INTEGRATED MODELING APPROACH FOR FATE AND TRANSPORT OF SUBMERGED OIL AND OIL-PARTICLE AGGREGATES IN A FRESHWATER RIVERINE ENVIRONMENT

Faith A. Fitzpatrick, U.S. Geological Survey; Rex Johnson, Global Remediation Technologies, Inc.; Zhenduo Zhu, University of Illinois Ven Te Chow Hydrosystems Laboratory; David Waterman, University of Illinois Ven Te Chow Hydrosystems Laboratory, Richard D. McCulloch, LimnoTech, Inc., Earl J. Hayter, U.S. Army Corps of Engineers; Marcelo H. Garcia, University of Illinois Ven Te Chow Hydrosystems Laboratory; Michel Boufadel, New Jersey Institute of Technology; Timothy Dekker, LimnoTech, Inc.; Jacob S. Hassan, U.S. Environmental Protection Agency; David T. Soong, U.S. Geological Survey; Christopher J. Hoard, U.S. Geological Survey; and Kenneth Lee, Fisheries and Oceans (Canada) and the Australian Commonwealth Scientific and Industrial Research Organisation

Abstract The Enbridge Line 6B pipeline release of diluted bitumen into the Kalamazoo River downstream of Marshall, Michigan, U.S.A., in July 2010 was one of the largest oil spills into freshwater in North American history. A portion of the oil interacted with river sediment and submerged requiring the development and implementation of new approaches for detection and recovery of oil mixed with river sediment. Hydrodynamic and sediment transport modeling became an integral part of containment and recovery operations for decision support about the potential fate and migration of submerged oil and oiled sediment. Three models were developed for the U.S. Environmental Protection Agency to cover a range of spatial scales of interest to onsite operations. Two-dimensional (2D) hydrodynamic and sediment transport models from the Environmental Fluid Dynamics Code and the sediment bed model SEDZLJ[1] were used to simulate potential resuspension, migration, and deposition of submerged oil and oiled sediment along a 38-mile reach of the Kalamazoo River affected by the oil from Marshall to Kalamazoo. An algorithm was added to SEDZLJ to represent three additional particle size classes of oil-particle aggregates (OPAs) with a range of sizes, specific gravities, and settling velocities. Field and laboratory experiments and flume tests were done to support the numerical modeling of OPAs. A three-dimensional hydrodynamic model was developed to simulate hydrodynamics and OPA tracking through Morrow Lake, the most downstream impoundment. This model incorporated wind and dam operations into high and low flow, lake drawdown, and containment simulations. Finally, a 2D unstructured grid model, HydroSed2D, was used to simulate flows and sediment transport along 1- to 2-mile segments of the Kalamazoo River around islands and through side channels and backwater areas that are particularly prone to submerged oil deposition.

Integrated models could be developed quickly due to the availability of information and services combined with spill response operations that included: bathymetry and topography data, field-based geomorphic mapping of submerged oil, and discharge measured at U.S. Geological Survey streamflow gauges. Modeling results were included in a multiple-lines-of-evidence approach that was used by the Federal On-Scene Coordinator and operations staff for decision-making related to assessment and recovery of submerged oil, as well as net environmental benefit analysis. Similar modeling approaches will likely be useful for future oil spills in riverine environments.

[1]Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

BACKGROUND

The Enbridge Line 6B pipeline release of diluted bitumen (dilbit) into the Kalamazoo River downstream of Marshall, Michigan in July 2010 was one of the largest freshwater oil spills in North American history (Fig. 1). Only the 2004 Delaware River (Philadelphia) spill of about 265,000 gallons of heavy crude oil (U.S. Coast Guard, 2005) and the nearly 800,000 gallon spill of diesel fuel into the Monongahela River, near Pittsburgh in 1988 (Clark and others, 1990) are comparable in size to the 843,000 gallon release reported by Enbridge from Line 6B (http://www.epa.gov/enbridgespill/). The spill happened during a flood with a 4 percent exceedance probability (Hoard et al., 2010). Much of the floating oil was recovered quickly following the spill using conventional methods such as surface containment, absorbent boom, vacuum trucks, and drum skimmers (Dollhopf et al., 2014). However, the remaining oil mixed with river sediment, submerged, and deposited along 38 miles of the river, requiring the development and implementation of new approaches for detection and recovery of submerged oil and oiled sediment (Dollhopf et al., 2014). These approaches included the development of integrated hydrodynamic models to better understand and predict the fate and transport of the residual oil and its association with sediments over the range of environmental conditions encountered as a consequence of changes in river flow and spill response operations.

