The Proposed Buenos Aires Outfalls: Outfall Design

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Abstract
Designs for the two outfalls proposed to discharge into the Río de la Plata are presented. The average wastewater flows for the two outfalls are large: 18.5 and 25.0 m^3/s. The river is shallow, well-mixed vertically and is fresh water. The currents are dominated by the tides and recirculate the wastewater back over the diffuser several times before it is flushed away. The overall flushing is determined by the total flow in the Río de la Plata, which is about 400 times larger than the wastewater flows so no overall problem water quality problems are anticipated. Design constraints include the proximity of the outfalls to water intakes.

Because of the shallow water and low flushing currents, it is not possible to achieve the very high near field dilutions typical of deep water marine outfalls. The effluent will quickly mix over depth and the hydrodynamic model is depth-averaged, so it reproduces near field mixing at moderate and high current speeds and re-entrainment due to the reversing tide. Corrections at low current speeds were applied to account for dilution due to the momentum of the discharging jets.

The proposed outfalls are tunneled with risers extending to the river bed. The near field jet-induced dilution was modeled by an entrainment model to determine the port configurations and riser spacing, and Lagrangian particle tracking to predict the fate and transport of effluent. The final recommended diffuser lengths are 1400 and 2300 m. Water quality modeling for the final recommended outfall and diffuser designs was then conducted and the results were compared with water quality regulations

Keywords
Outfall, diffuser, modeling, Buenos Aires, Río de La Plata.

1. Introduction

Two outfalls and treatment plants at Berazátegui and Riachuelo that will discharge into the Río de la Plata are proposed as shown in Figure 1. In support of the design of the outfalls, and to predict their environmental impacts, extensive studies have been under way since June 2009. In an accompanying paper, Villegas and Roberts (2011), the field data were analyzed and the hydrodynamic mathematical modeling of the Río de la Plata was described. It was shown that the model closely reproduced the observed current and water levels in the vicinity of the proposed outfalls. The purpose of this paper is to present fate and transport modeling and diffuser details for the outfalls.

Figure 1. Proposed outfalls

2. Vertical and Lateral Mixing

Any material released into the river will eventually become vertically well-mixed due to natural turbulence present in the river. The distance x_1 at which this occurs can be estimated by (Fischer et al., 1979):

$$x_1 = 0.1\frac{\overline{u}H^2}{\varepsilon_v} \quad (1)$$

where $\bar{u}$ is the mean river current speed, H the water depth, and ε_v the vertical turbulent diffusion coefficient, given by:

$$\varepsilon_v = 0.067 H u^* \tag{2}$$

where $u^* \approx \bar{u}/10$ is the friction (or shear) velocity. For these outfalls, $\bar{u} \approx 0.22$ m/s and $H \approx 4.8$ m. Therefore, $u^* \approx 0.022$ m/s, $\varepsilon_v \approx 0.0071$ m^2/s, and $x_1 \approx 70$ m so material will mix over depth about one hundred meters downstream. This rapid vertical mixing is also reflected in the CTD profiles that show the river properties to be always essentially homogeneous over depth.

The lateral diffusion coefficient for rivers ε_t can be estimated from (Fischer et al., 1979):

$$\varepsilon_t = 0.60 H u^* \tag{3}$$

which leads o $\varepsilon_t \approx 0.063$ m^2/s. The ADCP measurements show the currents to be primarily tidal and flow along well-defined axes approximately parallel to the local shoreline. However, there is a significant (although much smaller) component of the currents perpendicular to these axes that can significantly enhance lateral mixing and diffusion. In order to assess this effect, simulations with a Lagrangian far-field model, FRFIELD, were done. This model uses the actual currents measured by the ADCPs to predict far field advection of particles released from the diffusers. Based on these simulations, the lateral diffusion coefficient ε_t was estimated to be 0.32 m^2/s, much higher than the estimate based on Eq. 3, but considered to be more representative of lateral diffusion in this highly unsteady tidal environment. Transport of effluent to the Bernal intake and the local shoreline is primarily due to lateral diffusion. Therefore, use of the higher value of the lateral diffusion coefficient is a more conservative estimate of potential impacts at these locations.

3. Fate and Transport Modeling

The primary design criteria for the outfalls and diffusers are near field dilution and bacterial impacts on the water intakes and shoreline. Far field modeling is simulated by two Lagrangian approaches, the particle tracking module Delft3D-PART, and FRFIELD.

