Analysis of Release and Transport of Ammonia from the Atlas Tailings pile and its Fate in the Colorado River

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1. Introduction

The tailings pile at the Atlas site near Moab Utah releases ammonia and other pollutants to the Colorado River through the groundwater pathway. Current releases may exceed standards for the protection of fish and fish larvae in the river. This report addresses whether a tight clay cover on the pile would reduce releases of ammonia from the pile, and lead to concentrations in the river that comply with current standards.

The tasks involved with evaluating the effectiveness of the remediation are listed below:

- Estimate the rates of ammonia being released from the site presently and during site operation. Also estimate the release rate of ammonia into the river from discharging groundwater, and the discharge rate of ammonia in the river itself. Account for possible mechanisms for ammonia release other than discharge to the river.

- Use the estimated ammonia fluxes to back-calculate the likely fluxes of water through the tailings pile, and the effectiveness of the low-permeability cap.

- Estimate the concentrations likely to occur in the river under present-day and remediated conditions in the future.

2. Estimating Ammonia Fluxes

Estimation of the release of ammonia from the site during the active operation of the pile and the rate of water infiltrating the site is important to estimate the effectiveness of the remediation. The ammonia fluxes from the pile, through the groundwater, and into the river were calculated from observed data and proved to be consistent. The three approaches for estimating the ammonia fluxes are:

- Calculate the flux of ammonia emanating from the pile as the product of the infiltration or drainage flux of water, the sampled ammonia concentration at wells in or near the pile, and the top surface area of the pile.

- Calculate the groundwater flux from the surface aquifer into the river by integrating the product of the flux measured at sampling points close to the bank and the calculated groundwater flow rate.

- Calculate the flux of ammonia *in* the Colorado River by integrating the product of the calculated surface water flow rate and measured ammonia concentrations in the river at one cross-section.

2.1 Estimation of flux of ammonia in water emanating from pile

It is assumed that the rate of fall of the measured water level in the pile is indicative of the seepage rate when there was standing water on the pile. The pond surface area is 3,868,102 ft^2. The average concentrations in pumping wells PW2 and PW6 is 3205 mg/l for ammonia. Assuming that the initial drainage from the pile is related to the drop in piezometer level lead to an estimate of approximately 50 gallons per minute (NRC study cited in CNWRA report, 1998). The estimated flux of ammonia leaving the pile is therefore approximately 0.9×10^6 grams/day. The groundwater travel time from the pile to the river is on the order of 10 years. Therefore, releases at the river today are probably the direct result of releases from the pile when it had standing water on top. This flux of ammonia from the pile has diminished as the pile dewatered by natural drainage and forced pumping, but the lower release has not yet reached the river.

2.2 Flux of ammonia estimated from groundwater seepage into river

The ORNL/CG (ORNL, Jan 8, 1998) estimated the flux of ammonia of 150,000 grams/day at the river bank from sampled ammonia concentrations in the piezometers, an assumed hydraulic gradient of 0.004, a measured hydraulic conductivity of 22 ft/day and an assumed aquifer thickness of 40 ft. Staff repeated the calculations, but used estimates of the hydraulic gradient at many points taken between individual piezometer, and estimated a flux of ammonia of 230,000 grams/day. The manual calculations of the ammonia flux are summarized in Table 1.

Measurement points in the water table on the flood plain indicate higher concentrations in the center than on either the upgradient or downgradient ends. One interpretation is that this represents a region of high flux that is propagating through the aquifer, and will discharge sometime later. A more likely explanation is that the water table is fluctuating from large changes in the river's stage, and that the fluctuation in concentration reflects the cyclical nature of transport in the aquifer (see discussion on bank flow transients).

2.2.1 Effect of Tamarix on water balance and ammonia flux.

There is a dense stand of Tamarix (a.k.a. saltcedar) on the banks of the Colorado River. The depth of the grove between the edge of the pile and the Colorado River is a minimum of about 800 ft and is as great as 3500 ft. Tamarix is a phreatophyte, and is known to transpire large quantities of groundwater. Phreatophytes usually take their water directly from the water table instead of the unsaturated soil zone (McWhorter, 1977). Estimates of Tamarix transpiration range from 1.4 to 10.5 ft/yr (Weisenborn, 1996). A study by the U.S. Bureau of

Reclamation at Bernardo New Mexico, about 60 miles south of Albuquerque on the banks on the Rio Grande River, may be used as an analog to conditions existing at the Atlas site (Gay and Fritschen, 1979) The New Mexico site is further south than Atlas, but is at higher elevation. It has a thick stand of Tamarix up to approximately 15 ft tall. Detailed measurements and energy budget calculations undertaken in a 5-day field trial under warm, mostly dry and cloudless conditions led to an annularized rate of transpiration of about 9.6 ft/year. However, the projected annual average transpiration for the site was estimated to be about 4.3 ft/year.