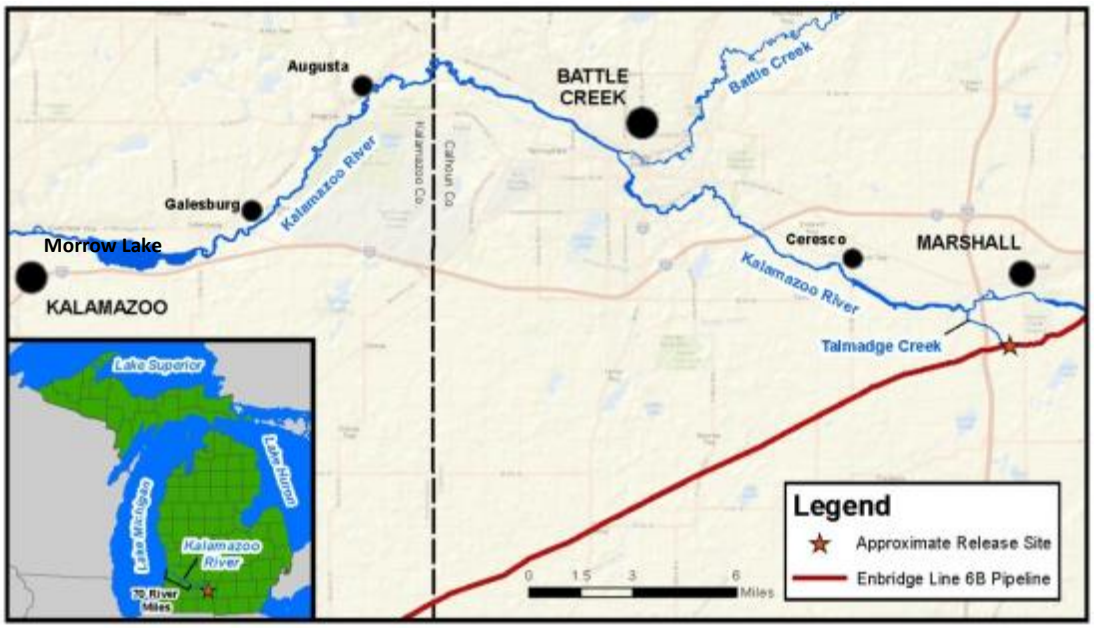

Figure 1 Location map of the Kalamazoo River affected by the July 2010 Enbridge Line 6B oil spill.

Hydrodynamic modeling originated with Enbridge in 2011 to help answer operational questions about the resuspension and downstream deposition of remaining submerged oil under different river flows scenarios and whether the oil could migrate past the most downstream impoundment, Morrow Lake (Enbridge Energy, L.P., 2012a, b). River flows in the Kalamazoo River can quickly increase by an order of magnitude, ranging from summer low flows of about 300 ft^3/s to rainfall or rain-snowmelt related runoff flows of greater than 3,000 ft^3/s. A set of hydrodynamic and sediment transport models using the 2-dimensional (2D) Environmental Fluid Dynamics Code (EFDC) was developed by Tetra Tech for Enbridge in 2011-12 to simulate river water levels, flows, velocities, shear stresses, sediment loads, and erosion and deposition patterns and rates along the 38 miles of the oil-affected Kalamazoo River (Enbridge Energy, L.P., 2012a, b).

A main assumption of the Enbridge modeling was that the transport characteristics of silt-sized sediment could be used as a surrogate for submerged oil. This assumption was based on the consistent spatial association of the remaining submerged oil with fine-grained soft sediment in slow-moving depositional areas of the river (Dollhopf et al., 2014) (Fig. 2). The Enbridge models were rapidly developed (within 3 months) using available data including topography from light detection and ranging (lidar) flown along the oil affected river corridor in 2011, and bathymetry from thousands of elevations associated with sediment poling assessments (agitation of river sediment using an aluminum pole with an 8-in diameter metal disc) for submerged oil (Enbridge Energy, L.P., 2012a). Data sets from two recently constructed HEC-RAS models for the upper and lower portions of the oil affected reach (Hoard et al., 2010; AECOM, 2011a, b; U.S. Army Corps of Engineers, Hydrologic Engineering Center, 2002, 2010) also were used for model setup and calibration. Discharge data from U.S. Geological Survey (USGS) gauging stations provided upstream and downstream boundary conditions as well as model calibration and validation comparisons. Water levels and oil marks collected by Enbridge and the U.S. Environmental Protection Agency (EPA) provided additional validation data.

Figure 2 Photos from the Kalamazoo River: (A) Oiled soft sediment in the vicinity of the Ceresco impoundment in 2012 and (B) typical oil sheen and globs on the water surface near soft sediment deposits in the Battle Creek Millponds in 2013.

Starting in 2013, a team of scientists and modelers continued the hydrodynamic and sediment transport modeling for EPA by updating the Enbridge models with additional data. Efforts were focused on expanding simulations using additional spatial scales and operational considerations including containment and water-level drawdowns in impoundments. The physical properties of the oiled sediment, including its persistence in the environment, were also reassessed in terms of the original representation of submerged oil as being transported with silt particles in the models. Repeated visual observations of spontaneously releasing globs from agitation of sediment during poling assessments, observations of oil globs in sediment cores, and ultraviolet epi-fluorescence microscopy of oil and sediment mixtures indicated that the oiled sediment was likely in the form of oil-mineral aggregates, similar to those that readily form in marine environments (Lee, 2002; Lee et al., 2011; Lee et al., 2012; Dollhopf et al., 2014). Aggregates were renamed oil-particle aggregates (OPAs) for the Kalamazoo River in recognition that a portion of the particulate matter is composed of organic as well as mineral particles. With the addition of the new field and laboratory data, a new set of sediment classes representing typical OPAs for dilbit in the Kalamazoo River were added to an existing sediment transport model. Updated and new models were developed to help answer operational considerations for continued recovery of submerged oil in the Kalamazoo River through the 2014 dredging efforts (Dollhopf et al, 2014).