Near field dilution: As shown above, the effluent quickly mixes over the water depth, so near field dilution is mainly determined by the current speed, flow rate, diffuser length, and water depth. At low current speeds, however, jet-induced dilution becomes more important. A further complication is that the wastefield is recirculated by the tide several times back and forth over the diffuser before being flushed away, reducing the near field dilution. These effects are discussed below.

The currents flow predominantly perpendicular to the diffusers and are strongly tidal, reversing back over the diffusers. Tidal recirculation can be assessed by approximating the tidal current as a sinusoidal variation:

$$u = u_{mean} + u_T \sin\left(\frac{2\pi t}{T}\right) \tag{4}$$

where u is the instantaneous velocity, u_{mean} is the mean (flushing) velocity, u_T is the tidal amplitude, t is time, and T is the tidal period which is about 12.4 hrs for the semidiurnal tide. The mean tidal (scalar) speed is:

$$\bar{u}_T = \frac{2}{\pi} u_T \tag{5}$$

The length of a tidal excursion (the maximum distance traveled by a particle over a tidal cycle) is:

$$L_{ex} = \bar{u}\frac{T}{2} \tag{6}$$

and the migration length due to the mean current is:

$$L_{mean} = u_{mean} \frac{T}{2} \tag{7}$$

The multiple reversals of discharged effluent over the diffuser before being flushed by the mean drift. This can be expressed by the "reversal ratio:"

$$R = \frac{L_{ex}}{L_{mean}} = \frac{\bar{u}_T}{u_{mean}} \tag{8}$$

The variability of dilution around the mean value depends on the value of R. If $R < \sim 1$ there is little variability, but if $R > \sim 1$ there will be considerable variation. For Berazategui, $u_{mean} \approx 0.073$ m/s and $u_T \approx 0.31$ m/s, so from Eqs. 5 and 8, $\bar{u}_T \approx 0.20$ m/s and $R \approx 2.7$. This implies significant tidal variability in dilution and near field concentrations. The tidal excursion, $L_{ex} \approx 4.5$ km.

Assuming that the effluent is quickly mixed over the water depth (which will be the case here), the mean dilution S_{mean} is given by:

$$S_{mean} = \frac{u_{mean} HL + Q}{Q} \tag{9}$$

where H is the water depth, L the diffuser length, and Q the discharge rate. This gives rise to a "background" mean concentration, c_b:

$$c_b = \frac{c_o}{S_{mean}} \tag{10}$$

where c_o is the concentration of some conservative contaminant in the effluent.

The mean water depth near the Berazategui diffuser is $H \approx 4.8$ m, the tentative diffuser length $L \approx 2{,}300$ m, and the discharge rate $Q = 25$ m^3/s. Therefore the mean dilution from Eq. 9 is $S_{mean} = (0.073 \times 4.8 \times 2300 + 25)/25 = 33$.

These equations underestimate the actual dilution for two main reasons. First is that the effective width of the effluent plume is greater than the diffuser length L because of the lateral velocity fluctuations. The plume width broadens due to these fluctuations as it passes back and forth over the diffuser. This is called the "extended source region" in Roberts et al. (2010). Second is the jet-induced entrainment and dilution caused by the diffuser, which will be especially important at low current speeds. The combined effects of background concentration and jet-induced dilution give rise to an "effective" dilution, S_{eff}:

$$S_{eff} = \frac{\left(uHL + Q\left(S_j + 1\right)\right)}{\left(\left(uHL + S_j Q\right)/S_{mean}\right) + Q} \tag{11}$$

where S_j the jet-induced dilution. Eq. 11 assumes the entrained flow contains the background concentration, c_b. This is a conservative assumption, as some of the entrained flow should be "clear" background water. Eq. 11 is equivalent to superimposing the background concentration on the near field (jet) model.

At high current speeds, dilution is mainly effected by "forced entrainment" due to the ambient current and dilution is predicted by Eq. 9. At low current speeds, jet-induced entrainment is mostly responsible for dilution when the forced entrainment due to the current becomes small. In the limit, at slack water when $u = 0$, Eq. 11 becomes:

$$S_{eff} = \frac{S_{mean}\left(S_j + 1\right)}{S_{mean} + S_j} \tag{12}$$

The diffusers are designed to effect a near-field (jet) dilution of at least 50:1. The PART simulations discussed below use these techniques to correct the predicted dilutions.

