Chapter 6

Quasisteady Approximation in Long-Term Morphological Simulation

This chapter begins with the long-term calibration and validation of bed evolution of the Lautrach reservoir making use of the simplifications proposed in Chapter 5. Sensitivity analysis was conducted on the estimated model parameters; critical erosion shear velocity, erosion coefficients, critical deposition shear velocity, and settling velocity. Furthermore, investigations were performed on the validity of quasisteady approximation based on short-term events, revealing various useful characteristics.

A study was also conducted on the capability of mixed-quasisteady-unsteady simulation in comparison to the validated fully-unsteady simulation, by setting criteria for the assumption of long quasisteady steps. The result indicated that quasisteady simulation can well be implemented with large time step $\triangle T$, for flows lower than the critical erosion discharge (around 200 m^3/s) without major discrepancy in the sense of long-term simulation. The relative amount of cumulative sediment deposition of the overestimated and underestimated steps converged gradually in the long-term simulation. The peak flows were separately treated as the averaging dampened the erosive effect of flows. Fully-unsteady simulation or quasisteady step of short time step $\triangle T$ can be implemented at peaks, of which, the fully-unsteady simulation were used in this study. The study also compared bed evolution prediction for 2025 using fully-unsteady and mixed-quasisteady-unsteady simulation, resulting in a good agreement. A prediction was also done till 2055 using data averaged over the whole period of simulation, which behaved differently.

6.1 Long-term model calibration and validation

Model calibration and validation were performed using the fully-unsteady flow and transport algorithms. Although the model size was small and simplifications were made with preliminary tests on the modeling techniques, the model was time demanding. A single run of the model for four years took 3 weeks on the AMD 3400+, 990 MHz, 480 MB RAM, PC used; excluding preprocessing. This made the calibration procedure to demand a very long computational time.

The database used for the calibration and the validation were organized and analyzed in Chapter 4. Furthermore, investigations made on the modeling techniques in Chapter 5 were integrated in the data use of long-term simulation. The input data include the discharge and suspended sediment concentration, see Section 4.2.4; a constant water level of 601.53, see Section 5.1; a grid refinement of the type 10 & 20 m and time step of 10 s, see Section 5.2, uniform sediment, see Section 5.1; k-ϵ turbulence model, see Section 5.4; critical evolution ratio (change in bed evolution/water depth) of 0.05; solver accuracy of 1E-4 for flow, 1E-9 for $k - \epsilon$ and 1E-6 for transport, see Section 5.5; erodible depth of 0.5 m for each run; and wherever necessary all relevant numerical and physical parameters were assumed using literature values.

Model calibration for the period 1988-1992

The model was calibrated by tuning the critical shear velocity for erosion (u_{ce}), critical shear velocity for deposition (u_{cd}), erosion coefficient (M) and Manning-Strickler coefficients (K_{st}), spatially by dividing the model into four zones. Zone I was the approach channel to the reservoir, Zone II was the a transition zone to the reservoir, Zone III was chosen at the central portion of the reservoir with the maximum width, and Zone IV as the part of the reservoir at narrowing banks. It was also assumed that the models had only a single sediment layer and the sediment parameter variability with depth was neglected. The initial reservoir bottom geometry used in the calibration step was the geometry of the year 1988. Parameter tuning was made to produce the bottom topography of the year 1992 through the simulation. The parameters estimated for the calibration are shown in Table 6.1. A field investigation on the critical shear stress for erosion is similar to point No 2$*$ in Figure 4.7 and Table 4.3. The measured critical shear stress is in agreement with the critical shear stress for model calibration. The result of the model calibration on the spatial distribution of bed evolution is shown in Figure 6.2.

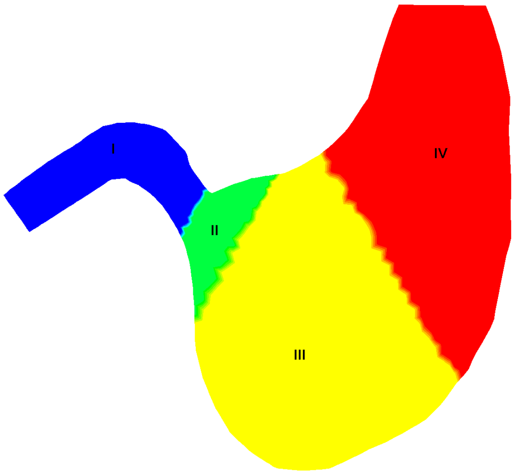
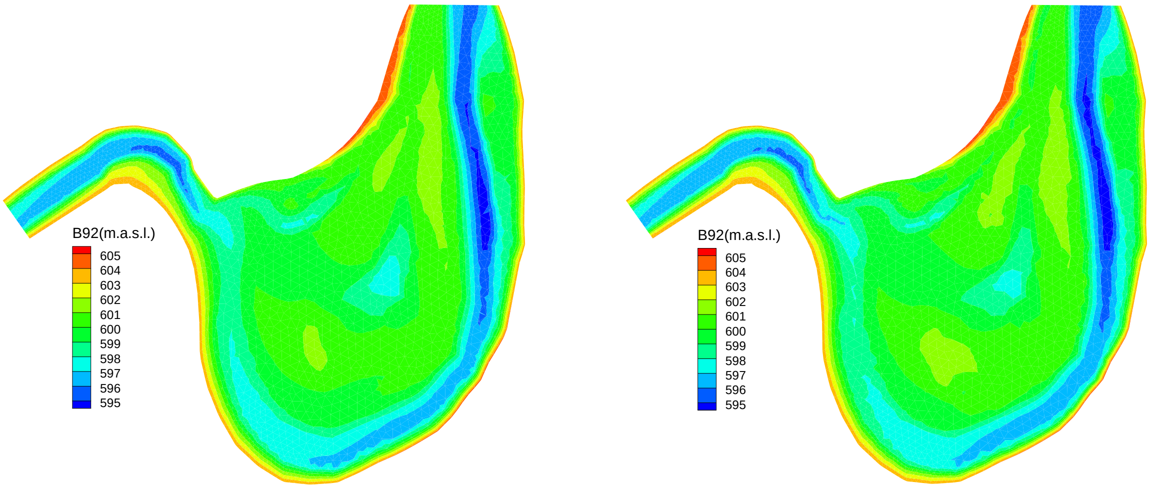


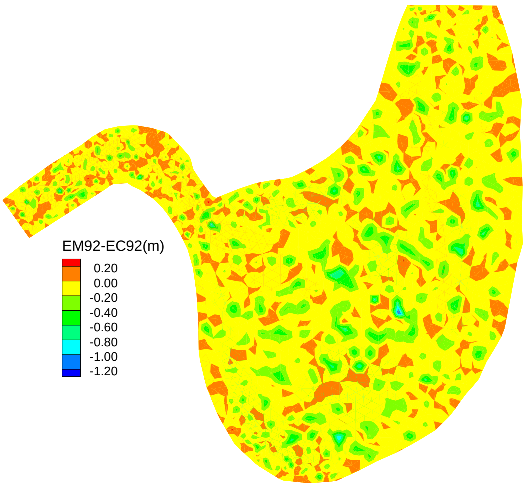
Figure 6.1: Partitioning the erosion and deposition parameter inputs

Regions	$u_{ce}(m/s)$	$u_{cd}(m/s)$	$M(Kg/(m^2 s)$	$K_{st}(m^{1/3}/s)$
I	0.04	4E-4	8E-6	37.6
II	0.025	4E-4	8E-6	39.0
III	0.02	4E-4	8E-6	40.0
IV	0.021	4E-4	8E-6	41.0

Table 6.1: Parameter estimation for the calibration of bed evolution of the Lautrach reservoir



a) Measured bed elevation b) Calculated bed elevation



c) Difference in bed elevation

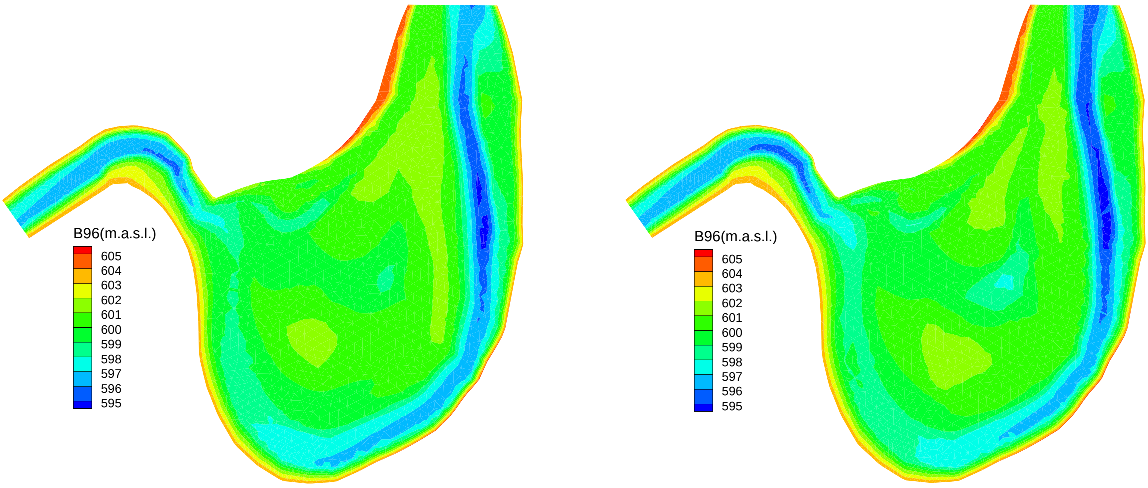
Figure 6.2: Measured and calculated bottom evolution for the year 1992; calculation started in 1988

Figure 6.2 a) shows the measured reservoir bottom elevation in 1992 and b) shows the calculated bottom elevation in 1992. The difference between measured and calibrated bottom elevations is as shown in c). There are points where the differences are big, but for most of the domain the discrepancy lies with a limit of 0.2 and -0.2 m. Obtaining a perfect match in spatial distribution of sedimentation is a big challenge in long-term simulation of morphological modeling involving several approximations. The result is quite satisfactory.

Model validation for the period 1992-1996

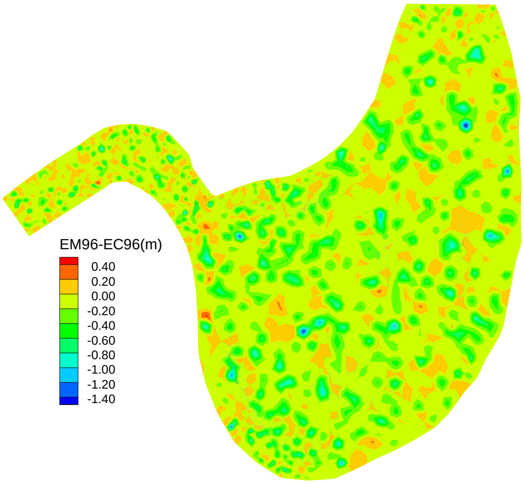
For model validation, the bed morphological change between the year 1992 and 1996 as well as the bed change between the year 1996 and 2002 was investigated using the parameters estimated for the step of calibration as shown in Table 6.1.

In Figure 6.3 a) shows the measured bed of the year 1996, b) shows the calculated bed of the year 1996 with initial bed of 1992 and c) shows the difference between measured and



a) Measured

b) Calibrated



c) Difference

Figure 6.3: Validation of the bed evolution model on the period 1992-1996

calculated bed elevation. Similar to the step of calibration most of the difference is between -0.2 and 0.2 m. It was concluded that the model is well-validated. The estimated erosion and deposition parameters are therefore used for the model prediction studies.

A test made to improve the model by further adjustment of the critical shear stress for erosion closer to the measured value indicated no improvement for regions of the model with major deficiencies on calibration and validation steps.

The volume of reservoir at a water level of 601.53 for the measured bed and calculated bed cases are given in table below.

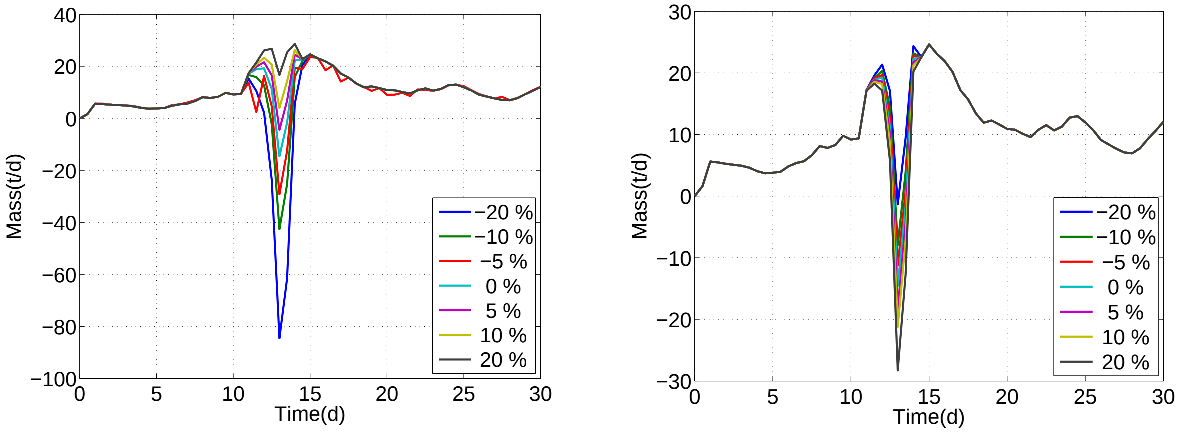
Year	measured(m^3)	simulated(m^3)	error(%)
1992	1,142,774	1,137,916	-0.42
1996	1,043,546	1,059,129	1.49

Table 6.2: Calibration and validation of reservoir water volumes

The model calibration on the spatial distribution as well as on the volume indicate that the model is well-calibrated and validated and that long-term prediction can be made on the calculated model paraments. The measurement of 1999 and 2002 lacks several details relevant to the bottom evolution in order to efficiently compare the bottom elevation of the measured and calculated results.

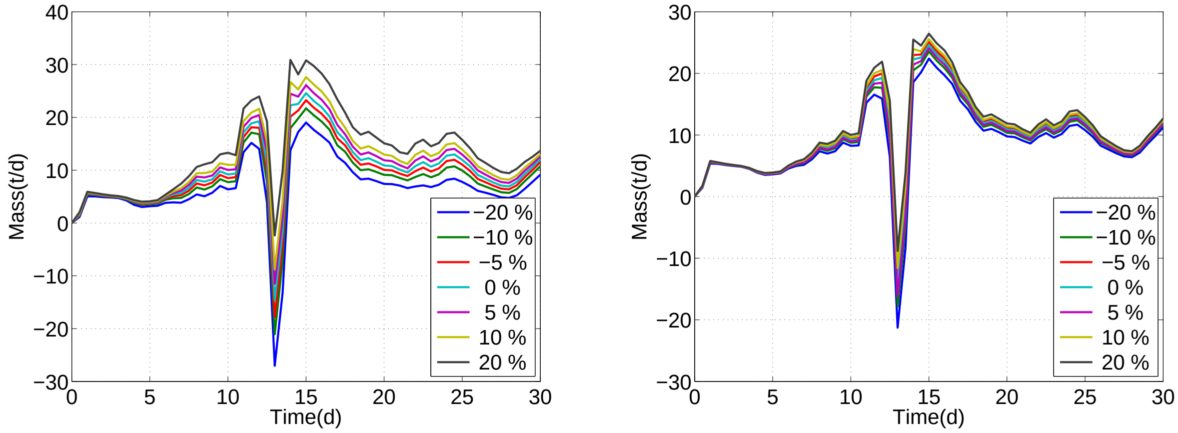
6.2 Sensitivity test on estimated parameters

Using the monthly data indicated in Figure 5.1, a sensitivity analysis were performed on the erosion and deposition parameters. The result of the analysis are shown as the rate of sediment mass deposition shown in Figure 6.4 below. The erosion parameters have an influence at the peak flows as shown in a) and b). The deposition parameters on the other hand showed an influence all through the low and peak flow periods, as shown in c) and d). The model was found to be more sensitive to the critical erosion velocity than the erosion coefficient, and also more sensitive to the critical deposition velocity than the settling velocity.



a) Erosion shear velocity, u_{ce}

b) Erosion coefficient, M



c) Deposition shear velocity, u_{cd}

d) Settling velocity, v_s

Figure 6.4: Sensitivity analysis on erosion and deposition parameters with a ± % change from the validated values

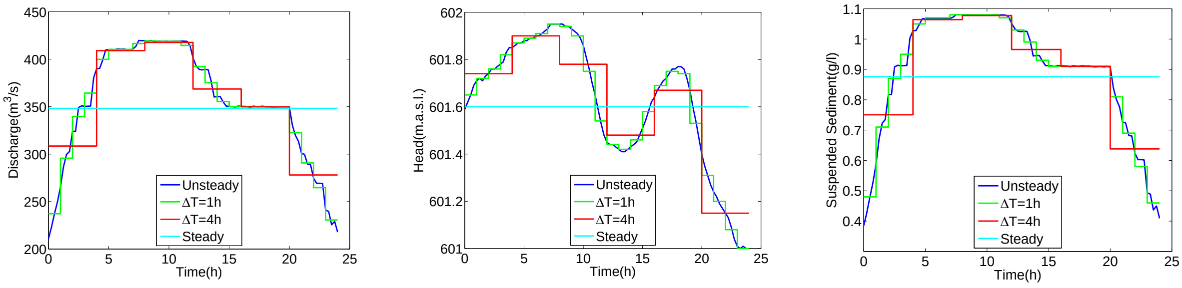
6.3 Validity of quasisteady approximations for the Lautrach reservoir

In this section, the investigation made on the validity of quasisteady approximation for the Lautrach reservoir is presented. Various discharge and sediment input behaviors are evaluated to define the ranges where such an approximation are feasible in a sense of long-term simulation. The quasisteady algorithm of the TELEMAC-SUBIEF was used, based on its relative advantage in approaching the fully-unsteady simulations, see Section 3.4. Numerical tests were made using short-term events (daily and monthly) and long-term events (annually and decades). For short-term events, analysis were made on the use of short time quasisteady steps $\triangle T$ as an approximation for the unsteady simulations. For long-term events, the mixed-quasisteady-unsteady were investigated for their effectiveness in approaching the fully-unsteady simulations. The calibrated parameters in Section 6.2 were used all throughout this section.