The effects of Tamarix on the water balance are likely to be significant. As an example of this hypothesis, consider a location near the river and that has the steepest gradient, for which Tamarix is likely to have the least impact. The trace length of the Tamarix grove is about 800 ft. The water table gradient would be about 5.7 ft/800 ft. The estimated hydraulic conductivity from a pump test in the aquifer is 22 ft/day (ORNL, 1998), and the aquifer thickness is estimated to be 40 ft (ORNL, 1998). The groundwater flow into the river at this point without any effect from Tamarix is calculated by Darcy's law to be:

$$q = kiH = 22ft/day \times \frac{5.7ft}{800ft} \times 40ft = 6.27ft^3/(day\ ft)$$

The annual consumption by Tamarix in the same reach, using the Bernardo NM data would be:

$$q_t = 4.3ft/yr \times 800ft \times year/365\ days = 9.3\ ft^3/(day\ ft)$$

These estimates reflect the part of the system least affected by Tamarix. Where the distance to the river is greater and the gradient smaller, the effect of Tamarix would be greater. It is likely therefore, that the Tamarix is having a significant effect on the flux of groundwater from the site and the flux of the dissolved pollutants reaching the river. Ammonia taken up by the roots of the Tamarix would either be metabolized by the plant or at least released to the atmosphere. Tamarix are well known for their ability to take up water with high dissolved minerals, and there is no reason to believe that ammonia or ammonium ion would be excluded from this uptake (Smith, 1999).

Despite these apparently large amounts of water being transpired, there are still significant releases of ammonia to the river. The main conclusion from the above analysis is that the flux of water and ammonia leaving the pile is larger than estimated entering the river, and the measured constituents at the river represent that which escape the Tamarix roots. Other factors in this analysis are:

- The transpiration of the Tamarix would be seasonal, and the larger releases of contaminants to the river may coincide with periods of low transpiration. In fact, the water table fluctuations might be daily, and fluxes into the river could depend on the

time of day. See for example, Figure 1 taken from McWhorter (1977). This could be a factor in measurements of concentrations in the river itself.

- There may be hydraulic short-circuits through the shallow aquifer, such as lenses of coarse alluvium, which could allow contaminants to bypass the effects of the Tamarix.

Observations at the site indicated that the Tamarix may be effective at removing contaminants in the plume emanating from the pile. In the central part of the plume where concentrations are highest, the vegetation is being stressed, as evidenced by its off-color appearance and thinner density. Alternative explanations for this plant stress could be fires and surface dumping, however.

2.3 Flux of ammonia in the Colorado River

Atlas contracted with Harding Lawson Associates (HLA) Inc to monitor contaminants in the Colorado River near the site (HLA, 1998). It was possible to estimate the flux of ammonia in one of the river cross-sections by integrating the product of the river flow rate and concentration in the area covered by the sampling stations. Necessary parameters of this analysis include river flow rate and stage, cross-section of the river, variations of river velocity with location in the cross section, and location of the water samples. River flow rate was recorded at the time samples were taken, but the exact location of the samples was not indicated in the HLA report. Furthermore, river velocities were not measured at the sample locations. The cross-section of the river was a rough estimate based on large-scale maps aimed mainly at flood studies, and not detailed enough for the current task (Mussetter, 1994). Depths at 10, 25 and 50 ft from the near bank were recorded at a few downstream locations in conjunction with the river sampling studies. River stage above the thalweg (lowest point in the river channel) and water velocity were also taken from Mussetter.

The cross-section selected, 3-3a, is not the most downstream reach of the affected part of the river, and therefore does not account for the total amount of ammonia reaching the river. However, most of the release is predicted to occur prior to this location.

The flow rate and velocity of water in the river within 50 ft of the shore were estimated from the following procedure:

- Represent the river cross-section by M points with M-1 straight-line segments. Therefore, the river is represented by M-1 trapezoidal segments.

