MODELING FLOW AND SEDIMENT TRANSPORT IN WATER BODIES AND WATERSHEDS

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LIST OF PAPERS

This thesis is based on the following papers, which are referred to in the text by their Roman numerals:


Papers not attached in the thesis:


ABSTRACT

The research focus is on the various modeling aspects of flow and sediment transport in water bodies and watersheds. The interaction of flow with a mobile bed involves a complex process in which various turbulent scales characterized by coherent structures cause a chaotic sediment motion. In many rivers and natural waterways secondary flows that are dominating flow structures bring about more complications. In estuaries and open waterbodies thermal stratification and internal mixing control the flow structure besides the flow interaction with the mobile bed. To adequately model these processes 3D coupled flow and transport models are needed. The research is based on use and adaptation of open source codes for 3D hydrodynamic and sediment transport model known as Estuarine Coastal Ocean Model (ECOMSED) and the Soil and Water Assessment Tool (SWAT) model. A bed load transport model was developed and coupled to ECOMSED. The flow and sediment transport characteristics in a curved channel and a river reach were successfully captured by the model. Improvements in ECOMSED were made to study the effect of wind and basin bathymetry on mixing and flow exchange between two estuaries. Using spectral analysis the hydrological component of SWAT model was investigated for its applicability under limited data conditions in three Ethiopian catchments.

Key words: Bed load transport model, ECOMSED, Hydrology, Hydrodynamics, Spectral Analysis, SWAT.

INTRODUCTION

This introduction gives a brief overview of flow and sediment transport modelling in water bodies and watersheds. It continues with a discussion of key aspects of flow dynamics and transport processes at different levels of the governing equations, followed by a description of objective and structure of the thesis.

Overview of flow modeling in water bodies and watersheds

Flow dynamics in water bodies and watersheds is governed by the universal laws of conservation of mass, momentum and energy. The system of conservation equations is closed when combined with constitutive laws, boundary conditions and initial conditions. The equation of state relates density, temperature and salinity; and the Stoke’s viscosity law relates stresses to deformations. In many instances simplifications are made for specific flows to facilitate computational efficiency. Such simplifications lead to different variants of the conservation equations that include: incompressible flows when the fluid density is assumed to be constant; Euler flows when viscous effects are neglected; Boussinesq approximation when the density variation contributes to fluid motion while the variation is yet small; boundary layer approximation for flows with no recirculation and with gradual variation of geometry; and hydrostatic pressure approximation when the vertical flow acceleration is neglected.

Flows in the ocean, coastal, estuarine, lakes, rivers and over watersheds are almost always turbulent and can be represented by various simplifications of the Navier Stoke’s equations. Bardina et al (1980) classified the numerical approaches to predict turbulent flows into six categories. The classification ranges from simple correlations of friction factor as a function of the Reynolds number that does not require the use of a computer; to solving all of the motions in a turbulent flow using the direct numerical simulation (DNS). DNS requires that all the relevant length scales of the flow, which vary from the smallest eddies to scales on the orders of the physical dimensions of the problem domain, be resolved. This approach is limited to flows with simple geometry and low Reynolds number. Another approach is known as large-eddy simulation (LES), in which the large-scale structure of the turbulent flow is computed directly and only the effects of the smallest (subgrid-scale) and isotropic eddies are modelled.
The main thrust of present-day research in computational fluid dynamics is through the time averaged Navier-Stokes equation also known as the Reynolds averaged Navier-Stokes (RANS) equation. These equations are derived by decomposing the dependent variables in the conservation equations into time-mean (obtained over an approximate time interval) and fluctuating components and then time averaging the equations.

RANS contains new terms, which can be interpreted as “apparent” stress gradients and turbulent scalar fluxes associated with the turbulent motion. The new terms cannot be represented uniquely in terms of mean quantities and turbulence models are needed to close the new system of equations. Turbulence models vary from simple zero order equations that consider increasing the viscosity by a constant to the Reynolds stress models that bring additional partial differential equations for the various correlations.

In predominantly 2D flows the RANS equations are integrated over the depth. The resulting equations are called shallow water equations or the Saint Venant (SV) equations and contain momentum flux and pressure correction factors (Yen 1973, 1975). The usual assumption in depth averaged equations is that bottom shear stress magnitude is the same as in steady uniform flows and that its direction is the same as the direction of the depth averaged velocity.

Integration of the shallow water equations across the width yields the dynamic wave equation which is widely used for flood routing. Further simplification of the dynamic wave equation by neglecting pressure and inertial terms results in the kinematic wave approximation which is used to route overland surface water runoff to the nearest channel. Overland flow routing can also be done by using the continuity equation with an additional relationship between storage, outflow and inflow (like the stage discharge curve).

Regarding flow processes in the watershed, partial differential equations describing overland flow and channel flow are used by representing the watershed by a cascade of plane elements and channel segments whereby flow is routed from one segment to another.

**Overview of sediment transport modeling in water bodies and watersheds**

Hydrodynamic computations precede sediment transport computations as flow is the driving force to transport sediment from catchments and river beds. The governing equation for sediment concentration in rivers and water bodies is the sediment advection-diffusion equation. However, estimation of sediment flux from the bed continues to be a challenging problem.

For sediment flux from the bed empirical equations are used to determine the sediment transport capacity of a specific flow condition. The sediment transport rate is usually related to part of the boundary shear stress that acts on the grains. Empirical and semi-empirical formulas that are often used to estimate sediment transport capacity include Meyer-Peter & Mueller (1948), Yalin (1972), van Rijn (1989), Einstein (1950), Engelund & Hansen (1967), Ackers and White (1973), Yang (1973), Zhang & Xie (1993), Wu et al (2000).

