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MIKE 3 as a modeling tool for flow characterization: A review of applications on water bodies

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Abstract

MIKE 3 is a computer program that simulates flows, cohesive sediments, water quality, and ecology in lakes, rivers, estuaries, bays, coastal areas and seas in three dimensions. This paper presents a review of MIKE 3 studies carried out in this field, with the objective of developing an understanding of how and where it can be applied. Existing work has tended to focus around the analysis of MIKE 3 for flow characterization. MIKE 3 presents a number of opportunities in characterization of fluid flows, there is always a room for development as software resources become more advanced. The compilation of the mathematical bases of these models would be useful to determine the situations, problems or conditions for which the models are most suitable, their full potential uses, the accuracies and uncertainties expected, and directions for their enhancements or new developments.

***Keywords*- MIKE 3; water quality; hydrology; flow pattern; river discharge.**

I. INTRODUCTION

The purpose of this paper is to summarize the progress of MIKE 3 models for flow problems. MIKE 3 is a computer program that simulates cohesive sediments, flows, water quality, and ecology in lakes, rivers, estuaries, bays, coastal areas and seas in three dimensions. MIKE 3 was developed by Danish Hydraulic Institute (DHI) Water & Environment (Denmark). MIKE 3 models are more suitable as a simulation tools if you need to model three-dimensional (3D) free surface flows and associated sediment or water quality processes.

MIKE 3 is fully 3D model and solves the momentum equation and continuity equations in the three Cartesian directions. MIKE 3 simulates unsteady flow by taking into consideration bathymetry, density variations and external forcing such as tidal elevations, meteorology, currents and other hydrographic conditions.

MIKE 3 is widely recognized as the gold standard for environmental and ecological studies. For assessment of hydrographic conditions MIKE 3 can be used for construction, design and operation of structures and plants in stratified waters, environmental impact assessment studies, coastal and oceanographic circulation studies, including fine sediment dynamics, lake hydrodynamics, sea ice simulations, analysis of cooling water recirculation and desalination, water pollution studies and restoration projects, water quality and ecological forecasting and phenomena whenever 3D flow structures is an important factor.

MIKE 3 is composed of three fundamental modules: The hydrodynamic (HD) module, the advection-dispersion (AD) module and the turbulence module. Various features such as free surface description, density variations and laminar flow description are optionally invoked within these three fundamental modules. A number of application modules have been used and can be invoked optionally. These are AD of conservative or linearly decaying substances, nutrients and hygienic problems, a water quality (WQ) module describing BOD-DO relations, a mud transport (MT) module simulating transport along with erosion and deposition of cohesive material, an eutrophication (EU) module simulating algae growth and primary production. A Lagrangian based particle (PA) module can also be invoked for simulating e.g. sediment transport, tracers or the spreading and decay of *E.coli* bacteria.

In this study it is represented that the flow is decomposed into mean quantities and turbulent fluctuations. The closure problem is solved through the Boussinesq eddy viscosity concept which is related to Reynolds stresses to the mean velocity field. For handling of density variations, the equations for conservation of salinity and temperature are added. The transport of scalar quantities, such as salinity and temperature, is solved using AD module with the help of explicit, finite difference technique based on quadratic upstream interpolation in three dimensions. The finite difference scheme, which is accurate to fourth order, has impactful properties concerning numerical dispersion, stability and mass conservation.

The modeling system is based on the conservation of mass and momentum in three dimensions of a Newtonian fluid. In continuum mechanics, a fluid is said to be Newtonian if the viscous stresses that arise from its flow, at every point, are proportional to the local strain rate (the rate of change of its deformation over time.). Newtonian fluids are the simplest mathematical models of fluids which mainly accounts for viscosity. While no real fluid applicable to the definition perfectly, many common liquids and gases, such as water and air, can be assumed to be Newtonian for practical calculations under ordinary condition [1-3].

MIKE 3 includes a very wide range of hydraulic phenomena in case of the simulations and it can be used for almost any kind of 3D application. It is usually suitable for studying phenomena like tidal flows, wave-driven flows, storm surges, density-driven flows, oceanographic circulations.

MIKE 3 is applicable to flow problems in which density variations and turbulence are most important features. Partial differential equations are required for mathematical modeling of such flows. MIKE 3 HD simulates the water level variation and current velocities with respect to a variety of forcing functions in lakes, bays, estuaries and coastal areas. The currents and the water levels are resolved on a curvilinear grid, rectilinear grid, a triangular element mesh or any combination hereof covering the area of interest. The paper presents the importance of MIKE 3 model over a flow characterization on water bodies which is discussed in this study explained in “Estuarine and Coastal Hydraulics and Oceanography”, a short description by DHI (2012).