Far field modeling: The fate and transport of the effluent in the far field was modeled by the particle-tracking module Delft3D-PART. Particle tracking models have a moving (Lagrangian) grid system and represent the bacteria as particles. The particles are advected (transported) by the local current with a random walk formulation to represent turbulent diffusion. The particles can be assigned properties, such as mass and age, which makes the method particularly well suited to bacterial predictions. The particles are followed over time, and time-varying concentration distributions are obtained from the mass of particles in the model grid cells.

The hydrodynamic model, Delft3D-FLOW, was first run as discussed in Villegas and Roberts (2011) to obtain the velocity field and other hydrodynamic conditions. PART was then run for various outfall and diffuser candidates. Particles are injected into the grid cells that lie along the diffuser axis, so the near field dilution is then automatically given by Eq. 9. Hence, the PART simulations are a good approximation to the near field mixing and no separate near field model is required. In addition, the "old" particles released previously in the tidal cycle are swept back into the grid cells, so recirculation over the diffuser is also correctly incorporated. Correction is needed to account for jet-induced entrainment at low current speeds, however, as previously discussed.

Selected frames at four-hour intervals from animations showing the temporal variation of E. coli concentrations for diffuser combination R1B1 are shown in Figure 2.

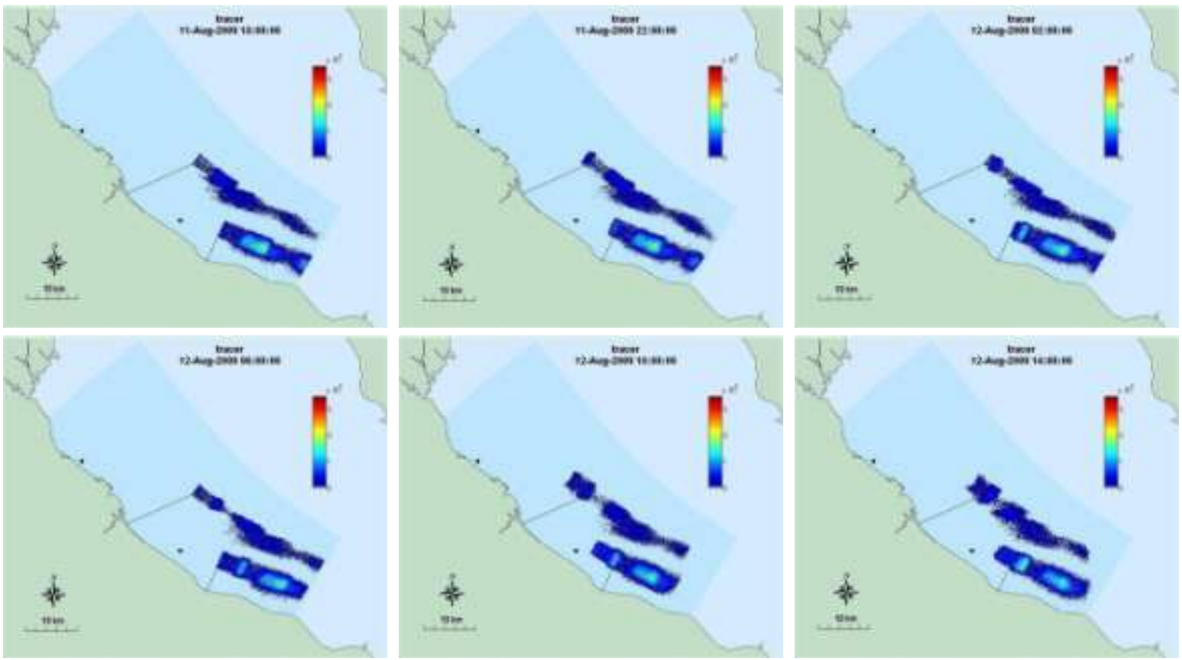

Figure 2. Frames from PART E. Coli nested grid animation, 11 August at 18:00 to 12 August 14:00, 2009. Outfall alternatives R1 and B1.