Modeling the overland sediment transport and estimating sediment loads from watersheds is even more difficult. Here, surface erosion is induced by the kinetic energy of raindrops and the mechanical force of surface runoff. Surface runoff transports the soil particles and chemical substances that are detached by raindrops. Bennet (1974) described the sediment dynamics at any point along a surface flow path using a mass balance equation similar to that for kinematic water flow.

Many empirical equations are available to estimate sediment yield among which the Universal Soil loss Equation (USLE) is the most widely used. However the transferability of USLE to other watersheds than where it was tested is limited. As a result there is a rapid evolution of erosion models from the empirical USLE to event-oriented semi-deterministic models that work on a GIS-platform.
Objective and structure of the thesis

Research in the field of Ethiopian water resources development is by far limited due to financial constraints, poor water resources database and lack of skilled human resource. To prompt research in Ethiopian universities capacity building programs in terms of research cooperation is undergoing. The focus is on arriving at useable tools for dealing with erosion, flooding, water quality and other water resources related problems. Developing scientific skills in modeling flow and transport in water bodies and watersheds is of paramount importance for the country.

The objectives of this research are to use open source codes of advanced hydrodynamic and hydrological models to investigate technical and scientific nature of selected problems of interest, to discuss the strength and limitations of the models in the selected problems and to improve the predictive abilities of the models. The specific objectives are:

- Improving the predictive ability of ECOMSED for flow and sediment transport modeling in rivers. Improved model is validated using a curved channel (paper I) and applied to River Klarälven to identify possible erosion and sedimentation regions of the river as a result of man made changes (paper II).

- Investigating the effect of wind and basin bathymetry on the mixing and exchange processes between two estuaries using ECOMSED with further improvements (paper III).

- Assessing the applicability of SWAT to predict stream flow in three watersheds in Ethiopia based on spectral analysis of the available nearby climatic and hydrological data (paper IV).

The thesis is organized in four sections. The next section gives a brief description of the methods used. The thesis continues with the summary of the appended papers. The final section presents thesis summary and conclusion where the research contributions are highlighted.

METHOD

The research methodology consists of using two open source codes of advanced hydrodynamic and hydrological models; one is a fully integrated 3D hydrodynamic and sediment transport model known as ECOMSED and the other is a watershed hydrological model known as SWAT. Both models have several components and the following section will only provide a brief description of the modules used in this thesis. Spectral analysis of available rainfall-runoff data is used to constrain the time scales of the SWAT model.

ECOMSED model

The ECOMSED model developed by Blumberg & Mellor (1987) is a fully integrated 3D hydrodynamic and sediment transport model. It has a free surface and a bottom following \( \sigma \)-coordinate system with an orthogonal curvilinear grid in the horizontal plane. Here follows a brief description of the governing equations, boundary conditions, the turbulence model and the solution algorithms which are related to the present study.

The governing equations in ECOMSED are the Reynolds averaged Navier Stokes equations and the advection diffusion equations for the mean temperature, salinity and sediment concentration. The equations can be written as follows assuming that the pressure is hydrostatic and the Boussinesq approximation is valid.

\[
\frac{\partial U}{\partial t} + \frac{\partial}{\partial y} \left( U \frac{\partial U}{\partial y} + V \frac{\partial U}{\partial z} \right) + \frac{\partial}{\partial z} \left( U \frac{\partial U}{\partial z} + W \frac{\partial U}{\partial x} \right) - fV = -\frac{1}{\rho_b} \frac{\partial P}{\partial x} + \frac{\partial}{\partial z} \left( K_U \frac{\partial U}{\partial z} \right) + \frac{\partial}{\partial x} \left( 2 A_{Ux} \frac{\partial U}{\partial x} + A_U \left( \frac{\partial U}{\partial y} + \frac{\partial V}{\partial x} \right) \right)
\]

\[
\frac{\partial V}{\partial t} + \frac{\partial}{\partial y} \left( U \frac{\partial V}{\partial y} + V \frac{\partial V}{\partial z} \right) + \frac{\partial}{\partial z} \left( U \frac{\partial V}{\partial z} + W \frac{\partial V}{\partial x} \right) + fU = -\frac{1}{\rho_b} \frac{\partial P}{\partial y} + \frac{\partial}{\partial z} \left( K_U \frac{\partial V}{\partial z} \right) + \frac{\partial}{\partial x} \left( 2 A_{Uy} \frac{\partial V}{\partial y} + A_U \left( \frac{\partial U}{\partial y} + \frac{\partial V}{\partial x} \right) \right)
\]
\[ \rho g = -\frac{\partial P}{\partial z} \]

\[ \frac{\partial (\theta, S)}{\partial t} + U \frac{\partial (\theta, S)}{\partial x} + V \frac{\partial (\theta, S)}{\partial y} + W \frac{\partial (\theta, S)}{\partial z} = \]

\[ \frac{\partial}{\partial z} \left( K_{\theta} \frac{\partial (\theta, S)}{\partial z} \right) + \frac{\partial}{\partial x} \left( A_{\theta} \frac{\partial (\theta, S)}{\partial x} \right) + \frac{\partial}{\partial y} \left( A_{\theta} \frac{\partial (\theta, S)}{\partial y} \right) \]

\[ \frac{\partial C}{\partial t} + \frac{\partial UC}{\partial x} + \frac{\partial VC}{\partial y} + \frac{\partial(W - W_c)C}{\partial z} = \]

\[ \frac{\partial}{\partial z} \left( A_{\theta} \frac{\partial C}{\partial z} \right) + \frac{\partial}{\partial x} \left( A_{\theta} \frac{\partial C}{\partial x} \right) + \frac{\partial}{\partial y} \left( A_{\theta} \frac{\partial C}{\partial y} \right) \]

In which \( U, V \) and \( W \) are time-averaged velocities in the \( x, y \) and \( z \) directions respectively; \( f \) is the Coriolis parameter; \( \rho_o \) is the reference density; \( P \) is the mean pressure; \( K_{\theta} \) and \( A_{\theta} \) are the vertical and horizontal mixing coefficients for the momentum; \( \rho \) is the mean density; \( g \) is the gravitational acceleration; \( \Theta, S \) and \( C \) are the mean temperature salinity, and sediment concentration; \( K_{\Theta} \) and \( A_{\Theta} \) are the vertical and horizontal diffusion coefficients; and \( W_c \) is the settling velocity of sediment particles.

