Methods for Delineating the Mixing Zones

The numerical model CORMIX is employed to simulate the effluent plume. Output from the model is a steady-state delineation of the edge of the mixing zone in three dimensions. The analysis considers only the existing outfalls' configurations, without modifications such as a diffuser. A tracer study was conducted to measure actual plume geometry under representative critical conditions and then to calibrate the simulation model.

OVERVIEW OF OPEN-WATER PLUME MIXING PROCESSES

Before presenting a numerical model for delineating mixing zones, physical mixing processes are described. Mixing of a discharge plume into a river can be divided into three hydraulic effects, each described next:

(1) Near-field, momentum-induced, lateral mixing;

(2) Near-field, momentum-induced, vertical mixing; and

(3) Far-field, ambient turbulent mixing.

In practice, the regulatory mixing zone can encompass either the near field where discharge characteristics control mixing behavior or the far field where ambient conditions predominate the mixing process.

Lateral Mixing (Effect #1)

Lateral mixing is caused by a plume's momentum directing it across a channel. The distance of this initial lateral mixing in the mixing zone study reach can be estimated from visual observations during lower river flow rates. Lateral mixing during higher river flow rates would be relatively inconsequential because currents in the receiving water would overwhelm any lateral momentum. Yountville WWRF's outfall directs effluent almost perpendicular to the channel, causing significant lateral mixing.

Vertical Mixing (Effect #2)

Depending on channel conditions, the discharge may plunge down to the riverbed or float over denser river water. Vertical mixing generally occurs within a distance of 50 times a river's water depth. The deeper pool by the outfall causes less vertical mixing, while shallower depths farther downstream enhance vertical mixing.

Ambient Turbulent Mixing (Effect #3)

Ambient turbulent mixing is the dispersion of a mass of liquid caused by turbulent eddies in the ambient water. This effect is of greatest interest in cases where the two previous mixing effects do not completely mix the plume. Lateral mixing caused by ambient turbulence generally occurs over the longest distances among the three effects. The Napa River's slight meandering and irregular banks with shrubs and rocks enhance ambient turbulence.

CORMIX MIXING ZONE MODEL

CORMIX is a mixing zone model for environmental impact assessment of regulatory mixing zones resulting from continuous point source discharges (Jirka et al., 1996)[2]. CORMIX is a recommended analysis tool in key guidance documents (USEPA, 1991a and 1991b) on the permitting of point source discharges into receiving waters. Receiving water depth and flow rate, outfall configuration, and discharge flow rate are the most important input parameters.

The submodel CORMIX3 is used to simulate buoyant surface discharges into ambient water bodies (Jones et al., 2007; Jirka, 2007). CORMIX represents a receiving water channel with a rectangular cross-section. While each cross-section is relatively uniform (i.e., rectangular), the longitudinal slope varies dramatically as the water depth decreases from over four feet to less than one foot under typical low-flow conditions. A single, representative cross-section must be input to represent this range of water depths.

CORMIX model results delineate the edge of the mixing zone under steady-state conditions. The plume shape is conservatively delineated by the surface area containing one standard deviation (i.e., 68%) of the plume in a Gaussian distribution-shaped cross-section. Dilution (s) in CORMIX is presented as the ratio of initial concentration to concentration at a given location, which is the inverse of 'fraction of effluent' and equivalent to D+1 as described above in section "Dilution Equations". In other words, dilution credit $D = s - 1$.

TRACER STUDY

During a discharge event on December 22, 2009, a tracer study was conducted to calibrate the numerical model. This section includes a description of the fieldwork and calculations of mixing of the effluent plume.

Tracer Study Field Work

A fluorescent dye, Rhodamine WT, was dosed into the effluent pipeline approximately 0.5 miles upstream of Outfall E-1. Rhodamine WT is generally a good tracer because it is (1) water soluble, (2) highly detectable [strongly fluorescent], (3) fluorescent in a part of the spectrum not common to materials generally found in water [reducing the problem of background fluorescence], (4) harmless in low concentrations, (5) inexpensive, and (6) reasonably stable in a normal water environment.