The beginning, August 11 at 18:00, is near the end of an ebbing tidal current. The plume is swept downstream with no recirculation of old effluent; its lateral spreading rate is low and it has very high dilution. Later, near slack water the dilution is low and patches of high concentration form over the Berazátegui diffuser. These patches are then advected back and forth with the tide, and as they travel they attenuate and mix due to diffusion and longitudinal dispersion, so their concentrations decrease with time. Often, the old plume is advected back and forth over the diffuser several times. For the period shown, the typical upstream excursion is about 5 km, close to the previously estimated average value. Some are much longer, however, up to about 10 km, which takes it beyond the Bernal water intake. At these times, the plume passes within a few hundred meters of the intake, although no actual impacts on the intakes were predicted for these simulations.

Near field concentrations of E. coli were obtained at observation points located approximately 200 m downstream from the center of each candidate diffuser, and at the Bernal and San Martin water intakes. The time variability of E. coli near the Berazategui diffuser is shown in Figure 3.

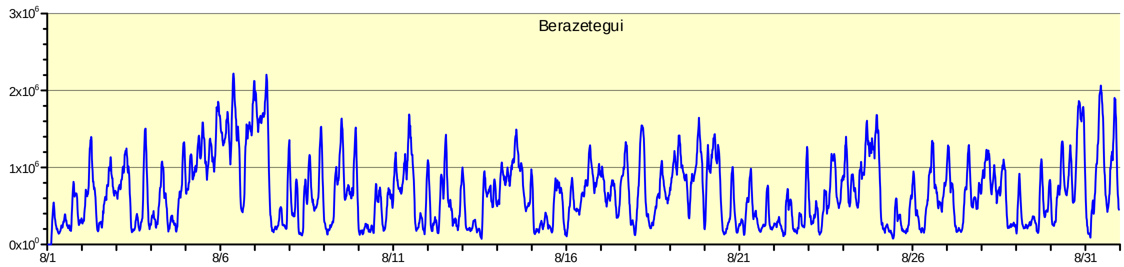

Figure 3. Near field E. coli concentrations (per 100 ml).

The E. coli concentrations vary widely due to the wide range in current speeds from about 7.2×10^4 to 2.2×10^6 with an average of 6.8×10^5 per 100 ml. This corresponds to dilutions ranging from 10 to 305 with an average of 32.

As previously discussed, these results must be corrected to account for the jet-induced dilution and mean concentration buildup. The mean dilution S_{mean} was first computed from Eq. 9 assuming the vector mean velocities measured by the ADCPs. The effective lowest values of dilution for zero current speed were then computed from Eq. 12 assuming a jet-induced dilution S_j of 50:1. Any dilutions computed from the PART simulations that were lower than this were then replaced by this lowest dilution. Various statistics of the resulting time series of dilution were then computed. The results are shown graphically in Figure 4 as the 10 percentile dilution versus diffuser length.

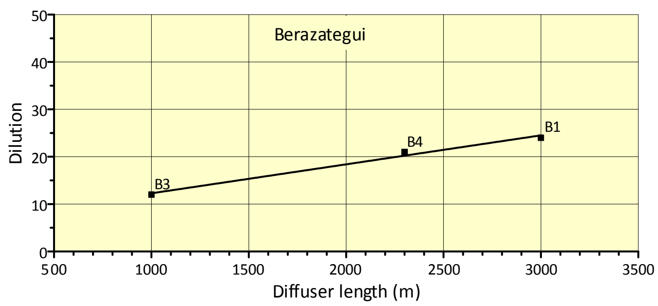

Figure 4. Effect of diffuser length on 10 percentile near field dilution

Dilutions are lower than is typical for marine discharges, of order 20 to 50, because of the tidal recirculation, low mean current speeds, and shallow water. Because of the wide range of tidal velocities, however, the dilution varies widely and is sometimes very high. It is clearly not feasible nor desirable to build diffusers long enough to achieve dilutions usually exceeding 100:1. Therefore, we adopt the criterion that the lowest value of near field dilution should exceed 20:1 for at least 90% of the time. This is consistent with practices in countries such as Denmark and Scotland where offshore water use is limited (Jirka, 2004). No water contact use is expected in the waters near the proposed discharges. Note that these dilutions are achieved very close to the diffuser, well within the mixing zone limits of 1000 m. For reasons discussed previously, it is expected that the dilution calculations are conservative, i.e. actual dilutions in the field should exceed those computed here.