6.3.1 Analysis on short-term daily and monthly events

Typical daily discharges of various magnitudes with their corresponding head and suspended sediment fluctuations were taken from the database of the Lautrach reservoir. The input functions were then divided into quasisteady input steps of $\triangle T$. Simulations were run for the complete unsteady assumption as well as the quasisteady conditions based on the TELEMAC-SUBIEF algorithms.

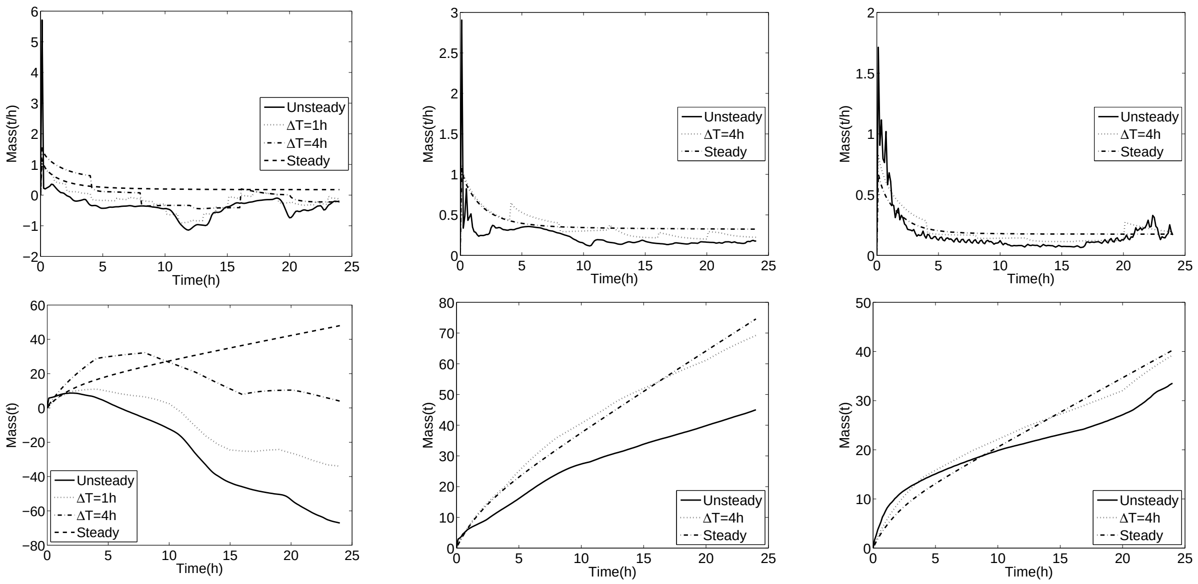
In the Figure 6.5 an unsteady input data are divided into a step function of 1 hour, 4 hours, and 1day. Several other test cases were performed by considering the variability of input of the discharge and concentration hydrographs. The mass balance of the three selected cases representing peak, mean and minimum flow conditions are given in the Figure 6.6 below.



a) Inflow discharge b) Downstream head c) Sediment concentration

Figure 6.5: A typical quasisteady input at peak flow

The transport model thus uses the last output of the steady-state hydrodynamics for a steady-state simulation. At the beginning of each step function, a jump is observed in the rate of mass deposition. The reason is the change in the initial condition and the unsteady solution algorithm used. It takes some time related to the residence time to reach the steady-state rate of sediment mass deposition. For long-term simulations where the steady-state



a) Peak flow with t_{th}=1h b) Median flow with t_{th}=2.5h c) Low flow of t_{th}=6h

Figure 6.6: Rate (above) and cumulative (below) sediment mass deposition for various discharge patterns

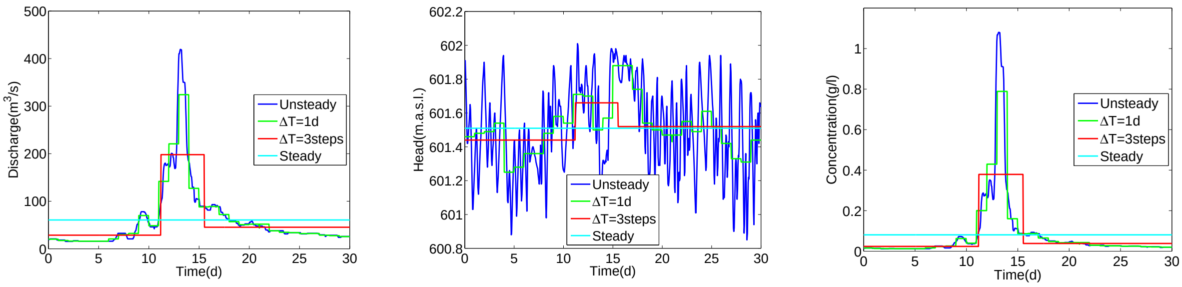
averaging takes long time steps, these jumps are not significant. The steady-state simulation saves computational time in a way that long computational time step can be used and flow does not need to be updated as only the hydrodynamic field of the final time step is used.

From the investigations made the following important points can be put forward:

- there is an indication that for the peak discharge as shown in a), where the theoretical residence time is shorter than the quasisteady steps analyzed, quasisteady refinement improved the result significantly. For low and medium flows, the refinement did not improve the result over considering the steady simulations.
- initial conditions and discontinuities at each quasisteady steps showed jumps in the rate of mass deposition as a result of the previous time step boundary condition consideration. The highest discrepancies occurred at the discontinuities and peaks.
- the time required to reach the condition of constant rate of mass deposition is strongly related to the theoretical residence time.
- generally, the smaller the time step $\triangle T$, the lower is the discrepancy from fully unsteady simulation.

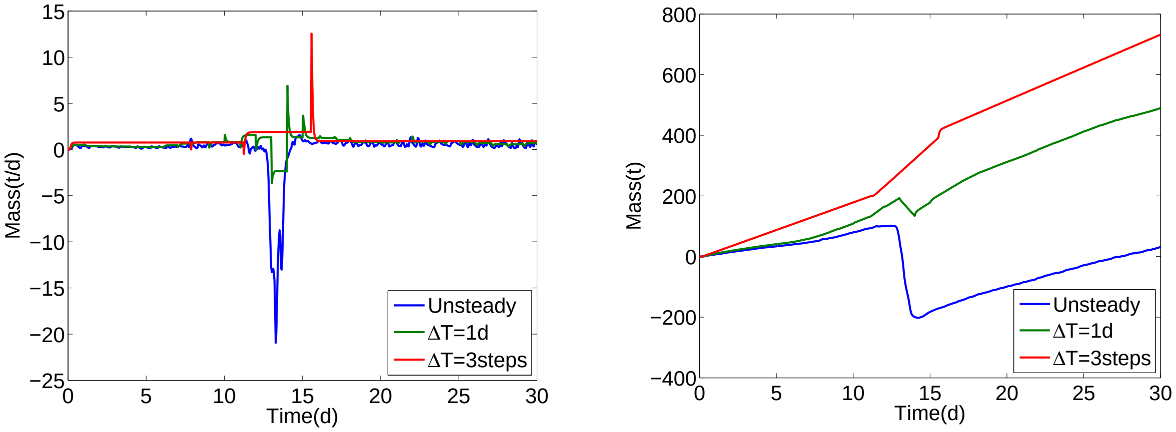
Similar analysis were made on a monthly flow data shown in Figure 6.7. The result of daily and cumulative mass of sediment deposition for the unsteady and various quasisteady steps are shown in Figure 6.8. From the numerical runs the following can be concluded:

- during low flow periods, the discrepancy between the unsteady and the steady simulation was minimal, see Figure 6.8 a) from 1 to 12 days and from 17 to 30 days. This



a) Discharges for upstream BC b) Heads for downstream BC c) Sediment inputs

Figure 6.7: A quasisteady input aggregation on a typical monthly event comprising the low and peak flows



a) Daily mass deposited b) Cumulative mass deposited

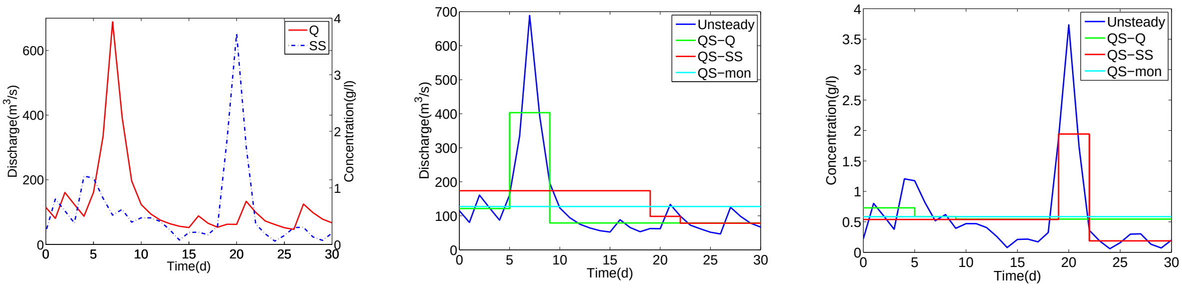
Figure 6.8: Sediment mass deposition for inputs of various aggregation with quasisteady steps of $\triangle T$

indicate long step of $\triangle T$ can be assumed in long-term simulation for low flow periods. At peak flow period between days 12 and 17, the discrepancy in mass deposition is the highest. This condition must be treated with fully-unsteady simulation or sufficiently refined $\triangle T$.

- the discrepancy of the cumulative mass deposition grows even for shorter daily step functions.
- jumps in the rate of mass deposition at initial conditions/discontinues of the quasisteady simulations are the source of uncertainty in replacing the fully-unsteady simulations.

Shift between peak discharge and peak concentration

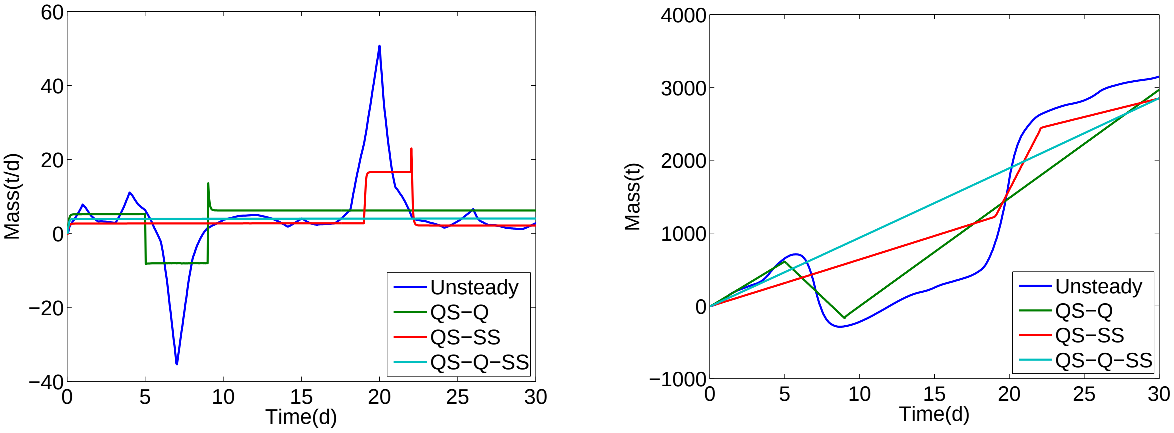
In order to investigate the effect of quasisteady approximation on the shift between peak flow and peak suspended sediment concentrations, a hydrograph showing the significant shift between discharge and concentration were selected from part of the long-term data of the Lautrach. The discharge and sediment inputs on daily basis were considered as an unsteady input as in Figure 6.9 a). In Figure 6.9 b) and c) the quasisteady assumptions for the discharge and the concentration are shown. In the Figure QS-Q in b) and c) are the discharge and sediment concentration aggregated following the discharge Q respectively; QS-SS in b) and c) are the discharge and sediment concentration aggregation following suspended sediment concentration SS respectively, and QS-mon is the aggregate of both the discharge and the concentration for the whole month for the steady simulation. Figure 6.10



a) Q and SS data b) QS assumption following Q c) QS assumption following SS

Figure 6.9: Quasisteady input aggregation showing the significance of a shift in peak discharge and concentration

shows the amount of sediment mass deposited under fully-unsteady simulation, the quasisteady simulation following the discharge (QS-Q), the quasisteady simulation following the concentration (QS-SS) and the quasisteady simulation based on averaging both discharge and concentration over the whole computational period of 30 days, QS-Q-SS.



a) Daily mass deposition b) Cumulative mass deposition

Figure 6.10: Sediment mass deposition for inputs with a shift between peak discharge and concentration

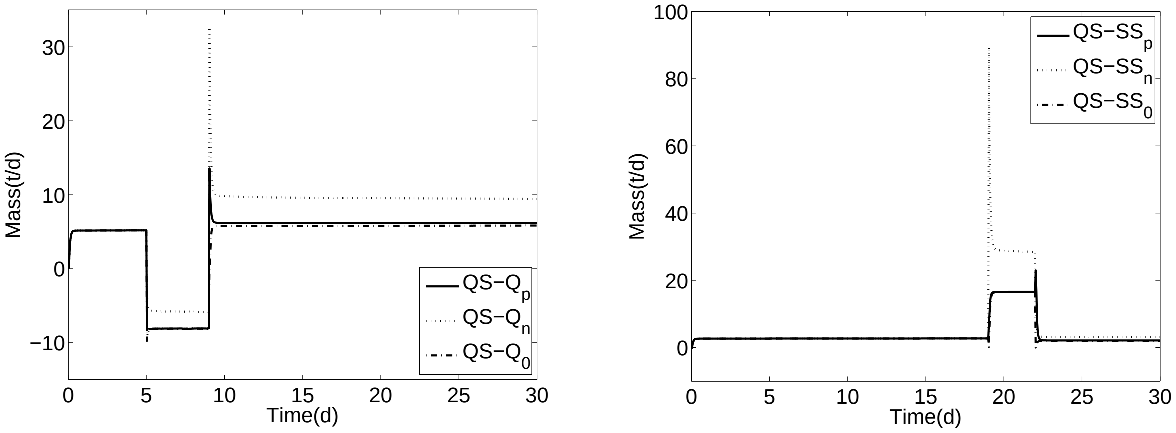
From the numerical analysis made on the shift between discharge and suspended sediment concentration the following points can be concluded:

- the quasisteady approximation of peak concentrations resulted in similar deviation from fully-unsteady simulation. The refinement is required not only for the peak discharge but also for the peak concentration.

- jumps in rate of mass deposition are observed at initial conditions and discontinuities of the steps of steady input in the quasisteady simulations.

Initial conditions at discontinuities of quasisteady steps

Further investigations were made on the assumptions of initial conditions at quasisteady steps. The quasisteady steps are not purely steady, as the algorithms are based on the unsteady formulation, see Section 3.4. Three assumptions can be made. The concentration of previous step is set as an initial condition for the new quasisteady step, the new input concentration is defined as the initial concentration for the whole domain, and initial concentration is set to zero all throughout the domain. Some time comparable to the residence time is required till a steady rate of sediment mass deposition is reached. The assumptions of initial conditions have shown an influence on the nature of jumps and discontinues.



a) QS following discharge b) QS following concentration

Figure 6.11: Effect of initial conditions on the quasisteady approximation on assuming previous ($QS - SS_p$), new ($QS - SS_n$), and zero concentration ($QS - SS_0$)

In the Figure 6.11, QS-Q$_p$, QS-Q$_n$, and QS-Q$_0$, respectively are the rate of mass deposition for the initial condition consideration of; concentrations of previous quasisteady step, concentration of the new quasisteady step, and concentration of zero, for the conditions of input aggregation following the discharge peak. Similarly the QS-SS$_p$, QS-SS$_n$, and QS-SS$_0$ indicates the daily mass deposits under the assumption of previous, new and zero suspended sediment input as an initial condition, for the input aggregation following sediment concentration . The results indicate:

- the cases of assuming previous or zero concentration resulted in a closer outcome compared to the case of assuming new initial concentration for each step of the quasisteady approximations. This is in line with the time requirement for the concentration field to reach steady-state, under the driving forces of flow, erosion as well as sedimentation, requiring a time comparable to the residence time.

- the gap between the assumption of previous concentration and zero concentration is not significant. For the long-term simulation studies in this work, previous concentrations were assumed at each transition.

6.3.2 Analysis on long-term events of the order of years

The assumption of a mixed-quasisteady-unsteady approximation was examined for cases of steady steps having large $\triangle T$. For the periods 1988-1992 three levels, for the period 1992 to 1996, two levels and for the period 1996 to 2005 one level of refinements were examined. In the Figure 6.12 QS_1 is a steady assumption over the whole computational period, and QS_2 and QS_3 are steady assumption for the discharge lower than 200 m^3/s, which is the critical erosion discharge. In Figure 6.12 a) between 1990.5 to 1991.4, QS_2 and QS_3 represent a steady and unsteady assumption respectively. The suspended sediment concentration were taken to be steady for the periods of steady discharge assumptions.