The settling velocity of noncohesive sediment particles is calculated from the effective diameter of the suspended sediment using the semi-empirical formulation of Cheng (1997)

\[ W_s = \frac{v}{D_{50}} \left[ 25 + 1.2D_s^2 \right]^{0.4} - S \]  

\[ D_s = \left[ \frac{(s - 1)gD_{50}}{v^2} \right]^{1/3} \]  

In which \( v \) is the fluid kinematic viscosity; \( D_{50} \) is particle diameter for 50% finer of bed material; \( D_s \) is the dimensionless grain size; and \( s \) is specific density.

The density is computed as a function of temperature and salinity, according to an equation of state given by Fofonoff (1962). The vertical mixing coefficients, \( K_{\theta} \) and \( A_{\theta} \) are obtained by appealing to a second order turbulence closure scheme (Mellor & Yama-
In which $S_{M}$, $S_{H}$, and $S_{q}$ the stability functions. The stability functions $S_{M}$ and $S_{H}$ depend on the Richardson number $G_H$.

\[ G_H = \left( \frac{N l}{q} \right)^2 \]  \hspace{1cm} (7a-b)

\[ N = \left( -\frac{g}{\rho}\frac{\partial \rho}{\partial z} \right)^{1/2} \]

In which $N$ is the Brunt-Vaisala frequency.

Following Galperin et al. (1988) the stability functions are:

\[ S_M = \frac{A_1 \left( 1 - 6A_1 \right)}{1 - 3A_1 g_H (6A_1 + B_1)} \]  \hspace{1cm} (8a-b)

\[ S_H = \frac{B_1^{1/3} - 3A_1 g_H (B_1 - B_2) \left( 1 - 6A_1 \right)}{1 - 3A_1 g_H (6A_1 + B_1) \left( 1 - 9A_1 g_H \right)} \]

The empirical constants given in Mellor & Yamada (1982) are: $(A_1, A_2, B_1, B_2, C_1, E_1, E_2, S_q) = (0.92, 0.74, 16.6, 10.1, 0.08, 1.8, 1.33, 0.2)$ respectively.

In stable stratified flows, the turbulence macroscale is limited (Galperin et al. 1988) according to;

\[ l \leq \frac{0.53 g}{N} \]  \hspace{1cm} (9)

The horizontal diffusivities, $A_{M}$ and $A_{H}$, are related to the scales of motion being resolved in the model to the local deformation field as suggested by Smagorinsky (1963).

\[ A_m = c \Delta^2 \frac{1}{2} \left[ \left( \frac{\partial U_i}{\partial x} + \frac{\partial U_i}{\partial y} \right) \right]^2 \]  \hspace{1cm} (10)

In which $c = 0.01$; $\Delta^2 = \Delta x \Delta y$; and Einstein convention is used. $\Delta x$ and $\Delta y$ are the grid spacing in the $x$ and $y$ directions respectively.

The horizontal diffusivity $A_{H}$ is usually set equal to $A_{M}$.

**Boundary conditions**

The boundary conditions are specified at the surface, at the bottom and at open boundaries.

**Free surface:** The boundary conditions at the free surface, $z = \eta(x, y, t)$, are

\[ \rho K_m \left( \frac{\partial U_i}{\partial z} + \frac{\partial V_i}{\partial z} \right) = (\tau_{nx}, \tau_{ny}) \]  \hspace{1cm} (11a-d)

\[ q^2 = B_1^{1/3} u_n^2 \]

\[ q^2 \ell = 0 \]

\[ W = U \frac{\partial \eta}{\partial x} + V \frac{\partial \eta}{\partial y} \]

In which $(\tau_{nx}, \tau_{ny})$ is the surface wind stress vector with the surface friction velocity, $u_n$, being the magnitude of the vector.

**Bottom boundary:** The boundary conditions at bottom boundary, $z = H(x, y)$, are

\[ \rho K_m \left( \frac{\partial U_i}{\partial z} + \frac{\partial V_i}{\partial z} \right) = (\tau_{nx}, \tau_{ny}) \]  \hspace{1cm} (12a-d)

\[ q^2 = B_1^{1/3} u_n^2 \]

\[ q^2 \ell = 0 \]

\[ W = -U \frac{\partial H}{\partial x} - V \frac{\partial H}{\partial y} \]

In which $(\tau_{nx}, \tau_{ny})$ is the bottom stress vector with the bottom friction velocity, $u_\phi$, being the magnitude of the vector.

In ECOMSED the bed shear stress is determined by matching velocities with the logarithmic law of the wall.

\[ \tau_s = \rho C_s |\nabla| \nabla' \]  \hspace{1cm} (13)
With the value of the drag coefficient \( C_D \) given by

\[
C_D = \left[ \frac{1}{k} \ln \left( \frac{H + z}{z_o} \right) \right]^2
\]  

(14)

In which \( z_h \) is the elevation of the grid point nearest to the bottom and \( V_h \) is the corresponding resultant horizontal velocity. The parameter \( z_0 \) depends on the local bottom roughness.