Based on these criteria, the recommended diffuser lengths are 1400 m for Riachuelo and 2300 m for Berazategui. There is little advantage to making the diffusers longer which only slightly increases near field dilutions and leaves dilutions and impacts far from the diffusers essentially the same.

The diffuser lengths slightly exceed the dilution criterion of 20:1 for 90% of the time. This allows for a factor of safety for variations in data obtained in other months and seasons. It should be noted that the 10 percentile dilution depends primarily on the mean (vector) current speed which flushes the river. This in turn depends on the average discharge rate in the rivers that feed the Río de la Plata. For the period simulated, the average discharge was 23,800 m^3/s, slightly higher than the long-time annual average of 22,300 m^3/s (see Villegas and Roberts 2011, Figure 4). Therefore, the river discharges, and hence the mean current speed used, are comparable to their expected long-time average values, so the 10 percentile dilution based on the present simulations are considered to be representative of their long-time values.

4. Diffuser Details

The primary purpose of the diffuser is to obtain high dilutions, rapid vertical mixing, and a laterally homogeneous wastefield close to the diffuser. This can be accomplished by releasing the effluent as high velocity jets that discharge radially from multiport risers extending to just above the river bed. The dilution modeling and design of these risers is discussed below.

Jets with no current: The diffuser is intended to produce a dilution of 50:1 at zero current speed. A sketch of a jet at zero current speed is shown in Figure 5.

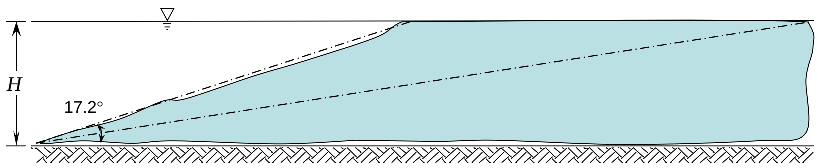

Figure 5. Sketch of jet at zero current speed

The average dilution S_a due to jet-induced entrainment is given by (Fischer et al., 1979):

$$S_a = 0.28\frac{z}{d} \tag{13}$$

where z is the distance along the jet centerline and d the nozzle diameter. The width w of the jet (defined as four standard deviations of the Gaussian velocity profile) is:

$$w = 0.30z \tag{14}$$

which leads to a jet spreading angle Θ:

$$\Theta = 2\tan^{-1}\left(\frac{0.30}{2}\right) = 17.2° \tag{15}$$

For Berazátegui, the water depth is 4.8 m, therefore, assuming the jet is oriented upwards at an angle 17/2 = 8.6° means that the jet centerline impacts the water surface at a distance of about 32.1 m. Eq. 6 then yields a port diameter, d = 180 mm to achieve a dilution of 50:1. For Riachuelo, the corresponding port diameter is 195 mm.

Effect of currents: Consider now the riser spacing and number of ports. The number of risers, and therefore their spacing, determines the distance from the diffuser where the plumes from the individual risers merge and the wastefield becomes horizontally homogeneous. This merging results from a combination of jet dynamics and entrainment and lateral diffusion due to ambient turbulence. There is no mathematical model presently capable of simulating the mixing of multiple jets discharged at various angles into shallow water subject to ambient turbulence and unsteady tidal currents.

It is profitable, however, to investigate the effects of riser spacing by simulating the jet dynamics under steady-state conditions with an entrainment model. For this purpose, simulations were performed with the mathematical model VISJET developed by the University of Hong Kong. This is a Lagrangian entrainment model with built-in visualization capabilities. The objective is a reasonably uniform downstream distribution of the jets under typical conditions that will lead to rapid lateral mixing. For average tidal current speed and wastewater flow for Berazátegui, Figure 6 shows that this can be achieved by 47 risers spaced 50 m apart (which yields the required diffuser length of 2300 m). The vertical downstream plane that is shown in this and the following images is located 100 m from the diffuser.