Total sediment mass deposition

Peak flows of erosive behavior should not be dampened by considering large quasisteady step $\triangle T$. Either refined quasisteady steps of short $\triangle T$ or fully-unsteady simulation need to be considered for the peaks. A fully-unsteady simulation was used for flows higher than the critical erosion discharge in the analysis. The cumulative sediment mass deposition was given in the lower part the figure below.

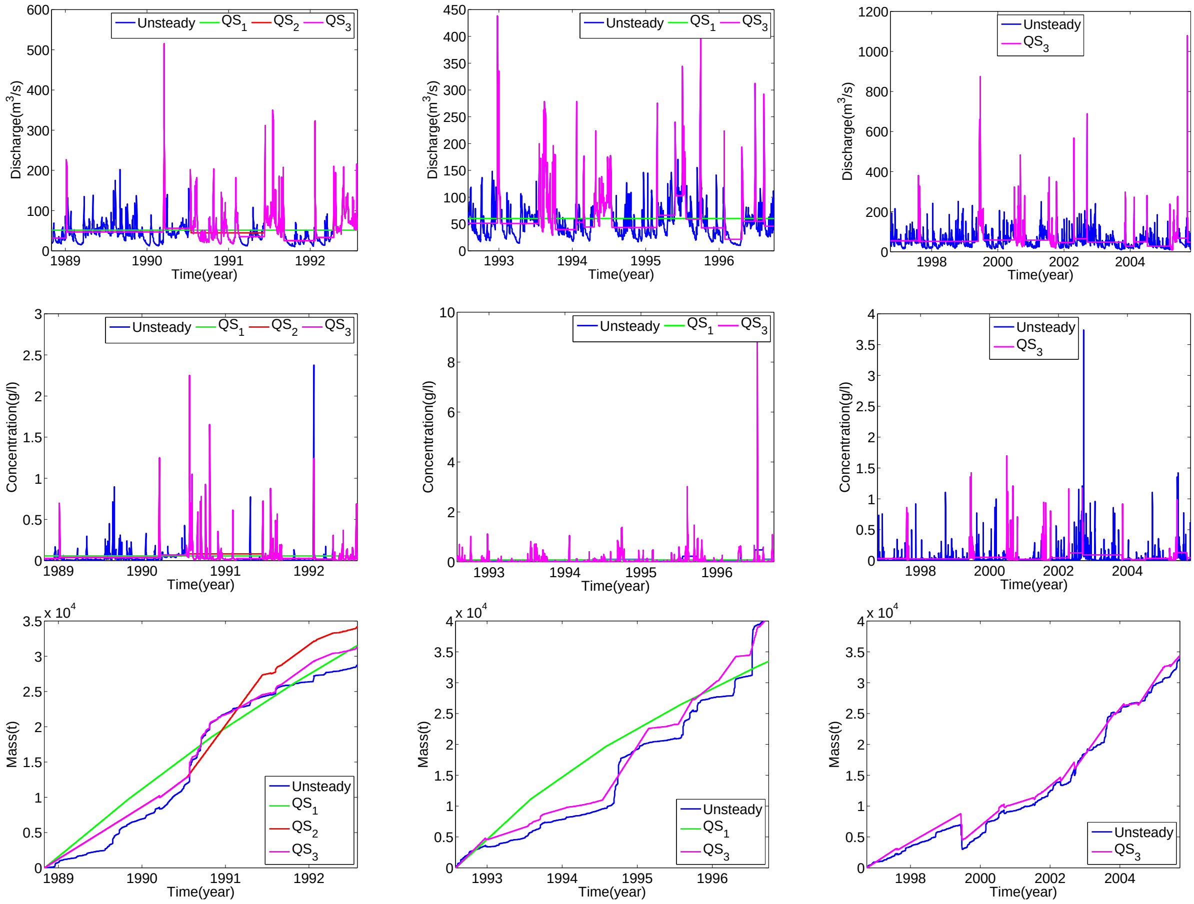
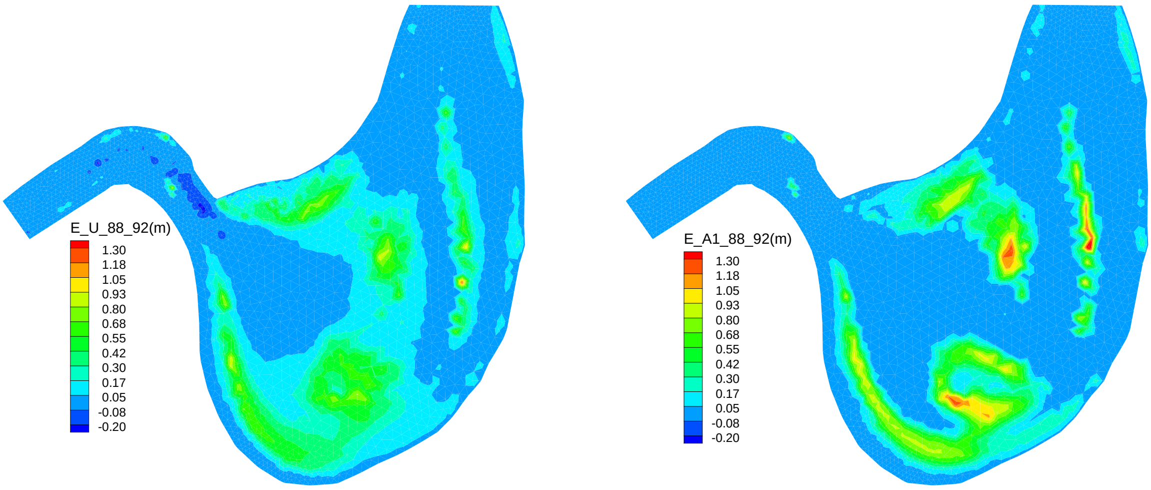


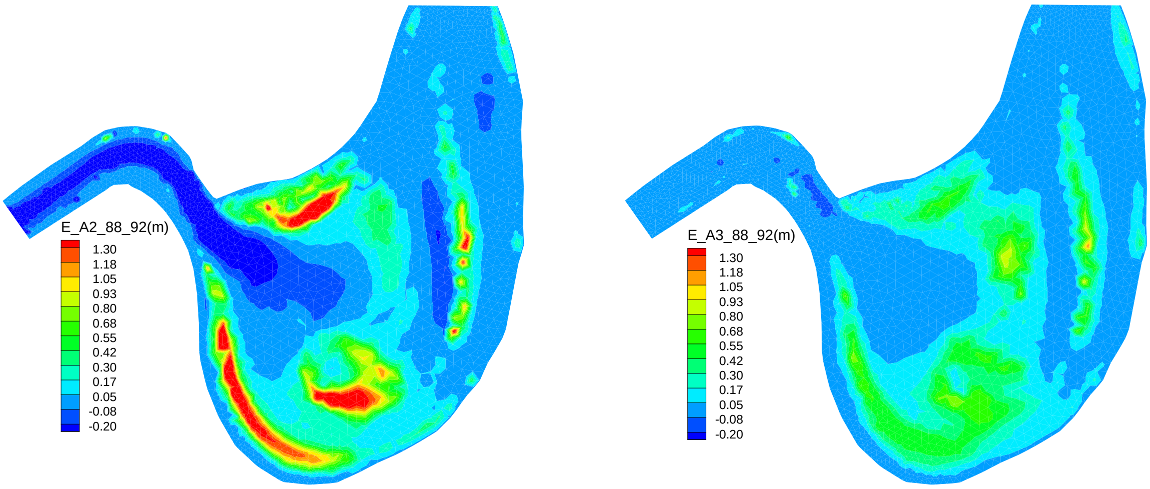
Figure 6.12: Flow and sediment input aggregations versus sediment mass deposition using unsteady, steady(QS_1), and mixed-quasisteady-unsteady (QS_2 and QS_3) simulations

Spatial distribution of sedimentation

The spatial distribution of the sediment deposition at the end of simulation for the period 1988-1992 are given in the Figure 6.13 below, for the unsteady a), steady b), and mixed-quasisteady-unsteady c) and d) assumptions. From the long-term simulation investigated over the validity mixed-quasisteady-unsteady investigations, the following can be concluded:



a) Unsteady b) Steady QS_1



c) Mixed-quasisteady-unsteady QS_2 d) Mixed-quasisteady-unsteady QS_3

Figure 6.13: Comparison of the spatial distribution of sediment mass deposition for unsteady, steady, and mixed-quasisteady-unsteady approximations, 1988-1992

- for all the cases investigated; unsteady, steady, and mixed-quasisteady-unsteady showed similarity with regard to the net deposition of sediment in long-term simulations. Furthermore, the spatial distribution of sedimentation with respect to the locations of deposition/erosion are similar.
- the simulations conducted using critical erosion discharge as a dividing criteria well represents the unsteady simulation assumptions.

- the aggregation of suspended sediment concentration needs to be carefully treated in order to reduce the discrepancies.
- as the length of computational period increased, the relative difference between unsteady and mixed-quasisteady-unsteady simulation were generally reduced.
- only the peak flows need to be modeled under complete unsteady condition and the low flow periods can be approximated by a quasisteady assumption with large $\triangle T$.
- the mixed-quasisteady-unsteady simulation reduced the computational time in long-term by an order of 60%.

6.3.3 Guidelines for long-term simulations

The application of quasisteady approximation can be influenced by the structure of the tool in use. For a coupled flow and sediment transport model, where the updating of the bed evolution is done with numerical time steps, the validity can be investigated with less processing, but with costly computation. In using a decoupled flow and transport model, based on an unsteady algorithm, the investigation on a refined quasisteady steps require tedious updating through file exchanges, and the validity of long quasisteady steps $\triangle T$ need to be investigated. A general guideline can be formulated for methods of applying the quasisteady assumptions in long-term morphological simulations. The following steps can be followed:

- investigate a model simplification by preliminary tests on the optimal requirement for grid refinement, data aggregation, sediment fraction aggregation etc., see Chapter 5.
- validate a model under fully-unsteady simulation for a reasonable period of time depending on the model size and computational requirement, to acquire model parameters (u_{ce}, u_{cd}, M, K_{st}). An alternative can be to validate a model with mixed-quasisteady-unsteady approach directly, which is more reasonable for large reservoirs of complex geometry having highly fluctuating flows. In this work, the model was calibrated and validated using an unsteady simulation, see Section 6.1. The reservoir is small and could thus be modeled with fully-unsteady assumption in a reasonable time though it tended to be very costly (a single run for 4 years required 3 weeks of pure computational time).
- perform preliminary tests on the degree of refinement of the quasisteady steps $\triangle T$ required at various patterns of flow. This analysis would be particulary useful, if the model algorithm is quasisteady and the flow and transport are internally coupled at numerical time steps or at a time step of reasonable criteria. The analyses were carried out on daily flow fluctuations, monthly flow fluctuations as in Section 6.3. An alternative can be to begin with an assumption of steady-state model over the whole computational period , and observe periods of major discrepancy from the fully-unsteady simulation, so that refinement of the steps in the mixed-quasisteady-unsteady can be formulated accordingly.

- model the periods of major difference as a fully-unsteady simulation or quasisteady simulation of refined $\triangle T$ until a good agreement is obtained between the mixed-quasisteady-unsteady simulation and the fully-unsteady simulation.

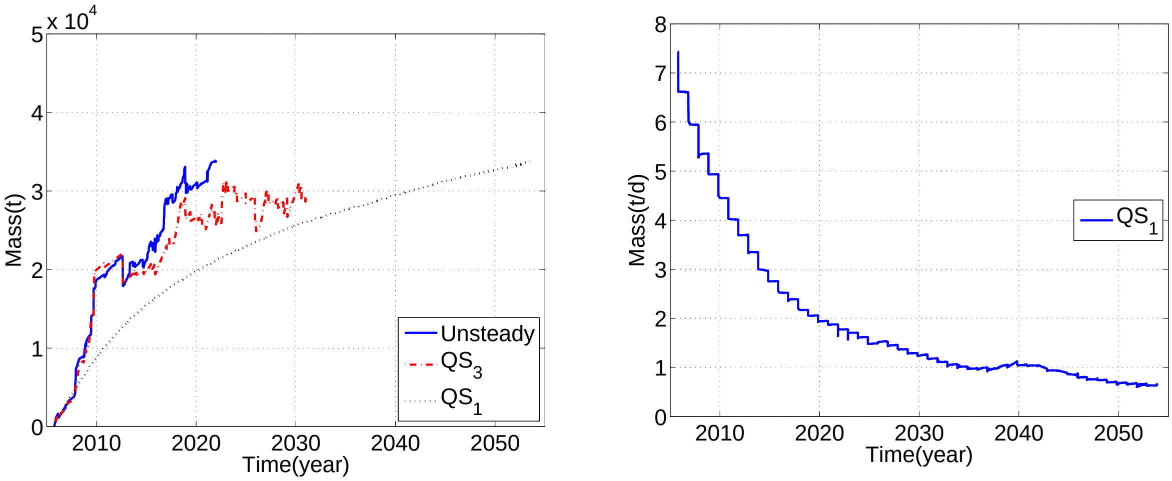
- note the criteria in a calibrated mixed-quasisteady-unsteady simulation and validate the mixed-quasisteady-unsteady simulation for other flow periods.

- use the mixed-quasisteady-unsteady model for long-term prediction of morphological development investigations.

- in this study it was noted that major discrepancies occurred at peak discharges and peak suspended sediment concentration at low flows, when a large step $\triangle T$ was used. Hence the critical erosion discharge was set as a dividing criteria for quasisteady and fully-unsteady assumptions, resulting in a reasonable approximation.

6.4 Long-term prediction

Long-term morphological prediction were made using unsteady till 2023, steady (QS_1) till 2055 (input discharge aggregated from 1996-2001) , and mixed-quasisteady-unsteady (QS_3) till 2032. The discharge and sediment data of the year 1992-2005 were assumed to repeat in the predictive step, see Figure 4.5. Figure 6.14 below shows the sediment mass deposition predictions for unsteady, mixed-quasisteady-unsteady and steady simulations. The result shows that there is a gradual reduction of sedimentation over time. The amount of mass deposited was about 35,000 tons in 20 years as compared to 30,000 tons in four years between 1988 and 1992. The steady-state simulation as in Figure 6.14 b) shows the rate of mass deposition decreased faster at beginning of predictive simulation (2005) and reached the step where the drop is insignificant, indicating the trend to equilibrium stage.

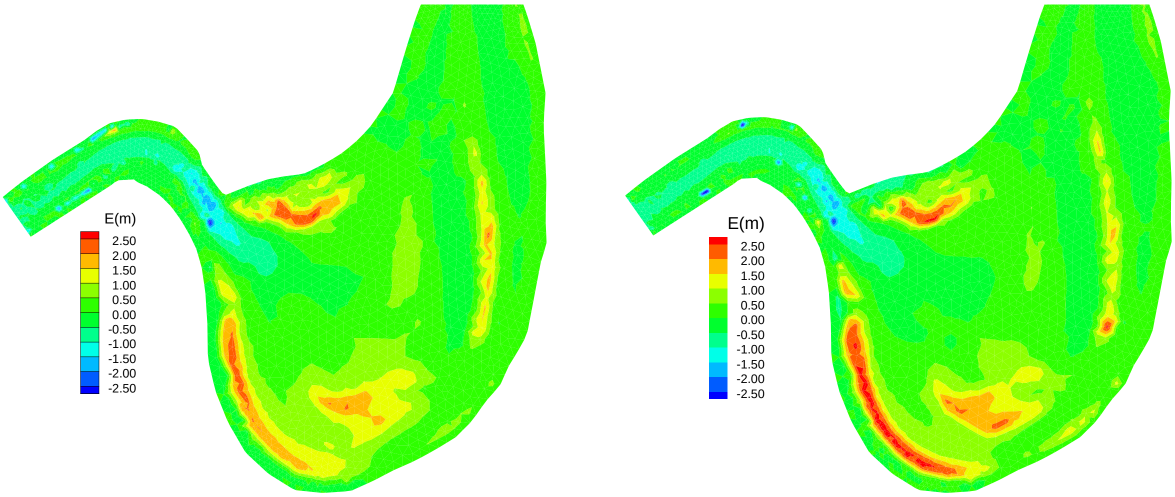


a) Cumulative sediment deposition

b) Rate of mass deposition

Figure 6.14: Prediction of sediment mass deposition; unsteady, mixed-quasisteady-unsteady (QS_3), and steady(QS_1); $\triangle T$=1 year for QS_1: simulations from 2005

The spatial distribution of sedimentation for the unsteady and the mixed-quasisteady-unsteady simulation at the end of 2025 is shown in Figure 6.15. The simulations started on the bed elevation of the year 1996. In which the period of the 2005-2025 were simulated under the unsteady and mixed-quasisteady-unsteady assumptions. The bed evolutions shown are the cumulative from the 1996 to 2025.



a) Unsteady

b) Mixed-quasisteady-unsteady QS_3

Figure 6.15: Spatial distribution of bed evolution prediction: 2005-2025

The mean and standard deviation of depth of deposition are 0.137 m and 0.629 m for the unsteady simulation and 0.127 m and 0.675 m for the mixed-quasisteady-unsteady simulations respectively.