**Open lateral boundary:** Lateral open boundary conditions are needed in 3D numerical modeling unless the computational domain is closed, as in global simulation, or the domain is completely surrounded by solid boundaries, as in lake simulations. When modeling flow exchange between adjacent water bodies through a connecting strait, the computational domain is usually cut off at the straight ends.

ECOMSED utilizes an open boundary condition developed by Reid & Bodine (1968) that allows long wave to radiate through open lateral boundaries.

\[
\eta = \eta_o + \lambda U \left[ \frac{g}{D} \right]^{-1/2}
\]  

(15)

In which \( \eta \) is the sea level at the open boundary; \( \eta_o \) is the known (assigned) tidal and perhaps low frequency sea level variation at the grid cell; \( \lambda \) is the LaGrange multiplier; \( U \) is the model-predicted velocity perpendicular to the open boundary and \( D \) is the depth of the grid cell. The LaGrange multiplier \( \lambda \) is calculated each time step to allow modification of the sea level due to long wave radiation.

**Numerical methods**

All the equations in ECOMSED are transformed into an orthogonal curvilinear coordinate system in the horizontal direction and into a sigma coordinate system in the vertical direction that increases model efficiency in treating irregularly shaped boundaries. The \( \sigma \)-transformation is given by

\[
\sigma = \frac{z - \eta}{H + \eta}
\]  

(16)

The vertically and horizontally transformed set of equations is approximated by a finite difference scheme using a spatially staggered grid. The leap frog scheme with the Courant-Friedrichs-Levy (CFL) computational stability condition and a weak filter to remove solution splitting at even and odd time steps is employed for time differencing.

The hydrodynamic module (ECOM) is 3D with a split external-internal mode algorithm (Simons 1974, Madala & Piacsek 1977); the external mode explicitly solves the depth integrated equations with short time steps to resolve fast moving waves and to determine the water surface elevation. The internal mode uses the computed water surface elevation and implicitly solves the vertical structure of the flow with a shorter time step. The internal mode then updates some of the variables of the external mode for the next time step to begin.

**Pressure gradient errors**

Models based on topography following \( \sigma \)-coordinate systems are effective in resolving the bottom boundary and surface layers. This however is not without cost. The problem arises in calculating the pressure gradient force in a steep topography (Haney 1991). The source of the problem is that in sigma coordinates, the x-component of the internal density gradient is written as (Thiem & Bernsten, 2006);

\[
\frac{\partial \rho}{\partial x} = \frac{\partial \rho}{\partial \sigma} \frac{\partial \sigma}{\partial x} = \frac{\partial \rho}{H \partial \sigma}
\]  

(17)

Near a steep topography the two terms on the right may be large, comparable in magnitude, and often opposite in sign. This may cause large errors in the estimates of the internal pressure and produces artificial flows in which case the estimated circulation will be wrong. According to Thiem & Bernsten
(2006) the error will decrease as the vertical and horizontal grid sizes are reduced. Several algorithms are available (McCalfin 1994, Chu & Fan 1997, 2003, Song 1998; Song & Wright, 1998, Shchepetkin & McWilliams 2003) that attempt to reduce the size of the internal pressure errors.

**SWAT model**

SWAT is a daily basis watershed model originally developed by Arnold *et al* (1998). The objective in model development is to predict the impact of management on water, sediment and agricultural chemical yields in large ungauged basins. The availability of both the FORTRAN source code and interfaces in Windows, GRASS and Arc View has contributed to its wide application. The hydrological component of the SWAT model is validated for several watersheds throughout the U.S. (Arnold *et al* 1998, 1999, Saleh *et al* 2000, 2003).

The hydrologic component of SWAT is based on the water balance equation for each hydrologic response unit (subdivision of the watershed based on soil type and land use):

\[
SW_i = SW_0 + \sum_{j=1}^{i}(R_{surf} - Q_{surf} - E_a - w_{vad} - Q_{gw}) \tag{18}
\]

In which \(SW_i\) is the final soil water content, \(SW_0\) is the initial soil water content on day \(i\), \(t\) is the time (days), \(R_{surf}\) is the amount of precipitation on day \(i\), \(Q_{surf}\) is the amount of surface runoff on day \(i\), \(E_a\) is the amount of actual evapotranspiration on day \(i\), \(w_{vad}\) is the amount of water entering the vadose zone from the soil profile on day \(i\), and \(Q_{gw}\) is the amount of return flow on day \(i\).

Here follows a brief description of the methods used in SWAT to estimate surface runoff volume, evaporation, recharge to shallow aquifer, groundwater flow to the main channel, and channel routing.

SWAT uses a modification of the SCS curve number method (USDA Soil Conservation Service 1972) or the Green and Ampt infiltration method (Green & Ampt 1911) to estimate the surface runoff volume from each hydrologic response unit.


The amount of water that moves from the soil layer to the vadose zone (unsaturated zone between the bottom of the soil profile and the top of the aquifer) is calculated using storage routing methodology. Once the water exits the soil profile an exponential decay weighting function (Venetis 1969) is used to account for the time delay in shallow aquifer recharge.

The ground water contribution, \(Q_{gw}\), is estimated with the assumption that the variation in groundwater flow is linearly related to the rate of change in water table height. The steady-state response of groundwater flow to recharge is computed using the equation by Hooghoudt (1940) and water table fluctuations due to non-steady-state response of groundwater flow to periodic recharge is calculated using the equation by Smedema & Rycroft (1983).

Once the net flow to the main channel is computed the flow is routed through the channel using a variable storage coefficient method developed by Williams (1969) or the Muskingum routing method.

