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Metal TMDL Dry Weather Modeling for Ballona Creek

by
C.P. Lai, Ph.D., P.E.
Los Angeles Regional Water Quality Control Board

1.0 Introduction

Water quality data collected indicate that portions of the Ballona Creek do not meet standards for copper, lead, and zinc. This report will describe the development of a model for use in identifying the pollutant sources in Ballona Creek and present the simulation results of existing daily load based on the data collected to help for the development of load reduction scenarios in dry weather.

The variable nature of pollutant sources from storm drains in Ballona Creek during dry weather required an approach that relied on detailed analyses of flow and water quality monitoring data to identify and characterize sources. This TMDL used data collected from dry-weather samples to develop a model that represents water quantity and water quality associated with dry-weather in-stream flows from various storm drain discharge.

To represent the linkage between source contributions and in-stream response, a dynamic water quality model was developed to simulate source loadings and transport of metal concentration in the impaired streams and streams flowing to impaired coastal area. This model simulates the metal concentrations to develop load allocations and to allow for future incorporation of new data.

The mixing and dispersion of the wastewater discharge from a discharge point or storm drains can be conceptually divided into two phases: (i) near field mixing, (ii) far field diffusion and buildup. The near field phenomenon occurs in a matter of minutes and within a region measured out to several hundred meters. The far field diffusion is a time scale of hours to a few days and a distance scale of a few hundred meters to a few kilometers. In the near field, the mixing is dominated by discharge jet momentum and in the far field the diffusion and transport are dominated by ambient current or flow field. In this report, we will present the fundamentals of theory, description of the model, and calibration and validation of the water quality model for far field diffusion and transport.

2.0 Theoretical Background of Water Quality Model (RMA2 and RMA4)

Essentially, the water quality model, as presented in the following, adopts the finite element method to provide more detailed analysis of pollutant's diffusion and transport. It takes into account the complex geometry, such as structure in the stream, river geometry and other environmental factors. In other words, the vertically integrated 2-D model considers the depth-wise variation in an average sense. Variations in the flow field in both the space and time are considered and included in the model. Given the stream geometry, its outfalls or storm drains, and its environmental conditions, the model can be more readily applied to the detailed water quality simulation for verification and application purposes.

2.1 Model Description

The numerical simulation is performed based on the RMA2 and RMA4 models first developed by Norton, King and Orlob (1973), of Water Resources Engineers, for the U.S. Corps of Engineers. Subsequent enhancements have been made by U.S. Army Engineer and Development Center (ERDC) at the Waterways Experiment Station (WES) Coastal and Hydraulics Laboratory.

RMA2 is a two-dimensional depth average finite element hydrodynamic numerical model. It computes water surface elevations and horizontal velocity components for sub-critical, free-surface two-dimensional flow fields. RMA2 computes a finite element solution of the Reynolds form of the Navier-Stokes equations for turbulent flows. Frictions is calculated with the Manning's or Chezy equation. Both steady and unsteady (dynamic) problems can be analyzed.

The water quality model, RMA4 is designed to simulate the depth-average advection-diffusion process in an aquatic environment. The model can be used for the evaluation of any conservative substance that is either dissolved in the water or that may be assumed to be neutrally buoyant within the water column. The model is also used for investigating the physical processes of migration and mixing of a soluble substance in reservoirs, rivers, bays, estuaries and coastal zones. The model utilizes the depth-averaged hydrodynamic flow field results from RMA2.

The numerical models are developed by using Galerkin' s finite element method to solve the depth-integrated equations of flow mass, momentum conservation, and energy of the transport and mixing process in two horizontal directions. The shape functions are quadratic for velocity, concentration, and linear for depth. Integration in space is performed by Gaussian integration. Derivatives in time are implemented by a nonlinear finite difference approximation.