One of the limitations in long-term simulation of the bed evolution was the drying effect. As the reservoir filled up with sediments, numerical problems happened, which resulted in a jump in the rate of mass deposition.

Reservoir volume

The model outcomes indicate that the water volume of the reservoir is gradually reducing as a result of sedimentation. The simulations using the unsteady and mixed-quasisteady-unsteady as well as steady showed similar trend regarding the reduction in reservoir volume. The water surface area is roughly 6E5 m^2 and the reservoir volume loss between 1996 and 2023 is 1.1E5 m^3. The average depth of sedimentation thus 0.183 m; slightly higher as compared to the nodal mean depth of sedimentation from the numerical model. The mass of sediment deposited between 1996 and 2023 is 7E4 tons. Converting to volume with the bottom concentration of 500 kg/m^3 assumed in the computation. The volume is 1.46E5 m^3. The mass overestimated the volume by 21%. The result is reasonable compared to a large number of approximations used and the numerical problems involved. Wetting and drying effects, jumps at discontinuities are also to be mentioned.

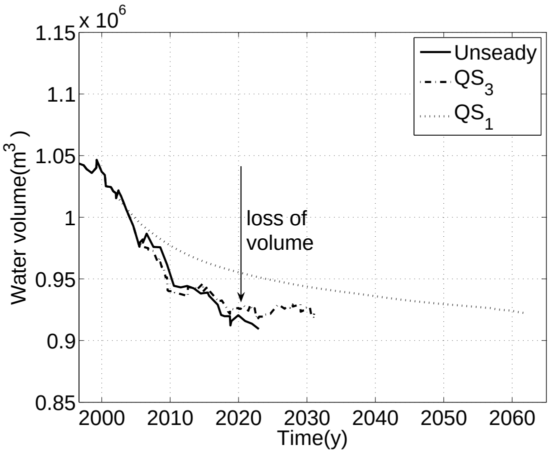
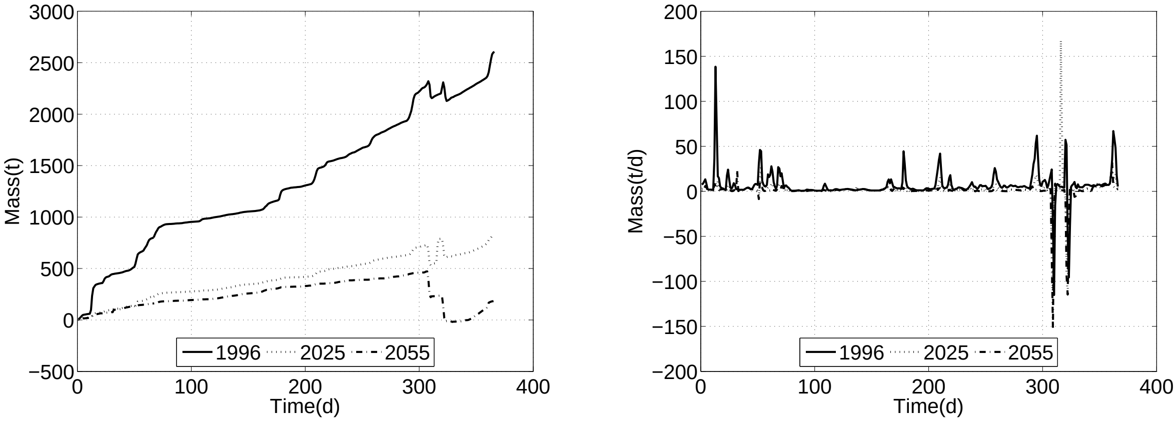


Figure 6.16: Volume of the reservoir at the water level of 601.53 m.a.s.l. under the unsteady, mixed-quasisteady-unsteady(QS_3), and steady (QS_1) simulation assumptions

Equilibrium stage of the reservoir

Once the reservoir reaches a quasi-equilibrium condition, the amount of mass deposition over a typical flow year should approach zero. As can be seen in Figure 6.14, the amount of mass deposit is reducing over time, but the rate at which no sediment deposition occur was not reached under all the predictive simulations.

A test was made on how the predicted morphology of the year 2025 and 2055 behave if a typical annual flow is applied. The flow used was that of the year 1996. The amount of sediment mass deposited were simulated; for the 1996 using initial bottom morphology of 1996; for the year 2025 using the initial bottom morphology of the predicted (using unsteady) bed of 2025; and for the year 2055 using the initial bed predicted (using quasisteady) bed of 2055.



a) Cumulative deposition b) Rate of deposition

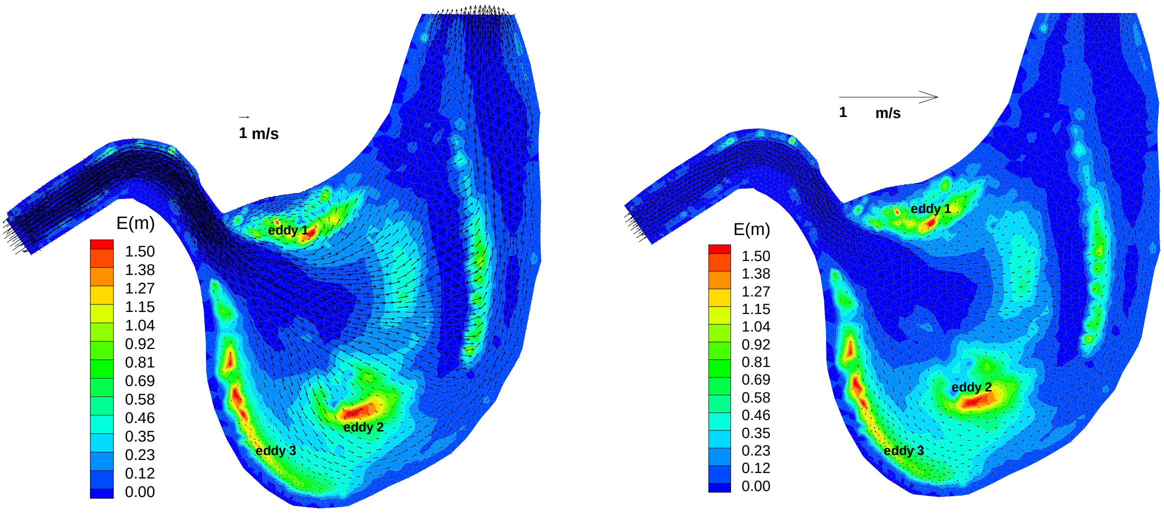
Figure 6.17: Mass of sediment deposition for a typical annual input: for the initial bed evolution of the year 1996, predicted bed of 2025 using unsteady simulation, and predicted bed of 2055 using steady simulation

The result shows that the simulation on the initial bed of 2055 resulted in nearly equilibrium transport for the typical year considered. It also shows that it is not only the volume of reservoir lost that brings the reservoir to equilibrium but also the spatial distribution of sedimentation. It can be concluded that the reservoir will reach an equilibrium condition in the year 2055 under the steady transport assumption. Under the unsteady assumption the equilibrium stage was not fully reached till 2025. There is however a clear trend visible that the reservoir is approaching an equilibrium stage, see e.g. Figure 6.17

The equilibrium condition of the reservoir is reached in the years between 2020 and 2030 with the reservoir volume of about 0.92 million m^3 (42 % loss), see Figure 6.14, and Figure 6.16.

6.5 Mitigation of reservoir sedimentation

Numerical studies conducted on sediment transport behavior of the Lautrach reservoir showed that the wide central part of the reservoir exhibit a continuous sedimentation irrespective of discharge. The erosive effect of the flow never reaches the regions depicted in the Figure 6.18 as eddies. This is a good example to show the influence of geometry induced sedimentation. The velocity distribution for peak and low discharges and the formation of eddies in some part of the reservoir has a good indications for regions of erosion and sedimentation. The bed evolution shown in the Figure is that between the year 1996-2004. Only the deposition are indicated in the Figure and the erosion is set to zero. Numerical test made to mitigate the reservoir by flushing method indicates that the possibility of flushing sediments are limited only to the locations close to the outlet and inlet and is of marginal importance in overcoming the sedimentation process in the reservoir. This is an indication of reservoir shape which plays a major role in sediment mitigation strategies. Reservoirs sites



a) Peak flow of around 800 m^3/s

b) Low flow of around 50 m^3/s

Figure 6.18: Typical velocity field at peak and low flows: predominant deposition at regions with low velocities and eddies; the bottom evolution from 1996 to 2004 with erosion set to zero is shown

must be carefully selected to appropriately manage reservoir sedimentation. The Lautrach reservoir is not the best site of choice to mitigate sedimentation by operational means.

Summary

Long-term numerical simulation of bed evolution of a reservoir is very challenging; uncertainties are involved in data, in model formulation, in model parameters and the computational cost is very high. An attempt was made to try to calibrate and validate the bed evolution of the Lautrach reservoir and suggest a predictive mixed-quasisteady-unsteady simulation in order to reduce the computational requirement. The result indicated that the mixed-quasisteady-unsteady simulation is close to the unsteady simulation whereas there is a bigger gap when assuming steady simulation all throughout. The trend is however, similar for all the predictions.

A guideline to implement a simplified mixed-quasisteady-unsteady approximation were proposed and tested. It can be concluded that for sufficiently long-term simulations, the mixed-quasisteady-unsteady simulation predicts equivalently as the fully-unsteady simulation. It can be stated that model complexity may not improve the degree of accuracy in modeling reservoir sedimentation in the sense of long-term prediction over a decade or a century. A mixed-quasisteady-unsteady simulation can fairly predict the behavior of reservoir sedimentation in order to propose an engineering concept for reservoir planning.

The following chapters continue with a complementary approach developed in order to model statistically the spatial distribution of sedimentation. Chapter 7 reviews the fundamentals in regression modeling and Chapter 8 presents the work done in modeling the Lautrach reservoir using regression techniques.

Part II

Data-Driven Modeling Approach

Chapter 7

Review of Data-Driven Modeling

The so-called data-driven models, are based on a limited knowledge of the process and rely on the data describing input and output characteristics. These method, however, are able to make abstractions and generalizations of the process and play often a complementary role to physically-based models.

A simple type of data-driven model is a regression model. Coefficients of regression equation are identified ("trained") on the basis of the available existing data. Then, for a given new value of the independent (input) variable, it gives an approximation of an output variable. More complex data-driven models are highly non-linear allowing many inputs and outputs. They need a considerable amount of historical data to be trained, and if this is done properly, they are able not only to approximate practically any given function, but also generalize, providing a correct output of previously "unseen" inputs, see Solomatine 2002 [115].

The study of a data analysis aimed at discovering how independent variables affect other dependent variables is termed as regression. It is commonly used wherever a relationship is to be formulated in almost all fields. Simple regression, multiple regression, linear regression, nonlinear regression, partial least square regression, latent root regression, and principal components regression are some of the important regression methods mentioned in standard statistical and multivariate statistics. The method of least squares is the basis for fitting regression models. The disadvantage of using regression models are the need for large amount of data to develop models and that they may poorly predict for the ranges of the data use outside the conditions under which the regression parameters are determined.

7.1 Simple linear regression

Suppose the variable to be predicted (dependent variable) is given as $\mathbf{y}$ and the independent variables as $\mathbf{x}$ the simple linear regression is given by

$$\mathbf{y} = \beta_1 \mathbf{x} + \beta_o + \boldsymbol{\epsilon} \tag{7.1}$$

where β_o is the y intercept, β_1 is the slope and $\boldsymbol{\epsilon}$ is the random error.

The least squares principle is used to fit the data for prediction using a simple linear regression. The least square estimators are given by

$$\begin{aligned} \beta_1 &= \frac{SS_{xy}}{SS_{xx}} \\ \beta_o &= \bar{\mathbf{y}} - \beta_1 \bar{\mathbf{x}} \end{aligned} \tag{7.2}$$

where $SS_{xx} = \sum_{i=1}^{n}(x_i - \bar{x})^2$ and $SS_{xy} = \sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})$.

Using the least squares prediction equation to estimate the mean value of y or predict a particular value of y for the values of x that fall outside the range of values of x contained in a sample data may lead to prediction errors.

7.2 Multiple linear regression

Multiple regression is a method of multivariate regression analysis in which the observation is a matrix of n rows by p vectors. The regression is simultaneously made between the dependent and independent variables using the least square principle. Suppose **y** is a vector of dependent variable and **X** is a matrix of independent variables the regression equation is then given as,

$$\mathbf{y} = \mathbf{X}\boldsymbol{\beta} + \boldsymbol{\epsilon} \tag{7.3}$$

where $\boldsymbol{\beta}$ is the vector of the regression parameters, and **X** is a matrix of $[\mathbf{1} \quad \mathbf{X}]$.

The least squares solution of the vectors of the regression parameters is given as

$$\boldsymbol{\beta} = (\mathbf{X^T X})^{-1}\mathbf{X^T y} \tag{7.4}$$

where $\mathbf{X}^T$ and $\mathbf{X}^{-1}$ are the transpose and the inverse of the matrix **X** respectively.

The measure how well the multiple regression model fits the data is evaluated by multiple coefficient of determination, R^2 is given as

$$R^2 = 1 - \frac{SSE}{SS_{yy}} \tag{7.5}$$

where the sum of squares error is given by, $SSE = \sum(y_i - \hat{y}_i)^2$ and the sample variation of **y** given by $SS_{yy} = \sum(y_i - \bar{y})^2$, and $\hat{y}_i$ is the predicted value of y_i for the multiple regression.

When highly correlated predictors are used in a multiple linear regression model, multicollinearity (mutual correlation) can become the cause of statistically imprecise and unstable estimates of regression coefficients, incorrect rejection of variables, and numerical inaccuracies in computing the estimates of model coefficients, Jennrich 1995 [67].

When the database of the matrix **X** is large, methods to reduce the dimensionality of database can be very useful in subsequent statistical analysis. One of the most commonly used method is the projection of the database into new coordinate systems that can express the original database with possibly few dimensions as compared to the original. This is the commonly known as Principal Components Analysis (PCA) or Empirical Orthogonal Functions (EOF).

7.3 Principal components analysis and regression

The central idea of principal component analysis is to reduce the dimensionality of data sets consisting of a large number of interrelated variables, while relating as much as possible of the variation present in the data set. This is achieved by transforming to a new set of variables, the principal components (PCs), which are uncorrelated, and which are ordered so that the first few retain most of the variation in all of the original variables, see Jolliffe 2002 [70]. The principal components transform an original storm of data to new coordinate systems on the principle of variance maximization. The first principal component show the direction of highest variance of the database. The second PC is orthogonal to the first PCs and is in the direction of the second highest variance. The loadings on each principal component correspond to its eigenvectors. The eigenvalue represent the variance of the data in the corresponding the PCs. The contribution of the components to the total variation reduces from step to step. Methods how to choose representative PCs without significant loss in variances can be referred in Wilks 1995 [131], Jolliffe 2002 [70] etc.

The purpose of the principal components regression (PCR) is to estimate the values of a variable at the basis of selected principal components (PCs) of explanatory variables. There are two main reasons for regressing the response variable on the PCs rather than the directly on the explanatory variables. Firstly, the explanatory variables are often highly correlated which may cause inaccurate estimations of the least squres regression coefficients which are avoided in using the PCs which are uncorrelated. Secondly, the dimensionality of regression is reduced by taking only a subset of the PCs for prediction, see Filzmoser [45].

Books and articles are cited that include applications in agriculture, biology, chemistry, climatology, demography, ecology, economics, food research, genetics, geology, meteorology, oceanography, psychology and quality control etc.

Some examples on the use of the principal components are mentioned. Hidalgo et al. 2000 [60] used principal components regression procedures for dendrohydrological reconstruction of stream flows; Woodhouse et al. 2006 [136] conducted similar study on the Colorado river for stream flow reconstruction; Wotling 2000 [137] used PCs to regionlize extreme precipitation distribution; Brown 1992 [18] studied the usefulness of PCA to laboratory chemical and petrographic data to asses physical and hydraulic properties of the carbonate-rock aquifers in central Pennsylvania; works of Cardoso [23], Solow 2003 [116], Pandžić 1992 [94], Bouvier 2003 [10] etc. can be mentioned as an application of PCA in atmospheric sciences.

A short review is given on the mathematical aspects of the PCA in order to have a better insight into the approach. Suppose $\mathbf{x}$ is a vector of p random variables, the first step is to look for a linear function $\boldsymbol{\alpha}_1^T\mathbf{x}$ of the elements of $\mathbf{x}$ having maximum variance, where $\boldsymbol{\alpha}_1$ is vector of p constants, so that $\boldsymbol{\alpha}_1^T\mathbf{x} = \alpha_{11}x_1 + \alpha_{12}x_2 + \ldots + \alpha_{1p}x_p = \sum_{j=1}^{p} \alpha_{1j}x_j$. Next look for a linear function of $\boldsymbol{\alpha}_2^T\mathbf{x}$, uncorrelated with $\boldsymbol{\alpha}_1^T\mathbf{x}$ having maximum variances, and so on, so that the k^{th} linear function $\boldsymbol{\alpha}_k^T\mathbf{x}$ is found that has the maximum variance subject to being uncorrelated with $\boldsymbol{\alpha}_1^T\mathbf{x}, \boldsymbol{\alpha}_2^T\mathbf{x} \ldots, \boldsymbol{\alpha}_{k-1}^T\mathbf{x}$. The k^{th}derived variable $\boldsymbol{\alpha}_{k-1}^T\mathbf{x}$, is the k^{th} PC. Up to p PCs could be found but it is hoped in general, that most of the variation in $\mathbf{x}$

will be accounted for by m PCs, where $m << p$. The k^{th} PC of $\mathbf{x}$ is

$$\boldsymbol{\alpha}_k^T\mathbf{x} \tag{7.6}$$

and the variance

$$var[\boldsymbol{\alpha}_k^T\mathbf{x}] = \lambda_k \tag{7.7}$$

where λ_k is the k^{th} largest eigenvalue of covariance matrix, and $\boldsymbol{\alpha}_k$ is the corresponding eigenvector.