Effluent was discharged at a steady rate during fieldwork (~3 hours) at approximately 33% of river flow rate (10 cfs river flow and 0.23 MGD effluent flow, resulting in 30:1 dilution). Dye was dosed continuously through a peristaltic pump (**Figure 3**) during fieldwork at a rate such that it was visually detectable in undiluted effluent but quickly diluted below the visible range (~15 ug/L).

[2] See also http://www.cormix.info/index.php.

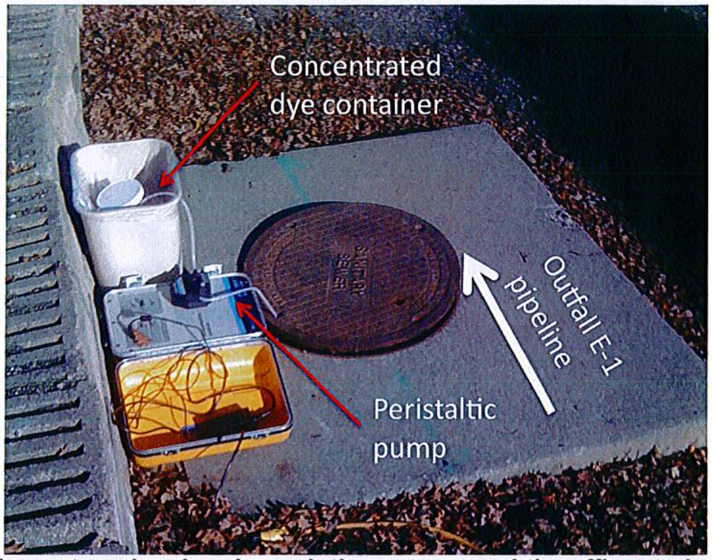
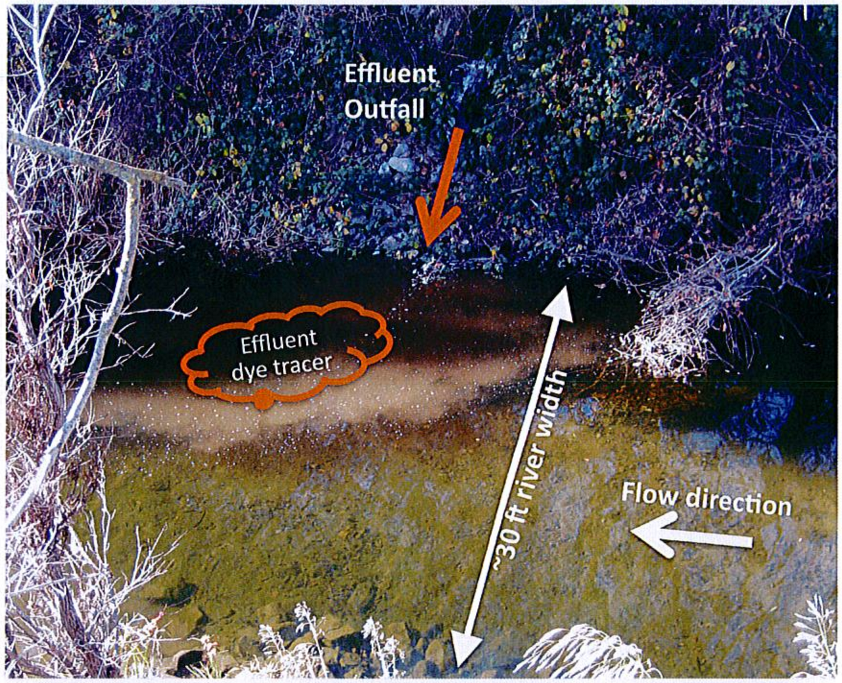