The objectives of the 2013-14 EPA models are summarized in the following questions:

- Where and under what streamflow conditions will the remaining submerged oil and oiled sediment resuspend, transport, and settle along the river?
- What will happen to the remaining submerged oil and oiled sediment after dredging the impoundments and sediment traps?
- Will more submerged oil migrate into Morrow Lake and what conditions will allow it to pass through Morrow Dam?
- What are the effects of containment and recovery strategies on the migration potential of remaining Line 6B submerged oil?

This paper describes the design and framework of EPA's integrated modeling approach for simulating the fate and transport of submerged oil and OPAs in the Kalamazoo River following the 2010 Enbridge Line 6B release of dilbit. Whereas the final results of the modeling effort were not available for release at the time of this writing (October 2014),updated and new model results were used as they became available, during the decision-making process for remaining oil in the river in the Fall of 2012 through 2014.

THE KALAMAZOO RIVER

The Line 6B pipeline release happened in a wetland adjacent to Talmadge Creek 2 miles upstream of its confluence with the Kalamazoo River near Marshall, in Calhoun County Michigan (Figure 1). The drainage area of the Kalamazoo River near Marshall is 449 mi^2 and more than doubles in size at the downstream end of the oil-affected reach near Comstock with a drainage area of 1,010 mi^2 in large part because of the addition of Battle Creek, a tributary with a drainage area of 241 mi^2. The downstream end of the oil-affected reach is approximately 70 miles upstream of the river's confluence with Lake Michigan. The Kalamazoo River experiences a continental climate with about 32 in. of precipitation and over 40 in. of snowfall annually. Average July temperatures are 72° F and January temperatures are 24° F. Surficial geology mainly consists of glacial outwash composed of sand and gravel, as well as medium to coarse textured glacial till (Monaghan and Larson, 1984). Soils have mainly sandy loam textures (U.S. Department of Agriculture, 1994).

The oil-affected reach between Marshall and Kalamazoo has three impoundments – Ceresco, the Mill Ponds near the City of Battle Creek, and Morrow Lake. Flows are minimally affected by power plant releases at Marshall, on Battle Creek, and at Morrow Dam. The width of river varies between about 75 and 200 ft and is generally wide with a width/depth ratio of 40 and a gentle slope of 0.06 percent (3.14 feet/mile) (Tetra Tech, 2011). Water depths range from about 1 to 4 ft. The bottom is composed of gravel, cobble and boulders in the main channel in riffles and thick deposits of organic-rich muck in impoundments. Aquatic vegetation is abundant in summer months. The floodplain of the river is almost completely forested wetland which gives the suspended and bottom sediment a relatively high organic matter content, on the order of 20 percent or more. The river contains many islands, bars, and oxbows. Deposition of submerged oil associated with the Line 6B release occurred along channel margins, backwaters, side channels, oxbows, and in impoundments. Resuspension of submerged oil and settling downstream was evident in repeated poling assessments following floods (Dollhopf et al., 2014).

MODELING DESIGN AND FRAMEWORK

The updated modeling efforts encompassed three main modeling types for simulating submerged oil and oiled sediment transport resuspension, migration, and settling in areas of the river with continued issues with submerged oil: (1) a 2D EFDC model (Hamrick, 1992) of the 38-mile oil-affected reach of the Kalamazoo River; (2) a 3D EFDC model (Hamrick, 1992) for Morrow Lake that accounted for wind and subsurface withdrawals at Morrow Dam; and (3) nested sub-models of enhanced sediment traps using HydroSed2D (Zhu, 2011). These three models, with updated sediment transport algorithms and sediment properties, were needed to address questions at the appropriate spatial scales being asked by operational response staff. It was necessary to have a multidisciplinary modeling team for this work including expertise in heavy oil and sediment transport to be able to develop new algorithms for OPA resuspension, migration, and settling. The USGS, GRTusa, and Weston, Inc. provided coordination, oversight, and direction for the new models, as well as direct and rapid communication with operations staff and the Federal On-Scene Coordinators (FOSCs). They also worked with Tetra Tech and reviewed the 2012 Enbridge model. LimnoTech, Inc. updated the 2D EFDC model. The U.S. Army Corps of Engineers (USACE) developed the OPA algorithm that was coupled to SEDZLJ and conducted onsite SEDFLUME tests (Perkey et al., 2014). The University of Illinois Ven Te Chow Hydrosystems Laboratory (VTCHL) developed the 3D EFDC model, the HydroSed2D model, and conducted *in situ* flume tests and laboratory experiments for OPA. Oil experts from the New Jersey Institute of Technology, and the Canada Offshore Oil, Gas and Energy Research Centre at the Bedford Institute of Oceanography (COOGER) guided laboratory experiments and flume tests and overall modeling approaches.

