Technical Note

Computation of the Mixing Energy in Rivers for Oil Dispersion

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Abstract: With the increase in transport of oil by rail, the probability of oil spills in rivers has increased. Traditionally, focus has been placed on oil slicks moving on the water surface. However, the density of bitumen oil carried by rail within and from Canada to the United States can exceed that of freshwater, causing this oil to get submerged in the water column. This also has the potential of forming oil particle aggregates (OPAs) upon interaction with suspended sediments. The energy-dissipation rate is a key parameter for predicting the formation of oil droplets, and for this purpose, expressions are developed to estimate the energy-dissipation rate at various depths in the river using easily measured quantities such as water depth, streambed slope, and streambed roughness. The formulation showed that for a stream 30 m wide with a natural slope of 1/1,000 and roughness height of 1.0 cm, the average and maximum energy-dissipation rates are 0.01 and 0.22 W/kg, respectively. The average value is comparable to spilling breakers of height around 0.3 m, and the maximum value is comparable to those obtained from plunging breakers of 0.30-m-high waves. The large average value suggests that breakup of droplets in streams is higher than in the open sea under regular waves. **DOI: 10.1061/(ASCE)EE.1943-7870.0001581.** *© 2019 American Society of Civil Engineers.*

Introduction

The frequency of oil spills in rivers has increased due to the increased transport of oil by rail in the United States (National Academies of Sciences, Engineering and Medicine 2016), especially the bitumen-type oil produced in Canada (Lee et al. 2015). Traditional approaches dealing with oil spills in rivers focused on the transport of oil on the water surface (Shen et al. 1991; Yapa and Shen 1994). However, the spill of approximately 4.0 million L of diluted bitumen in the Kalamazoo River, Michigan, in 2010 (Dollhopf and Durno 2011) revealed that a considerable amount of oil formed droplets that spread downward in the water column, and some of them formed oil particle aggregates (OPAs) (Zhao et al. 2016, 2017), as addressed in recent works (Fitzpatrick et al. 2015; Jones and Garcia 2018). The formation of oil droplets from a slick increases with the mixing energy, namely with the energy-dissipation rate in the water (Baldyga and Podgorska 1998; Hinze 1955). The formation of oil droplets from a slick is labeled dispersion in the oil spill literature, which is different from shear dispersion commonly used in earth science (Rutherford 1994). Numerous investigations have evaluated the energy-dissipation rate due to waves (Drennan et al. 1996; Terray et al. 1996; Wickley-Olsen et al. 2007, 2008), and applications to produce the droplet-size distribution have been reported in various works [for example, by Zhao et al. (2014)]. Thus, if one needs to use a model to produce the droplet size, one needs to know, among others, the energy-dissipation rate in the river.

Using detailed computational fluid dynamic (CFD) models could produce the energy-dissipation rate. Examples of such codes include ANSYS Fluent and Delft3D. However, using CFD codes is very demanding, and for this reason, an analytical approach is proposed herein that uses easily measured properties of the river.

Approach

When the hydraulics in a river reach of length L (for example, $L = 10$ or 100 m) can be approximated as uniform and at steady state, the average velocity V in the river may be obtained using the Manning's equation (Bedient et al. 2013)

$$V = \frac{1}{n} R_h^{2/3} S_e^{1/2} \quad (1)$$

where V = average water speed (m/s) in the cross section; n = Manning friction coefficient, which represents the streambed roughness, whose values are commonly estimated visually as indicated in Table 1; R_h = hydraulic radius (m), which is the ratio of the cross section area to the wetted perimeter of the cross section and could be obtained based on estimation of the depth and width of the river (say by assuming a rectangular cross section); and S_e = slope of the energy head line (energy grade line), given by

$$S_e = \frac{\Delta H}{L} \quad (2)$$

where ΔH = drop in the energy head (m). For a uniform flow, the slope S_e is equal to the streambed slope, which could be estimated based on the topography along a bank of the stream. Thus, Eq. (1) can be rewritten

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Table 1. Typical values of Manning's n

Channel surface	n
Glass, PVC, and HDPE	0.010
Smooth steel and metals	0.012
Concrete	0.013
Asphalt	0.015
Corrugated metal	0.024
Earth excavation, clean	0.022–0.026
Earth excavation, gravel and cobbles	0.025–0.035
Earth excavation, some weeds	0.025–0.035
Natural channels, clean and straight	0.025–0.035
Natural channels, stones or weeds	0.030–0.040
Riprap lined channel	0.035–0.045
Natural channels, clean and winding	0.035–0.045
Natural channels, winding, pools, and shoals	0.045–0.055
Natural channels, weeds, debris, and deep pools	0.050–0.080
Mountain streams, gravel and cobbles	0.030–0.050
Mountain streams, cobbles and boulders	0.050–0.070