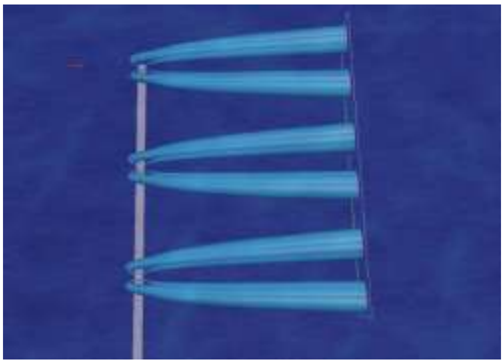

Figure 6. Plan view of VISJET simulations for average flow (25 m^3/s) and average current speed (0.22 m/s)

The behavior of the jets depends on wastewater flow rate and current speed. Visualizations for the expected tidal ranges of currents and diurnal wastewater flows for Berazátegui were made. The specified riser configuration results in reasonably dispersed jets for all anticipated conditions. The risers consist of six ports of nominal diameter (depending on final hydraulics calculations) of 180 mm. The ports are arranged uniformly around the riser at 60° intervals. The first port is angled at 30° to the current (60° to the diffuser axis) so that no jets discharge directly into the current which would result in lowered dilutions. The ports are angled upwards at 8.6° to the horizontal (see Figure 5) to avoid scouring the river bed and to promote rapid vertical mixing. The recommended designs are summarized in Table 1.

Table 1. Summary of recommended diffuser designs

	Berazátegui	Riachuelo
Diffuser length	2300 m	1400 m
Number of risers	47	29
Riser spacing	50 m	50 m
Number of ports per riser	6	6
Nominal internal port diameter	180 mm	195 mm
Nominal internal riser diameter	0.52 m	0.63 m

5. Effect of River Flow on Dilution

In addition to the diffuser length and water depth, dilution and flushing of the effluents discharged from the diffusers depends on mean current speed, tidal currents, and effluent flow rate. The recommended diffuser lengths were based primarily on the requirement to achieve a near field dilution of 20:1 for at least 90% of the time. Flows in the la Plata tributaries can vary widely, however, and in this section we discuss the effect of this variation on the outfalls.

The variation of the tributary flows over the simulation period was shown in Figure 4 at Villegas and Roberts (2011). The average monthly flows and currents measured by the ADCPs nearest to the diffusers (numbers 5 and 6) were computed and are plotted in Figure 7 as the variation of mean current versus flow rate. The mean current is close to linearly proportional to the mean flow.

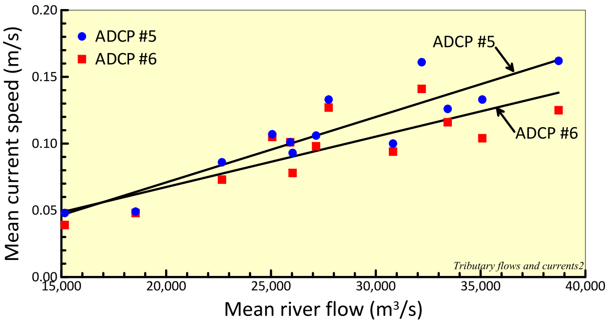

Figure 7. Mean currents measured by ADCPs as functions of combined mean river discharges from the Paraná and Uruguay rivers

To investigate the monthly variations, dilutions were computed by the same procedure previously discussed: first compute a "mean" dilution, S_{mean} (Eq. 9) due to the mean (flushing) current, and an "effective" dilution, S_{eff} (Eq. 12) that includes jet-induced dilution, S_j and background contaminant concentration. Then correct the dilutions computed by PART.

This procedure was done on a month-by-month basis using the mean currents, the simulated currents, the recommended diffuser designs, and the assumed wastewater flows. The results are summarized in Table 3. It can be seen that the effect of river flow is mainly on the ten percentile dilution. Although it may drop below 20:1 at low river flow rates, median dilutions remain high.

Table 3. Monthly variations of dilution

Month	River flows (m^3/s)	Berazátegui		Riachuelo	
		10 percentile	Median	10 percentile	Median
Jul-09	18,670	17	43	17	43
Aug-09	22,660	21	41	21	49
Sep-09	26,030	22	48	22	53
Oct-09	27,150	24	57	24	61
Nov-09	35,080	25	72	26	70
Dec-09	38,720	28	70	29	70
Jan-10	33,430	26	68	26	65
Feb-10	32,910	26	65	26	66
Mar-10	27,750	23	57	23	58
Apr-10	25,060	22	53	22	50
May-10	30,820	25	62	25	62
Jun-10	25,920	22	55	22	55

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