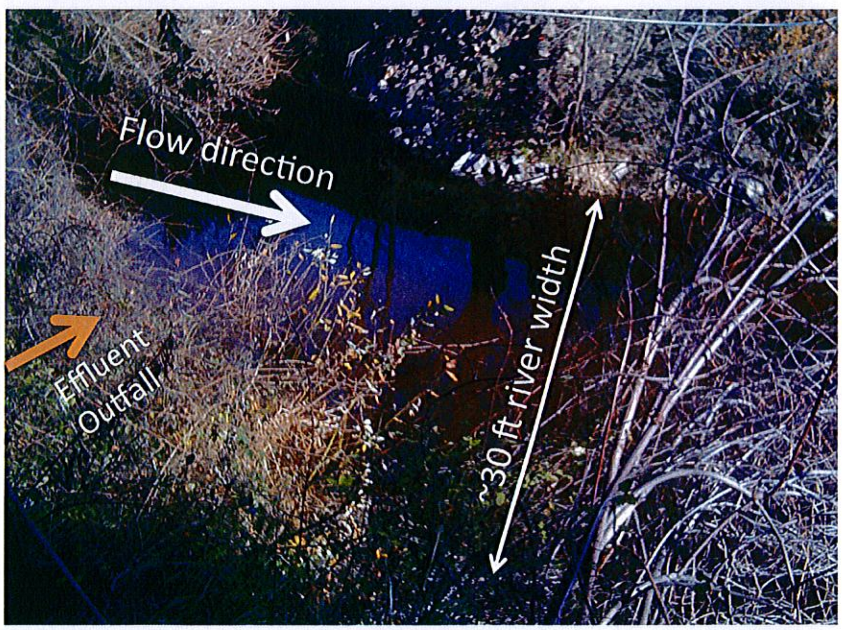
Figure 3. Dye dosing setup showing dye solution, pump, and the effluent pipeline below grade.

The field crew measured the geometry of the outfall, including the approximate angle, width and depth of the discharge where it entered the river, and the bank slope. The field crew then collected field measurements and made visual observations to delineate the effluent plume discharged from Outfall E-1 under the conditions encountered. The field crew measured transects at the following distances, in an upstream to downstream progression relative to the outfall:

- 20 ft upstream (representing background)
- 0 ft within a turbulent pool of undiluted effluent below the outfall box culvert, before effluent plunges into the river
- 10 ft downstream
- 40 ft downstream (measured by rope and pulley from the streambank)
- 200 ft downstream
- 300 ft downstream

The reach between 40 feet and 150 feet downstream was largely inaccessible because of thick vegetation along the banks and deeper water (>4 feet deep, the limit of access in waders). The dye tracer was measured using a calibrated field fluorometer in flowing water along each transect at 2-ft spacing. Visual observations confirmed the presence of dye in undiluted effluent at the expected concentration, strong initial lateral mixing, and subsequent dilution to below visual detection (**Figure 4**).


Effluent
Outfall
Effluent
dye tracer
~30 ft river width
Flow direction
a)


Flow direction
Effluent
Outfall
~30 ft river width
b)

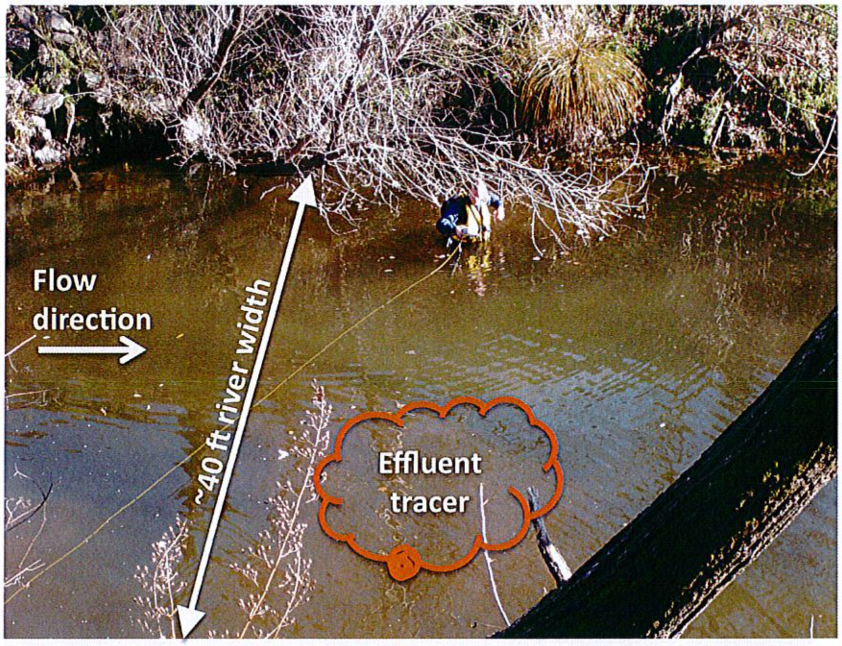
c) 