II. CASE STUDIES

A. A Three-Dimensional Model of Gota Alv for Water Quality Simulation

A three-dimensional HD model (MIKE 3) in combination with a WQ model (ECOLab) is used to find out the impact from point sources along the River Gota Alv which is situated in the western coast of Sweden.

The HD model (MIKE 3) is based on a flexible mesh concept. After the further improvement, the HD model in combination with the WQ model can be used to simulate microbial contamination at the scale of the whole river as a result of point and non-point sources of fecal bacteria created by human activity as well as test predictive scenarios.

The microbial impact from diffuse sources mainly deals with urban and rural surface runoffs and contamination from livestock and potentially from wild animals and from birds. As per the former study the Waste Water Treatment Plant (WWTP) effluents represent the major source for spreading of pathogens in Gota Alv [4].

This study accounts for the WWTPs and registered Combined Sewer Overflows (CSOs) and Sanitary Sewer Overflows (SSOs) as pollution sources in both HD model and WQ model. The water quality in this river is monitored through continuous measurements at seven monitoring stations. These stations measure basic parameters of raw water such as pH, turbidity, conductivity and redox potential.

The main objective of this study was to develop a model tool for the maintenance of microbiological water quality at the river scale as well as to have a better basis for decisions on protection against water-borne diseases. Furthermore, the objective of this study was to calibrate and validate the model, and run the model to assess the transport from a subset of wastewater point pollution sources. This was done by using a 3D HD model in MIKE 3 Flexible Mesh (FM). The modeling of the microbial transport of the indicator bacteria *E.coli* was analyzed with a water quality template in the model ECOLab.

Numerical solution of the 3D incompressible Reynolds-averaged Navier-Stokes (RANS) equations are applied in this study based on MIKE 3 model system developed by DHI Water and Environment, Denmark (2008). The modeling system contains continuity, temperature, momentum, salinity and density, where the density calculations mainly depend on the temperature and the salinity.

In this 3D model (MIKE 3), the free surface motion is taken into account using a sigma-coordinate transformation approach. The spatial discretisation of the governing equations is performed using a cell-centered finite volume method. Computational mesh shaping is the first step in this work, which requires information about boundary conditions and bathymetry. The meteorological forcing data collected from a database under the administration of the Swedish Meteorological and Hydrological Institute (SMHI). It includes data of sea temperature, wind, salinity, water level, river and tributary flows and also the wastewater discharges. In this study sensitivity study is performed for wind parameter and Rhodamine test is done to measure flushing rates of pollutants in the river which is done in 1972 by Svensson and Cederwall.

This dispersion model can give a practical and yet accurate tool for quantifying the dispersion process of chemical or pollutant discharges in the river Gota Alv after some further refinement of input data. On the basis of the reasonably good comparisons with field measurements, the model has the potential to be used successfully in predicting dispersion processes in river Gota Alv.

This study represents a first step towards high resolution modeling of the Gota Alv, which provides a great knowledge of the water quality management. It combines a HD model and a WQ model together. The approach used in this study provides a better understanding for the management of microbiological water quality at the scale of the whole river and a better basis for decisions on protection from water-borne diseases through drinking water consumption [5].

B. MIKE 21 & MIKE 3 Flow Model FM; Mud Transport Module

The MT module includes a mud transport model that simulates the transport, erosion, settling and deposition of cohesive sediment in brackish, marine, and freshwater areas. If polluted sediment is deposited in ecologically sensitive areas it may greatly affect local flora and fauna and also water quality in general. With the flexible mesh (FM) series it is possible to combine and run the modules dynamically. If the morphological changes within the area of interest are within the same order of magnitude as the variation in the water depth, then it is possible to take the morphological impact on the hydrodynamics into consideration.

Computational features of MIKE 21 and MIKE 3 are multiple bed layers, multiple sediment fractions, hindered settling, flocculation, inclusion of non-cohesive sediments, bed shear stress from combined currents and waves, morphological update of bed, consolidation, and tracking of sediment spills. The bed interaction/update and the settling velocity factors are handled in the MT module with the help of MIKE 21 & MIKE 3 models.

In this 3D model, the suspended sediment concentration near the bed is simply equal to the sediment concentration in the water cell just above the sediment bed. While in the 2D model, two different approaches are possible for computing suspended sediment concentration near the bed.

