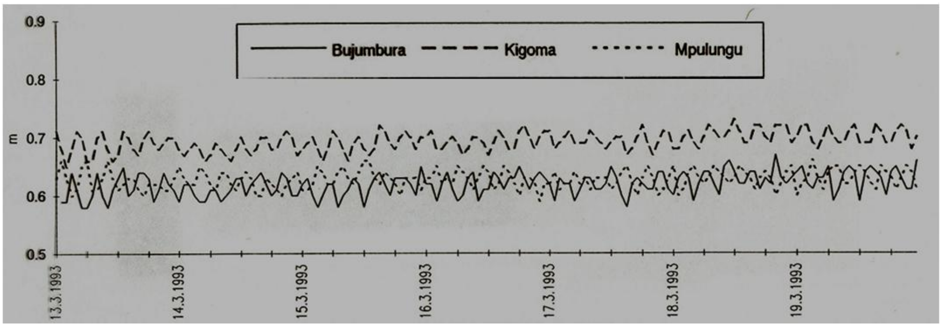


Buoy based meteorological station and thermistor chain down to 300 m

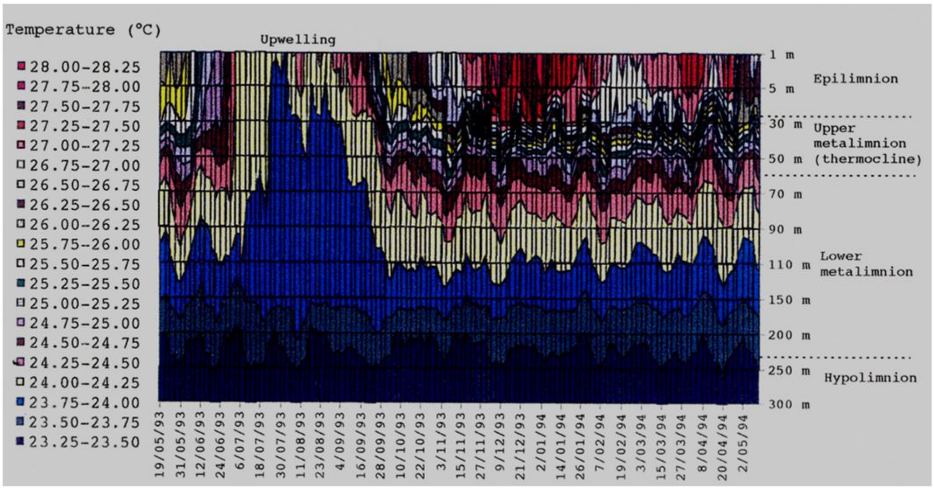
Flow cylinders with a bouy. attached t to a surface buoy Postioning with GPS.

R/V TANGANYIKA EXPLORER, chartered vessel for the LTR; two masts for a weather station on the roof; the ship ADCP was installed on the starboard side next to the open gate.

Buoy based on ACDP ready for deployment

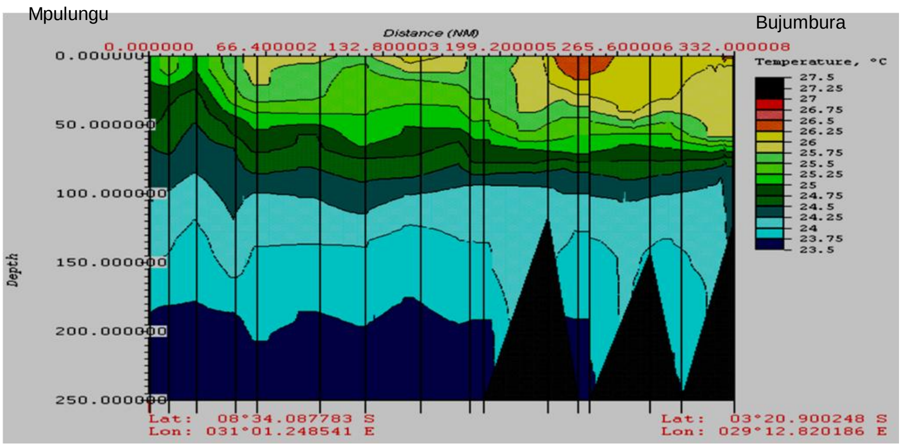


- Surface seiche: typical period 4.7 h, phase sift of 180^0 between Bujumbura and Mplungu