Figure 4. Effluent tracer from Outfall E-1 seen immediately downstream at the surface, a) from East bank showing the outfall, b) from West bank showing the channel constriction, and c) from West bank attempting to measure transect 40 feet downstream. Dye was not visible beyond ~50 feet downstream from the outfall.

Calculating Fully Mixed Conditions

The Technical Support Document notes that the mixing zone boundary is "usually" defined as the location where measurements across a transect vary by less than 5%, but that a 25% variation across the width is accepted as being completely mixed if other uncertainties exist. Simulation results presented later are assumed to delineate the mixing zone boundary with similar levels of transect variability. Percent mixed of a tracer at any transect (P_m) can be estimated by a formula provided by the US Geological Survey (Kilpatrick and Cobb, 1985):

$$P_m = 100 - \frac{50}{\bar{c}Q}\sum_{i=1}^{N}|c_i - \bar{c}|Q_i$$

Where $\bar{c}$ = Average concentration across the transect

Q = River flow rate (total)

N = total number of points i along a transect

c_i = Concentration at transect point i

Q_i = River flow rate represented by transect point i

In Yountville's case, water depth was used as a surrogate for flow rate at each transect point (d_i rather than Q_i). This substitution assumes that the cross-sectional velocity is uniform such that flow rate is only dependent on water depth.

Tracer Study Results

Dye concentration measurements portray the lateral mixing of the effluent plume in the near-field reach of the Napa River downstream of Outfall E-1 (**Figure 5**). The shaded portion of each cross section contains 68% of the dye at its average concentration within the plume. The percentage of the effluent plume along each transect was estimated from the sum of the products of dye concentration and water depth at each point along the transect from the point of maximum concentration.

Strong lateral mixing caused by the momentum of the discharge (Effect #1) was observed within the first 10 feet downstream of the outfall. The effluent plume was measured to mix initially across 20-25 feet of the width of the river as the water's width increased from 30 feet to 40 feet. The first two transects (10 ft and 40 ft downstream) the plume obviously billowed randomly—a transect several minutes later could have measured peak dye concentrations anywhere within 20 feet of the West bank. But regardless, the plume containing 68% of the dye was already diluted by 12:1 at both the 10-ft and 40-ft transects. In other words, effluent was mixed more than 12:1 (the proposed dilution credit) within one channel width's distance downstream.

Between 40 ft and 200 ft downstream of the outfall, the channel depth decreased from over 4 ft to approximately 1 ft. By 200 ft downstream effluent was completely mixed vertically and the plume centerline had migrated across the channel towards the East bank—opposite the discharge bank. At 200-300 feet downstream, the slope of the dye concentration indicated higher concentrations on the far bank. Dye concentrations across the width at the 300-ft transect varied by 16%, within the range of 5-25% variation that the TSD indicates usually describes completely mixed. In other words, the tracer's plume was *fully* mixed (~30:1 dilution) within 200-300 feet downstream of the outfall.

