1 INTRODUCTION

The petroleum industry is absolutely critical for global production and people's living. However, many oil spills have been occurring due to human activities associated with oil exploitation and transport, including oil well blowouts, oil tankers accidents, and oil pipeline ruptures. Regardless of the high cost of cleanup work, oil spills cause tremendous environmental and human health problems in both short and long terms (Dew et al. 2015).

The 2010 Kalamazoo River oil spill in the state of Michigan (see Fig. 1) is one of the largest inland oil spills in U.S. history (Dollhopf & Durno, 2011), where approximately 1.1 million gallons of heavy crude oil due to a pipeline rupture were released. Following the oil spill, extensive oil cleanup and environmental remediation efforts have taken place (Dollhopf et al. 2014). The cleanup work took about 1.2 billion dollars as of 2014.

Although most of the spilled oil was collected, the spill is believed to have long-term impacts on the environment. One main reason is the formation and transport of oil-particle aggregates (OPAs), which are the mixture of oil droplets and sediment particles (Fitzpatrick et al. 2015). Figure 2 shows a simplified diagram of the processes associated with OPA formation. First, oil droplets are formed at the interface between surface floating oil and water body. Those droplets can be entrained into water body due to turbulence and mixing energy, where they can interact with particles such as suspended sediment particles. Due to the negative buoyancy of OPAs, they deposit on the river bed and can be resuspended and transported under different hydrodynamics scenarios. To understand the fate and transport of OPAs is very important for the cleanup work and future management during accidents.
Natural sediment traps along Kalamazoo River, e.g. cutoff channel and meanders, are very critical areas for the cleanup work and future management because high concentrations of OPAs can be expected to deposit there. Some artificial sediment trap structures were planned to be installed in order to promote deposition of OPAs in those areas and collect OPAs with dredging. Mahajan et al. (2013) built a two-dimensional (2D) model for a 38-mile reach of the Kalamazoo River quickly after the oil spill and used preliminary model results to evaluate the efficiency of artificial sediment traps. However, due to its structured mesh and limited mesh resolution, it was practically impossible to capture complex geomorphic features in the river system.

In this study, a 2D model with unstructured triangular mesh was developed and fine mesh resolution was applied to represent complex river geomorphology. The objectives are to understand the fate and transport of OPAs and how OPAs deposit in a sediment trap. Among many sediment traps in the waterway, MP14.75 sediment trap was selected for modeling purposes (Fitzpatrick et al. 2015b). Figure 1 shows the location and geomorphic features of the MP14.75 sediment trap. Two flow scenarios were simulated: the April 2013 high flow scenario and July 2013 low flow scenario.

2 MODEL DESCRIPTION

A code developed at Ven Te Chow Hydrosystems Laboratory, HydroSed2D, was used in this study. HydroSed2D was originally developed as a coupled two-dimensional shallow water model and bedload sediment transport model (Liu et al. 2008). Zhu (2011) implemented suspended sediment transport model into HydroSed2D. The model has been tested and applied to many studies helping to understand sediment transport problems (Zhu et al. 2011; Liu et al. 2012; Goodwell et al. 2014). The continuity and momentum conservation equations are described in the following.

\[
\frac{\partial h}{\partial t} + \frac{\partial (hU)}{\partial x} + \frac{\partial (hV)}{\partial y} = 0
\]

(1)

\[
\frac{\partial (hU)}{\partial t} + \frac{\partial (hUU)}{\partial x} + \frac{\partial (hUV)}{\partial y} - v_I \left( \frac{\partial^2 (hU)}{\partial x^2} + \frac{\partial^2 (hU)}{\partial y^2} \right) = -gh \frac{\partial h}{\partial x} - \frac{\tau^I_v}{\rho} + hfV
\]

(2)

\[
\frac{\partial (hV)}{\partial t} + \frac{\partial (hVU)}{\partial x} + \frac{\partial (hVV)}{\partial y} - v_I \left( \frac{\partial^2 (hV)}{\partial x^2} + \frac{\partial^2 (hV)}{\partial y^2} \right) = -gh \frac{\partial h}{\partial y} - \frac{\tau^I_v}{\rho} - hfU
\]

(3)

where h is water depth; (U, V) are depth-averaged velocities in x and y directions, respectively; \(v_I\) is turbulent viscosity; g is the gravitational acceleration; \(\tau^I_v\) and \(\tau^I_s\) are bed shear stresses in x and y directions, respectively; and f is the Coriolis parameter.