Based on the assumption of constant water density, the equations governing the flow are uncoupled from those controlling the water quality distributions, and can be solved independently. Therefore, the simulation of the water quality far field diffusion involves a two-step procedure: first, the hydrodynamic simulation is used to calculate the flow velocities and water elevations; second, the water quality simulation is applied to estimate the water quality distributions resulting from pollutant discharge based on the results of hydrodynamic simulation.

The basic formulations and the numerical techniques are explained in the following sections. Detailed simulation procedures such as model setup and verification are also included.

2.2 Governing Equations

The governing equations for hydrodynamic simulation are the continuity and momentum equations. For two-dimensional case, the governing equations are as follows:

$$\frac{\partial H}{\partial t}+\frac{\partial (Hu)}{\partial x}+\frac{(\partial Hv)}{\partial y}=0 \qquad (1)$$

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+g\frac{\partial \eta}{\partial x}-fv+\frac{\tau_x^b}{H}-\frac{\Psi_x}{H}-\frac{1}{H}[\frac{\partial}{\partial x}(H\varepsilon_x\frac{\partial u}{\partial x})+\frac{\partial}{\partial y}(H\varepsilon_x\frac{\partial u}{\partial y})\ ]=0 \ (2)$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+g\frac{\partial \eta}{\partial y}+fu+\frac{\tau_y^b}{H}-\frac{\Psi_y}{H}-\frac{1}{H}[\frac{\partial}{\partial x}(H\varepsilon_y\frac{\partial v}{\partial x})+\frac{\partial}{\partial y}(H\varepsilon_y\frac{\partial v}{\partial y})\ ]=0 \ (3)$$

In the above equations, all the dependent variables are vertically averaged quantities. Variable u and v are the velocity components in x and y directions, x direction is in the east and y direction is in the north; t the time; H the water elevation, *f* the Coriolis parameter; η the height of free water surface above the mean water level; τ^b the bottom shear stress; Ψ the surface shear stress; and ε the eddy viscosity.

The equation governing the distribution of water quality in water is the advective-diffusion equation based on the energy conservation as follows (for two-dimensional case):

$$\frac{\partial Q}{\partial t}+V\bullet\nabla Q-\frac{1}{H}\nabla\bullet(HK_c\bullet\nabla Q)+S_c+G_c=0 \qquad (4)$$

where Q is the concentration of water quality in the water body, V is the velocity vector in the flow field, K_c the diffusion-dispersion coefficient tensor, S_c the source/sink and the growth/decay of each water quality constituent, G_c the kinetic reaction of each water quality constituent that represents all important chemical and biological kinetic reactions involving the mass balance of substance. This interaction and mutual dependency are imbedded in the formulation of the source and sink and the kinetic reaction term which may involve a substance other than itself in the equation.

2.3 Principal Assumptions

The principal assumptions adopted in deriving the governing equations and numerical models are summarized as follows:

(1)The density of water is constant.
(2)The pressure in the water is hydrostatic.
(3)The vertical distribution coefficients of the velocity components are equal and constant throughout the simulation domain.
(4)The shear stresses from the vertical velocity component are neglected.
(5)Only the gravity and Coriolis forces are considered.
(6)The bottom shear stress is calculated according to the following equation (Dronkers, 1964):

$$\tau_b = \frac{gn^2|V|}{H^{\frac{1}{3}}}$$

where n is Manning' s roughness coefficient.

(7)The surface shear stress is correlated to wind speed, and is estimated by the following equation:

$$\varphi = \frac{C_d \rho_a V_w |V_w|}{\rho}$$

where ñ$_a$ and ñ are the densities of air and water respectively, V_w the wind velocity vector at 10 m above the water surface, and C_d the wind drag coefficient.