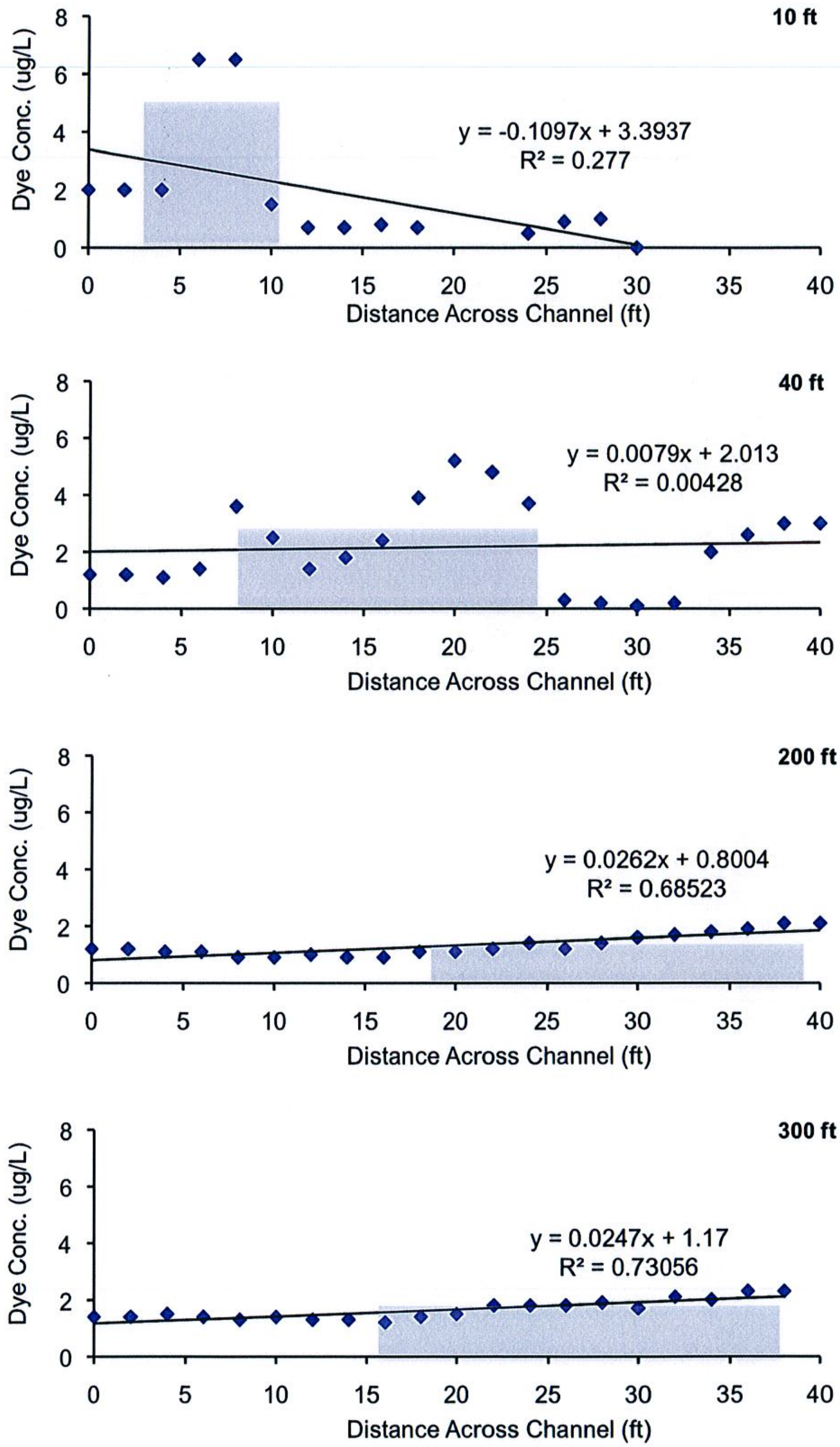


Figure 5. Dye tracer concentrations at transects downstream of Outfall E-1. Shading encompasses 68% of the plume. The plume is initially mixed 25 feet across the channel, reaching the far bank within 200 feet downstream of the outfall.