**Time scale parameters in SWAT**

SWAT incorporates a surface runoff storage feature using the SURLAG parameter to lag a portion of the surface runoff release to the main channel. The GW_DELAY parameter accounts for the time delay in shallow aquifer recharge whereas the ALPHA_BF parameter (the base flow recession constant) is a direct index of groundwater flow response to changes in recharge. The storage time constant, \(K\), accounts for the wedge storage in the channel.

**Spectral Analysis**

In rainfall runoff modeling under limited data conditions it is important to study the correlation between the available input variables.
and the stream flow so that the watershed dynamics can be well characterized for predictive purposes. Correlation analyses provide indications of what can and cannot be predicted using different models and this helps to avoid model over-parameterization. Islam & Sivakumar (2002) used ideas from non-linear dynamical theory to characterize and predict runoff dynamics. To get information on the temporal scales of variability of the rainfall-runoff relationship Labat et al. (2000) used wavelet analysis of rainfall rates and runoffs and wavelet rainfall-runoff cross-analysis. Labat et al. (2001) also introduced multifractal analysis to study the scale-properties of rainfall-runoff relationships for karstic springs. The relationships between spatial and temporal scales of compartmental models in hydrology were particularly analyzed by Dirac & Destouni (2007) and Xu et al. (2007).

In this study spectrum analysis was used to extract evidence regarding the relationships between different temporal scales of the available daily rainfall and runoff series reflecting the spatial scales of three watersheds in Ethiopia. The purpose was to analyze the effects of data limitation on the temporal and spatial scales suitable to account for in SWAT.

**SUMMARY OF PAPERS**

Brief summaries of the included papers are given below. The papers address flow and sediment transport processes in water bodies and watersheds.

**Paper I: 3D flow and sediment transport modeling in curved channels**

The study of flow and sediment transport characteristics in curved channels is an important research field due to its significant practical value in river engineering applications. The essential flow feature in a curved channel is the spiral motion (secondary flow structure) and its interaction with loose bed material. This transverse secondary flow is driven by the local imbalance between the centrifugal force and the transverse pressure force generated by super elevation of the water surface. The secondary motion transports the material eroded from the river bed in the transverse direction of a bend settling it as point bars. Typical erosion and sedimentation patterns observed in river bends are the result of this flow process.

3D numerical models are becoming powerful tools to investigate the flow and sediment transport in curved channels. The availability of more accurate numerical methods, improved turbulence models and the increasing computational capacities is contributing to this development. However, there is a need to test and improve the predictive ability of numerical models.

ECOMSED, 3D open source code, was selected for this study. ECOMSED has a long history of successful applications to oceanic, coastal, and estuarine waters. Regarding the application area, river applications of the code are scarce. ECOMSED considers only suspended sediment transport, as the contribution of bed load movement in large water bodies such as lakes and oceans is insignificant. Thus, the bed elevation change due to suspended sediment transport is assumed small and the bed is not allowed to evolve. However, the bed load contribution and the bed elevation change can be considerable in the case of rivers. ECOMSED uses central difference scheme for advection of momentum and turbulence which is not recommended for a high advection-diffusion ratio.

The purpose of this study was to improve ECOMSED to address these issues. A separate subroutine for the bed load transport and bed evolution was included in the code. The Gaussian smoothing was also implemented in the code to filter out high local topography gradients so that numerical noises that will propagate and pollute the variables near the bed will not be produced. An advanced upwind scheme is also implemented for advection of momentum and turbulence as the advection-diffusion ratio is high in most river flows.

Experimental results by Yen (1970) were used to validate the proposed bed load transport and bed evolution model. Yen measured the erosion and deposition patterns on a
meandering channel for different width-depth ratios. Validation was made using a width-depth ratio of 18 and Froude number of 0.3, which Yen described as representative of a large natural river. The hydrodynamic simulation was run until a converged steady state solution was obtained. The simulation for sediment transport was run for 100 hours that corresponded to the experiments. The predicted and measured erosion-deposition patterns were compared (Fig. 1). The bed changes were normalized by the average flow depth. Except some deviations at the entrance to the second bend, the predicted erosion-deposition patterns agreed with the experimental results. Yen emphasized that the thalweg paths, traces of the deepest part of the channel, cross abruptly from one side of the meander to the other side at about the lower end of the straight section. However, Fig. 1a shows that the transition was smoothened. A similar discontinuity was also observed in the numerical results. Good agreements were also obtained between predicted and observed bed shear stress distribution as well as between the observed and predicted ratios of the normalized maximum radial velocities.

**Paper II: 3D numerical modeling of flow and sediment transport in rivers**

River flows are characterised by complex secondary flow patterns that are responsible for the transverse movement of sediment particles. 3D numerical models are important tools to study river flow problems. However, as emphasized in paper I, there is a need to test and improve the predictive ability of numerical models.

This paper is an extension of paper I for a river application. The paper addresses identification of possible erosion and sedimentation regions of River Klarälven as a result of man made changes. In this study the bed load transport and bed evolution model validated using a curved channel (paper I) together with a suspended sediment transport module of ECOMSED was applied to the River Klarälven. The River Klarälven enters Sweden in the north of the county of Värmland. Its course in Värmland is south down to the river mouth on lake Vänern. The river bifurcates into an east and west channel at the city of Karlstad. A one kilometre reach of the river where it bifurcates to east and west channels was modelled.