For most practical cases a sample covariance matrix $\mathbf{C}$ or correlation matrix $\mathbf{R}$ are used in the PCA analysis. The covariance matrix $\mathbf{C}$ for the data matrix $\mathbf{X}$ can be given as:

$$\mathbf{C} = \frac{1}{n-1}[\mathbf{X}']^T[\mathbf{X}'] \tag{7.8}$$

where $\mathbf{X}' = \mathbf{X} - \frac{1}{n}\mathbf{X}$. The correlation matrix $\mathbf{R}$ is the variance-covariance matrix of standardized variable and can be given as:

$$\mathbf{R} = \mathbf{D}^{-1}\mathbf{C}\mathbf{D}^{-1} \tag{7.9}$$

where $\mathbf{D}$ is the diagonal matrix whose diagonals are the standard deviation of the rows of a matrix.

The choice of correlation or covariance matrices for PCA depends on nature of data. A major argument for using correlation rather than covariance matrices to define PCs is that the results of analysis for different sets of random variables and are more directly comparable than for analysis based on covariance matrices. The big drawback of PCA based on covariance matrices is the sensitivity of PCs to the units of measurement used for each element of $\mathbf{x}$, then those variables whose variance are largest will tend to dominate the first few PCs. This might be entirely appropriate if all the elements of $\mathbf{x}$ are measured in the same unit.

The scores of PCs for each observation are given by

$$\mathbf{U} = \mathbf{X}\boldsymbol{\alpha} \tag{7.10}$$

where the $(i,k)^{th}$ element of $\mathbf{U}$ is the value (score) of the PC for the i^{th} observation, $\boldsymbol{\alpha}$ is a p by p matrix whose k^{th} column is the k^{th} eigenvector of $\mathbf{X}^T\mathbf{X}$. Because $\boldsymbol{\alpha}$ is orthogonal, $\mathbf{X}\boldsymbol{\beta}$ can be written as, $\mathbf{X}\boldsymbol{\alpha}\boldsymbol{\alpha}^T\boldsymbol{\beta} = \mathbf{U}\boldsymbol{\gamma}$ where $\boldsymbol{\gamma} = \boldsymbol{\alpha}^T\boldsymbol{\beta}$. This transform the standard regression model to principal component regression model $\mathbf{y} = \mathbf{U}\boldsymbol{\gamma}$ which replaced the predictor variables by their PCs in the regression model. Because the PCs are orthogonal the method overcomes problem of multicolinearity. More details can be referred in Wilks 1995 [131] and Jolliffe 2002 [70].

Application in this study

In this work the statio-temporal bed evolution of the numerical results from the fully-unsteady simulations were taken for the investigation of principal components regression modeling approach. For the daily input flow Q, and suspended sediment concentration SS, the daily depth of bed evolution at the numerical grid simulation is given by **E**, having the dimension (n×t), where n is the node number and t is the time in days. The variance-covariance matrix of the spatio-temporal bed evolution were calculated upon which the principal component analysis were preformed, as in the sketch below.

$$\underbrace{\begin{pmatrix} E_{11} & E_{12} & \dots & E_{1t} \\ E_{21} & E_{22} & \dots & E_{2t} \\ \vdots & \vdots & \ddots & \vdots \\ E_{n1} & E_{n2} & \dots & E_{nt} \end{pmatrix}}_{spatio-temporal\,evolution} \underset{VCA}{\Longrightarrow} \underbrace{\begin{pmatrix} \sigma_{11}^2 & C_{12} & \dots & C_{1t} \\ C_{21} & \sigma_{22}^2 & \dots & C_{2t} \\ \vdots & \vdots & \ddots & \vdots \\ C_{t1} & C_{t2} & \dots & \sigma_{tt}^2 \end{pmatrix}}_{Variance\,covariance\,matrix} \underset{PCA}{\Longrightarrow} \underbrace{\begin{pmatrix} \alpha_{11} & \alpha_{12} & \dots & \alpha_{1t} \\ \alpha_{21} & \alpha_{22} & \dots & \alpha_{2t} \\ \vdots & \vdots & \ddots & \vdots \\ \alpha_{t1} & \alpha_{t2} & \dots & \alpha_{tt} \end{pmatrix}}_{eigenvectors\,of\,evolution} \tag{7.11}$$

Compared to the numerical simulations, the method is computationally efficient. The extraction of eigenvalue-eigenvector pairs demanded several hours depending on the size of the matrix of the spatio-temporal bed evolution **E** analyzed. Data preparation from the numerical model was tedious. A PCA programmed in FORTRAN was used based on the routines in Press et al. 1992 [98]. For multiple regression models the capability of MATLAB was exploited.

Summary

A brief review was presented on the data-driven modeling with a focus on the linear regression techniques. The mathematical formulations of three types of regression were discussed: simple linear regression, multiple linear regression, and the principal components regression. Capter 8 discusses the application of regression modeling with emphasis on principal components analysis, and regression applied to the Lautrach reservoir.

Chapter 8

Regression Modeling on Lautrach Reservoir Sedimentation

This chapter presents a complementary regression modeling approach for the prediction of the amount and spatial distribution of sedimentation. The results of numerical simulation on the amount and the spatial distribution of sedimentation on a daily basis were used in the investigation. This is a step forward in the assimilation of data and dynamics to supplement one another in the prediction of long-term bed evolution development of large and geometrically complex reservoirs.

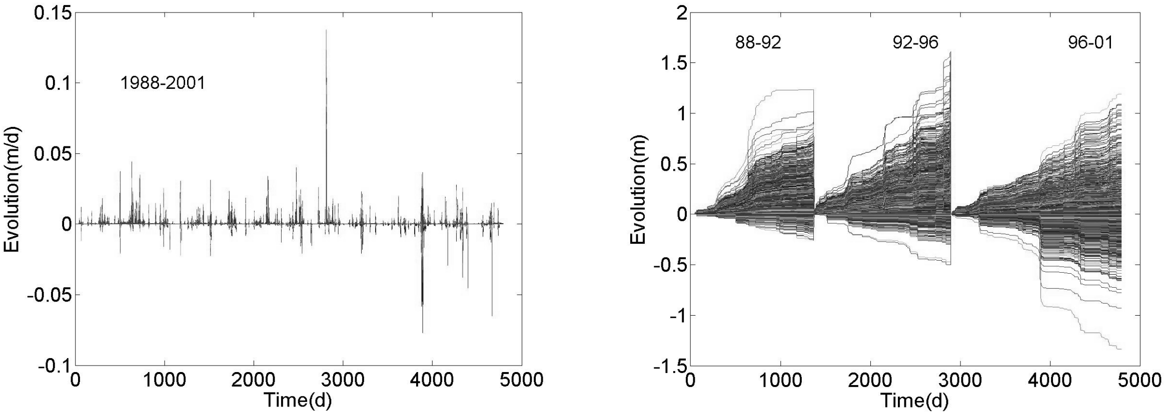
The estimation of a quantity of interest via data assimilation involves the combination of observational data with the underlying dynamic principles governing the system under observation. The modeling of data and dynamics is a powerful methodology which makes possible, efficient, accurate, and realistic estimations which might not otherwise be feasible, see Robinson and Lermusiaux 2000 [104]. The regression modeling of the reservoir sedimentation was attempted with the concept of assimilation of numerical results with statistical methods in order to propose strategies in long term simulations.

In modeling the spatial distribution of sedimentation, the relation between the averaged daily discharge (Q) and the suspended sediment concentration (SS) inputs were analyzed with regard to the daily depth of deposition/erosion at the computational grid of the numerical model. The database from the simulation result of the bed evolution data of the Lautrach reservoir performed in Chapter 6 of the work was assumed in developing the regression model.

Two approaches were evaluated. Firstly, simple regression in which the regression model was made between evolutions at each node and the input daily discharge and suspended sediment concentration. Secondly, principal components regression, in which the dimensionality of the bed evolution data were reduced, and regressions performed between the coefficient of the principal components and the discharge and the sediment concentration. The principal components regression were found to be an efficient technique in modeling bed evolution of reservoirs. An attempt was also made to model the amount of sedimentation making use of the amount of sedimentation corresponding to the daily input discharges and sediment concentrations with the numerical results of the rate of mass of sedimentation. The regression models implemented indicated significant improvements when multiple regression was performed rather than using simple regression.

In the numerical models, the initial bed condition of the years 1983, 1988, 1992, 1996 were used to generate the finite element grids. The mesh generation was performed in a way that each of the nodes for the meshes generated (1983, 1988, 1992, 1996), have an exactly matching coordinate points for suitable data handling. The number of nodes used in the models were 2614.

The database used for the analysis was resulted from of unsteady simulation of the numerical models calibrated and validated over years. Three periods used for the morphological model were used in the investigation. Figure 8.1 below, in which a) shows the daily bed evolution at all the computational node for the time series, 1988-1992, 1992-1996, 1996-2001 were used in separate analysis as they are based on different initial geometric conditions, see Section 6.1. The corresponding cumulative bed evolutions of the years 1988-1992, 1992-1996 and 1992-2001 are shown in b).



a) Daily bed evolution b) Cumulative bed evolution

Figure 8.1: Daily and cumulative bed evolution at the computational grids of the numerical model for the period: 1988-1992, 1992-1996, and 1996-2001

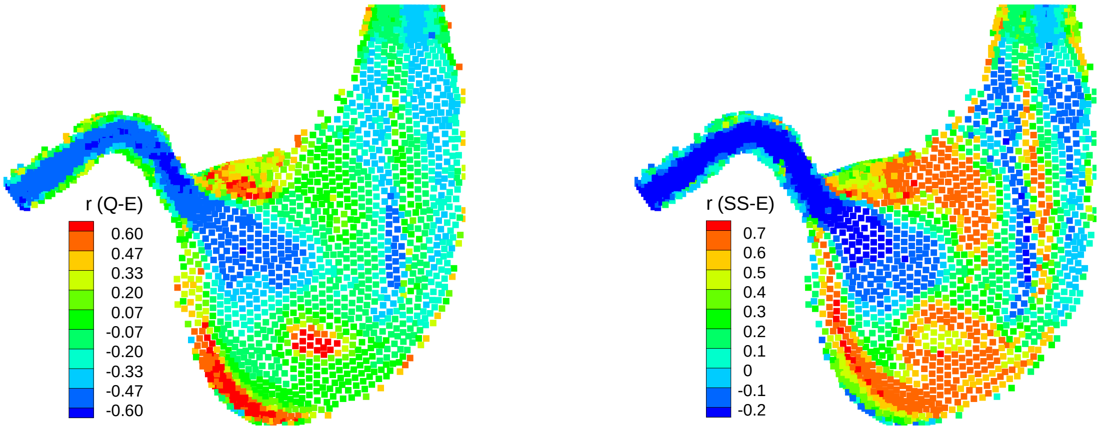
8.1 Spatial distribution of sedimentation

8.1.1 Simple linear regression model

A simple linear regression models were tested between daily bed evolution at each computational node of the numerical grid and time series of discharges as well as suspended sediment concentrations. For each daily discharge or sediment input, the corresponding daily bed evolution $E(Q,x,y)$ and/or $E(SS,x,y)$ computed at the numerical grid points yielding the regression equation of the form

$$\begin{aligned} E(Q,x,y) &= \beta_{0q} + \beta_q Q \\ E(SS,x,y) &= \beta_{0s} + \beta_s SS \end{aligned} \tag{8.1}$$

where the β_{0q}, β_q, β_{0s}, β_s are regression coefficients. Each point has a different regression coefficient. The spatial distribution of the correlation coefficients (r) between the bed evolution and discharge is shown in the Figure 8.2 a) and that between bed evolution and suspended sediment concentration is shown in b). Only points with non-zero evolution were integrated in the analysis.

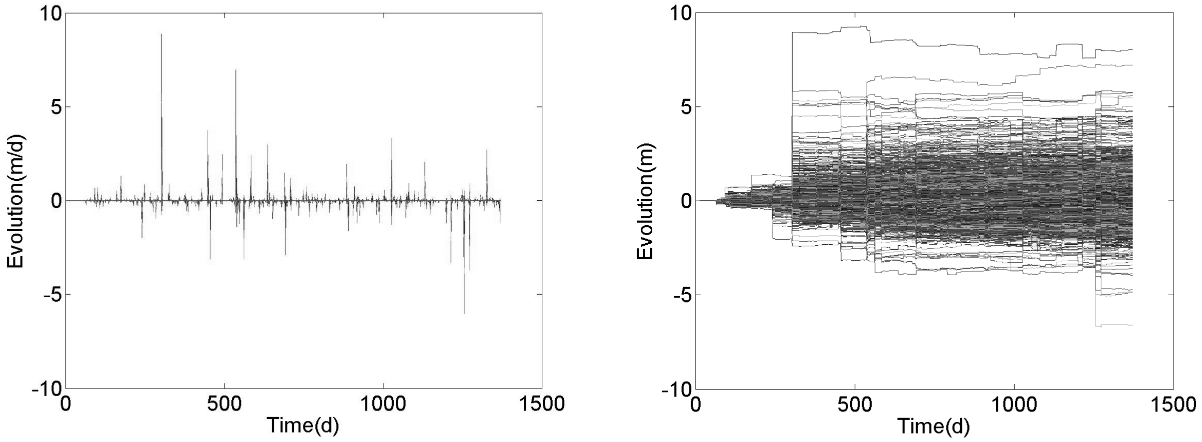


a) Correlation coefficients (r) between Q and E b) Correlation coefficients (r) between SS and E

Figure 8.2: Spatial distribution of the correlation coefficients for the year 1988-1992

From the figure above there is a clear indication that the degree of correlation goes well with regions of predominant erosion and deposition. Negative correlation were observed in regions of predominant erosion and positive correlation in regions of predominant deposition, compare with Figure 6.13 a).

The reconstruction of bed evolution from the regression prediction equation was tested. Figure 8.3 below shows the daily and cumulative depth of sedimentation/erosion calculated from the back substitution of the coefficients for the periods 1988-1992, compare with Figure 8.1. The following remarks can be made from the simple linear regression model investigated and the estimation at the computational nodes:



a) Daily bed evolution a) Cumulative bed evolution

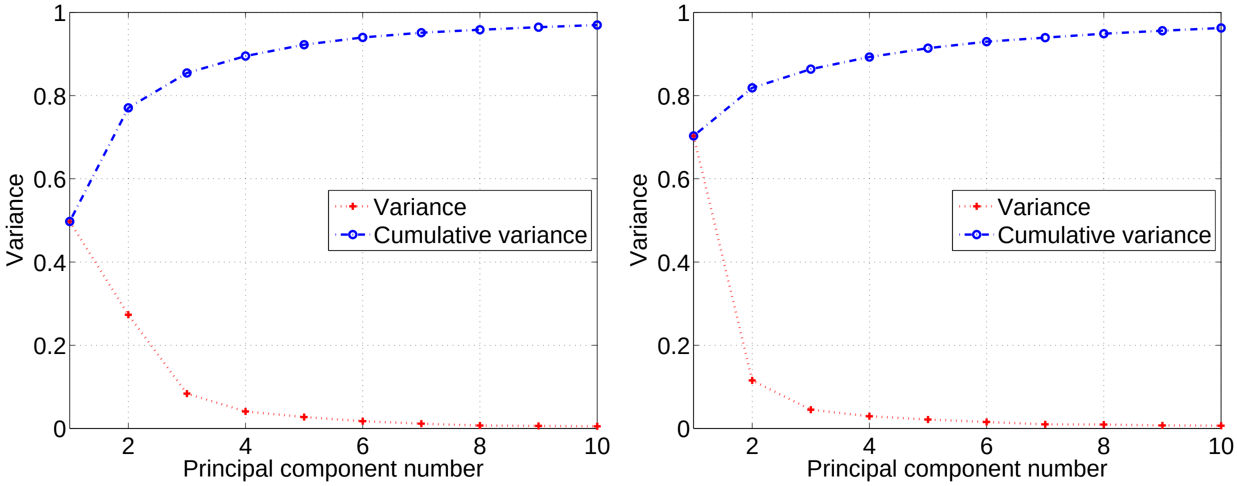
Figure 8.3: Simple regression prediction on the bed evolution of the year 1988-1992

- the spatial display of the correlation between the discharge and bed evolution has showed a good correlation in the regions of predominant deposition/erosion.
- the reconstruction of the bed evolution from regression equation with discharge was not satisfactory, see Figure 8.3. The prediction with suspended sediment resulted in similar discrepancy though slightly better.

Linear regression between spatio-temporal bed evolution at each of computational grid points and the input discharge and concentration as well as their fluctuation were performed by first compressing the bed evolution data by use of the principal component analysis, which substantially reduced the dimensionality of the bed evolution data.

8.1.2 Principal components regression model calibration

The principal component analysis performed on the spatio-temporal bed evolution data for various periods indicated that only the first few principal components can sufficiently present the database, with an excellent reduction of dimensionality. As shown in Figure 8.4 the first few principal components represent some 90 percent of the total variance indicating the possibility of developing a regression model based only these few principal components.