The modeled flows encompassed a range of flow conditions (Table 1). The updated 2D EFDC models overlapped with two flow simulations included in the Enbridge model for comparison purposes. For the floods, the peak flow associated with the July 2010 flood during the oil spill had a 4-percent probability of the event being equaled or exceeded in any given year for the Marshall USGS streamflow gauge and a 20-percent probability downstream of the Battle Creek confluence (Hoard et al., 2010). The April 2013 high flow also had an exceedance probability of 20 percent, and had corresponding velocity measurements and suspended sediment samples. For the October-November 2011 high base flow period, these flows were equaled or exceeded 20 percent of the time over the period of record and the time period was chosen that overlapped with velocity measurements. The July 2013 low flow was included to represent depositional conditions in the river with flows being equaled or exceeded 50 percent of the time over the period of record. The July 2013 low flow also was chosen to examine the potentially erosional effects in Morrow Lake during low flow from the bottom draw turbines at Morrow Dam. The August 2012 low flow period was used to simulate containment effects on flows when there were corresponding velocity measurements. Lastly, mean daily flows from July-October and November-January from the Kalamazoo River near Battle Creek streamflow gauge were used for simulations of water level drawdowns in Morrow Lake to assist in decision making on whether to dredge oiled sediment in Morrow Lake delta or excavate in the dry.

Table 1 Types of models and in-common flow scenarios for 2D EFDC, 3D EFDC, and HydroSed2D. [H, hydrodynamic; S, sediment transport; PT, particle tracking; O, Oil-particle aggregate transport]

Model Description	Jul 2010 Oil spill flood	Oct-Nov 2011 High base flow	Aug 2012 Low flow	Apr-May 2013 flood	Jul 2013 Low flow	Flood 1-percent exceedance probability	Mean daily Jul-Oct, Nov-Jan
2D EFDC	H[1]	H[1], S[1], O		H	H, S		H[2]
3D EFDC			H[3]	H, PT	H, PT		H[2]
HydroSed2D				H	H	H, S	

[1]Updated simulations for comparison with the Enbridge model.
[2]Simulated Morrow Lake drawdown.
[3]Containment added in Morrow Lake delta.

The Enbridge 2D EFDC model was assembled from new and existing bathymetric and topographic data collected up through the fall 2011 (Enbridge Energy, L.P., 2012a, b). Boundary conditions were established using available streamflow data at five USGS gauges along the Kalamazoo River and its tributaries between Marshall and Comstock. Suspended sediment concentration and particle size data were not available for the streamflow gauges in the modeled reach and had to be assembled from a larger geographic area of representative locations on upstream and downstream streamflow gauges on the Kalamazoo River and on adjacent streams. Some sediment transport parameters were estimated from existing published literature. Bathymetry data were generated from poling assessment data points, combined with surveyed longitudinal profile points, single beam survey of Morrow lake bathymetry conducted in September 2010, channel cross sections measured for the HEC-RAS modeling, and flood inundation mapping. For floodplain topography, 1-ft contours were generated from the 2011 Enbridge lidar data used in the HEC-RAS modeling and flood inundation mapping for the entire area within the 100-yr floodplain boundary (AECOM, 2011a, b). Banklines for the riverine grid were drawn in a geographic information system (GIS) from November 2011 aerial imagery raster files at a scale of 1:100. Streambed characteristics for particle sizes were applied to the grids from 2011 surficial core data assigned to specific geomorphic mapping units and supplemented with substrate types recorded in poling assessments.

The updated 2D EFDC hydrodynamic-sediment transport model was compared with the Enbridge model, as well as used to run new simulations for 2013 high and low flows. The updated model was run with the Sandia National Labs version of EFDC (SNL-EFDC), which incorporates the sediment transport algorithms of SEDZLJ (Jones and Lick, 2001) instead of the standard sediment transport module included in the Enbridge model. Similar to the Enbridge model, the updated model had a domain of the entire oil-affected reach of the Kalamazoo River and consisted of two base grids, one for in-channel flows, called the riverine grid, with a boundary fitted curvilinear-orthogonal horizontal grid network, and another for out-of-bank flows, called the floodplain grid, with a finer-scaled Cartesian grid network with cells of approximately 15 x 15 m. The Cartesian grid network was needed for simulating overland flood flows beyond the sinuous channel. The sediment transport and OPA simulations were run only using the riverine grid. The updated 2D EFDC hydrodynamic model provided flow inputs and

checks for the HydroSed2D models and overall checks with the 3D EFDC model for the upstream delta portion of Morrow Lake.

The domain of the 3D EFDC model (Hamrick, 1992) was Morrow Lake and its dam (Fig. 1). The model incorporated wind data and a 3D view of the gates and turbines at Morrow Dam. This was important to consider because the turbines withdraw a substantial amount of flow, especially during low flow conditions. It was thought originally that outflows from the updated 2D EFDC model would serve as inflows for the 3D EFDC model at the upstream end of Morrow Lake; however, measured water levels at the upstream end of Morrow Lake were used instead because it was thought that measured water elevations were more quantitative for upstream boundary conditions than simulated flows. The 3D EFDC hydrodynamic model provided simulations of the effects of a water level drawdown in Morrow Lake on velocity and bed shear stresses in the upstream delta area. A simplistic design of subsurface containment curtains in Morrow Lake delta were also explored for a July 2012 low flow period that had corresponding velocity measurements along the containment curtains.