- Estimate the relative flow in each of the trapezoidal river segments using assumptions of steady open-channel flow and uniform friction factors (Manning's n coefficient) across the river. This can be expressed by (Codell, et al, 1982):

$$q_j = Q \frac{\sum_{i=1}^{j} \overline{z_i^{5/3}} (\Delta y)_i}{\sum_{i=1}^{M-1} \overline{z_i^{5/3}} (\Delta y)_i}$$

where z_i = the average depth in trapezoidal river segment i, Δy_i = the distance between two points making up the line segment, q_j is the cumulative flow at the end of segment j, and Q is the total discharge in the river.

- Calculate the ammonia flux in each river segment as the product of the average water flux and average concentration in the segment.

- Sum the ammonia flux of all river segments to get the total ammonia flux in the river.

The calculation of the river flux at station 3-3a is shown in Table 2. For the stated conditions, the average flux of ammonia in the river at the station is about 262,000 grams/day. This table does not include any concentrations beyond 50 ft from the shore or downstream from cross-section 3-3a, although we believe that most of the ammonia has been accounted for at that cross-section in the river.

3. Dilution in Colorado River

There have been several field studies of dilution in the Colorado River to measure the concentrations of pollutants seeping from Atlas. The State's measurements have been taken only as "grab" samples at the near and far shore of the river (Utah, 1996 and Utah, 1997), whereas the Licensee's measurements have looked at multiple stations from the shoreline to 50 ft offshore, and at multiple depths (HLA, 1998). The field studies often disagree by large measures, with the Licensee's values being of generally lower concentration where they could be compared, i.e., at the shoreline. It is not clear why there is this discrepancy, but a few of the possibilities are:

- The samples were not collected at the same locations. The State claims only that their samples were "grab" samples taken at the shoreline. If the samples were very close to a seep into the river, then concentrations could vary markedly in only a few feet from the bank. Also, the locations along the bank could have been different.

- The river stage during the sampling was different.

- There could be experimental error in the measurements.

- The releases from the bank are transient, caused by bank storage.

Integration of river concentrations from the Licensee's samples was generally consistent with expected discharges of ammonia to the river from the groundwater pathway. No such comparison could be made with the State's river data because they were collected only at the shoreline. However, projecting the State's concentration data by a direct scaling of the HLA measurements, and then applying this result to a mass balance of ammonia in the river would have predicted a much larger ammonia flux in the river than could be accounted for by release from the pile or groundwater flux. For this reason, we do not believe that the State's data on ammonia in the river represent steady state fluxes.

3.1 Effect of river stage on dilution and extent of mixing zone.

Most of the sampling programs of concentration in the Colorado River were conducted at flow rates at about average river stage. Concentration and mixing zone limits however appear to apply at any time. Factors that control concentration in the river include release rate of ammonia from the groundwater to the surface water, the location of the release and the flow rate in the river. The phenomena of mixing of the contaminant plume in the river as a function of river stage are complex, and have not been explored fully for this case because of the lack of time and site-specific data. The problem is further complicated by the transient interaction of groundwater, river water, and the contaminants resulting from changes in the river stage.

3.1.1 River flow rate

The record low flow rate for the period of record on the Colorado River at the nearest upstream gage near Cisco, Utah was 558 CFS in 1934. However, the river has been regulated by upstream dams since the early 1950's, and it is not likely that such a low flow would occur again. There has been significant regulation by the Blue Mesa Reservoir since 1965. A cumulative distribution function (CDF) of flow rate at the Cisco gage since Jan. 1, 1965 is shown in Figure 2. The lowest daily flow since January 1965 has been 1100 CFS. The mean and median daily flows in that period have been 7283 and 4500 CFS, respectively. The 10th percentile low flow (i.e., 90 percent of the daily flows are greater) was 2550 CFS.

3.1.2 Dilution in River under conditions of steady groundwater release

For hypothetical steady releases of pollutants, concentrations and the extent of the mixing zone in the river will be negatively correlated (but not directly proportional) to river flow rate. The relationship between concentration in the river and flow rate is not simple. The staff did not attempt a complete model of dispersion in the Colorado River because it would have required too much time, and adequate data were lacking. However, the staff estimates empirically, based on general considerations of mixing in open-channel flow, the likely effect of dilution in the river, and estimates how changes in river flow rate will affect the concentration of ammonia. The following two factors went into the estimation of the effect of flow rate on the peak concentration and the extent of the mixing zone:

3.1.2.1 Effect of flow on peak concentration

Regulations call for the compliance in the river with a maximum concentration anywhere of less than 1.92 mg/L ammonia. This concentration will be determined by the depth of the river, the velocity in the river, and the points or areas of entry of the contaminant groundwater plume. As river flow decreases, the velocity in the river and the stage will also decrease. Decreased stage leads to a decrease in the river width.