- Internal seiche (Podsetchcine & Huttula, 1996):
  - At Mplungu buoy during dry season the period for uninodal internal seiche was 23.4 d and during wet season 34.8 d
  - Kigoma buoy during wet season period was 26.3 d

Temperature isolines during an expedition 24.8.-4.9.1997



Wedderburn numbers (Verburg et al. 1998) www.fao.org

$$W = \frac{g'h^2}{u_*^2 L_m}$$

Table 2. Mean seasonal Wedderburn numbers and values of g', an indication of the density jump across the thermocline (n.a. = not available).

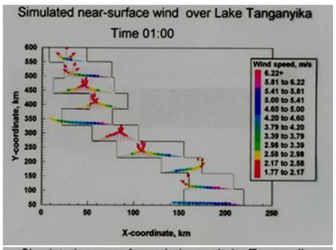
W	Mpulungu	Kigoma	Bujumbura	g'	Mpulungu	Kigoma	Bujumbura
June-Aug							
1993	0.30	n.a.	n.a.	mean	0.0076	0.0081	0.0079
1994	0.47	1.42	n.a.	min	0.0015	0.0053	0.0045
1995	1.36	1.58	1.69	max	0.0133	0.0124	0.0126
1996	1.31	1.51	n.a.				
Nov-March							
1993-94	2.94	2.07	2.98				
1994-95	3.03	n.a.	2.60				
1995-96	3.69	2.35	3.04				

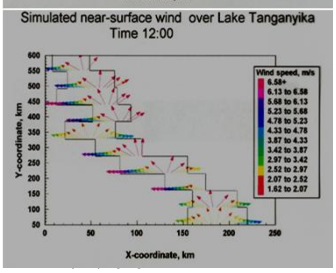
Table 3. Number of days per year on which the Wedderburn number < 0.5, off Mpulungu.

	Number of days
1993	99
1994	89
1995	79
1996	38

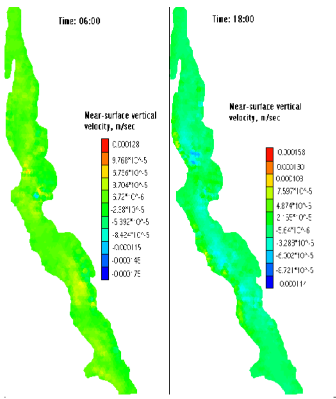
- Intensity of stratification, mixing, and the influence of wind stress (Monismith, 1986)
- High values= stable conditions,
- Low values = intensive currents and mixing
- h = mixing depth, g' = the reduced acceleration of gravity change across the thermocline, u* = shear velocity and Lm = lake length, $g' = 2g(\rho_2-\rho_1)/(\rho_2+\rho_1)$, ρ_1, ρ_2 = densities of epilimnion and hypolimnion respectively, g = acceleration of gravity,
- $(u_*)^2 = (\rho_{air}/\rho_{water})C{*}V^2 = 0.0011 * 0.0014 * V^2$, C = wind drag coefficient, V = wind speed
- Water density by Chen and Millero's (1977) equation from water temperature and salinity,
- Salinity from conductivity (dissolved salt content, $g.kg^{-1}$ = 0.5 x conductivity, $mS.cm^{-1}$)

Atmospheric model Savijärvi (1995, 1997)