3.0 Model Development

3.1 Hydrodynamic Model Set-up

3.1.1 Computational Grid and Model Parameters

A finite element computational grid layout was set up for hydrodynamic and water quality simulations for the storm drain discharges into Ballona Creek. The computational grid system shown in the Figure 3.1 covers an alongshore distance of about 10 kilometers (Km) and extends offshore about 4.0 kilometers (Km) and a 14 Kilometers long Ballona Creek. The purpose of this extended computational domain is to correctly simulate the hydrodynamic characteristics in the Ballona Creek and avoid the effect of boundary on water quality simulation. The computational grid system is constructed by describing the geometry of the area with quadratic triangular elements. The total number of elements is 1210 and that of nodal points is 2782. The dimension of the elements in the Ballona Creek area is from 12x50 to 25x100 meters (m). The mesh size of the grid is chosen in such a way as to provide a satisfactory resolution of the water elevation and water quality distribution in the Ballona Creek. The bottom elevation of Ballona Creek and bathymetry topography of coastal area were provided by the U.S. Army Corps of Engineers at Los Angeles District.

The values of Manning n used in the hydrodynamic simulation to calculate the bottom friction is from 0.015 in the Creek to 0.025 in the estuary area. These values are well documented in the literature for concrete type of channel. The computation time step Ät is 15 minutes for the computational grid. Internal stresses and wind induced surface stresses are of less importance, so their effects were not simulated.

3.1.2 Boundary Conditions of Hydrodynamic Model

For initial conditions, velocities u, v (x and y components) and water elevations have to be specified for every point in the model region. The model may be started from either a cold condition or a prestarting function. For the case of cold start, velocities at all the nodal points are set to be zero and the water elevations are level.

The simulations adopt a cold start, which means that the water elevations are level and velocities are zero everywhere in the computational grid system.

At the solid boundaries, zero normal flow is assumed as corresponding boundary condition except for the upstream boundary at Cochran which is specified as a constant flow rate with measured data for each simulation event. In addition, the computational grid system has three open boundaries, all of which are implemented as water-level boundaries, i.e., water elevations are specified at boundary nodal points. The predicted tide data (National Oceanographic Data Center, 2003) at El Segundo which are shown in the Figures 3.2 are used as the basis of water elevations along the open boundaries.

3.2 Water Quality Model Set-up

3.2.1 Water Quality Model Parameters

The computation time step Ät used in water quality simulation is 30 minutes.

The dispersion coefficients are the major parameters among the controlling factors in determining the solutions of the pollutant transport equation. It is very important to take into considerations their physical meanings and numerical implications when values are selected for the modeling. In general, the dispersion coefficients vary locally according to velocity distribution, water depth, bottom roughness, etc. For this model, the diffusion coefficients are calibrated through dye study results.

The dye study was conducted by Dr. John Dorsey at Loyola Marymount University on November 7, 2003. In the dye study, there were five sampling stations of measured concentrations, which are shown in Figure 3.3. The location of dye injection was located at 100 meter upstream of sampling station 1. The mass loading of dye was 30 g in 36 sec. The modeling results of concentration at first three stations are compared with measured results of dye study for different diffusion coefficients. They are shown in Figure 3.4 to Figure 3.6. It can be seen from these figures that the diffusion coefficient of 10 m^2/sec is the best fit of concentrations with the measured data.

3.2.2 Boundary Conditions of Water Quality Model

Water quality simulation is based on the flow field resulting from the hydrodynamic simulation using the same computational grid system. The model requires a proper initial condition, which will specify water quality at every nodal point in the simulation domain at time zero. Usually, the model starts with a uniform water quality distribution with a typical value for the modeling area. In the model, computation starts with a uniform zero concentration throughout the simulation grid system. At the land boundary nodes, perpendicular flux is assumed to be zero except for the upstream boundary at Cochran which is specified as a constant flux with measured flow rate and concentration for each simulation event.

4.0 Calibration and Validation of the Model

4.1 Calibration of the Model

After the model was set-up or configured, model calibration and validation were performed. This is generally a two-phase process, with hydrodynamic calibration and validation completed before repeating the process for water quality. Upon completion of the calibration and validation at selected locations, a calibrated dataset containing parameter values for each modeled pollutant was developed.