The spatial discretisation of the primitive equations is performed by using a cell-centered finite volume method. In this study in the horizontal plane an unstructured grid is used while in the vertical domain in the 3D model a structured mesh is used.

The input requirements are settling velocity, critical shear stress for erosion, erosion coefficients, critical shear stress for deposition, suspended sediment, power of erosion, concentration at open boundaries, dispersion coefficients, thickness of bed layers or estimate of total amount of active sediment in the system, transition coefficients between bed layers and dry density of bed layers. The main output possibilities are suspended sediment concentrations in space and time, net

sedimentation rates, sediment in bed layers given as masses or heights, computed bed shear stress, computed settling velocities and updated bathymetry. This module is operated through a fully Windows integrated Graphical User Interface (GUI) given in “MIKE 21 & MIKE 3 Flow Model Fm Mud Transport Module study” by DHI as a short description.

C. 3D Simulation of Wind-Induced Currents Using MIKE 3 HS Model in the Caspian Sea

In this case, three dimensional simulations of wind-induced flow patterns have been done using hydrostatic version of MIKE 3 model in the Caspian Sea. HD equations are solved using the mass conservation and the RANS equations. In the MIKE 3 models, factors such as eddy viscosity, bed friction, flood and dry major rivers inflow and water outflow through the Bay, wind stress and atmospheric pressure at the sea level, precipitation, evaporation has been included.

The Caspian Sea is divided into three distinct physical regions: the Northern, Middle, and Southern Caspian as reported [6]. Caspian Sea based on the approach of diagnostic simulations by numerical HD models. In this investigation the wind-driven currents simulated by using MIKE 3 HS FLOW MODEL in order to occur the flow patterns in different layers and also flow velocity component in x and y direction in the solution domain.

The hydrostatic (HS) model in MIKE 3 HD is a general numerical modeling system for simulation of unsteady 3D flow in bays, estuaries, and coastal areas as well as in lakes and oceans. It simulates flows taking into consideration bathymetry and external forcing such as tidal elevations, meteorology, currents and other hydrographic conditions as per the manual of MIKE 3 given by DHI.

In this study meteorological forcing in most HD models is undertaken by defining wind stress and/or pressure fields. Wind stress is an important factor in the observed circulation patterns and mainly, its effect on the surface currents. In this present work the wind data including wind speed (m/s) and wind direction (degree) components in 10 meter high from the sea surface and also surface pressure (hpa) as varying in space and time available from a re-analysis data of National Oceanic and Atmospheric Administration site (NOAA) was used.

The model used bathymetric data obtained from the ETOPO2 datasets. The coastline and the bathymetry digitized data were used from the Navigation Map of the Caspian Sea published by the Navigation and Oceanography Department of the Defense Ministry of the USSR in 1987.

Seasonally mean resulting of MIKE 3 HS model analyzed in four layers in 3 separate parts (respectively, North Caspian Basin, Middle Caspian Basin and South Caspian Basin) during 3 month. The purpose of this study is using MIKE 3 software to evaluate wind-driven flow patterns for different layers in the Caspian Sea [7].

D. A Study on Impact of Storm Surge by Typhoon in Saga Lowland and Surroundings Using Hydrodynamic Numerical Modeling

This HD modeling is to find out the impact of storm surge due to the typhoon that ever crossed the region especially in Saga Lowland area and the surroundings. There are 3 typhoons that gave big damages to the nation - typhoon Muroto (1934), Makurazaki (1945) and Ise-wan (1959). Most of the areas in Saga Prefecture are adjacent to the Ariake Sea mainly lowland areas which has a very small slope, so once the sea water enter these areas it will immediately create a large inundated area even knowing the fact that these areas are being used for offices, agricultural, residential, airport etc.

Typhoon characteristics is high wind speed with the wind direction changing and the higher the wind speed is accompanied by lower air pressure. The MIKE 3 Flow Model Flexible Mesh (MIKE 3 FM) developed by DHI in the frame of MIKE ZERO packages is used in this study.

The MIKE 3 FM is applicable to the simulation of hydraulic and related phenomena in lakes, bays, estuaries, coastal areas and seas. The input data requirements are bathymetrical data, topographical data, wind data (speed and direction), some of the water level at stations, and time step of simulation.

Songda, Nabi, and Wilda typhoons are compared taking into account the factors such as water level and current speed. Bathymetric data are obtained from the Ariake Project of Saga University in the form of water depth in the Ariake Sea and other areas in the southern of Kyushu Island. Topographic data are obtained, supplied by Geospatial Information Authority of Japan. Wind Data is collected in the form of wind speed and wind direction at Nagasaki station. The water level in some stations is also used for the calibration of the model.
It was found that the highest water level index belongs to typhoon Songda and highest current speed index produced by typhoon Wilda. The purpose of this study is using MIKE 3 software to evaluate the impact of these typhoons [8].