Source: Data from Bedient et al. (2013).
Note: HDPE = high-density polyethylene.

$$S_e = \frac{n^2}{R_h^{4/3}} V^2 \tag{3}$$

Combining Eqs. (2) and (3), one obtains the loss of energy head (m), which is given by

$$\Delta H = n^2 \frac{L}{R_h^{4/3}} V^2 \tag{4}$$

The total energy dissipated over a distance L is represented by the weight of the water multiplied by the head loss

$$E = \rho g \forall \Delta H \tag{5}$$

where ρ = water density; $\forall$ = volume of water of interest; and E = energy (J) dissipated over a distance L. To obtain the energy loss per unit mass, one divides by the mass, which is equal to $\rho\forall$. Thus, the quantity $g\Delta H$ is the energy loss per unit mass. Finally, to obtain the energy-dissipation rate, one needs to divide by time, T, resulting in

$$\bar{\varepsilon} = \frac{g\Delta H}{T} = g \cdot n^2 \frac{L}{T R_h^{4/3}} V^2 \tag{6}$$

where the second equality was obtained by substituting for ΔH by its expression from Eq. (4). Given that $L = V \cdot T$ and $R_h \approx h$ for a wide river, Eq. (6) becomes (W/kg)

$$\bar{\varepsilon} = \frac{g\Delta H}{T} = g \cdot \frac{n^2}{R_h^{4/3}} V^3 = g \cdot \frac{n^2}{R_h^{4/3}} \frac{1}{n^3} R_h^2 S_e^{3/2} = \frac{g}{n} R_h^{2/3} S_e^{3/2} \tag{7}$$

Thus, after solving Manning's equation [Eq. (1)] for the velocity V, one can compute the average energy-dissipation rate in the cross section using Eq. (7).

To obtain the energy-dissipation rate at various depths of the cross section, one could use the logarithmic law of the wall, which states that local energy-dissipation rate is given by

$$\varepsilon = \frac{u_*^3}{\kappa \cdot z} \tag{8}$$

where u_* = friction velocity; κ = von Karman constant ($\cong$0.4); and z = elevation from the local streambed. The value of z has to be larger than the roughness height z_o, which is on the order of centimeters in natural systems.

Integrating Eq. (8) over the depth and dividing by the total depth provides the average energy-dissipation rate. Thus, one has

$$\frac{\int_{z_o}^{h} \varepsilon dz}{h} = \frac{\int_{z_o}^{h} \frac{u_*^3}{\kappa \cdot z} dz}{h} = \frac{u_*^3 \cdot \ln\left(\frac{h}{z_o}\right)}{\kappa \cdot h} = \bar{\varepsilon} \tag{9}$$

The friction velocity is given by

$$u_*^3 = \frac{\kappa \cdot h \cdot \bar{\varepsilon}}{\ln\left(\frac{h}{z_o}\right)} \tag{10}$$

Furthermore, the energy-dissipation rate at various elevations from the bottom is given by

$$\varepsilon = \frac{\bar{\varepsilon}}{\ln\left(\frac{h}{z_o}\right)} \cdot \frac{h}{z} \tag{11}$$

Although z_o might not be well-determined (centimeters), its logarithm [in Eq. (11)] does not vary by much. For example, for a depth $h = 1.0$ m, the difference between selecting $z_o = 0.01$ m or 0.10 m (an order of magnitude difference) affects the estimation of ε [Eq. (12)] by only twofold, because $\ln(1.0/0.01) = 4.60$ is only the double of $\ln(1/0.1)$.

Relation to Bottom Shear Stress

The shear stress at the bottom of the river is used commonly to determine the suspension of deposited sediments. It is an important parameter used in modeling sediment transport and could be measured in the laboratory. The shear stress is given by

$$\tau_o = \frac{1}{2} \rho u_*^2 \tag{12}$$

Using Eq. (12), one obtains

$$\tau_o = \frac{1}{2} \rho \left(\frac{\kappa \cdot h \cdot \bar{\varepsilon}}{\ln\left(\frac{h}{z_o}\right)} \right)^{2/3} \tag{13}$$

Thus, one could use the shear stress from sediment-transport models to estimate the average energy-dissipation rate using Eq. (13).