Hydrodynamics or hydrology is the first model component calibrated because simulation of water quality loading relies heavily on flow prediction. The hydrology calibration involves a comparison of model results to in-stream flow observations at selected locations. After comparing the results, key hydrologic parameters were adjusted and additional model simulations were performed. This iterative process was repeated until the simulated results closely represented the system and reproduced observed flow patterns and magnitudes.

The calibration of hydrodynamic and water quality model was performed using data of May 2003 sampling event in Ballona Creek. The calibration was completed by adjusting flow rates of upstream boundary to reflect observed in-stream flow conditions and to reflect observed in-stream water quality concentrations. This is based on the assumption that the measured flow rate and mass loading from storm drains are correct. In this study, the field data collected at 12 in-stream stations were used for model calibration and validation. The input data used for calibration and validation are summarized in Table 4.1. The sampling locations of storm drain and in-stream are presented in the Figure 4.1.

The results of hydrodynamic simulation for in-stream flows are presented in Figure 4.2. The goal of calibration was to minimize the difference between observed in-stream flows and modeled flow at each measured station. It can be seen that the predicted flow results agree well with the field observation.

The mass loading applied to the model are specified as the sampling stations BC60, 71, 90, 100, 110, 120, 130, 150, 175, 199, 200, 210, 250, 350, and 360. The storm drain load is assumed to be constant through the simulation time in a conservative side. During water quality simulations, sufficient simulation time was used in each run to assure quasi steady-state conditions. It was found that the solutions reach steady state after about 7 hours of continuous storm drain discharge. The results of water quality simulations for total copper, lead, and zinc are presented in the Figure 4.3 through Figure 4.5 respectively. In these Figures, the concentration rise versus the distance along the Creek to represent the direct effects on the Creek due to these storm drain discharge scenarios. The reference point of distance is situated at the Pacific Avenue and the distance of 12 cross sections in the Creek are also indicated in the Figures. In the Figure 4.3, the agreement for total copper against in-stream values during the May sampling event is quite good, although the model is predicting on the high end of the measured values. Similarly for the total lead results shown in the Figure 4.4, the calibration also is relatively good, although slightly underpredicts. It should be noted that originally there were only five mass loading from storm drains were input into the Creek and eight in-stream sampling results where lead was reported were compared with the model results. But in order to take into account the nondetect values of total lead when measured value is below the detection limit, one- half of the detection limit is used as a value in the model for each nondetect value. Therefore, there are total fourteen mass loading from storm drains and ten in-stream sampling results are compared with the model results. Thus, considering this situation, the calibration is actually quite good. The calibration for zinc is presented in the Figure 4.5, which is the best of all.

4.2 Validation of the Model

To further examine the model's ability to predict a real physical situation, a subsequent testing of a pre-calibrated model to additional field data is required. This process is usually called *validation of the model.* In this study, the field data collected at 12 in-stream stations in July and September 2003 were used for model validation. The input data used for validation are also summarized in Table 4.1. The results of model validation for in-stream flows are presented in Figures 4.6 and 4.7. The results of model validation for total copper, lead, and zinc in the Creek are presented in Figure 4.8 and 4.13, respectively. It can be seen that the validations for total copper during July and September are quite good except for three stations at National, La Cienega, and Fairfax in July sampling event. For total lead, the model prediction is quite close to the measured values, although slightly underpredicts for July sampling event. For total zinc, the model validation against in-stream values in July and September is quite good, except for three stations at National, La Cienega, and Fairfax in July sampling event.

Overall, during model calibration the model predicted well in-stream flow rate at different stations. The validation results of three metal concentrations also showed a good fit between modeled and observed values, thus confirming the applicability of the calibrated hydrodynamic and water quality parameters to the Ballona Creek.