The HydroSed2 model code was previously developed at the VTCHL (Liu et al., 2008; Zhu, 2011). The model was chosen to run simulations at a subset of enhanced sediment traps at mileposts (MP) along the spill-affected reach of MP 10.4, MP 10.5, MP 14.75, and MP 21.5 because its unstructured triangular mesh could be detailed enough to represent complex river geomorphology of backwaters (MP 10.4, 10.5), side channels and islands (MP 14.75), and meander cutoffs and oxbows (MP 21.5). An example sediment transport run was included for MP 14.75 and part of the Mill Ponds impoundment.

Common outputs for all models included maps of velocity magnitudes and bed shear stress for the hydrodynamic models. Results from the hydrodynamic models were felt to be the most robust because of the relative wealth of water level, velocity, and discharge data available for calibrations and validation. Initially, velocities of less than 30 cm/s were associated with submerged oil depositional areas and a critical bed shear stress for erosion of 0.4 Pa was used as a conservative estimate of areas where erosion was likely.

Sediment transport runs were more time consuming and had less validation data. Keeping this in mind, fewer runs were done for the 2D EFDC and HydroSed2D models. Typical output included maps of net erosion and deposition. For the 3D EFDC model, less time was spent on sediment transport and instead a Lagrangian particle-tracking model was developed for OPAs.

At the time of this writing (October 2014), documentation for the individual models (2D EFDC, 3D EFDC, HydroSed2D, OPA algorithm) were in the technical review stage. By the time of the SEDHYD 2015 conference, the documents should be available to the public. Some of the datasets that made these models possible to develop relatively quickly for submerged oil and OPAs are highlighted below.

UPDATED DATA SOURCES

The Enbridge models were calibrated in the Spring 2012 to discharge, water surface elevation, and velocity using USGS data from streamflow gauges and other measurements collected by Enbridge and the USGS in 2010-2011 (Enbridge Energy, L.P., 2012a, b). Erosion and sedimentation rates and sediment loads could not be calibrated or validated because no sediment data were available; however, historical suspended sediment data were used from an upstream streamflow gauge at Albion, Michigan and outputs were visually checked against depositional

areas mapped in the geomorphic surfaces unit maps. Model sensitivity analyses were performed on several input parameters to assess how small variations might affect model outputs. Results from these analyses indicate that the models were most influenced by flow and bathymetry and that more data were needed for these and for sediment transport characteristics.

The three new sets of models included major updates of bathymetry, floodplain topography, tributary flow inputs, dam configurations and ratings, channel roughness, and suspended sediment characteristics from data collected in 2012-14 (Table 2). Inclusion of wind data in the 3-D model was important because the majority of Morrow Lake is less than 6 ft deep, which allows for wind to establish strong vertical circulation cells with upwellings and downwellings. The stage/discharge curve was developed for Morrow Dam with the help and experience of the dam operators.

Table 2 Selected major updates in data inputs and calibration for the U.S. Environmental Protection Agency updated 2D EFDC, 3D EFDC, and HydroSed2D models.

Data Type	**Description**
Grids	2D EFDC grids same as Enbridge model, new grids for 3D EFDC and HydroSed2D
Bathymetry and HEC-RAS	Based on multiple sources – poling assessments, surveyed elevations and cross sections, acoustic surveys. Updated with additional data collected in 2012-13, including new HEC-RAS cross sections. Redeveloped bathymetry raster melded with topography at banklines.
Floodplain topography	New county lidar. Redeveloped topography raster.
Tributary flow inputs	Tributary flows redistributed based on drainage area
Dam configurations	Configurations for all dams updated, including dam geometry. Headwater elevations and 3-part stage/discharge rating curve were need for the powerplant operations at Morrow Dam.
Channel roughness	Roughness recalibrated using additional stage and velocity data
Suspended sediment concentration and particle size	Concentration/discharge curves updated with suspended sediment data collected at five U.S. Geological Survey streamflow gauges during six events 2012-14.

Even though there were major data gaps and the Enbridge 2D EFDC model had to be constructed quickly, preliminary model results for flow, water levels, velocity, and shear stress were carefully considered by operations staff. The models helped to verify areas of the river that likely changed from depositional during lows to erosional during high flows. The models also were used for prioritizing and verifying the depositional characteristics of enhanced sediment traps during a range of flows (Mahajan et al., 2013).

Recent developments in remote sensing made it possible to construct detailed, complex hydrodynamic models for a long stretch of the river relatively quickly. High-resolution lidar data were available for constructing detailed topography of the floodplain. High-resolution survey-grade global positioning systems were used to collect the geospatial coordinates of several thousand poling assessment points, which could be used for bathymetry. Powerful and organized onsite GIS capabilities made it possible to construct detailed and complex maps on a daily basis. Acoustic/sonar methods, combined with survey-grade GPS, were used to collect reliable and detailed velocity (e.g., stationary and transect data) and discharge measurements.