In summary, given n and the river properties, one solves the Manning's equation to obtain the average velocity V by Eq. (1). Then, the average energy-dissipation rate is computed from Eq. (7). The energy dissipation at various elevations z from the bottom is provided using Eq. (11), and the shear stress at the bottom is computed from Eq. (13). Therefore, there is a direct relation between the energy-dissipation rate and shear stress.

Example

Scenario

Consider an oil spill that occurred in a river whose width is 30 m, water depth is 1.0 m, and streambed slope is 1/1,000, with a natural channel containing stones and weeds.

Solution

Based on Table 1, Manning's n is between 0.03 and 0.04, and it reasonable to pick a value of 0.035. The average water speed V is obtained by Eq. (3)

$$V = \frac{1}{n} R_h^{(2/3)} S_e^{1/2} = \frac{1}{0.035} \left(\frac{1 \times 30}{2 + 30} \right)^{2/3} (0.001)^{1/2} \cong 0.90 \text{ m/s}$$

Thus, the average energy-dissipation rate is

$$\bar{\varepsilon} = g \frac{n^2}{R_h^{4/3}} V^3 \cong g \frac{(0.035)^2}{(1.0)^{4/3}} (0.9)^3 \cong 0.01 \text{ W/kg}$$

The resulting value is comparable to the energy-dissipation rate near the water surface (top 10 cm) of a spilling breaker of height 0.30 m (Wickley-Olsen et al. 2008).

Based on the properties of the streambed, it is reasonable to take $z_o = 1.0$ cm. Therefore, the energy-dissipation rate as a function of elevation z from the streambed is given by

$$\varepsilon = \frac{\bar{\varepsilon}}{\ln\left(\frac{h}{z_o}\right)} \cdot \frac{h}{z} = 2.2 \times 10^{-3} \cdot \frac{1}{z}$$

At the stream bottom, the value of the energy dissipation is obtained by setting $z = z_o = 0.01$ m, resulting in $\varepsilon_{\text{bottom}} = 0.22$ W/kg, which is comparable to plunging breakers of 0.30-m-high waves (Wickley-Olsen et al. 2007). Thus, the energy-dissipation rate at the streambed is an order of magnitude larger than the average value.

Using the law of wall all the way to the water surface results in an energy dissipation that reaches its minimum at the water surface. But in reality, the energy-dissipation rate would increase as approaching the surface from below to the friction of the water with air, especially if wind is present. However, the value there would still too small in comparison with the average energy-dissipation rate [Eq. (7)].

Conclusions

The formation of oil droplets from an oil slick in rivers plays an important role in the transport and fate of oil. The formation of oil droplets depends on, among other factors, the energy-dissipation rate in the water column. Using the Manning's equation, which is a good descriptor for river hydraulics of a slowly varying water level (with space and time), this paper provided a formulation [Eq. (7)] to calculate the average energy-dissipation rate, which could be used as a first approximation for mixing in a particular river. Using additional information on the streambed (roughness height or shear stress), and assuming negligible friction of the water surface with the atmosphere, an equation [Eq. (11)] has been provided to obtain the energy-dissipation rate at various depths in the river. An example was provided for illustration, and it showed that for a stream that is 30 m wide and has a natural slope of 1/1,000, the average energy-dissipation rate is equal to 0.01 W/kg. The maximum value for a roughness height of 1.0 cm was found to be equal to 0.22 W/kg, a value comparable to those obtained from plunging breakers of 0.30-m-high waves. This indicates that oil volumes entrained into the water column (due to rills, for example) are likely to break further, generating smaller droplets. The smaller the size of the droplets (for a given mass of oil), the higher their probability for colliding with sediment particles and forming OPAs. In addition, the formed OPAs are more likely to sink to the bottom of the river due to the lower buoyancy of the small droplets.

The approach presented herein depends on the assumption of a slowly varying hydraulics in the river. Thus, the approach could apply to estuaries provided the water surface variation with time is small compared with the horizontal velocity of water, such that the pressure distribution with depth remains close to hydrostatic, an underlying assumption of the Manning's equation. Also, the formulation neglected energy loss due to sediment movement, which would increase the steepness of the water slope locally and thereby potentially invalidate the applicability of Manning's equation at that location. However, the authors believe that Eqs. (7) and (11) remain reasonable as first-order approximations for the energy-dissipation rate in rivers.

References

Baldyga, J., and W. Podgorska. 1998. "Drop break-up in intermittent turbulence: Maximum stable and transient sizes of drops." *Can. J. Chem. Eng.* 76 (3): 456–470. https://doi.org/10.1002/cjce.5450760316.