E. Numerical Modeling Approaches for Assessing Improvements to the Flow Circulation in a Small Lake

The goals of this paper were to investigate various options to improve the quality of water in the northern part of the lake by altering the local hydraulic flow conditions. 3D hydraulic and transport models were adopted in this paper to examine the hydraulic conditions under various wind forces and causeway structures.

The focus of this study is to find out possible options based on the numerical modeling results to improve flow conditions and water quality around Mask Island by partially opening-up the existing causeway structures to stimulate more flow activities.

The data used to drive and verify the model were collected from the field sites. Meteorological data was collected in the study area. Wind speed and direction, air temperature, relative humidity, and long and short-wave solar radiation were collected by National Water Research Institute (NWRI).

The wind sensors were provided for calculating the wind speed. An Acoustic Doppler Current Profilers (ADCP) was deployed to measure flow velocity vertical profile.

In this study a well-established 3D HD model, “MIKE 3,” developed by the DHI was used. It is a finite volume-based model with hydrostatic approximation, using an unstructured and flexible mesh.

MIKE 3 simulates unsteady 3D flows, taking into account bathymetry, density variation and external forces arising from meteorology, currents, water elevations and other hydrographical conditions. The mathematical foundation in MIKE 3 is the mass conservation equation, the RANS equations in three dimensions which include the effects of turbulence and variable density together with the conservation equations for salinity and temperature.

Several parameters in this model were adjusted and optimized, such as the bottom friction coefficient, calculation scheme for the horizontal and vertical eddies and the adjustment for the effects of the land and obstacles on the wind speed, but the modeled results did not show significant changes.

As expected from the simulation of wind-induced flows, agreements between the modeled and measured flows are found to be best in the surface layer. However, the comparisons also show a surprisingly good agreement in the bottom layer, which indicates that the model can well reproduce the bottom reverse flow. The model may show a better performance if the comparisons between model outputs and measurements were made in the region near the shore [9].

F. Modeling of Impacts from a Long Sea Outfall Outside of the Venice Lagoon (Italy)

A new Adriatic Sea outfall has been designed in order to discharge the wastewater after treatment in the Fusina plant, a large treatment plant located in Porto Marghera in the industrial area of Venice (Italy).The master plan of this study aims to reduce the annual nutrients loads discharged to the lagoon in order to prevent the proliferation of macro algae and the risk of the environmental crises. The plan also aims to reduce the concentration of micro pollutants in water and sediments to levels that ensure the protection of human beings from adverse effects regarding the consumption of fish and shellfish.

The Fusina Integrated Project deals with the most densely populated part of the lagoon watershed. It is based on the certain simple concepts: use water twice, treat all waters to higher standards, reduce sewage flow and discharge the residual outflow to the sea, away from the lagoon. Scope of this study was to evaluate possible effects of the discharge on Adriatic Sea outside of the Venice Lagoon by using HD model.

The technical approach to the study has been to use a 3D numerical model that simulates currents and transport of sewage and pollutants in the Adriatic Sea and in the coastal waters of Venice.

Two versions have been implemented in this study, each addressing part of the problem, first one is a short-term model that describes in detail the plume trajectory and identifies impact areas during a limited period of time and second one is a coarser model that addresses longer-term effects during a one-year period.

Initial dilution in the near-field has been addressed by using integral plume model. The HD model is used based on DHI's general 3D oceanographic model, MIKE 3 FM. Transports and decay of *E.coli* is described using the general ECOLab process interface.

Short term analysis was carried out for monthly variations for the analysis of calm conditions and long term analysis was carried out for finding tropic effects on water quality (for 1 year). Using a 3D numerical model that has the capability to describe both the detailed impacts of the sewage plume from a submerged sea outfall and the long term effects for the influence of the discharge of treated sewage from the Fusina treatment plant has been investigated in this study.

The present study, investigating the impacts generated by transferring the residual pollutant load to the sea and thus proved that the new outfall location is also compatible with the preservation of the coastal environment. Short term impacts concerning the conservative tracer distribution, the concentrations of sediments in suspension and the concentrations of *E.coli* were studied using a high resolution model, under different wind conditions. Results obtained show no impacts on water quality with reference to coastal water activities like mussel farming and bathing. Also for longer term effects on water quality such as eutrophication- related aspects (nutrients, chlorophyll-a, oxygen), which were evaluated using a full one [10].