**Fig. 1. Erosion deposition pattern in a meander channel (normalized with average flow depth); a: Experimental result, b: ECOMSED simulation.**
The model was calibrated for a discharge of 285m$^3$/s using the measured water surface at the inlet and the discharge division between the two channels. The percentage of the discharge into west and east channels were 42% and 58%, respectively. The average water surface gradient was 0.0001. For the inlet flow boundary condition, a wake law velocity profile was fitted on the point velocity measurements. The shear velocity for the wake law was calculated from the average water surface gradient. Dirichelet boundary condition was used at the outlet for the water level. The simulation was run until a steady state solution was obtained. The normalized error in the computed flow division was -1.05% (west channel) and +1.05% (east channel) while the normalized error in the water level at the inlet varied from +7.3% to -4.5%. Adjustments were made in the bed roughness distribution to minimize the deviations.

The calibrated model was validated against a different set of measurements taken for a discharge of 138m$^3$/s. In comparison with field data, the normalized error in the observed water surface profile varied from 0.11% to 1.33%. The normalized error in the flow division was -1.56% for the west channel and +1.56% for the east channel. Regarding the flow field, stream lines as well as the local flow circulation region upstream of the river bifurcation agreed well with the field observations.

The sediment transport simulation was made using Neumann boundary conditions for bed load and suspended sediment concentration both at the inlet and at the outlet due to lack of sediment load data (the Neumann boundary condition allows having static bed conditions at the inlet and at the outlet). The simulation was run for 2 hours. The general pattern of bed changes after 2 hours (Fig. 2). The main features are: (1) the tendency for sedimentation at the entrance to the east channel and (2) the division of the main channel into two distinct regions of erosion and deposition. The model predicted the classical erosion patterns observed in the river bends. The sediment transport results are relevant as far as the short time response of the river is concerned. The simulations are useful in recognizing possible sedimentation and erosion regions.

![Fig. 2. Predicted bed level changes (mm) after 2 hours using ECOMSED (-ve shows erosion, + indicates the contour line for which the value is specified, length units in m).](image-url)
Paper III: Mixing and exchange processes between two Estuaries in Stockholm Archipelago, Sweden

The water quality of estuaries depends on internal mixing and the flow exchange rate through the straits that extend to the outer sea. One of the main problems is oxygen deficiency especially during summer periods. There is some evidence that dissolved oxygen concentration can be related to the topography. In a study of 30 fjords, Aure & Stigebrandt (1989) found that oxygen consumption in the basin water was related to the fjord topography.

The paper addresses application of ECOM (hydrodynamic module of ECOMSED) to investigate the effect of wind and basin bathymetry on the mixing and exchange processes between Farstaviken and Baggensfjärden estuaries in the Stockholm Archipelago. An attempt was also made to relate the results to water quality putting the focus on oxygen deficiency in Farstaviken during April to November 1997. The sensitivity of the circulation intensity to changes in the basin bathymetry is studied using a 2D Gaussian filter.

The study period extends from a well mixed spring turnover through a vertically stratified summer to a well mixed fall turnover. The model was forced by a tide from the inner Baggensfjärden estuary in addition to the most relevant factors such as wind, surface heat flux and flow from the catchment. An open boundary condition developed by Reid & Bodine (1968) that allows long wave to radiate through open lateral boundaries was used to represent the tide level at the connecting strait section. Flow reversals depending on the local water level gradient and bidirectional vertical distribution of flow are allowed at the open boundary. Temperature and Salinity data are available in the nearby Baggensfjärden station. The temperature and salinity profile at the inlet was assumed to be similar to the values of the nearby Baggensfjärden station.

The preliminary simulations showed a systematic deviation of simulated results from observed results (Fig. 3). The main reason is that the wind data was used as effective in the study area without any transformation. To use more relevant values the data had to be modified since the measuring station is located some kilometers away from Farstaviken. The wind speed magnitude was reduced until the agreement between observed and simulated temperature profiles was acceptable. The wind speed factors that produced the best agreement were found to be time variant.

The higher reduction of the wind speed in summer can be due to the fact that the Farstaviken estuary gets well sheltered as the surrounding forest fully recovers its leaves during this period. The beginning and end periods of the simulation correspond to the snow period when the canopy cover is highly reduced. In this study the local wind direction at Farstaviken was assumed to be the same as the wind direction measured at Stockholm-Bromma station. However, the local wind direction can vary from the nearby station due to different factors and this can influence simulation results as the Farstaviken is more vulnerable to East-west winds than north-south winds.

Model results (Fig. 3) clearly indicate that there can be a significant reduction in the temperature stratification if the estuary is exposed to the whole available wind energy. Baggensfjärden estuary has a larger surface area which gives more exposure to the wind and hence better mixing than Farstaviken.

During stratification periods the flow is characterized by the existence of epilimnion, metalimnion, and hypolimnion layers. The epilimnion region occupies 2.5%-17.5% of the flow depth. In the narrower deeper sections of Farstaviken eddies were entirely confined by the topography. Fig. 4a illustrates some of these features for a centre line longitudinal cross section (East-West direction). The corresponding schematized flow patterns (Fig. 4b). They represent the mean flow structure derived from the numerical results. Eddies can be characterized by their strength or circulation using the percentage of the vorticity normalized with the maximum vorticity of the original bathymetry (Fig. 4c). The velocity vectors were used to compute the
values of the vorticity. In the deeper part of Farstaviken the flow is stagnated and the circulation is almost zero (hypolimnion).

The flow exchange between Farstaviken and Baggensfjärden takes place across the narrow strait that connects the two basins. The temperature and density gradients between Farstaviken and Baggensfjärden are close to zero through the year (1997). Hence the exchange process is primarily controlled by wind action and tide that induce a two directional pressure gradient. About 4m of the top water layer in Farstaviken is available to Baggensfjärden. Two important parameters that characterize exchange processes are the rate of exchange and the detention time. Model results indicated that the percentage of flow exchange during April 22 to June 5 1997 is in the range 2.2%-7.9%. On the average 5% of the total water volume of Farstaviken is exchanged with Baggensfjärden on daily bases.