SEDFLUME AND IN SITU FLUME TESTS

In 2012, there was a lack of quantitative data that could be used for sediment transport model calibration and validation including oiled sediment and OPAs. River bed substrate was represented in the Enbridge model with selected sediment core data from 2011 applied to mapped geomorphic surface units with simplified sediment types (Enbridge Energy, L.P., 2012a). For the updated models, the Enbridge database was supplemented with additional data derived from sediment cores collected in 2012, onsite SEDFLUME tests of nine cores by the USACE (Perkey et al, 2014), and onsite *in situ* flume tests at five sites by the VTCHL (report in draft at time of this writing) in 2013.

The onsite flume-style erodibility tests were done in three general areas—the Mill Ponds, the downstream end of Morrow Lake (SEDFLUME only), and the upstream delta area of Morrow Lake (Perkey et al., 2014). Most of the tests were done to represent the cohesive layered organic-rich silt and fine sand deposits in Morrow Lake delta with moderate to heavy oiling conditions. *In situ* flume tests were done at a subset of the SEDFLUME core locations.

The two flumes measure potential erosion in different ways, making the results complimentary. The mobile SEDFLUME measures gross erosion rates with depth in a core at various shear stresses, as well as physical properties specific to vertical layering. The *in situ* flume tests measured erodibility of the near-surface sediment over a larger area than that of a single core. The *in situ* flume estimates bed shear stress and net erosion rates based on the mass of sediment eroded at a range of discharges which complements the SEDFLUME test results.

These tests were also done in areas that had repeated agitation toolbox techniques done as part of 2011 submerged oil recovery efforts (Dollhopf et al., 2014). Using a combination of results from these tests, literature values, and hydrodynamic results, bed layer properties of particle size, wet bulk density, critical shear stress for erosion, and erosion rates were generated for the updated 2D EFDC SEDZLJ model.

LABORATORY PROPERTIES OF OIL-PARTICLE AGGREGATES

Laboratory experiments and flume tests were done by VTCHL in 2013-14 to specifically characterize and quantify the weathering characteristics of Cold Lake Blend dilbit and the properties of OPAs formed by its subsequent mixing in the presence of Kalamazoo River sediment. The properties of interest for OPAs included the shape and arrangement (Fig. 3), oil droplet size, oil density, number of oil droplets in an OPA, size of OPA, density of OPA, settling velocity, and critical shear stress to entrain OPAs. The first laboratory tests were to weather the diluent from the bitumen while tracking oil mass loss and oil density and viscosity over a range of temperatures found in the Kalamazoo River. The results from these tests confirmed that weathered Cold Lake Blend remained positively buoyant at room temperature, similar to test results by Belore (2010).

The size distributions of oil globules within OPAs and the OPAs themselves were tested with an orbital shaker run at a range of mixing energies while held at room temperature. The globule size is a function of mainly the viscosity of the oil and amount of turbulence, which is commonly characterized with the turbulent kinetic energy dissipation rate. To form OPAs, the weathered bitumen was mixed in the shaker with Kalamazoo River sediment, and the mixing energy, time, sediment type, and sediment concentration were varied. Photography was used to capture the

size of the large globules and a Laser In-Situ Scattering and Transmissiometry (LISST) instrument was used for the small globules.

The OPA also was examined under an ultraviolet epi-fluorescence microscope using similar techniques as those used by Lee et al. (2012) and Ma et al. (2009). Preliminary results from these tests indicate that the OPAs generated in the laboratory tests were composed of complexly shaped aggregates of oil globules ranging from about 10 to 100 μm with attached particles of about 10 μm or smaller. The most common OPA type observed in the photomicrographs were the single and multiple droplet aggregates as illustrated in Figure 3A; solid-type aggregates were observed when unconventional mixing conditions were implemented.

Annular flume experiments were run to determine the critical bed shear stresses associated with re-entrainment of the OPA from the bed into the water column. In addition, a settling column was used to measure OPA settling velocities.

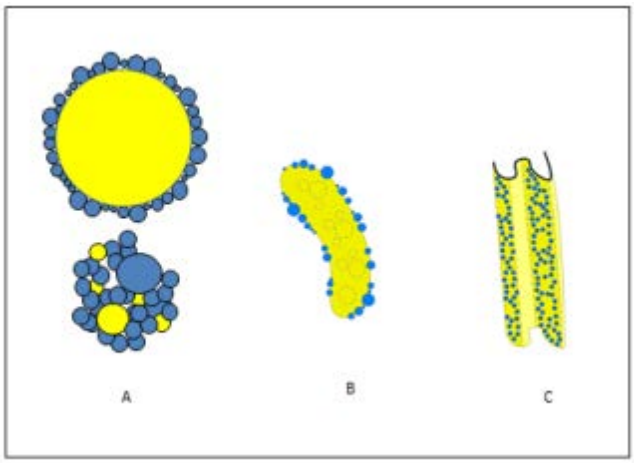

Figure 3 Types of oil-particle aggregates: (A) single and multiple droplet aggregate, (B) solid aggregate of large, usually elongated mass of oil with interior particles (dashed blue circles), and (C) flake aggregate of thin membranes of clay aggregates that incorporate oil and fold up (modified from Stoffyn-Egli and Lee, 2002). Blue color represents particles and yellow represents oil.