G. South Elizabeth Channel Silt Curtain Pilot Study

The study is to represent an open bay environment adjacent to a littoral zone and was chosen subject to existing and appropriate HD conditions (i.e., at a minimum, a flow regime that was reasonably steady and of sufficient velocity to disperse sediments) using the MIKE 3 software, such that safety, environmental protection and navigation were not comprised. In this study MIKE 3 HD model is used.
In the present study turbidity and Total Suspended Solids (TSS) monitoring was conducted for 5 different surveys. Mobile surveys were conducted using a vessel-mounted ADCP to measure HD conditions (current velocity). In this study the measurement of turbidity was carried out using optical backscatter sensors (OBS). Collection of discrete water samples are carried out for the gravimetric analysis of TSS concentrations and laboratory measurement of turbidity.

The study area was selected based on the criteria which indicates that sediments to be dredged at the site containing sufficient fines to expect generation of a distinct plume and hence facilitating observations of interactions between the curtain and the plumes and the proximity to a shallow littoral zone which provided an opportunity to monitor dredge induced re-suspended sediments which is near to an area where concerns for environmental resource protection are routinely raised by regulatory agencies.

The pilot study was developed to meet the requirements outlined in the stipulation and order to monitor the effectiveness of a silt curtain at limiting the transport of dredging-induced re-suspended sediment and to evaluate the feasibility of silt curtain use in future Harbor Deepening Project (HDP) dredging within the Newark Bay Study Area (NBSA). To fulfill these requirements, a comprehensive field study was carried out which includes the five field surveys as follows:
1: Ambient Conditions Prior To Silt Curtain Installation
2: Dredge Plume Characterization Prior To Silt Curtain Installation
3: Silt Curtain Installation
4: Dredge Plume Characterization with Silt Curtain Deployed
5: Silt Curtain Removal

The site placement for the silt curtain in this pilot study was chosen to meet the requirements of the Stipulation and Order and was selected to represent the best possible location for success based upon existing HD conditions, navigation safety and environmental protection within the NBSA. Based on these findings it is found out that any future deployment of a silt curtain within the NBSA for HDP construction or maintenance is considered infeasible according to "South Elizabeth Channel Silt Curtain Pilot Study", (2012).

H. Numerical Study on River Plumes on a Southern Hemisphere Coast

The freshwater from the coastal rivers, accompanied by sediment and nutrients, runs into the continental shelf in the place where the suspended material is deposited. In the process of the freshwater discharge the river flow plume is one of the major visual phenomena. The water circulation and transport in the plume can influence the coastal circulation, the sediment dynamics and the ambient ecosystem health.

It is well documented that river discharge is one of the major forces to determine the plume size which means that the plume size and the river discharge are well correlated [11, 12]. The relationship has also been confirmed by analyzing the simulation results in this study.

In this study, the dynamics of a plume has been studied using a 3D MIKE 3 model. It is of great importance to obtain a better understanding of river plume hydrodynamics, especially in flood season, as the river plume has significant impacts on the human health and aquatic environment [13]. The MIKE 3, as one product of DHI package, operates 3D, primitive equation model for simulations of flows in coastal areas and seas. The inflow of the river is of uniform density and discharges with uniform velocity.

In this study, the influence of wind and tides are avoided, and the temperatures of both the river discharge and ambient coastal water remain unchanged at 17^{o}C and the salinity is the time dependent variable. There are various factors which significantly affect the evolution of the river plume, such as the bathymetry, river discharge, winds, tides and other coastal processes. It is obvious that the plume size increases typically with the river discharge increasing.

For investigating the dynamics of a river plume on a Southern Hemisphere coast a numerical model has been used in this study. Discussion about the dynamic influences of the Coriolis force and the river discharge on the evolution of the buoyant plume is done in the present work.

The Coriolis Effect is a deflection of moving objects when they are viewed in a rotating reference frame. In a reference frame with clockwise rotation the deflection is found to be on the left of the motion of the object on the other hand with the counter-clockwise rotation, the deflection is found to be on the right of the object. In the early 20th century, the term Coriolis force began to be used in connection with meteorology which is given in the introduction of classical mechanics in the year 1997.

According to the results obtained from modeling simulation it has been shown that these influences in the Southern Hemisphere are different to the Northern Hemisphere. The anti-clockwise Coriolis force in the Southern Hemisphere drives the river inflow to the left in vicinity of the river mouth as expected and the river discharge is nearly connected to the plume size which indicates that the plume size increases as the river discharge increasing. By comparing with the same plume properties in the Northern Hemisphere, the river discharge gives larger contributions for increasing the plume size in the Southern Hemisphere which is based on the current conclusion [14].