This average value corresponds to a global retention time in Farstaviken of 20 days. However specific retention times for the bottom water could be higher as only about 4 m of the surface water in Farstaviken is in active circulation with Baggensfjärden.

To investigate the sensitivity of mixing to the changes in basin bathymetry, additional simulations were performed using a modified bathymetry. The original bathymetry was altered using the 2D Gaussian filter. The purpose of the filter was to smooth the bed topography by conserving the volume of sediment that is going to be cut and fill. The numerical results showed that both the intensities and penetration depths of eddies were increased in comparison with the initial bathymetry. An example is shown in Figure 4 a-f that compares the intensity of circulation in both cases; much of the water body in the modified bathymetry became part of the
active circulation. An enhanced circulation of the bottom water will also contribute to improvements in water quality.

**Paper IV: Hydrological modeling under limited data conditions in Ethiopian catchments**

Ethiopian water resources potential is extensive with estimates of roughly 120 billion cubic meters of mean annual flow from twelve major river basins (MoWR 1999). And yet only about 4.8 percent of the country’s irrigable land (which is estimated to be about 3.35 million hectares) and 4 percent of its hydropower potential (which is estimated at 60 billion kwhr) (MoWR 1999) has been developed while population pressure and land degradation continues to grow. As a result the country has faced frequent and severe droughts with periodic flooding in some areas. Fig. 5 shows Ethiopian major rivers, Lake Tana and the rift valley lakes. An extensive discussion regarding water resources potential, development, issues of sustainability, land tenure, public participation is given by Rahamato (1999). Currently various irrigation and hydropower projects are underway and the Ethiopian government has taken the initiative to establish basin institutions. The country receives limited financial and technical aid from international donors to develop its water resources. Due to the trans-boundary nature of Ethiopian rivers (Ethiopia has seven trans-boundary basins that carry over 95 percent of annual runoff) the Nile Basin Initiative has been launched in 1999 to build the capacity of the riparian countries taking into consideration the challenges of meeting their growing water needs in a sustainable manner. Research in the field of Ethiopian water resources development is by far limited due to financial constraints and poor water resources database of the country. Many water resources projects of various
Fig. 5. Ethiopian major rivers, lake Tana and the rift valley lakes.

sizes are being planned and executed under limited data conditions.

The purpose of this study is 1) to apply cross-spectrum analysis on the rainfall and discharge data in three watersheds in Ethiopia and, hence, 2) to analyze the effects of data limitation on the temporal and spatial scales suitable to account for in compartmentalized runoff models. Especially the performance of the hydrological component of SWAT model is evaluated in three watersheds; Gilgel Abay (1625 km$^2$), Gumera (1349 km$^2$) and Gilgel Gibe (2894 km$^2$) catchments.

From the testing period (1984 – 1999), 11 years of the daily stream flow record were used for calibration and the remaining 5 years were used for validation. In this study data from available nearby stations were used under the assumption that these data are somehow correlated with the unknown representative data.

The rainfall runoff time-series of the three watersheds was converted to the equivalent frequency domain using the Fourier transform. The spectral density shows both the rainfall and the runoff are highly seasonal in the three watersheds. The results indicate applicability of seasonal models in these watersheds. Fig. 6 shows the rainfall-runoff correlations. For higher frequencies (shorter time scales) there is no obvious correlation and the phase is erratic. This means that rainfall of periodicity (time scale) longer than about 50 days is manifested in terms of stream discharge response, whereas shorter-term fluctuations are not manifested. The most probable reason for the deviation from a continuously decreasing cross-correlation shorter than 50 days is that the rainfall data is spatially sparse (i.e. the rain gauge station is located outside the relatively large watershed). Though the data from the stations is relatively temporally dense, but each station covers a large area, so it is the spatial density that is too low for capturing the process details. From the phase plot one could draw the conclusion that there are periods down to
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Fig. 6. Cross spectra, coherence and phase: Top (Gilgel Abay), middle (Gumara) and bottom (Gilgel Ghibe).

50 days that is manifested in terms of a systematic lag between rainfall and discharge. Shorter frequencies in rainfall seem to have a random effect on discharge. With this data it is impossible to build a model that can predict shorter day variability than 50 days. The implication is that extreme flows cannot be predicted with the available rainfall data. Based on the spectral analysis the time scale parameters were identified as sensitive parameters that can help to smooth the SWAT predictions. The time scales for the surface runoff and groundwater flow (SURLAG, GW_DELAY and ALPHA_BF) were used for autocaliberation to match the daily observed stream flows. The time scales in the channel were not considered in this study because of lack of stream data. The spatial model parameters of SWAT were manually calibrated to match mean annual stream flow volume. Model performance of the daily stream flow response is compared to the Seasonal Model (SM) and the Original Linear Perturbation Models (OLPM). SM (Garrick et al. 1978) and OLPM (Nash & Barsi, 1983) both need previous seasonal behavior of the stream flow and hence cannot be used to predict responses due to changes in catchment characteristics and in ungauged catchments. SM model gives quite a good starting point by its own; $R^2$ values of 84%, 73%, 68% for calibration period and 77%, 66% 68% for validation period for Gilgel Abay, Gumera and Gilgel Ghibe, respectively. Further improvement to SM model by including rainfall information using the OLPM is not significant. $R^2$ values of 86%, 75%, 70% for calibration period and 78%, 67% 71% for validation period for Gilgel Abay, Gumera and Gilgel Ghibe, respectively. SWAT produced $R^2$ values of 80%, 71%, 64% for calibration period and 77%, 67% 60% for validation period for Gilgel Abay, Gumera and Gilgel Ghibe, respectively.
The spectral analysis results were clearly manifested in the best parameter values of the time scale parameters in SWAT. The \textit{SURL\_LAG} value for the three watersheds was exceptionally low (that corresponds many days of surface runoff delays) and the \textit{GW\_DELAY} values were high (many days of groundwater delay). Values for \textit{ALPHA\_BF} vary from 0.1-0.3 for land with slow response to recharge to 0.9-1.0 for land with a rapid response to recharge. Once the ground water is recharged the ground water flow process will be forced to follow the stream flow characteristics. In the three watersheds the auto calibration produced higher values of \textit{ALPHA\_BF} and this is consistent with stream flow characteristics of the three watersheds. The performance of the SWAT model, as tested in the three catchments, is comparable to SM and OILPM models provided that the time scales in SWAT are constrained based on spectral analysis of the available data.