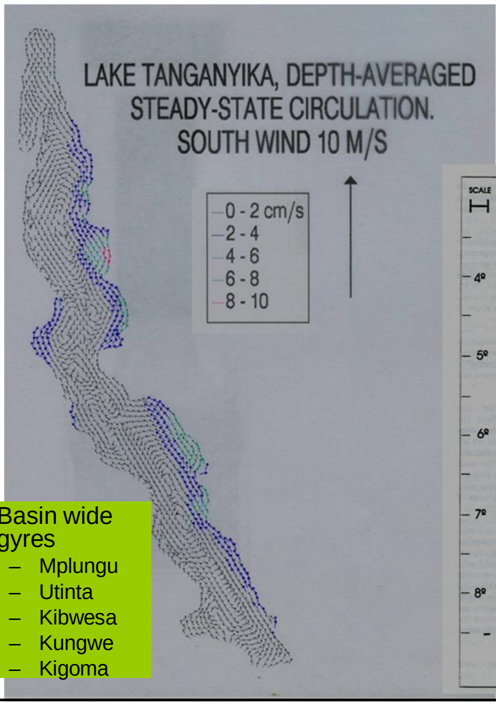


- 2D, hydrostatic moist sigma-co-ordinate model.
- 10 cross sections, grid cell size: 4 km, 11 atmospheric sigma levels, time step 8 s
- Simulations covered a typical dry season day in July with a SW trade wind of 2.5 ms^{-1}
- Output used for driving the 3D barotrophic lake model

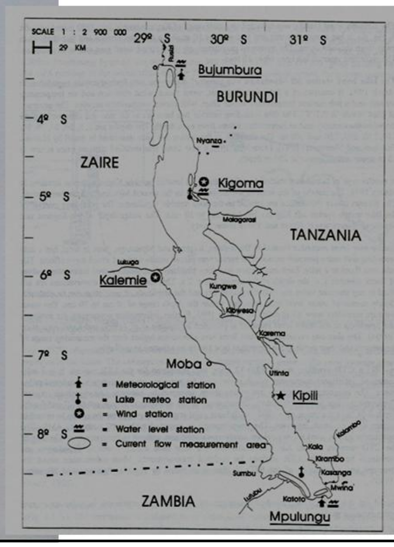


Calculated vertical velocity on 06:00 and 18:00 in July. Winds from 2D wind model applied in 12 transects along the lake.

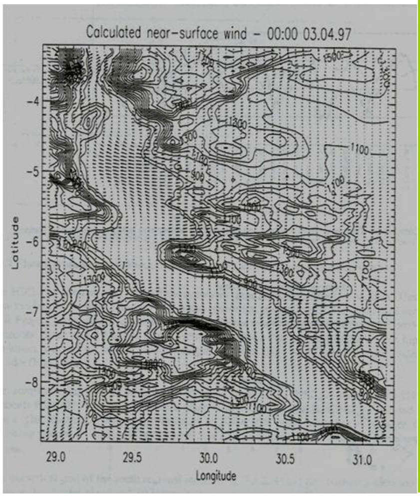
LAKE WIDE CIRCULATION, LTR model, Podsetchine et. al (1996)



- Basin wide gyres
  - Mplungu
  - Utinta
  - Kibwesa
  - Kungwe
  - Kigoma



HIRLAM



- High Resolution Limited Area Model application at FMI
- Grid:162 by 170 grid points with the grid length of 0.05° (5.5 km), 31 hybrid levels in the vertical
- Terrain altitude from the U.S. Geological Survey's Eros Data Cente
- Land use from UNEP's Global Resource Information Database
- Initial conditions from the ECMWF (European Centre for Medium Range Weather Forecasts) analysis
- Surface water temperature data was imported from CTD and buoy observations
- The first day of each month was a warm up-day, the actual forecasts were run for the following 7 days (2 - 8 for each month) in the period of March 1994-April 1995

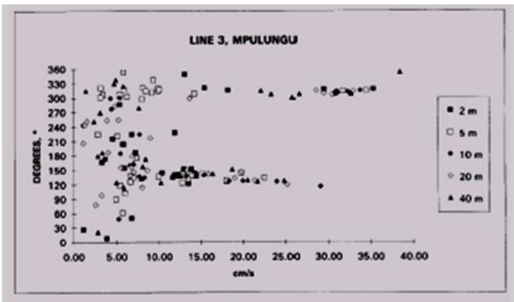


Figure 36. Current flow measurements: direction and speed (cm/s) of currents at line 3 Mpulungu July 1993 - December 1994.