It is assumed that a representative low flow in the river at the site could be chosen as the 10th percentile daily low measured at the Cisco gage (it will be shown later in section 3.2 that it is not necessary to pick a single low flow for determining peak concentration). The 10th percentile daily low flow would be approximately 2550 CFS, about 48% of the reference flow rate during the HLA sampling period (HLA, 1998) of 5275 CFS. At this flow rate, the river stage is predicted by the flow-stage hydrograph, Figure 3 (derived later in Section 3.2.1) to decrease about 1.9 feet from the reference level. However average velocity decreases from 1.64 to 1.24 ft/sec, a drop of only 24% from the reference level average velocity. At lower flow rates, turbulence will decrease, leading to a diminished rate of longitudinal and horizontal mixing in the river. However, the travel time to reach a fixed downstream point will increase, partially compensating for lower turbulence.

The entry of the groundwater seepage into the river will also change at lower flow. The location of the seepage will shift as the water level drops, as shown in Figure 4. It is assumed here that river stage and water table height are equal at the bank. This should be true most of the time. However, during periods when the river stage falls quickly, there may be seepage from the bank above the river's edge and overland flow to the river. The consequences from this seepage should not be greater than the case treated because such seepage would consist mostly of river water uncontaminated with ammonia. If we assume that the rate of groundwater flow is constant and that the river is the local sink for all groundwater flow, then the streamlines of groundwater will become compressed; i.e., the same amount of groundwater will be forced into a smaller vertical distance of aquifer. If the bank of the river is of constant slope, the groundwater plume will be smaller, leading to a higher flux density of ammonia where it enters the river. If the slope of the river bank decreases as one moves from the shoreline to the center, this will tend to spread out the groundwater streamlines, compensating for this compression effect. The river bank near the site however appears to be of reasonably constant slope up to about 50 feet out, so the latter effect (spreading of streamlines) is probably less important than the former (compression of streamlines).

In summary, lowering the river flow rate will cause the plume eventually to translate horizontally to a new fixed position. Groundwater discharge will be compressed vertically, tending to increase the flux density of ammonia entering the river, leading to higher concentration of ammonia in the river. The lower flow rate and velocity will also tend to increase the peak concentration close to the bank because of reduced turbulence. River velocity will decrease modestly, leading to somewhat lower horizontal spreading and dilution. Combining the various factors of (somewhat) smaller river velocity and compressed

groundwater streamlines, the increase in maximum concentration in the river at low flow should be less than a factor of two increase in peak river concentration over the reference condition.

3.1.2.2 Effect of lower flow rate on longitudinal extent of mixing zone

The downstream limit of the mixing zone, described by the concentration which exceeds the chronic regulatory limit of 0.38 mg/L, is more difficult to predict. It is somewhat easier to project the change in the concentration of fixed locations. Taking the present limit of the mixing zone as that fixed location is reasonable, as it already exceeds the length of the mandated mixing zone in some cases. Using the logic of the previous section on maximum concentration, the concentration should increase by less than a factor of two at the current extent of the downstream mixing zone.

3.2 Transient flow in the Colorado River

The Colorado River is subject to large fluctuations in flow and stage, especially because of runoff from the spring melt. Water stage along the bank can vary well over 10 feet during the large annual flood. Fluctuations in the river stage near the site have the following effects on the groundwater flow from the pile to the river:

- The water level in the water table aquifer will be affected significantly by the river level.
- During periods of high river stage, flow will reverse, going into the aquifer and bringing with it water uncontaminated with ammonia. The uncontaminated river water will act to back up the natural groundwater flow. Mixing between uncontaminated and contaminated water inside the bank will be modest.
- The peak in groundwater discharge of contaminated water following high stage may coincide at times with low river stage, leading to high concentrations in the river.
- Floods that significantly overflow the bank, allowing recharge of the water table from the surface, may cause a still greater effect of flushing of the aquifer.

The effect of fluctuations in the river level was explored by coupling a one-dimensional model of transient groundwater flow to a model of surface water flow in the river. River flow rates were taken from the record at the upstream Cisco Utah gage from 1965 to the present. A schematic depiction of the coupled system is shown in Figure 5.