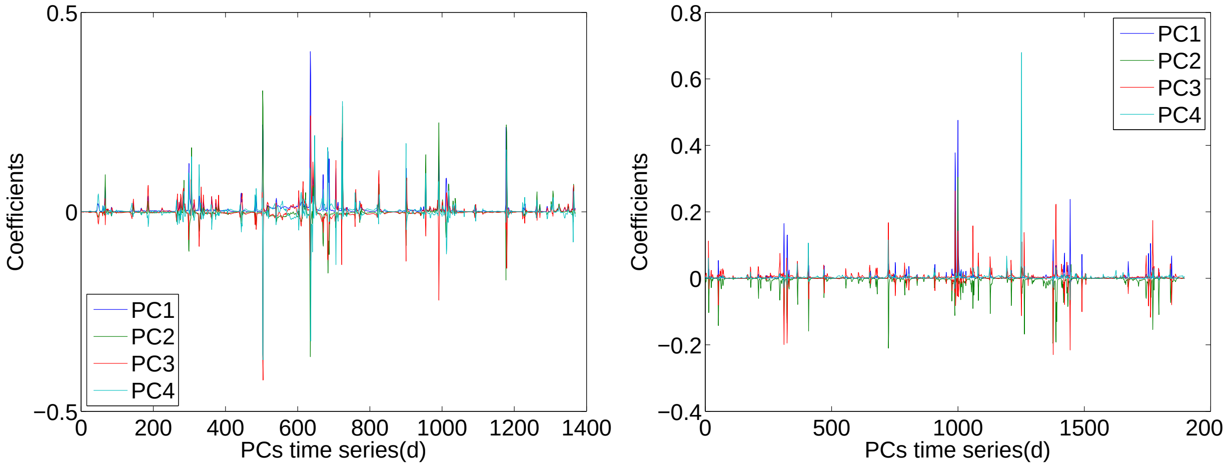


a) 1988-1992 b) 1996-2001

Figure 8.4: The variances explained by the first 10 principal components and their cumulatives

With only the first four PCs, 89 %, 93 %, 89.2 %, and 86.08 % of the variance were explained for the years 1988-1992, 1992-1996, 1996-2001 and 1988-2001 respectively. This implies the spatio-temporal bed evolution data from the cases under study could be expressed well in the first four dimensions. The regression analysis were therefore conducted making use of this advantage.

Figure 8.5 below indicate the time series coefficients (eigenvectors) of the first four principal components under similar conditions. The coefficients are representing the weight of the



a) The α of the first 4 PCs, 1988-1992 b) The α of the first 4 PCs, 1996-2001

Figure 8.5: The eigenvectors of the first four principal components for various periods

bed evolution on each day fulfilling the properties of orthogonality and orthonormality. The scores of principal components are given by

$$\mathbf{U} = \mathbf{E}\boldsymbol{\alpha} \tag{8.2}$$

where $\mathbf{U}$ is the principal components scores with dimension $[n \times t]$, $\mathbf{E}$ is the spatio-temporal bed evolution with dimension $[n \times t]$, and $\boldsymbol{\alpha}$ is the eigenvector of the variance-covariance matrix of bed evolution with the dimension [t $\times t$].

As can be seen from all the PC analysis made on various periods, the bed evolution data of the Lautrach can be presented by only few principal components without loosing significant variance. The spatial displays of the scores of the first four PCs for the year 1988-1992 for example is shown in Figure 8.6 The Figure shows that the spatial display of the behavior of bed evolution is quite similar to that of the numerical simulation and with only the first four principal components the data can be well represented.

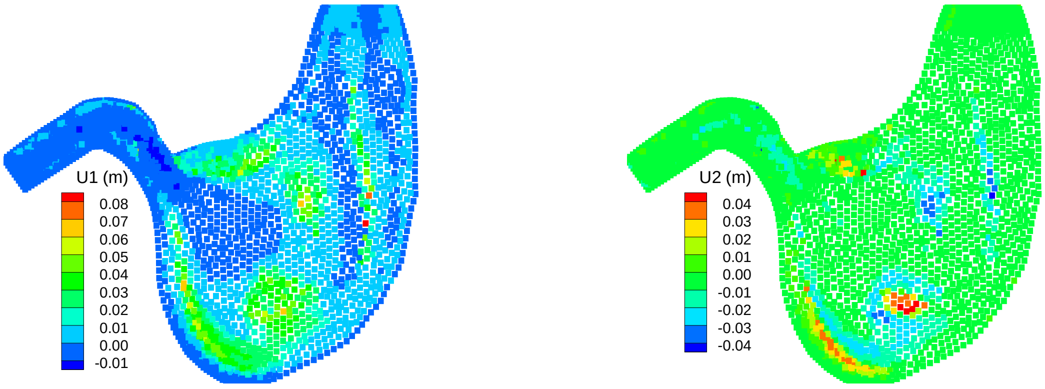
Various regression models were investigated between the coefficient of the first four PCs and the discharge and sediment inputs. The first model investigated was a simple linear regression based on averaged daily discharge (Q) and the coefficients of the first four PCs, the second was a simple linear regression between the differential discharge (DQ) between consecutive days and the first four PCs, the third was the simple linear regression between daily averaged suspended sediment concentration and the first four PCs, and the fourth was a multiple regression of the discharge, differential discharge, suspended sediment concentration with the coefficients of the first four PCs.

Before applying the regression model for prediction, their ability to reconstruct the spatio-temporal bed evolution were evaluated. The new principal components coefficients for various regressions investigated are given by:

$$\boldsymbol{\alpha}_n = \beta_{0q} + \beta_q Q \tag{8.3}$$

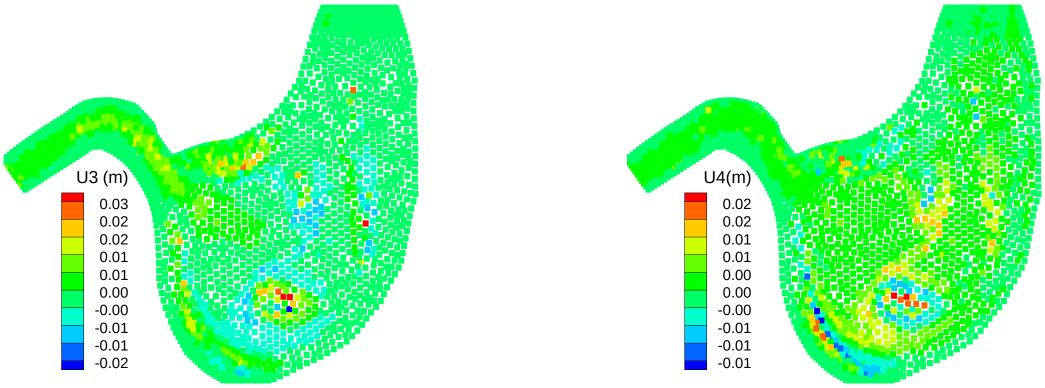
for analysis of the simple principal components regression with discharge, Q;

$$\boldsymbol{\alpha}_n = \beta_{0d} + \beta_{dq} DQ \tag{8.4}$$



a) U1=50% of the variance

b) U2=27% of the variance



c) U3=8% of the variance

d) U4=4% of the variance

Figure 8.6: Scores of the first four principal components for the year 1988-1992, representing 89% of the variance

for the simple principal components regression with differential discharge, DQ;

$$\boldsymbol{\alpha}_n = \beta_{0s} + \beta_{ss}SS \tag{8.5}$$

for the simple principal components regression with suspended sediment concentration, SS and

$$\boldsymbol{\alpha}_n = \beta_{0m} + \beta_{qm}Q + \beta_{dqm}DQ + \beta_{ssm}SS \tag{8.6}$$

for the multiple principal components regression with discharge Q, differential discharge DQ and suspended sediment concentration SS.

The new bed evolution $\mathbf{E}_n$ based on the regression model is given by an inverse equation.

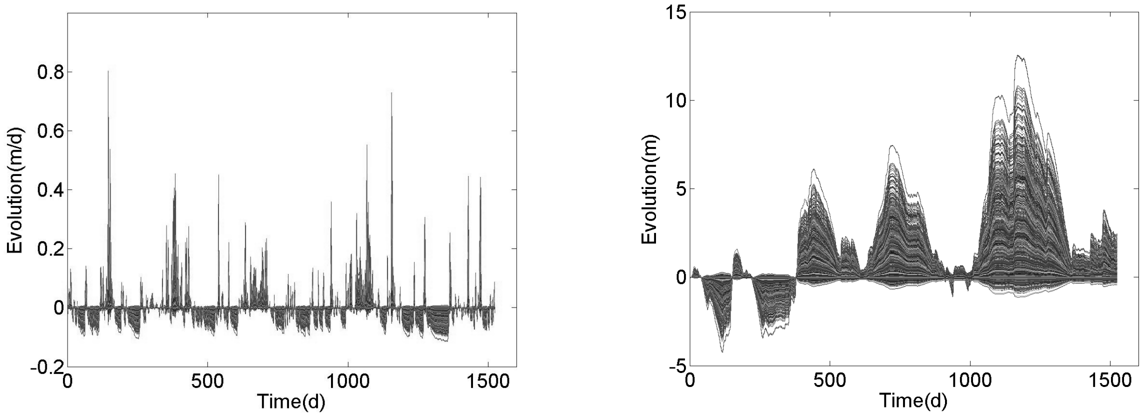
$$\mathbf{E}_n = \mathbf{U}\boldsymbol{\alpha_n}^T \tag{8.7}$$

This holds because of the principle of orthonormality in which the dot product, $\alpha\alpha^T$ is a unity which is the ground to overcome matrix inversion problems, as the inverse of the matrix is just its transpose.

A regression analysis were made in three time classes: 1988-1992, 1992-1996 and 1996 onwards, where the outcome of the numerical results being the basis for classification. Below, an example of the simple linear regression model analyzed for the period 1992-1996 is presented. The presentation then continues in more detail with multiple principal component regression for the periods 1988-1992-2001 followed by multiple regression analysis performed.

Simple linear regression between Q and PC coefficients

Regression analysis was made between discharge and the coefficient of the first few principal components representing 95 percent of the variation. In the Figure 8.7 below, the differential and cumulative evolution of the analysis made for the year 1992-1996 using PCR is shown. This univariate regression performed poorly over a temporal dimension in the reconstruction of the bed evolution compared to the numerical simulation inputs, see Figure 8.1, 1992-1996. The cumulative evolution at end of simulation generally performed far better than intermediate time steps.



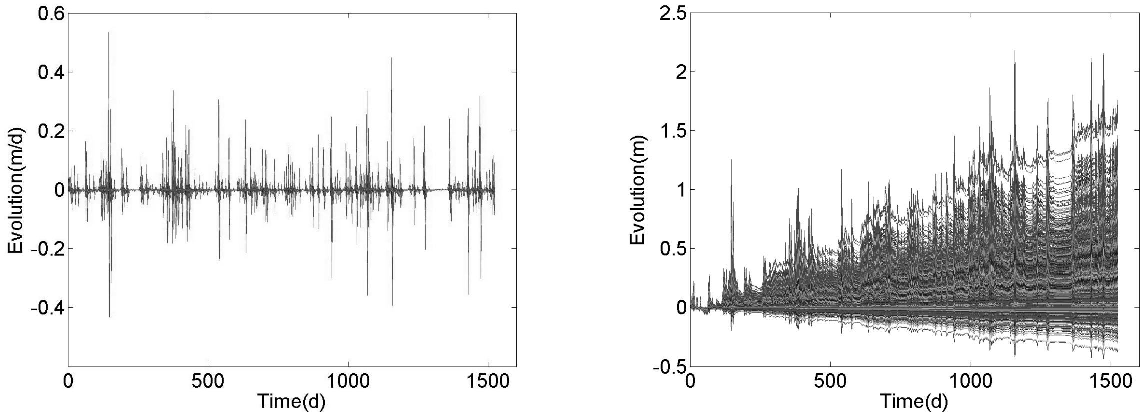
a) Daily bed evolution b) Cumulative bed evolution

Figure 8.7: Reconstruction of bed evolution based on regression between discharge Q and PC coefficients, 1992-1996

The results indicated that the bed evolution reconstruction by making use of regression of the eigenvectors with the discharge has not sufficiently reproduced the input evolution. The results at the end of the regression models were relatively in agreement with the numerical results.

Simple linear regression between DQ and PC coefficients:

Regression analysis was made between differential discharge, DQ and the coefficients of first four principal components representing 93 percent of the variation. The result showed an improvement as compared to regression performed with the averaged daily discharge Q, see Figure 8.1

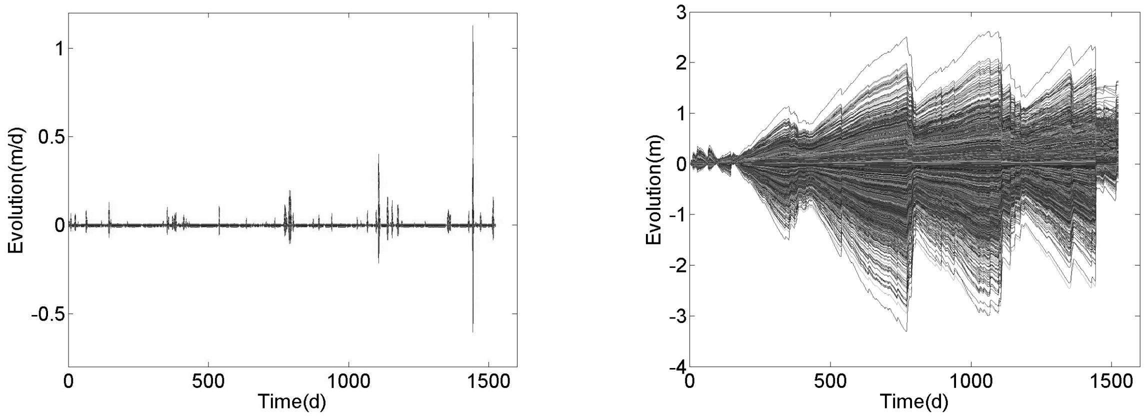


a) Daily bed evolution b) cumulative bed evolution

Figure 8.8: Reconstruction of bed evolution based on regression between differential discharge DQ and PC coefficients, 1992-1996

Simple linear regression between SS and PC coefficients:

Regression analysis was also made between suspended sediment and the coefficients of first four principal components representing 90 percent of the variation. The result of prediction with suspended sediment and the first few PCs was also reasonable in reconstructing the bed evolution as compared as that made with the discharge. Furthermore, the results for the computational period 1988-1992 and 1996-2001 were also found to have similar behavior in their performance in reconstruction the bed evolution with simple linear regression. See Figure 8.1.



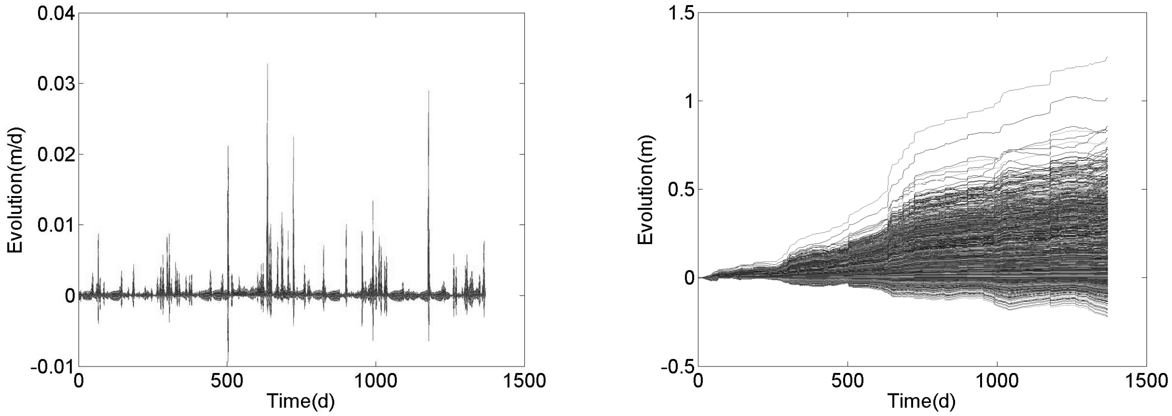
a) Daily bed evolution b) Cumulative bed evolution

Figure 8.9: Reconstruction of differential and cumulative bed evolution based on regression between sediment concentration SS and PC coefficients, 1992-1996

In the section below, the results obtained by making use of multiple linear regression between the first four principal components and the discharge, differential discharge and suspended sediment concentration. Various period are investigated to validate the application of the method.