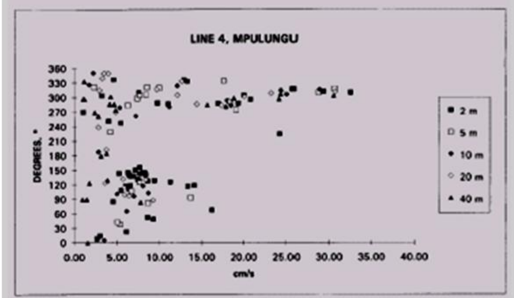
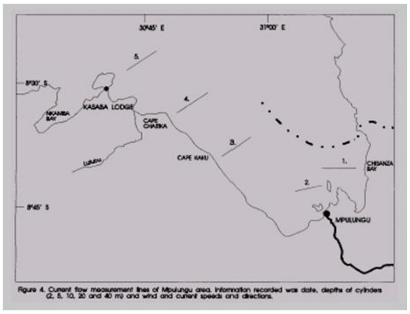


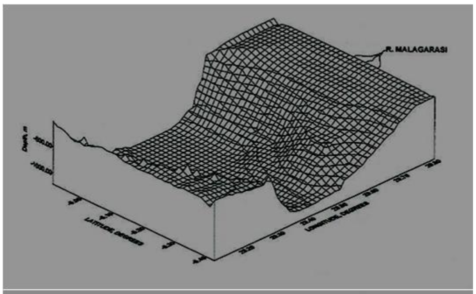
Figure 37. Current flow measurements: direction and speed (cm/s) of currents at line 4 Mpulungu July 1993 - December 1994.

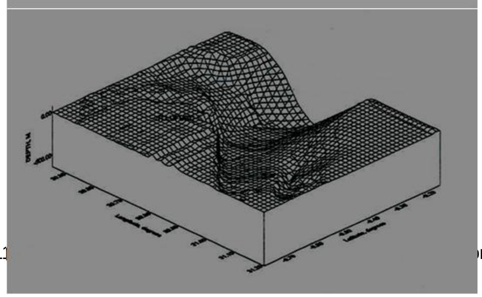
Water currents



- Current velocities up to 40 cm/s
- Seasonal and diurnal variation

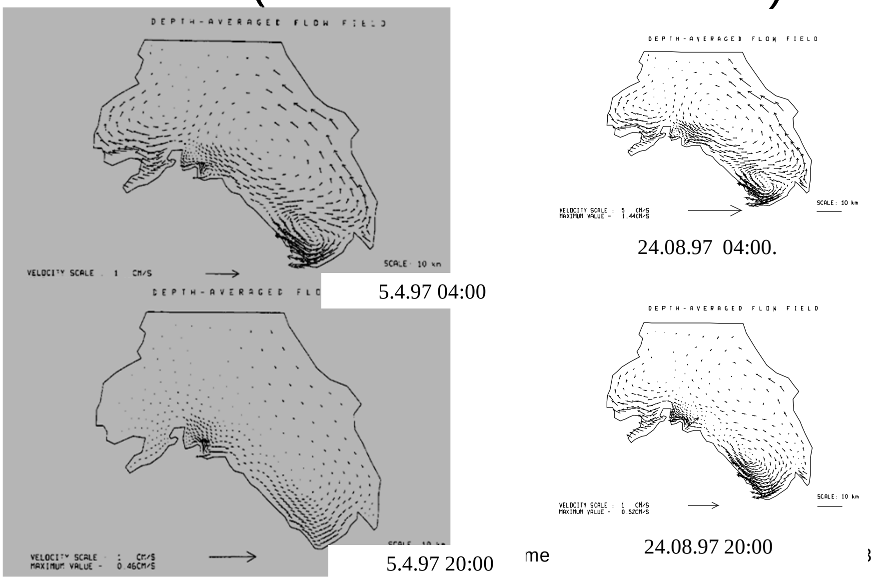
Regional flow and sediment transport models