The groundwater model assumes one-dimensional flow from upland, with a variable phreatic surface. The downstream boundary sets the head at the first node of the model equal to the river level as a function of time. The upland boundary condition assumes no flow (reflective), and is 1000 ft away from the river. These boundary conditions were chosen to eliminate the

flow of groundwater in the aquifer model under base-flow conditions (including any effects of transpiration from shoreline vegetation), and focus only on the changes in the fluxes of water resulting from changes in the water level. Calculations of contaminant transport, shown later in Section 3.2.4, add in the base flow velocity of the groundwater calculated from the observed hydraulic gradient.

3.2.1 Model of River Stage

The water flow in the Colorado River was related to river stage within the normal banks near the site by a conveyance model based on channel cross-section and roughness (Chow, 1959). Water level in the channel was calibrated from observed stage versus flow data and also projections from flood-routing studies (Mussetter, 1994). Channel cross-sections are approximate, and account for river stage only at the location approximately corresponding to location 3-3a from the Atlas field measurements (HLA, 1998). The cross-section used in this study is depicted in Figure 6.

For steady uniform flow, the flow rate Q is related to river stage by the Manning formula (Chow, 1959):

$$Q = K\sqrt{S}$$

where S is the hydraulic gradient in the direction of flow, and K is the "conveyance":

$$K = \frac{1.49}{n} A R^{2/3}$$

The term n is the Chezy roughness coefficient, and R is the hydraulic radius of the river channel, taken as the cross-sectional area A divided by the wetted perimeter (i.e., the distance along the river bottom of the cross-section and the water surface).

It is not necessary to know the values of n or S for the purpose of generating the stage versus river flow rate as long as we assume that the values of these two variables are constant over the river reach of interest. Knowing the river stage at a particular flow rate Q_0, the river stage at a different flow rates can be estimated implicitly from the following relationship:

$$Q = Q_0 \frac{K}{K_0} = Q_0 \frac{A R^{2/3}}{A_0 R_0^{2/3}}$$

Figure 3 shows the relationship between river flow rate and stage at the 3-3a cross-section for average to low-flow conditions. Zero stage on this figure is relative to the stage at the time of the HLA sampling (HLA, 1998) corresponding to 5275 CFS. The conveyance figure for all river flows includes estimates of stage from the flood-routing study conducted by Mussetter (1994), and is depicted in Figure 7.

The present analysis uses only the discharge at the Cisco gage, and does not account for any base flow in the approximately 31 miles between that gage and the site. Furthermore, the flood flows do not account for storm flows that might occur in sub-basins downstream of the Cisco gage, and therefore may underestimate the magnitude of some severe floods.

3.3.2 Groundwater Flow Model

Groundwater flow was calculated by assuming one-dimensional flow from upland to the river along a fixed 1000-ft length, which is the approximate distance between the river and the down-gradient end of the pile at average river stage. The present calculation does not include the natural gradient toward the river or transpiration from the Tamarix because its intent was to examine only the influence of transient river stage on flow and transport in the aquifer. For the purpose of estimating contaminant transport, the gradient-driven groundwater flow was added into the transient calculations by linearly summing the transient and steady state groundwater velocities. There is no provision in the present model for varying the length of the groundwater pathway in response to changing river stage.

The groundwater system was treated as unconfined flow with a phreatic surface, expressed by the equation:

$$\frac{\partial h}{\partial t} = \frac{k}{S_y}\frac{\partial}{\partial x}\left(h\frac{\partial h}{\partial x}\right)$$

where h = head above the reference river level, k = hydraulic conductivity, x = linear distance from shore, t = time, and S_y = storativity. This equation is nonlinear, and was solved numerically using the finite difference method with a backward-in-time implicit method. The 1000 ft interval was broken into 100 equal grid cells. Boundary conditions were fixed head at the river end and no-flow at the upland end. Hydraulic conductivity k was taken from the pump-test value in the alluvial aquifer of 22 ft/day. The storativity S_y was taken as 0.3. Most of the flow is probably occurring in the coarse gravel and sand, but this layer is overlain by a finer alluvial layer with greater quantities of silt and clay. The phreatic surface may extend into this overlying layer, which will affect the way the system responds hydraulically, and the way the contaminants will be transported.