Results from these tests were used, along with other field data, for characterizing OPA properties in SEDZLJ and 3D EFDC particle tracking models. Within these models, the OPA maintains a stable form. Future models could be developed from these data to simulate the mechanisms responsible for the formation and breakup of OPAs in freshwater riverine environments.

DEVELOPMENT OF AN OIL-PARTICLE AGGREGATE ALGORITHM

A preliminary simple algorithm for OPAs was developed by the USACE for inclusion in the Kalamazoo River SEDZLJ model. The algorithm represents oiling conditions in the river in 2012, after formation of OPAs. The algorithm uses existing data from other studies of OPAs (Lee et al., 2012), onsite observations from poling assessments and cores, and preliminary results from VTCHL experiments and flume tests. Three groups of OPAs have been included in the model, in recognition that there are likely multiple sizes and densities of oil globules and OPAs in the riverbed. The groups, which are considered substrate classes in SEDZLJ, range from a large 2-mm single oil globule with a 10-μm silt coating to more complex OPAs with multiple smaller globules and diameters of 31 μm and 100 μm. Densities range from just greater than the density of freshwater for the large oil globule with silt coating (1.034 g/cm^3) to somewhat

heavier and close to the density of organic matter for the OPAs (1.511 g/cm^3). Settling velocities range from 0.2 to 20+ mm/s, depending on the amount of oil relative to the size of the aggregate. A major assumption is that the OPAs stay intact, i.e., they do not breakup or disaggregate, during model runs. The bed layering in SEDZLJ required data on the mass fraction of OPA and its size, the density of the OPA, and erosion rate of each layer. The Kalamazoo River streambed from the 2012 Enbridge model was updated with SEDFLUME core data to obtain layer properties, and then further overlaid with 2012 oiled areas of the river to estimate properties of OPAs. The simplified transport algorithm for OPAs is a start for future modeling of OPA formation, transport, and deposition.

SUMMARY AND CONCLUSIONS

Multiple-scale hydrodynamic and sediment transport models were successfully developed in a rapid fashion to address operational questions regarding the fate and transport of submerged oil associated with the July 2010 Enbridge Line 6B spill. Preliminary hydrodynamic models covering several miles of river could be constructed quickly because of the relatively large amount of quickly collected bathymetry and topographic data during response operations and available discharge data at existing USGS streamflow gauges. An organized geographic information system allowed the daily addition of data that was made available immediately across a common platform for sharing inputs and results among models. Due to the length of the cleanup time, the 2012 Enbridge model was updated with more data on bathymetry, velocity, water levels, dam operations, suspended sediment, and streambed conditions. Results from the 2012 and updated models were part of a multiple-lines-of-evidence approach that was used by the Federal On-Scene Coordinator for decision-making related to assessment and recovery of submerged oil, as well as net environmental benefit analysis.

The updated models fill a niche in simulating submerged oil transport and fate, in that they are the first of their kind to model oil-particle aggregates (OPAs) in a riverine freshwater environment. It is hoped that the modeling approach used for the Kalamazoo River will be useful if future oil spills occur in similar freshwater environments and that characteristics of OPAs can be applied to lacustrine hydrodynamic models as well. Rivers in the Midwestern U.S. have characteristics conducive to formation, deposition, and resuspension of OPAs including suspended sediment in the water column (especially during floods), shallow depths, wide channels, relatively low gradient, abundant impoundments, and turbulent flows. These characteristics will likely result in the need for submerged oil recovery and oiled-sediment cleanup for both light and heavy crude oil spills, and a closer look at the ecological risks and potential benefits of physical oil dispersion mediated by the presence and availability of suspended particles.

REFERENCES

AECOM (2011a). “Kalamazoo River Flood Inundation Mapping—Hydraulics,” AECOM Technical Memorandum, June 2011.

AECOM (2011b). “Kalamazoo River Flood Inundation Mapping—Hydrology,” AECOM Technical Memorandum, June 2011.

Belore, R. (2010). “Properties and fate of hydrocarbons associated with the hypothetical spills at the marine terminal and in the confined channel assessment area,” Enbridge Northern Gateway Project, SL Ross Environmental Research LTD., Ottawa, Ontario, variable pagination.

Clark, R.M., Vicory, A.H., Goodrich, J.A. (1990). The Ohio River Oil Spill: A Case Study: Journal of American Water Works Association, 82(3), pp 39-44.

Dollhopf, R.H., Fitzpatrick, F.A., Kimble, J.W., Capone, D.M., Graan, T.P., Zelt, R.B., Johnson, R. (2014). "Response to heavy, non-floating oil spilled in a Great Lakes river environment: a multiple-lines-of-evidence approach for submerged oil assessment and recovery," Proceedings, 2014 International Oil Spill Conference, Savannah, GA, pp 434-448.

Enbridge Energy, L.P. (2012a). Kalamazoo River Hydrodynamic and Sediment Transport Model. Enbridge, 70 p., Attachments. Submitted April 20, 2012.