Multiple regression between Q, DQ, and SS with PC coefficients

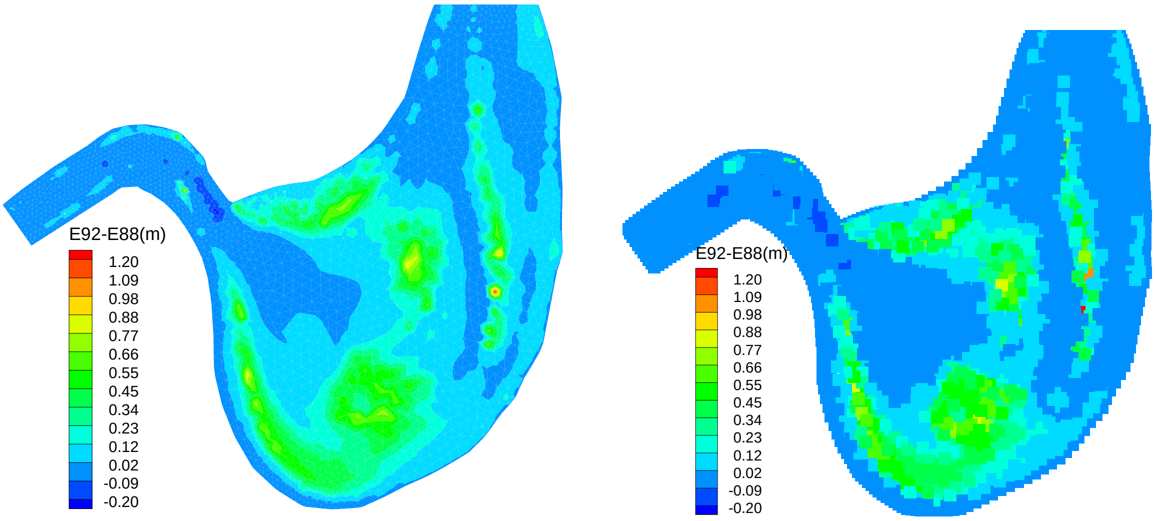
Regression analysis were conducted between the discharge, the differential discharge, and the suspended sediment concentration and the coefficients of first four principal components representing 90 percent of the variation. Figure 8.10 below shows the time series of bed evolution for all computational nodes, for the period 1988-1992. Compare with Figure 8.1.



a) Daily bed evolution b) Cumulative bed evolution

Figure 8.10: Reconstruction of bed evolution based on regression between Q, DQ, and SS with the PC coefficients, 1988-1992

Figure 8.11 below shows the spatial distribution of sedimentation for the years 1988-1992

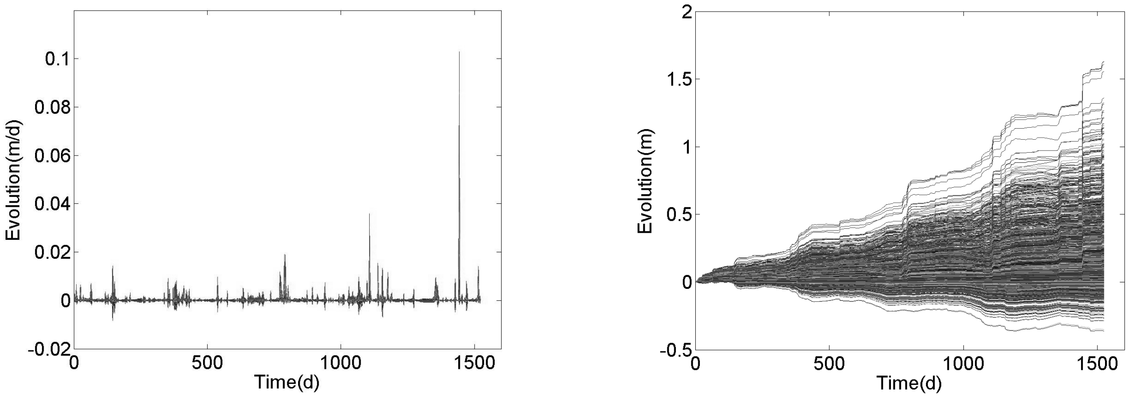


a) Numerical b) Principal components regression

Figure 8.11: Comparisons of spatial sedimentation between the numerical and the principal components regression model, 1988-1992

The results obtained by using the multiple regression of Q, DQ and SS with the principal component coefficients, were able to reconstruct in a very good manner the bed evolution of the numerical simulations. Compare with Figure 8.1.

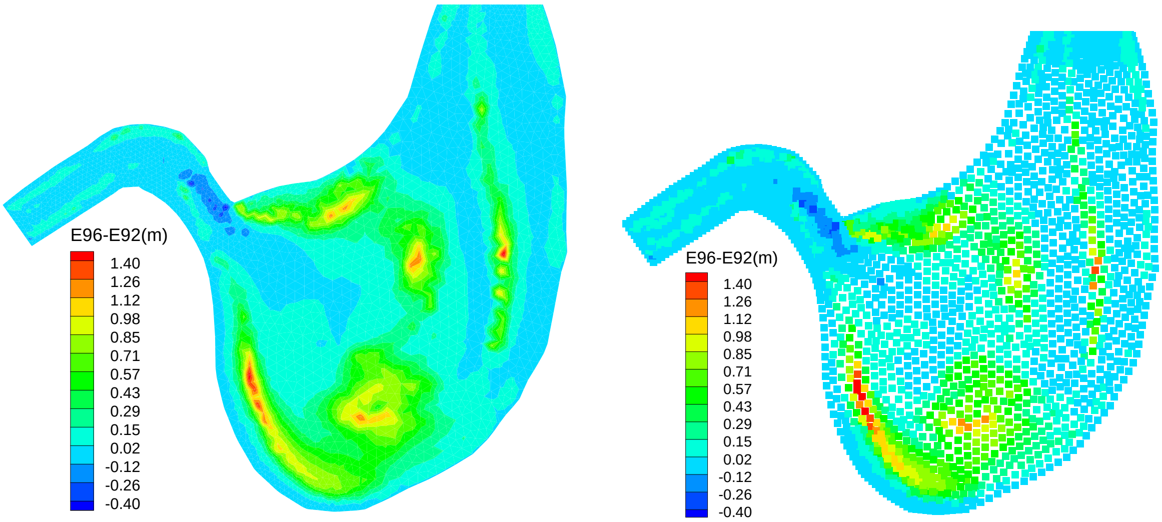
Similar analysis were made for other periods. Figure 8.12 below shows the bed evolution calculated from multiple principal components regression in reconstructing the bed evolution from the numerical result for the period 1992-1996. Compare with Figure 8.1.



a) Daily bed evolution b) Cumulative bed evolution

Figure 8.12: Reconstruction of bed evolution based on multiple regression between Q, DQ and SS with the coefficients of principal components, 1992-1996

Figure 8.13 below gives the spatial distribution of sedimentation at the end of the simulation period 1992-1996.



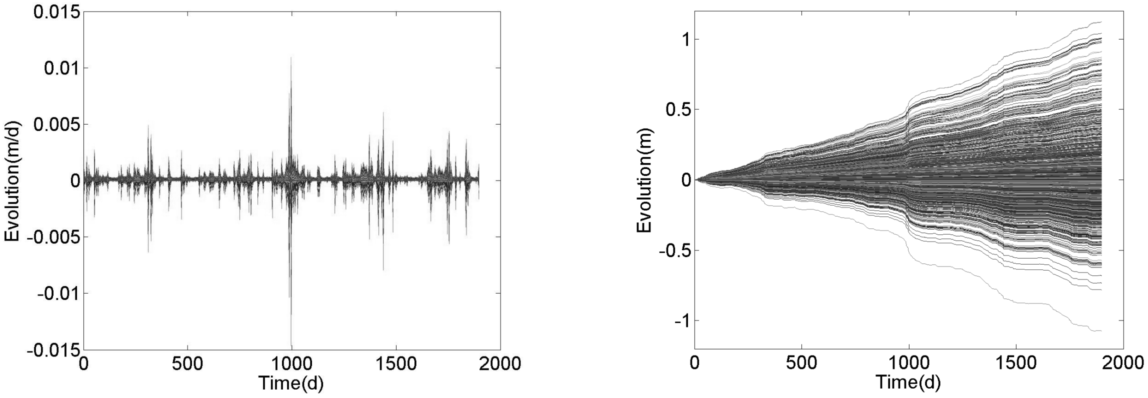
a) Numerical b) Principal components regression

Figure 8.13: Comparisons of the spatial distribution of sedimentation using the numerical and the principal components regression approaches, 1992-1996

Figure 8.14 below shows the differential and cumulative evolution for the computational results of the year 1996-2001 obtained by reconstruction using the principal components regression modeling.

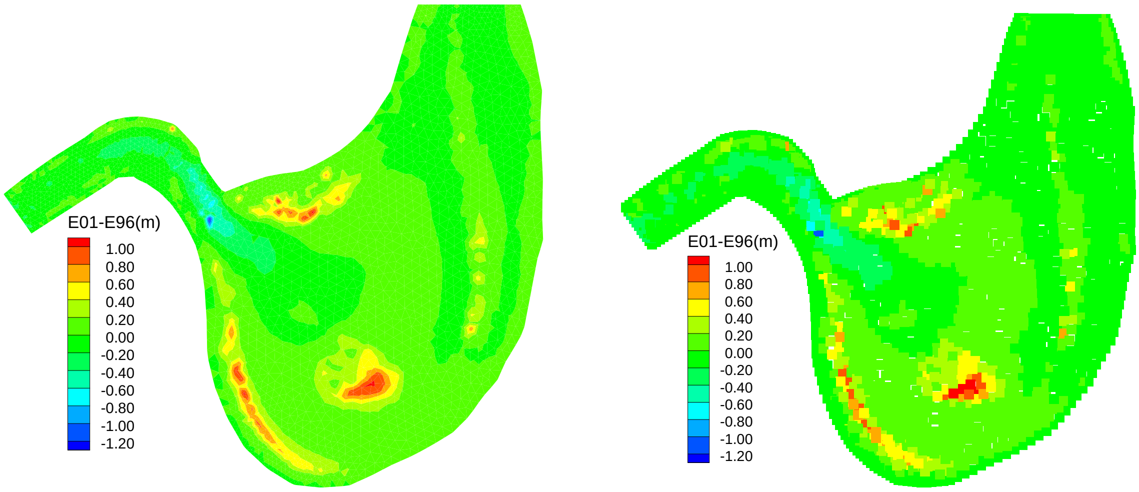
Figure 8.15 below compares the spatial distribution of depth of bed evolution from 1996 to 2001.

From the above analysis the following remarks can be made:



a) Daily bed evolution b) Cumulative bed evolution

Figure 8.14: Reconstruction of bed evolution based on multiple regression between Q, DQ and SS with the coefficients of principal components, 1996-2001



a) Numerical b) Principal components regression

Figure 8.15: Comparisons of spatial distribution of sedimentation using the numerical and the principal components regression approaches, 1996-2001

- the multiple linear regression among the first four principal components with discharge, differential discharge, and suspended sediment concentration were sufficient for a very good reconstruction of spatio-temporal bed evolution of the numerical results.

- simple linear regression of the principal components were insufficient for the proposed reconstruction of the bed evolution.

- the inclusion of more factors influencing the reservoir sedimentation could result in better ability to reconstruct the data.

Table 8.1 gives the regression coefficients between the eigenvectors of the first four principal components and the discharge, differential discharge and suspended sediment concentration. The correlation coefficient were high for the regressions in the periods 1988-1992 and 1992-1996. The period 1996-2001 had lower coefficient of determination, that may have been resulted from extreme flood event of the year 1999 showing distinct behavior as compared to the rest of the data series.

Year	PC No.	β_0	β_q	β_{dq}	β_{ss}	R^2
1988-1992	PC1	-8.6486e-004	9.7782e-006	-1.0620e-004	1.7782e-001	9.3441e-001
	PC2	-2.0570e-002	4.6377e-004	4.8895e-004	-6.7254e-002	4.7334e-001
	PC3	1.5050e-003	-4.0415e-005	-8.3383e-005	2.2451e-002	1.0123e-002
	PC4	5.9080e-003	-9.8954e-005	2.7296e-005	1.9995e-002	1.7820e-002
1992-1996	PC1	2.7950e-003	-7.4346e-005	-1.0847e-004	8.4077e-002	9.2019e-001
	PC2	-1.0656e-002	2.5152e-004	1.7686e-004	1.0280e-002	2.7991e-001
	PC3	1.6033e-002	-3.1110e-004	-2.1327e-004	1.3986e-002	3.3031e-001
	PC4	-3.1637e-004	-4.2408e-005	-1.1552e-004	-9.5615e-003	3.6255e-002
1996-2001	PC1	-2.4120e-003	1.03670e-004	-1.9563e-004	1.0277e-002	9.3325e-002
	PC2	-1.5806e-003	-6.3021e-005	1.2576e-004	-1.9614e-002	5.1772e-002
	PC3	4.6022e-003	-4.6322e-006	7.2910e-005	-8.1269e-003	5.8776e-003
	PC4	3.9543e-003	-1.0506e-005	-1.1927e-005	1.3165e-002	2.8229e-003

Table 8.1: Parameter estimation for multiple regression analysis between coefficient of the principal components with discharge, change in discharge, and suspended sediment concentration

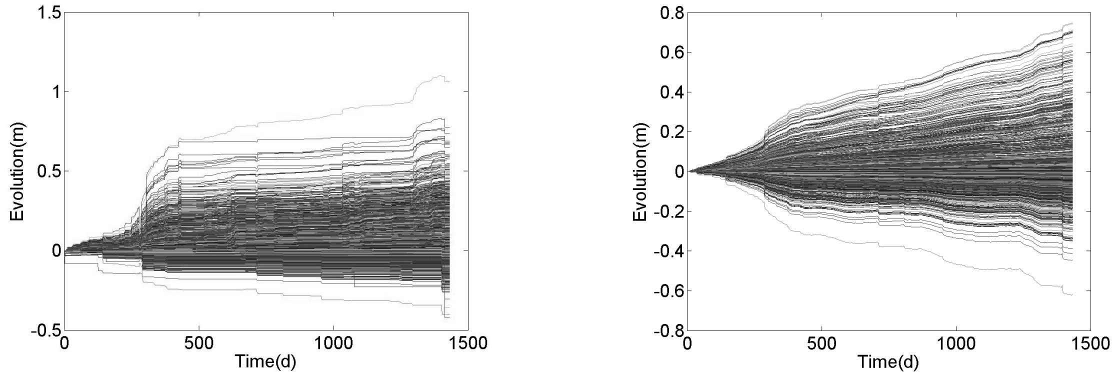
The results from the use of a multiple linear regression are satisfactory in reconstruction of the bed evolution of the Lautrach reservoir for the periods studied. The next section proceeds into the validation, i.e., using the regression parameters, $\boldsymbol{\beta}$, in a given period in which the model is well reconstructed and applying them in a different period. It can be seen that the coefficients are varying for the three periods investigated being influenced by the initial morphological conditions, flow and suspended sediment conditions that enforce the system to response differently.

8.1.3 Principal components regression model validation

The capability of the principal components regression model coefficient to be applied in a period other than that of the calibration were investigated. The use of the coefficient of the period 1988-1992 and 1992-1996, see Table 8.1, for the modeling of the bed evolution of the period 2001-2005 was not satisfactory. The use of the coefficients of the period 1996-2001, for the period of 2001-2005, was however satisfactory in validating the bed evolution using the principal components regression approach. This is an indication of model sensitivity to the regression coefficients which can very much be influenced by initial morphological conditions and the nature of inputs from which the regression coefficients are derived.

Figure 8.16 below shows the comparison of the bed evolution between numerical simulation and the principal components regression based on the regression coefficient of the period 1996-2001.

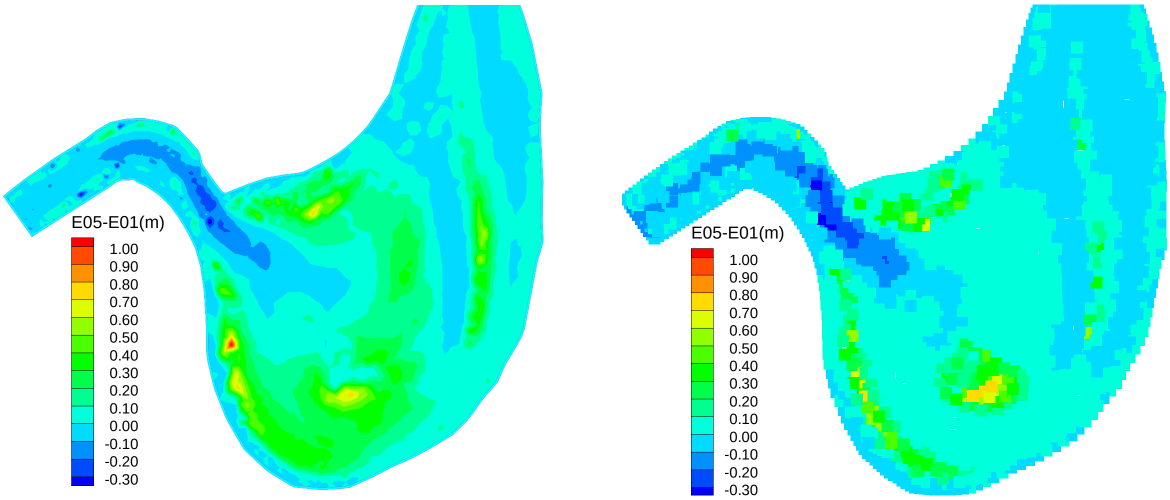
The spatial distribution of sedimentation calculated based on the numerical and statistical



a) Numerical b) Principal components regression

Figure 8.16: Validation of the cumulative bed evolution of principal components regression as compared to the numerical simulation, 2001-2005

method for the simulation period 2001-2005 is shown in Figure 8.17 below.



a) Numerical b) Principal components regression

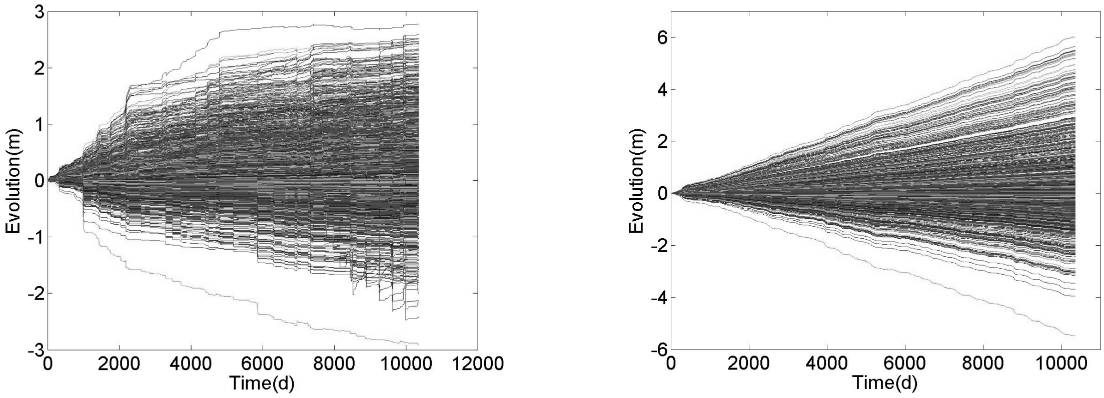
Figure 8.17: The spatial distribution of sedimentation for the numerical and the principal components regression approaches, validation step 2001-2005

The validation is satisfactory. The regression coefficients were determined from the sample data rather than the population data. Discrepancies are unavoidable in using the regression coefficients for predictive purpose.