2.1 Bedload Transport Equations

Meyer-Peter and Muller’s formula (1948) is implemented to compute bedload transport rate.

\[
\frac{q_b}{DgRD} = 8 \left( \max \left( \frac{\tau^I_b}{\rho gRD} - \tau^*_{c_b}, 0 \right) \right)^{3/2}
\]

(4)

where \(q_b=(q_{sx}, q_{sy})\) represents bedload sediment fluxes; D is the sediment grain size; R=\(\rho_s/\rho-1\); \(\rho_s\) and \(\rho\) are densities of sediment and fluid, respectively; \(\tau^*_{c_b}=0.047\) is non-dimensional critical shear stress.

2.2 Suspended Load Transport Equations

The 2D depth-averaged conservation equation for suspended sediment transport can be expressed as follows:

\[
\frac{\partial (hC)}{\partial t} + \frac{\partial (hUC)}{\partial x} + \frac{\partial (hVC)}{\partial y} = \frac{\partial}{\partial x} \left( hD_{xx} \frac{\partial C}{\partial x} \right)
\]

\[
+ \frac{\partial}{\partial y} \left( hD_{yy} \frac{\partial C}{\partial y} \right) + \frac{\partial}{\partial x} \left( hD_{sy} \frac{\partial C}{\partial x} \right) + \frac{\partial}{\partial y} \left( hD_{sx} \frac{\partial C}{\partial y} \right) + v_s (E_s - c_b) + Q_c
\]

(5)

where C is the depth-averaged concentration of suspended sediment; \(D_{xx}, D_{yy}, D_{xy}\) and \(D_{yx}\) are diffusion coefficients; \(v_s\) is the sediment fall velocity which relates to the size of the sediment particles; \(Q_c\) is external source term; \(E_s\) represents entrainment rate; and \(c_b\) represents near-bed concentration of suspended sediment which relates to settling rates, \(c_b=\tau_oC\). \(r_o\) is a parameter to relate near-bed concentration to depth-averaged concentration. It can be estimated as 2.0, or computed by the following expression (Parker et al. 1987):

\[
r_o = 1 + 31.5 \left( \frac{u^*}{v_s} \right)^{1.46}
\]

(6)

where \(u^*\) is the shear velocity. The sediment entrainment rate \(E_s\) can be estimated according to Garcia & Parker (1991, 1993), as follows:

\[
E_s = \frac{AZ_u^5}{1 + \frac{A}{0.3}Z_u^5}
\]

(7)

where the empirical constant \(A=1.3 \times 10^{-7}\), and

\[
Z_u = \frac{u_z R_{ep}^{0.6}}{v_s}
\]

(8)
where \( u_s \) is the shear velocity associated with skin friction (García, 2008).

### 2.3 River Morphological Equation

The 2D Exner’s equation can be used to calculate the river morphological changes due to the sediment transport, as follows:

\[
(1 - \lambda_p) \frac{\partial z}{\partial t} + \left( \frac{\partial q_{sx}}{\partial x} + \frac{\partial q_{sy}}{\partial y} \right) = v_s \left( c_b - E_s \right) \quad (9)
\]

where \( \lambda_p \) is the bed porosity.

### 3 MODEL SET UP

The model uses the finite volume method and unstructured triangular meshes. Unstructured triangular meshes allow modelers to deal with complex geometry. The computational meshes is shown in Figure 3. The number of computational grids is 23,272. The mesh size is five meters. The domain boundary is the boundary of the 100-year floodplain.

![Figure 3. Computational meshes](image)

The bathymetry data was provided by Weston Solutions, Inc. (2014). River bed elevation was interpolated to the center of each grid. The interpolated bed elevation of three sediment traps is shown in Figure 3.

Scenarios of April 2013 and July 2013 were simulated as representative scenarios of high flow and low flow, respectively. The April 2013 high flow has a flood exceedance probability of 4% (25-yr recurrence interval). Upstream flow discharge and downstream water stage level were extracted from the EFDC2D modeling performed by LimnoTech Inc. (LimnoTech, 2014) and used as boundary conditions (see Fig. 4).

![Figure 4. Boundary conditions of April 9-29, 2013 and July 11-19, 2013 scenarios](image)

### 4 RESULTS

#### 4.1 Distribution of Depth-Averaged Velocity

Figures 5-6 show the depth-averaged velocity magnitude of two flow peaks in the April 2013 high flow scenario. At the first bifurcation more water flows into the main channel than the side channel; while at the second bifurcation velocity in the north channel is larger than that in the south channel. Fig-
Figures 7-8 show more detailed flow path at those two bifurcations with the flow discharge of 1332 cfs.