Enbridge Energy, L.P. (2012b). Kalamazoo River Hydrodynamic and Sediment Transport Model Report Addendum. Enbridge, 4 p., Attachments. Submitted May 8, 2012.

García, M.H. (Editor-in-Chief) (2008). Manual of Engineering Practice 110, "Sedimentation engineering," Environmental and Water Resources Institute (EWRI), American Society of Civil Engineers (ASCE), 1150 p.

Hamrick, J.M. (1992). "A three-dimensional Environmental Fluid Dynamics Computer Code: Theoretical and Computational Aspects," *Special Report No. 317* in Applied Marine Science and Ocean Engineering, Virginia Institute of Marine Science, Gloucester Point, VA., pp 1-64.

Hoard, C.J., Fowler, K.K., Kim, M.H., Menke, C.D., Morlock, S.E., Peppler, M.C., Rachol, C.M., Whitehead, M.T. (2010). "Flood-inundation maps for a 15-mile reach of the Kalamazoo River from Marshall to Battle Creek, Michigan," U.S. Geological Survey Scientific Investigations Map 3135: pamphlet, 6 sheets, scale 1:100,000.

Jones, C., Lick, W. (2001). SEDZLJ: A Sediment Transport Model. Dept. of Mech. and Env. Eng., University of California, Santa Barbara.

Lee, K. (2002). "Oil-particle interactions in aquatic environments: influence on the transport, fate, effect, and remediation of oil spills," Spill Science and Technology Bulletin, 8(1), pp 3-8.

Lee, K., Boudreau, M., Bugden, J., Burridge, L., Cobanli, S.E., Courtenay, S., Grenon, S., Hollebone, B., Kepkay, P. Li, Z., Lyons, M. Niu, H. King, T.L., MacDonald, S., McIntyre, E.C., Robinson, B., Ryan S.A., Wohlgeschaffen, G. (2011). State of Knowledge Review of Fate and Effect of Oil in the Arctic Marine Environment: Report for the National Energy Board of Canada, Arctic Roundtable: State-of-Knowledge Review of Fate and Effects of Oil in Arctic Offshore. Fisheries and Oceans Canada. 259 p.

Lee, K., Bugden, J., Cobanli, S., King, T., McIntyre, C., Robinson, B., Ryan, S., Wohlgeschaffen, G. (2012). UV-Epifluorescence microscopy analysis of sediments recovered from the Kalamazoo River: Dartmouth, Nova Scotia, Centre for Offshore Oil, Gas and Energy Research (COOGER) Report, October 24, 2012.

Liu, X., Landry, B., García, M.H. (2008). Two-dimensional scour simulations based on coupled model of shallow water equations and sediment transport on unstructured meshes," Coastal Engineering, 55(10), pp 800-810.

Ma, X., Cogswell, A., Li, Z., Lee, K. (2009). "Particle size analysis of dispersed oil and oil-mineral aggregates with an automated ultraviolet epi-fluorescence microscopy system," Environmental Technology, 29(7), pp 739-748.

Mahajan, R., Rodriguez, H., Plis, M., Hamrick, J., and Davie, S. (2013). "Use of sediment transport model to support remediation in river oil spills," Environmental and Water Resources Institute, American Society of Civil Engineers Annual Conference Proceedings.

Monaghan, G.W., Larson, G.J. (1984). Glacial Geology of Kalamazoo County, Michigan. East Lansing, Mich., Michigan State University, Department of Geology, 35 p.

Perkey, D.W., Smith, S.J., Kirklin, T. (2014). "Cohesive sediment erosion field study: Kalamazoo River, Kalamazoo, Michigan," U.S. Army Corps of Engineers Research and Development Center, Coastal and Hydraulics Laboratory, Vicksburg, MS, Letter Report, 16 p. + appendixes.

Stoffyn-Egli, P. Lee, K. (2002). "Characterization of oil-mineral aggregates," Spill Science and Technology Bulletin, 8(1), pp 31-44.

Tetra Tech, Inc. (2011). Oil Mark Survey Technical Memorandum. Marshall, MI, March 18, 2011.

Thibodeaux, L.J., MacKay, D. (Editors) (2011). Handbook of Chemical Mass Transport in the Environment. CRC Press, Boca Raton, FL, 614 p.

U.S. Army Corps of Engineers Hydrologic Engineering Center (2002). HEC-RAS River Analysis System, Hydraulic Reference Manual, version 3.1, [variously paged].

U.S. Army Corps of Engineers Hydrologic Engineering Center (2010). HEC-RAS, River Analysis System Version 4.1.0. Davis, CA.

U.S. Coast Guard, 2005, T/S ATHOS I Evaluation Report: U.S. Coast Guard National Strike Force Coordination Center, Elizabeth City, NC, 57 p.

U.S. Department of Agriculture Soil Conservation Service (1994). State Soil Geographic (STATSGO) Data Base. Fort Worth, Tex., 113 p.

Zhu, Z. (2011). Simulation of Suspended Sediment and Contaminant Transport in Shallow Water Using Two-Dimensional Depth-Averaged Model with Unstructured Meshes. Master Thesis, University of Illinois at Urbana-Champaign.