The random nature of the observed stream flow (Fig. 7) can be better predicted by increasing the spatial density of the rain gauge stations and by incorporating landscape processes in the sub basins of the watershed to further divide the sub basin into a divide, hill slope and flood plain (Arnold \textit{et al} 2007). This can increase the spatial resolution and can improve both the stream flow prediction as well as transport mechanisms related to specific landscape positions. It should be noted that there is a need to provide representative distributed rainfall data and digital elevation data at a resolution fine enough to represent hill slopes.

\textbf{SUMMARY AND CONCLUSIONS}

The application of mathematical models in river engineering is an important branch of fluvial science that is progressing rapidly.
This has become possible by the significant advances made in numerical science and computer technology during the past three decades.

The interaction of flow with a mobile bed involves a complex process in which various turbulent scales characterized by coherent structures cause a chaotic sediment motion. In many rivers and natural waterways secondary flows that are dominating flow structures bring about more complications. In estuaries and open water-bodies thermal stratification and internal mixing control the flow structure besides the flow interaction with the mobile bed.

To adequately model these processes 3D coupled flow and transport models are needed. However, the main difficulty in using coupled models is our inadequate knowledge of sediment transport processes. In contrast to flow, these processes cannot be presented by theoretical equations. Here one needs to rely upon the use of semi-empirical formulas to estimate the sediment transport rates. Another major difficulty related to numerics is the grid representation of irregular model boundaries and specification of open boundary conditions.

The thesis examines the foregoing issues by the application of a fully 3D hydrodynamic and sediment transport model ECOMSED to three cases. These were curved channels, rivers and estuaries. The source code for ECOMSED was modified to adequately model the flow and sediment transport in curved channels and rivers. The bottom boundary condition for temperature was modified to include the effect of sediment-water heat exchange for model application to estuaries. The pressure gradient errors related to the sigma layer were reduced by including additional schemes in the code. The inlet boundary condition was modified to capture the scalar fluxes at the open boundary between an estuary and the open water body.

Regarding processes in the watershed the applicability of the hydrological model SWAT was tested in three watersheds in Ethiopia under limited data conditions. Spectral analysis was used to constrain the time scales of the model so that reliable estimates could be obtained based on available data.

The thesis contributions can be summarized as follows;

1. Improvements in the advection scheme of momentum and turbulence to cope up with the high advection-diffusion ratios that prevail in rivers.
2. To account for the dynamics of the mobile bed boundary, a bed load transport model was added in the code.
3. Shear stress partitioning was necessary to reproduce comparable results in a curved channel.
4. Additional bed boundary condition for the sediment-water heat exchange was included for the estuary application. This feature is also important for reducing numerical diffusion.
5. Pressure gradient error reducing scheme was included in the code to reduce pressure gradient errors that are typical problems of sigma layer models.
6. A local z-level coordinate was employed at the inlet to the estuary to capture the exchange with the open water-body.
7. Spectral analysis was used to constrain the time scales of SWAT to make the predictions compatible with the available data.

The aforementioned contributions were tested in different applications. The application of the improved ECOMSED model can be summarized as:

For a case of curved channel, the improved coupled model reproduced measured secondary currents, bed shear stress distribution, and erosion-deposition patterns in agreement with experimental results.

The application of the improved coupled model to 1-km reach of the River Klarälven (located in the north of the county of Värmland, Sweden) was successful in predicting the general flow patterns and sediment transport characteristics.

The estuary application of the model helped to investigate the effect of wind and basin bathymetry on the mixing and exchange processes between the two waterbodies. The
study results also indicated that a possible cause of the bottom oxygen deficiency in Farstaviken during April to November 1997 is the topography of the basin and the wind sheltering effect. The intensities and penetration depths of eddies were increased for a modified bathymetry in comparison with the original bathymetry. The enhanced circulation can also contribute to increase the content of dissolved oxygen near the bottom of Farstaviken.

ECOMSED, open source code, can be adapted to specific problems. It is an effective tool in addressing various practical problems in river engineering and other related fields. However, 3D models are still in their developing stage especially regarding sediment transport processes. Careful validation and calibration procedures are needed that require extensive field data.

The application of Spectral analysis of available data in the three watersheds of Ethiopia helped to investigate the effects of data limitation on the temporal and spatial scales suitable to account for in SWAT model. The spectral analysis time scale results were clearly manifested in the best parameter values of SURLAG and GW_DELAY that indicated many days of delay in stream flow response. The performance of the SWAT model, as tested in the three catchments, is acceptable provided that the time scales in SWAT are constrained based on spectral analysis of the available data. For better prediction of stream flow in the three watersheds the existing data needs to be complemented with aerial precipitation data from radars and satellites. Moreover landscape processes in the sub basins of the watersheds need to be included in the SWAT model so that the model compartment and hence the spatial resolution is increased.
REFERENCES


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