I. Implementation of a 3D Model for the North Sea and UK Surrounding Area

Increasing offshore activities in the North Sea have created a considerable interest in modeling of the oceanographic conditions and dynamics in this area, whose characterization is done by a strong tidal current system and high sea surface dynamics and hence the detailed knowledge of oceanographic conditions in this area is indispensable for marine transport and safety (harbours and navigation), coastal land planning (coastal cities with their beaches and outfalls) and marine resources (renewable energy, aggregates, aquaculture and fisheries, leisure and marine reserves). For fulfillment of these demands there is a requirement of higher level of resolution and accuracy from oceanographic modeling systems.

In North Sea the dynamic variability is influenced by temperature and salinity, tides and atmospheric forcing. This study is carried out to investigate these forcing and their effect in a modeling system. The influence of atmospheric pressure, wind speed, amount of sun light and ice coverage will also taken into consideration. The basic objective of this study is to implement and validate a high resolution 3D model (MIKE 3) of the North Sea under atmospheric, temperature forcing and tidal and salinity.

The data which is available on current speed, water level, bathymetry, salinity, temperature, air pressure, wind speed, cloud coverage, precipitation and evaporation are essential for analyzing HD condition, salinity and temperature distribution in the recent and past years for the development of baseline condition. Sensitivity analysis will be performed to study the relationship between model output and several input parameters.

The two modeling tools going to be applied in the present study are MIKE 21 FM and MIKE 3 FM, developed by DHI. MIKE 21 FM used to solve the depth integrated mass and momentum conservation equations while MIKE 3 FM used to deal with the three dimensional problem [15].

J. Hydrodynamic Modeling over a Sand Wave Field at Sao Marcos Bay, Brazil

The focus of this work is to characterize the small scale hydrodynamics using MIKE 3 model that control sediment transport at Sao Marcos Bay, along Ponta da Madeira Port Complex which is situated in Sao Luis.

Asymmetry, shape, height and migration of sand waves give the important information regarding sediment dynamics and orientation of bottom transport in estuaries and coastal channels.

The hypothesis generated by the model results which says that sediment transport gradients control migration patterns. Changes on bathymetric features and tidal phases also define the direction of subaqueous dunes migration. Activities that can potentially influence the hydrodynamics of these systems, such as mineral resources exploitation, aggregate mining, dredging, beach nourishment, navigation and port operations which requires the knowledge regarding sedimentary budget and transport directions, making sand waves to exercise a fundamental role in this relation.

In this study numerical modeling was based on topographic data, bathymetric campaigns, sediment samples and velocity ADCP monitoring stations along east margin of the bay. Velocity data was registered with an ADCP.

The application of numerical model which is HD module of the MIKE 3 software (DHI Water & Environment) is used [16]. It simulates unsteady 3D flows, taking into account density variations, bathymetry, tidal elevations, river fluxes and external currents. MIKE 3 simulates flow conditions discrediting momentum equations at a flexible mesh by using finite volume methodology. Field data analysis and HD modeling experiments provide the required and beneficial information to build up the knowledge about sand waves migration at Sao Marcos Bay.

K. Flow Structure through Pool- Riffle Sequences and a Conceptual Model for their Sustainability in Gravel-Bed Rivers

The analysis was held at the Red River Wildlife Management Area in Idaho in USA. The main aim of this study is to describe the pool-riffle flow structure and to relate it with the sustainability of this morphology using the MIKE 3 HD model. In this study flow jets (i.e. concentration of high flow velocities) are observed at all discharges and are characterized for different flow and pool bathymetry conditions. A calibrated 1D hydraulic model was used to simulate flow conditions through the entire meadow (MIKE 11).

The primary data used in the flow modeling contains grain size, channel topography and a measured stage-discharge relationship at the downstream boundary of the numerical domain. For model calibration, field measurements of Water Surface Elevations (WSE) and the velocity structure at a known discharge were used. Acoustic Doppler Velocimeter (ADV) and ADCP were used to measure discharge and vertical velocity profiles. The ADV worked better than the ADCP for the depths shallower than 20 cm. The ADCP was used for higher events. For bathymetry, water depth and water surface elevation the measuring tape which is attached to the GPS rod was used. Discharge was measured at 3 cross sections and four times the measurements are repeated per cross section to obtain an average value. MIKE 3 Flexible Mesh (FM) model was used in this work which is based on RANS equations.