Figure 5. Distribution of velocity magnitude (MP14.75, 4:00 April 14, 2013)

Figure 6. Distribution of velocity magnitude (MP14.75, 12:00 April 21, 2013)

Figure 7. Flow path at 2nd bifurcation and confluence (MP14.75, 0:00 April 20, 2013)

Figure 8. Flow path at 1st bifurcation and confluence (MP14.75, 0:00 April 20, 2013)

Figure 9. Distribution of velocity magnitude (MP14.75, 0:00 July 12, 2013)

Figure 8 shows that at the first bifurcation more water flows through the main channel than the side channel. Flow velocities are much lower in the side channel. Sediment can be expected to deposit due to reduced flow velocity and associated gradient in bed shear stress and sediment transport capacity. At the second bifurcation, more water flows into the north channel, but the south channel flow velocity is not reduced as much as in the first bifurcation. There is a low-velocity zone at the confluence where sediment may deposit. Also, there is a “dead zone” at the south end of the south bifurcation channel which is also a potential deposition area. Immediately after the second confluence, there is another small side channel which bypasses some of the flow into a large floodplain, where deposition would occur due to much lower velocities.

Figure 9 shows an example of the velocity distribution in the July 2013 low flow scenario. The discharge was 298 cfs at 0:00 on July 12, 2013. The difference between the velocity magnitude and inundation areas between the two scenarios is evident.
HydroSed2D model is capable of simulating wetting and drying automatically. The important characteristic of this sediment trap is the channel bifurcation (where flow separates) and confluence (where flow joins together). Sediment deposition and erosion occurs due to the distribution of flow discharge and the change of velocities as well as bed shear stress. Figure 9 shows that during low flows the flow follows the main channel only, so that no water and sediment can flow into the bifurcation channel. Also, the sediment load is usually so low that not much morphological change happens.

4.2 Distribution of Bed Shear Stress

Similarly to the above depth-averaged velocity plots, Figures 10-12 show distributions of bed shear stress under high and low flow scenarios.

Bed shear stress provides similar patterns to velocity magnitude in terms of distribution. Moreover, it is a better indicator for sediment transport, especially the fate and transport of oil-particle aggregates (OPAs). In-situ flume and lab experiments suggest that the critical bed shear stress for OPA resuspension may be as low as 0.1 Pa (Waterman, 2015a,b). The areas with less than 0.1 Pa bed shear stress are those that are most likely to experience heavy submerged oil deposition.

For the high flow scenario during April 20-23, 2013, Figure 11 shows that bed shear stresses for the side channel area are mostly around or higher than 0.1 Pa. A downstream partial barrier was installed here. It seems that such a feature is required for the trap during high flow scenarios. While for the low flow scenario in July 2013, Figure 12 shows that water is flowing only in the main channels where bed shear stresses are mostly higher than 0.1 Pa.

4.3 Sediment Transport Simulation (100-year Flood Scenario)

A 100-year flood steady flow scenario was also simulated and sediment transport simulation was performed. This flow scenario was only done for MP14.75 and the sediment transport was only simulated for this flow at MP14.75 sediment trap. The flow discharge was 6500 cfs. Figures 13-14 show depth-averaged velocity magnitude and bed shear stress, respectively. Moreover, suspended sediment transport was modeled. The inlet sediment concentration was 130.4 mg/l (Soong, pers. comm.). The sediment particle size $D_{84}$ was estimated as 0.2 mm. Figure 15 presents the concentration of suspended sediment. The change of concentration indicates how sediment is transported in the domain. The concentration in the sediment trap channel was found to be much lower than that in the main stream before flow separates. Therefore, the sediment carried by...
the flow coming into the sediment trap would deposit it because of reduced transport capacity.

2D hydrodynamics and sediment transport models were built for a selected sediment trap in Kalamazoo River by applying HydroSed2D. The natural sediment trap areas have different geometric and morphologic conditions which result in OPAs deposition in the sediment traps. The modeling results were in good agreement with the depositional patterns observed in the sediment traps.

The models worked well for complex topographies and wet-dry conditions. Two flow scenarios were simulated. One was the April 2013 high flow scenario, while the other was the July 2013 low flow scenario. During low flows, no water generally flows into sediment traps. Deposition happens during relatively high flows when water flows into sediment traps and OPAs would deposit due to gradients in sediment transport capacity associated with low velocities and bed shear stress that were captured by the model predictions.

The depositional areas indicated by the models agree in general with the areas of heavy submerged oil found during the field surveys. The developed models are useful tools in the ongoing cleanup work and may also be useful for future management efforts. For instance, they can be used to evaluate the effects of dredging sediment trapping areas or other engineering efforts for oil removal from the river and its floodplain. It is known that artificial sediment traps were implemented in order to either enhance the trapping efficiency of the natural sediment traps or to create additional trapping areas. The models can be helpful for evaluating the potential impact of such measures as well as in pinpointing what locations might be better suited to capture OPAs.

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