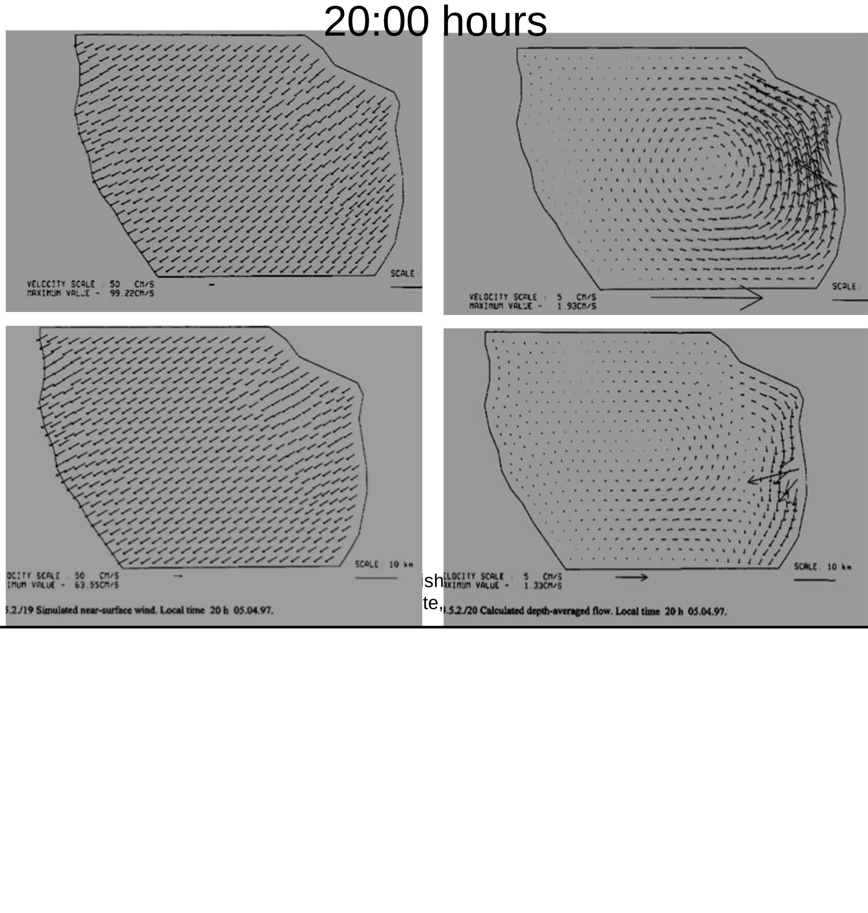


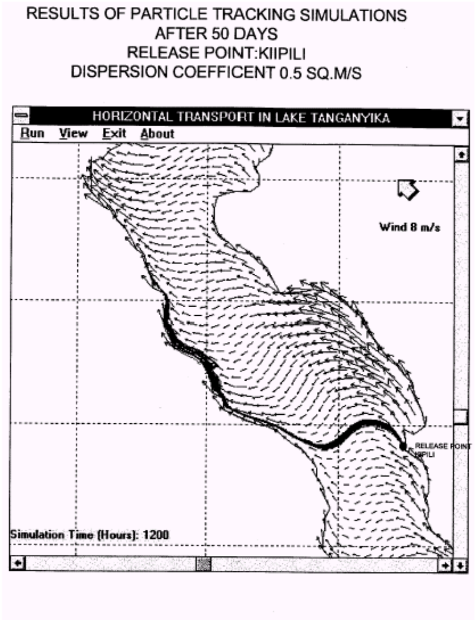
- Rusizi and Malagarasi river mouth as well as Mpulungu bay
- Expiditions and moored instruments
- Simulation periods
  - Wet April 1997
  - Dry: Agust 1997
- Wind fields from HIRLAM
- Water currents with 3DFemFlow

Circulation in Mplungu region, LTBP model (Podsetchine et al. 1997)



Winds and water currents near Malagarasi on 5.4.1997 at 04:00 and 20:00 hours




RESULTS OF PARTICLE TRACKING SIMULATIONS
AFTER 50 DAYS
RELEASE POINT:KIIPILI
DISPERSION COEFFICENT 0.5 SQ.M/S
HORIZONTAL TRANSPORT IN LAKE TANGANYIKA
Run View Exit About
Wind 8 m/s
RELEASE POINT
Simulation Time (Hours): 1200