To characterize the pool-riffle flow structure the MIKE 3 FM program was used in this study. Developed by DHI (Denmark), it is based on the three dimensional incompressible RANS equations, subject to the assumptions of the Boussinesq approximation and hydrostatic pressure. To describe the hydrodynamics, the model uses a comprehensive set of equations. The system of equations used in this study is very well described [17]. It was assumed that flux at the water surface (i.e. precipitation/evaporation) and infiltration at the sediment–water interface is negligible, with water entering or leaving the model domain only at the upstream and downstream cross sections. This was considered as a reasonable assumption as there was no noticeable difference in the discharge at the upstream and downstream boundaries of the study reach during each flow event.

3D hydraulic simulations and field observations for two self-formed pool-riffle sequences on a section of Red River, Idaho are analyzed in this study [18]. The predicted WSE and velocities agree well with the field observations which indicate that the numerical simulations are accurate and the model is well calibrated. The model is used to locate the spatial pattern of jets (or faster moving water in the cross section) through the study reach, with jets being defined as areas where the velocities exceed 90% of the maximum depth-averaged velocity for a given cross section.

Results obtained by implementing the HD model are satisfactory and gives the output data which is required for the proper analysis of flow pattern.

III. FLOW-GOVERNING EQUATIONS

The HD model is based on a flexible mesh approach. Numerical solution of the 3D incompressible RANS equations is applied based on MIKE 3 model system developed by DHI Water and Environment, Denmark (2008).

The modeling includes momentum, continuity, temperature, salinity and density, where the density calculations mostly depend on the salinity and on the temperature. In this 3D model, the free surface motion is taken into consideration by using a sigma-coordinate transformation approach. Using a cell-centered finite volume method the spatial discretisation of the governing equations is performed. In some studies in the horizontal plane an unstructured grid is used while in the vertical domain in the 3D model a structured mesh is used. HD equations are solved using the mass conservation and the RANS equations such as (only X-direction is shown for 2nd equation given in the manual of MIKE 3 (2007)):

$$\frac{1}{pc_s^2}\frac{\partial \rho}{\partial t}+\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=S_{MASS} \quad (1)$$

$$\frac{\partial u}{\partial t}+\frac{\partial uu}{\partial x}+\frac{\partial uv}{\partial y}+\frac{\partial uw}{\partial z}+2\omega(-v\sin(\emptyset)+w\sin(\emptyset)\ \sin(\lambda)=-\frac{1}{p}\frac{\partial p}{\partial x}+\frac{\partial}{\partial x}\left(\left(2v_t\frac{\partial u}{\partial x}\right)+\frac{\partial}{\partial y}\left(v_t\left(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}\right)\right)+\frac{\partial}{\partial z}\left(v_t\left(\frac{\partial u}{\partial z}+\frac{\partial v}{\partial z}\right)\right)+u_{SS}S_{MASS} \quad (2)$$

Where

ρ: Density
c_s: Speed of sound in water
u, v ,w: velocities in x, y, z directions
ω: Coriolis parameter
$\emptyset, \lambda$: Latitude, Longitude
V_t: Turbulent eddy viscosity
S_{MASS}: Source/sink term with
$S_{MASS} = \sum_{i_S=1}^{N_S} \delta\ (x-x_{s.is}, y-y_{s.is}, z-z_{s.is})qx_{s.is}$
δ: Delta function of source/sink coordinates m^{-3}
$x_{s.is}$, $y_{s.is}$, $z_{s.is}$: Coordinates of source/sink NO. i_s
q: Discharge at source/sink NO. is, m^3/s

IV. SUMMARY AND CONCLUSION

MIKE 3 presents a number of opportunities in the analysis of flow characterization, as evidenced by the various published studies. MIKE 3 is a computer program that simulates flows, cohesive sediments, water quality, and ecology in water bodies in three dimensions. MIKE 3 simulates unsteady flow taking into account density variations, bathymetry and external forcing such as meteorology, tidal elevations, currents and other hydrographic conditions. MIKE 3 is applicable to flow problems in which density variations and turbulence are important features. MIKE 3 provides the simulation tools if we want to model 3D free surface flows and associated sediment or water quality processes. MIKE 3 model is very significant for flow characterization. This model gives significant data which is very beneficial for analyzing water bodies. While conducting calibration and validation user friendliness in processing input data and analyzing output results must be also taken into account.