8.1.4 Principal components regression model prediction

Long-term prediction for the period 2005 to 2025 were performed by generating the new eigenvectors $\boldsymbol{\alpha_n}$ using the regression coefficients estimated for the period (1996-2001) and the predicted discharge and suspended sediment concentration till 2025, see Section 4.2.4.

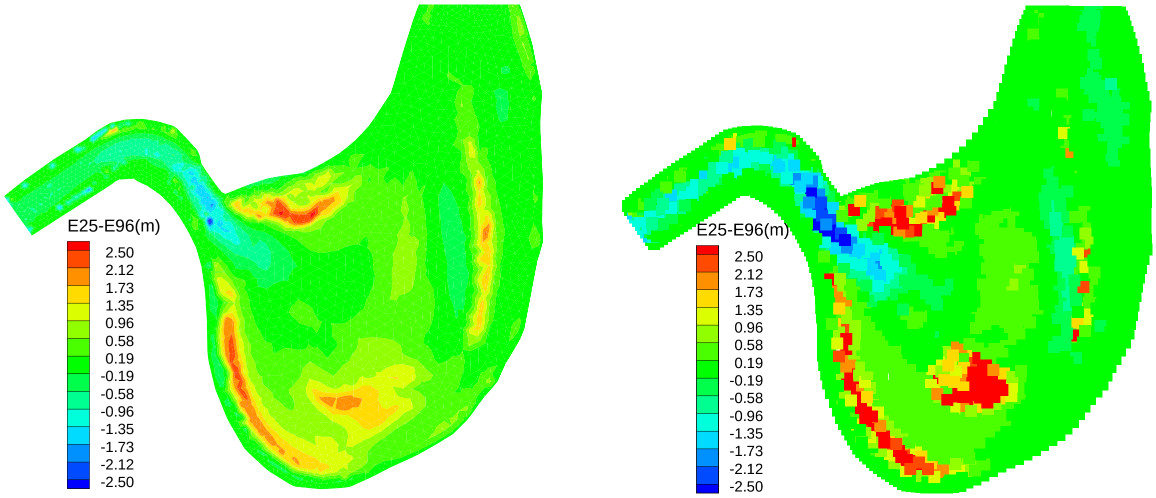
Figure 8.18 indicates the bed evolution prediction. The starting period for both numerical simulation and principal components regression was 1996. The spatial distribution of sedi-



a) Numerical b) Principal components regression

Figure 8.18: Prediction of the bed evolution using the numerical and the principal components regression approach, 1996-2025

mentation prediction at the end of the 2025 for numerical as well as principal components regression modeling is shown in the Figure 8.19 below. The prediction at the end of 2025 shows the spatial distribution of sedimentation of the numerical model and the statistical model are quite similar. The following remarks can be made from the analysis:



a) Numerical b) Principal components regression

Figure 8.19: Prediction of bed evolution using the numerical and the principal components regression approach, 1996-2025

- the morphological process of the reservoir bed is a complex dynamic process that normally approaches an equilibrium stage over time. The principal components regression showed an ever increasing/decreasing trend whereas the numerical model showed the approach towards equilibrium transport through time.

- the predictive capability of the principal component regression method employed can be significantly improved if the whole range of transport behavior are integrated rather than the sample data on which the regression is based. The use of population rather than sample principal components analysis can further improve the result significantly.

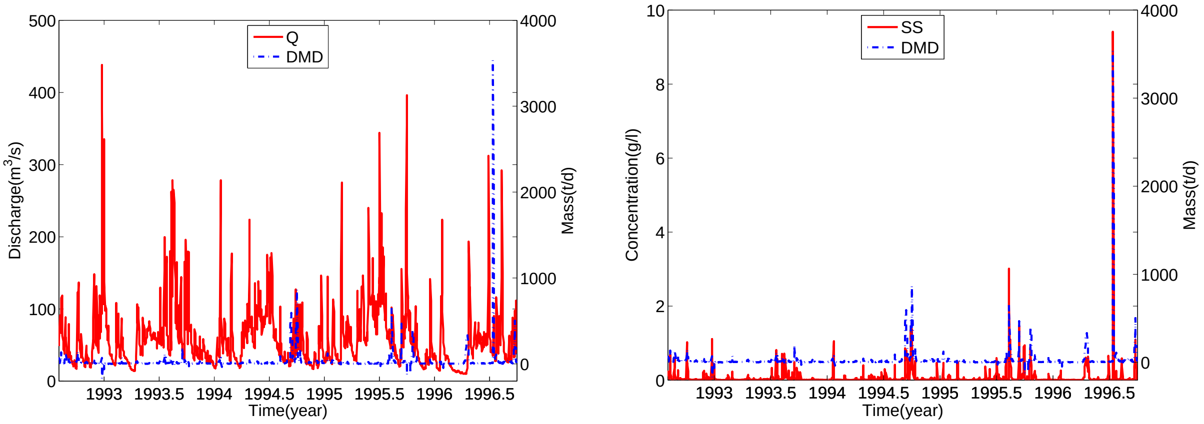
- the consideration of the nature of bed evolution by using a dynamic regression coefficient can improve the result satisfactorily, though not treated in this work.

- assimilation of data and dynamics, i.e. reusing the numerical model and the statistical model in series can help to overcome the challenges of morphological modeling with a reasonable accuracy.

8.2 Sediment mass deposition

The mass of daily sedimentation/erosion is another important parameter quantification in order to estimate the long-term sediment mass deposition. For the regression analysis on the amount of sedimentation, the daily sediment mass deposition (DMD) of the numerical models were taken from the numerical results, see e.g. Figure 8.20 for the period 1992-1996. The ranges for erosion and sedimentation and the nature of mass of sediment deposition are highly influenced by extreme flows and sediment concentrations at low discharge periods.

Simple linear regression between the daily mass deposition and the discharge, the differential discharge and the suspended sediment concentration indicated that there is a weak correlation. The r^2 values between the mass deposited and the discharge (Q), differential discharge (DQ), suspended sediment concentration (SS) and differential suspended sediment concentration, for the period of analysis 1988-1992, were estimated as 0.0038, 0.0208, 0.58, and 0.028 respectively.



a) Discharge and daily deposition (DMD) b) Concentration and daily deposition (DMD)

Figure 8.20: Comparison of the amount of sediment mass deposition with input Q and SS, 1992-1996

Multiple linear regression between the daily rate of mass deposition/erosion with the average daily discharge, differential discharge, suspended sediment concentration indicated higher correlation. Table 8.2 below gives the regression parameters and the coefficient of determination for the periods analyzed. Using the regression coefficients for the periods 1988-1992, 1992-1996, and 1996-2005 shown in Table 8.2, the prediction of the amount of sediment mass deposition was calculated. The results of the cumulative mass of sediment deposition for a variety of scenarios are shown in Figure 8.21.

Years	β_0	β_q	β_{dq}	β_{ss}	R^2
1988-1992	2.284e+001	-3.622e-001	-2.511e-001	2.965e+002	0.678
1992-1996	3.076e+001	-5.393e-001	-2.501e-001	3.583e+002	0.846
1996-2005	3.667e+001	-5.777e-001	1.968e-001	1.192e+002	0.361

Table 8.2: Parameter estimation for multiple regression analysis between daily mass of sediment deposition with the discharge, differential discharge, and suspended sediment concentration

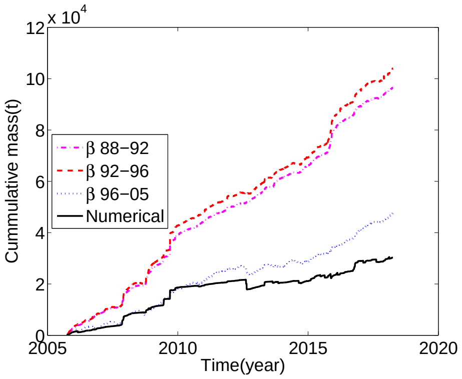


Figure 8.21: Prediction of the amount of sediment mass deposition using multiple regression as compared to the numerical results: $\boldsymbol{\beta}$ of multiple regression from the model of the three different periods, 1988-1992, 1992-1996, and 1996-2005

The following remarks can be made from the regression analysis on the amount of sediment mass deposition:

- the regression parameters, $\boldsymbol{\beta}$ are varying through time and their application for the predictive purpose must be carefully done. The parameters from the period 1988-1992, and 1992-1996 showed highly exaggerated results when used for prediction in a period different than reconstruction.

- prediction using the regression parameters derived from the period 1996-2005, resulted in a good outcome in the period close to the phase of reconstruction (1996-2005). The prediction of mass of sediment deposition was made till 2018 and the result is acceptable.

- on average, the rate of sediment mass deposition is gradually reducing. This is an indication of the reservoir approaching equilibrium over time.

- a time-varying regression coefficients can be implemented to improve the model capability.

- extreme events behave differently and therefore need to be treated separately.

Summary

The analysis performed using principal component regression modeling can be of great importance in modeling long-term simulation of reservoir bed evolution. It can overcome the problem of computational requirement with reasonable accuracy. The amount of mass deposition can be indirectly calculated from the spatial display of sedimentation by reintegrating it into the numerical model. This was however, not attempted in this work. Multiple regression showed superior results in all the analysis made. This is an indication of the joint effect of various parameters influencing the depositional behavior of reservoirs.

Multiple linear regression modeling of the amount of sediment mass deposition with the input discharge, suspended sediment concentration and their differentials showed a good agreement within a period of reconstruction. For prediction to be performed more accurately, time-dependent regression coefficients need to be implemented. This is due to the dynamic nature of reservoirs approaching a dynamic equilibrium over time.

The assimilation of the numerical models with the statistical models can be a method of significant importance in large scale and long-term morphological predictions of reservoirs where sediment transport issues need to be addressed.

Chapter 9

Conclusions and Outlook

9.1 Conclusions

Long-term simulation of reservoir sedimentation is a computationally demanding task involving model, parameter, and data uncertainties. This work has attempted to address simplifications that can be applied in the prediction of long-term reservoir sedimentation with limited computational resources and data.

Two principally different approaches were investigated. The first approach was the use of a simplified two-dimensional depth-averaged numerical model. The second approach was regression modeling with principal components regression applied to model spatio-temporal bed evolution. Furthermore, multiple regression was used to model the mass of sediment deposition. The two methods; the first based on the dynamics, and the second based on data modeling can be assimilated. This provides a more efficient method of handling large and complex morphological studies in riverine and/or coastal systems.

The following conclusions can be given from the step by step studies accomplished in this work:

9.1.1 Numerical approach

With the recent advances in computational science, numerical modeling of sediment transport is gaining momentum. Numerical approaches in general suffer from uncertainties in complex process description, model uncertainties, and very high computational costs. A thorough investigation was made on various aspects of the model simplification through the use of a two-dimensional depth-averaged model, as summarized below.

From the studies made on the hypothetical domains:

- investigation of the basic behavior of the reservoir response to unsteady inputs suggests that the ranges of flow and sediment input can be defined in an aggregate manner. Quasisteady steps can be designed relative to the residence time as an important criteria in setting quasisteady steps. Quasisteady steps shorter than the theoretical residence time has indicated no significant improvement in approaching the fully-unsteady solutions.
- the regular-shaped reservoir has a wider range of quasisteady approximation using

longer time steps as compared to the irregular-shaped reservoir, revealing the importance of geometry in widening the range of quasi-steady approximation.

- analysis of the non-dimensional aggregate results for relative concentration and mass of sediment deposition indicated that the numerical advection-dispersion model solution agreed well with the simple analytical solution of the PFR and the CSTRs. At low flows, the PFR performed better for the regular reservoir as compared to the irregular reservoir. For the irregular reservoir the opposite was true. At high flows both the solutions of PFR and CSTR are closer to the advection-dispersion solution. This is an indication of the significance of the simplified conceptual approach as a first-hand tool in modeling sediment related problems in reservoirs.

From the studies made on the Lautrach reservoir:

- investigation on the modeling techniques with respect to data aggradation, grid refinement, coupling methods etc. has given an insight into uncertainties involved in various aspects of modeling reservoir sedimentation. Simplifications that can be made with respect to reducing computational cost with a reasonable accuracy were also addressed.
- the bed evolution of the Lautrach reservoir was calibrated and validated to a reasonable accuracy. Creating a perfect match in the bed evolution for all spatial locations for long-term simulations is generally very challenging.
- investigations were made on the validity of the quasisteady approximation having long quasisteady time steps , $\triangle T$. The results indicated that for flows lower than the critical erosion discharge (around 200 m^3/s), large quasisteady step can produce a good agreement with the fully-unsteady simulations.
- the long-term prediction performed by steady, mixed-quasisteady-unsteady, and fully-unsteady simulations indicated that, the results are approaching each other. Mixed-quasisteady-unsteady simplifications were satisfactorily applied in predicting long-term sedimentation of the Lautrach reservoir.
- from the sedimentation management point of view, the reservoir has gradually lost its volume and conventional operational techniques are not efficient in overcoming the problem of sedimentation. In some parts of the reservoir there is always sedimentation, irrespective of flow peaks.
- in approaching the equilibrium stage of the reservoir, not only the amount of sedimentation but also the spatial distribution of sedimentation is necessary. The equilibrium condition of the reservoir will be reached in the years between 2020 and 2030 with a remaining water volume of 0.92 million m^3.

9.1.2 Regression modeling approach

In the framework of the applicability of regression techniques in modeling bed evolution of reservoirs, significant progress has been achieved. The method was constructed by making use of the data generated from the numerical simulations. The spatial distribution of sedimentation was studied by use of simple linear regression, multiple linear regression, and principal components regression. The principal component regression was found to be more effective in dealing with the spatio-temporal bed evolution processes. The amount of sediment mass deposition was treated with the multiple linear regression.

Spatial distribution of sedimentation

From the principal components regression on the spatio-temporal bed evolution data of numerical results of the Lautrach reservoir, the following conclusions can be put forward:

- the principal components regression was excellent in reconstructing the bed evolution of the Lautrach reservoir, applied for several test periods (1988-1992, 1992-1996, and 1996-2001).
- the univariate principal components regression was not sufficient. The multivariate principal components regression based on the regression of the coefficient of the first four principal components with the discharge, differential discharge and suspended sediment concentration was able to reconstruct the spatio-temporal bed evolution efficiently.
- for the validation (2001-2005) and prediction (1996-2025) periods tested, the principal components regression indicated acceptable results.
- the coefficients of the multiple regression are changing over time. It was found out that the initial morphological conditions on which the models were built have significant influence in the numerical model and correspondingly on the statistical model. The prediction at a time other than for the reconstruction, under the same initial geometric conditions yielded an acceptable results.
- extreme events (peak flows) behave differently and need to be treated separately in the regression.

The amount of sediment mass deposition

Simple linear regression and multiple linear regression were investigated. The following conclusions can be put forward from the analysis:

- the performance of the multiple linear regression between the daily mass of sediment deposition versus the discharge, the differential discharge, and the suspended sediment concentration yielded very good results for reconstruction.
- for prediction, the amount of sediment mass deposition yielded reasonably good results when using the regression parameters under which the model was reconstructed. Regression parameters different from the reconstruction period performed poorly. This is the result of the dynamic nature of the morphological processes which is not linear.

- the simple linear regression with sediment concentration had higher correlation than that with discharge or differential discharge.

9.2 Outlook

- further investigation on the validity of quasi-steady approximation considering complex processes like stratification and consolidation for large-scale reservoirs need to be done.
- further investigation is necessary on the numerical modeling of the flushing of reservoirs, and the incorporated challenges like wetting and drying effects.
- the work can be re-evaluated using a fully coupled, quasisteady flow and sediment transport model. The TELEMAC modeling system can be rebuilt in a way to accommodate the mixed-quasisteady-unsteady algorithm in which the updating of the morphology can be integrated with more efficient criteria.
- the methods investigated can be further developed towards the integrated modeling of the data and the dynamics in which prediction using the regression models can be reused for a geometric updating of the numerical modeling.
- a temporally varying regression coefficients can be implemented based on the dynamics of the sedimentation which generally is approaching equilibrium through time. The regression coefficients can also be built through generation of the variance-covariance matrix based on the population rather than the sample data. Furthermore, a trend analysis on the principal components can be investigated using the autoregressive moving average method for the suitability in the predictive studies.
- the regression model can be investigated at various time scales different from the daily basis. The time scale relevant to the theoretical residence time can be considered for further investigation.

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