5.0 TMDL Model Scenarios

5.1 Existing Daily Load

After completing model calibration and validation for hydrodynamics and water quality, the model is going to be applied to obtain TMDL allocation for the critical condition selected. Before we simulate the critical condition for TMDL, it is more instructive to know the representative existing daily loads to Ballona Creek in dry weather using the validated model. In general, it is not expected that the flows and loads vary substantially during dry weather since dry weather urban runoff makes up most of the input. For this reason, we recommended simulating a representative condition rather than a 7Q10 low flow or other critical condition. Two scenarios for this representative conditions are performed. One is using the average storm drain input of three sampling events and the other is using the storm drain input from July sampling event, which is found to be highest in-stream flow rate and concentration among three sampling events. The results of these two existing daily load scenarios are presented in Figures 5.1 through 5.3.

In Figures 5.1 through 5.3, the computed existing daily loads against measured in-stream values in 10 cross sections along the Creek. In the measured in-stream concentration data, the maximum, minimum and average values are indicated in the figures. The water quality criteria based on hardness of 100 mg/L and 300 mg/L are also marked in these figures. It can be seen that the scenario of using average storm drain inputs represents the most conservative estimate of the representative existing daily loads. However, these results are only based on the three sampling events in 2003.

5.2 TMDL Allocation

Based on the measured data of the previous sampling events, the concentrations along with their associated average daily flow are going to be used to generate the relationship between flow and concentration in the Creek. The TMDLs are then calculated based on the critical condition selected from relationship of in-stream flow and concentration. Predicted loads that fell above the load capacity are exceedances and were then divided by the total existing load to calculate the percent reduction required to achieve the beneficial use of the receiving waterbody.

6.0 References

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5. King I.P. and Norton W.R. (1978), Recent Application of RMA' s Finite Element Models for Two Dimensional Hydrodynamic and Water Quality, Finite Element in Water Resources.

6. Users Guide to RMA2 WES Version 4.5, U.S. Army, Engineer Research and Development Center, Waterways Experiment Station, Coastal and Hydraulic Laboratory, May, 2001.

7. Users Guide to RMA4 WES Version 4.5, U.S. Army, Engineer Research and Development Center, Waterways Experiment Station, Coastal and Hydraulic Laboratory, August, 2000.

Table 4.1 Input of Flow and Mass Loading of Storm Drains for three Dry Weather Events