Bedient, P. B., W. C. Huber, and B. E. Vieux. 2013. *Hydrology and floodplain analysis*. 5th ed. Upper Saddle River, NJ: Prentice Hall.

Dollhopf, R., and M. Durno. 2011. "Kalamazoo River\Enbridge pipeline spill 2010." In *Proc., Int. Oil Spill Conf.* Washington, DC: International Oil Spill Conference.

Drennan, W. M., M. A. Donelan, E. A. Terray, and K. B. Katsaros. 1996. "Oceanic turbulence dissipation measurements in SWADE." *J. Phys. Oceanogr.* 26 (5): 808–815. https://doi.org/10.1175/1520-0485(1996)026<0808:OTDMIS>2.0.CO;2.

Fitzpatrick, F., et al. 2015. *Oil-particle interactions and submergence from crude oil spills in marine and freshwater environments—Review of the science and future research needs*. Open File Rep. No. 2014. Reston, VA: USGS.

Hinze, J. 1955. "Fundamentals of the hydrodynamic mechanism of splitting in dispersion processes." *AIChE J.* 1 (3): 289–295. https://doi.org/10.1002/aic.690010303.

Jones, L., and M. H. Garcia. 2018. "Development of a rapid response riverine oil-particle aggregate formation, transport, and fate model." *J. Environ. Eng.* 144 (12): 04018125. https://doi.org/10.1061/(ASCE)EE.1943-7870.0001470.

Lee, K., M. Boufadel, B. Chen, J. Foght, P. Hodson, S. Swanson, and A. Venosa. 2015. *The behaviour and environmental impacts of crude oil released into aqueous environments*. Ottawa: Royal Society of Canada.

National Academies of Sciences, Engineering, and Medicine. 2016. *Spills of diluted bitumen from pipelines: A comparative study of environmental fate, effects, and response*. Washington, DC: National Academies Press.

Rutherford, J. C. 1994. *River mixing*. Chichester, UK: Wiley.

Shen, H., P. Yapa, D. Wang, and X. Yang. 1991. *A mathematical model for oil slick transport and mixing in rivers*. Hanover, NH: US Army Corps of Engineers.

Terray, E. A., M. A. Donelan, Y. C. Agrawal, W. M. Drennan, K. K. Kahma, A. J. Williams, P. A. Hwang, and S. A. Kitaigorodskii. 1996. "Estimates of kinetic energy dissipation under breaking waves." *J. Phys. Oceanogr.* 26 (5): 792–807. https://doi.org/10.1175/1520-0485(1996)026<0792:EOKEDU>2.0.CO;2.

Wickley-Olsen, E., M. C. Boufadel, T. L. King, Z. Li, K. Lee, and A. D. Venosa. 2007. "Regular and breaking waves in wave tank for dispersion effectiveness testing." In *Proc., 30th Arctic and Marine Oil spill Programs Technical Seminar*, 499–508. Edmonton, AB, Canada.

Wickley-Olsen, E., M. C. Boufadel, T. L. King, Z. Li, K. Lee, and A. D. Venosa. 2008. "Regular and breaking waves in wave tank for dispersion effectiveness testing." In *Proc., Int. Oil Spill Conf.*, 499–508. Washington, DC.

Yapa, P. D., and H. T. Shen. 1994. "Modelling river oil spills: A review." *J. Hydraul. Res.* 32 (5): 765–782. https://doi.org/10.1080/00221689409498713.

Zhao, L., M. C. Boufadel, X. Geng, K. Lee, T. King, B. Robinson, and F. Fitzpatrick. 2016. "A-DROP: A predictive model for the formation of oil particle aggregates (OPAs)." *Mar. Pollut. Bull.* 106 (1): 245–259. https://doi.org/10.1016/j.marpolbul.2016.02.057.

Zhao, L., M. C. Boufadel, J. Katz, G. Haspel, K. Lee, T. King, and B. Robinson. 2017. "A new mechanism of sediment attachment to oil in turbulent flows: Projectile particles." *Environ. Sci. Technol.* 51 (19): 11020–11028. https://doi.org/10.1021/acs.est.7b02032.

Zhao, L., J. Torlapati, M. C. Boufadel, T. King, B. Robinson, and K. Lee. 2014. "VDROP: A comprehensive model for droplet formation of oils and gases in liquids—Incorporationof the interfacial tension and droplet viscosity." *Chem. Eng. J.* 253 (Oct): 93–106. https://doi.org/10.1016/j.cej.2014.04.082.