Most of the work reviewed in this paper based on the concept of 3D fluid behaviors. This paper presents a review on MIKE 3, described their modeling requirements and outlined the important role of MIKE 3 in the context of flow characterization. In this paper, it is pointed out that MIKE 3 simulates unsteady flow taking into consideration bathymetry, density variations and external forcing such as tidal elevations, meteorology, currents and other hydrographic conditions. By taking into account these parameters we can easily assess the behavioral changes of water bodies. MIKE 3 contains a wide range of hydraulic phenomena in the simulations and it can be used for almost any 3D application. It is usually suitable for studying phenomena like storm surges, tidal flows, wave-driven flows, oceanographic circulations, density-driven flows.

MIKE 3 presents a number of approaches for analyzing the various flow pattern of fluid. MIKE 3 is composed of three fundamental modules: HD module, the AD module and the turbulence module. Various features such as free surface description, density variations and laminar flow description are optionally invoked within these three fundamental modules. The data requirements must be fulfill according to the respective analysis. Data requirements and from where the data is collected is mentioned in the reviewed studies. Implementation of MIKE 3 model for flow characterization is proved to be beneficial as evidenced by the various published studies.

The most extensive application of MIKE 3 to water body analysis has been in relation to flow characterization. For the various studies, the main focus of analytical interest has been in flow field predictions, flow behavior pattern, sediment, wind force effects and river discharge. In all of the studies reviewed, the flow parameters were taken into consideration, and either MIKE 3 FM, MIKE 3 HD or MIKE 3 HS models were used in the analysis. Flows were also most often assumed to be steady. Various modeling techniques have been applied for analysis of particulate behavior. Modeling procedures related to certain application areas are continually developing. MIKE 3 modeling can be implemented to allow the scope for betterment of a number of techniques to improve accuracy and also to adopt better modeling techniques.

The HD model is based on a flexible mesh approach and numerical solution of the 3D incompressible RANS equations which applied in these studies. The advantages of MIKE 3 are discussed in this paper and believed that HD model has a powerful potential for evaluating the flow patterns. Implementation of adequate models is also very important factor. In the context of modeling, the research for realistic constitutive flow models will be of greater importance because of different results may be obtained depending on the constitutive model.

V. SCOPE OF THE RESEARCH

For implementing better modeling techniques MIKE 3 module can be used for advancement of a number of techniques to improve accuracy. This modeling technique is very useful in analyzing fluid behaviour and hence advantageous to be implemented on water bodies as mentioned in the above studies.

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TABLE I. Experiments and their Purpose

Name of Experiments	Purpose	References
Rhodamine test	To measure flushing rates of pollutants in the river	Svensson et al. (1972)
Acoustic Doppler Current Profiler	To measure hydrodynamic conditions (current velocity)	US Army Corps of Engineers (2012)
Optical Backscatter Sensors	To measure turbidity	US Army Corps of Engineers (2012)
Acoustic Doppler Velocimeter	To measure discharge	Caamano et al. (2012)

TABLE II. Software implemented and Associated Studies

Software	Associated studies	References
MIKE 3 FM, ECOLab	A Three-Dimensional Model of Gota Alv for Water Quality Simulation	Zhang (2009)
MIKE21, MIKE 3	MIKE 21 & MIKE 3 Flow Model Fm-Mud Transport Module	DHI (2011)
MIKE 3 HS FLOW MODEL	3-D Simulation of Wind-Induced Currents Using MIKE 3 HS Model in the Caspian Sea	Sharbaty (2012)
MIKE 3 FM	A Study on Impact of Storm Surge by Typhoon in Saga Lowland and Surroundings using Hydrodynamic Numerical Modeling	Dundu et al. (2012)

MIKE 3	Numerical Modeling Approaches for Assessing Improvements to the Flow Circulation in a Small Lake	He et al. (2011)
MIKE 3 FM, ECOLab	Modeling of impacts from a long sea outfall outside of the Venice Lagoon (Italy)	Bocci et al. (2006)
MIKE 3 HD	South Elizabeth Channel Silt Curtain Pilot Study	US Army Corps of Engineers (2012)
MIKE 3 HD	Numerical Study on River Plumes on a Southern Hemisphere Coast	Yu et al. (2010)
MIKE 21 FM, MIKE 3 FM	Implementation of a 3D Model for the North Sea and UK Surrounding Area	Beg (2013)
MIKE 3 HD	Hydrodynamic modeling over a sand wave field at Sao Marcos Bay, Brazil	Samaritano et al. (2013)
MIKE 3 FM, MIKE 11	Flow structure through Pool- Riffle Sequences and a Conceptual Model for their sustainability in Gravel-Bed Rivers	Caamano et al. (2012)