		Total Copper			**Total Lead**			**Total Zinc**		
	Storm Drain	C (ppb)	Flow (cfs)	Mass (g/day)	C (ppb)	Flow (cfs)	Mass (g/day)	C (ppb)	Flow (cfs)	Mass (g/day)
5/17/2003	BC60	6.46	4.9092	77.6063	ND			ND		
	BC71	3.10	0.0167	0.1267	ND			4.61	0.0167	0.1885
	BC90	4.58	0.1380	1.5463	ND			31.34	0.1380	10.5838
	BC100	38.82	0.0406	3.8561	4.61	0.0406	0.4574	111.61	0.0406	11.0856
	BC110	4.63	0.0665	0.7544	3.80	0.0665	0.6193	17.26	0.0665	2.8102
	BC120	25.92	0.0870	5.5180	ND			22.24	0.0870	4.7338
	BC130	16.54	0.0090	0.3643	2.63	0.0090	0.0579	20.77	0.0090	0.4574
	BC150	11.30	0.0930	2.5708	2.23	0.0930	0.5078	36.45	0.0930	8.2927
	BC175	14.00	0.0030	0.1028	4.39	0.0030	0.0322	55.99	0.0030	0.4110
	BC199	5.52	0.0694	0.9374	ND			ND		
	BC200	14.10	0.0087	0.3010	ND			35.16	0.0087	0.7504
	BC210	16.62	0.1802	7.3297	ND			90.15	0.1802	39.7516
	BC250	15.77	0.0240	0.9259	ND			75.93	0.0240	4.4582
	BC350	6.79	0.8275	13.7412	ND			7.84	0.8275	15.8776
	BC360	5.43	1.0026	13.3165	ND			11.05	1.0026	27.1050
7/16/2003	BC41	94.00	0.0010	0.2300	33.00	0.0010	0.0807	370.00	0.0010	0.9052
	BC54	8.60	0.0010	0.0210	ND			26.00	0.0010	0.0636
	BC63	7.00	0.0010	0.0171	ND			24.00	0.0010	0.0587
	BC71	2.80	0.1097	0.7512	ND			2.30	0.1097	0.6170
	BC90	6.70	0.0122	0.1997	ND			11.00	0.0122	0.3279
	BC100	7.70	0.0200	0.3768	ND			18.00	0.0200	0.8808
	BC110	12.00	0.0022	0.0654	ND			81.00	0.0022	0.4415
	BC120	35.00	0.0450	3.8534	ND			17.00	0.0450	1.8716
	BC124	36.00	0.0010	0.0881	3.00	0.0010	0.0073	94.00	0.0010	0.2300
	BC130	14.00	0.0040	0.1370	ND			12.00	0.0040	0.1174
	BC150	9.70	0.1450	3.4411	ND			8.70	0.1450	3.0864
	BC160	7.90	0.0020	0.0387	ND			9.10	0.0020	0.0445
	BC175	16.00	0.0110	0.4306	8.00	0.0110	0.2153	130.00	0.0110	3.4986
	BC195	2.20	0.0010	0.0054	ND			8.70	0.0010	0.0213
	BC199	5.30	0.0836	1.0834	ND			6.80	0.0836	1.3900
	BC200	24.00	0.2005	11.7742	ND			22.00	0.2005	10.7930
	BC250	16.00	0.0130	0.5089	6.10	0.0130	0.1940	111.00	0.0130	3.5304
	BC299A	15.00	0.3551	13.0313	ND			13.00	0.3551	11.2938
	BC299B	8.80	0.0150	0.3229	ND			18.00	0.0150	0.6606
	BC350	7.90	0.3045	5.8852	7.90	0.3045	5.8852	12.00	0.3045	8.9396
	BC360	8.30	0.0056	0.1131	ND			14.00	0.0056	0.1908
9/24/2003	BC55	3.90	0.0010	0.0095	ND			30.00	0.0010	0.0734
	BC60	11.40	7.7498	216.1495	ND			18.00	7.7498	341.2887
	BC71	3.10	0.1000	0.7584	4.00	0.1000	0.9786	4.00	0.1000	0.9786
	BC88	6.60	0.0150	0.2422	ND			13.00	0.0150	0.4771
	BC90	1.70	0.1894	0.7877	ND			7.00	0.1894	3.2433
	BC100	4.30	0.0020	0.0210	ND			37.00	0.0020	0.1810
	BC110	16.00	0.0022	0.0872	12.00	0.0022	0.0654	117.00	0.0022	0.6378
	BC120	22.20	0.0010	0.0543	ND			107.00	0.0010	0.2618
	BC150	13.30	0.0280	0.9111	ND			151.00	0.0280	10.3441
	BC195	1.60	0.0130	0.0509	ND			35.00	0.0130	1.1132
	BC199	77.70	0.1604	30.4949	50.00	0.1604	19.6235	266.00	0.1604	104.3971
	BC200	9.40	1.3368	30.7435	3.00	1.3368	9.8118	82.00	1.3368	268.1881
	BC210	27.80	1.1864	80.6935	10.00	1.1864	29.0265	64.00	1.1864	185.7693
	BC250	28.70	0.1240	8.7069	6.00	0.1240	1.8203	225.00	0.1240	68.2595
	BC350	20.30	0.3119	15.4917	ND			ND		
	BC360	16.00	0.2822	11.0473	ND			28.00	0.2822	19.3328