Figure 8 is the measured response in piezometer ATP-2-S, which is located approximately 800 ft from the river, and the corresponding river level at times between 1/14/89 and 3/1/94. Figure 9 is the simulated response in the aquifer at two locations, 500 and 1000 ft from shore and the simulated river stage in response to the flow at the Cisco gage. The simulated piezometer levels are plotted as if the river datum and aquifer datum were at the same level, but since the land slopes approximately 4 ft/1000 ft, the 500 ft and 1000 ft curves should be shifted up 2 and 4 ft, respectively. When this is taken into account, the agreement of the model and prototype is quite good. This comparison lends credibility to the hydraulic model of the groundwater/surface water system.

Figure 10 shows the net recharge and discharge of the aquifer at the bank in response to the water level fluctuations over an arbitrarily chosen 1000 day period. This figure shows large fluctuations of up to 40 cubic feet per day per ft of river bank. The corresponding base flow under natural gradient conditions at the closest distance between the pile and the river would be about 3.5 cubic feet per day per foot of bank width. If the model and parameters are correct, then there are periods when bank storage far exceeds natural seepage from the aquifer. Some anecdotal information on the likelihood of this large outflow is contained in a memorandum from the William Sinclair to Don Ostler (State of Utah, May 3, 1995). The letter speaks of an area of seepage on the river bank, discovered by the National Park Service and others in early April, 1995, immediately below the Atlas tailings embankment. The seeps spanned 50 to 200 yards and were about 2 feet above the river's level on April 5, 1995. Estimated flow in the seeps was on the order of 10 gallons per minute.

3.2.3 Effect of fluctuating river level on ammonia concentration in river

The rate of groundwater flow from and to the banks are related, but not directly proportional, to the flow rate of water to the river. During high stage, the river recharges the banks with uncontaminated water. There would be some mixing of contaminated and uncontaminated water in the aquifer. As a first approximation, the river water and groundwater can be considered to be moving in "piston" flow, simply displacing one another, but the effects of mixing or dispersion are also treated.

The largest phenomenon affecting the release and concentration in the river is likely to be that the infusion of river water to the bank will reverse the groundwater gradient, thereby stopping the release of contaminated groundwater. When this is happening, the releases of contaminants from the pile will be unrelenting, and simply be stored in the building hydraulic mound in the bank. When the river recedes, the flow again reverses, but with increased driving force and inventory of contaminated water, thereby increasing the release of contaminants to the river as a pulse. The length of these fluctuations in water level is variable, but the biggest fluctuations, associated with spring runoff floods, can persist more than one hundred days.

3.2.4 Ammonia groundwater transport model

In order to simulate the likely increases in river concentration resulting from the pulses of groundwater discharge from the bank, the groundwater flow model was enhanced to include the transport of tracer particles from the pile to the river. The particles released from the upland end of the model represent only those particles that would normally reach the river, and not those that would be taken up by transpiration of the Tamarix. The tracer particles were released, one per computational time step, at the upland end of the groundwater model, 1000 ft from the river. The particles move toward the river under the influence of the calculated steady state gradient at about 0.3 ft/day, but this must be added to the velocity calculated in the groundwater resulting from the transient water level fluctuations. The effective porosity in the aquifer was taken to be the same as the storativity of 0.3. Particles

moved at the velocity of the groundwater, and left the system permanently when they passed a boundary taken as 5 ft from the river end of the model. The effect of longitudinal dispersion was taken into account by the "random walk"[1] method, where the position of the particles can move a random distance upgradient or downgradient after each time step:

$$x' = x + v\,\Delta t + \sqrt{|v|\Delta t\ \alpha} \times N$$

where x is the initial position, x' is the position after the time step, v is the advective velocity, α is the dispersivity, and N is a normally distributed random number with mean zero and standard deviation 1.0.

The concentration in the river is taken as the rate of release of tracer particles divided by the river flow at the time of particle release. The rate of release of particles to the river is out of phase with river flow rate, because the release is delayed from the bank. This can lead to situations of large bank release and low river flow, i.e., high concentration.

Because there are a limited number of particles released, peak concentration may be exaggerated if too few particles are used to represent the continuum of dissolved ammonia concentration. Furthermore, longitudinal hydrodynamic dispersion in the aquifer may be important in smoothing out the higher peaks. The effect of dispersion on C_f in the river is shown in Figure 11 for $\alpha = 0$ and 1 ft. Including dispersion drops the highest peak levels dramatically. Figure 12 shows the concentration, in terms of particles per 10 ft grid cell, at the end of the 37 year calculation. The calculation without dispersion is evidenced by its large spikes in concentration. Adding dispersion to the model reduces these spikes significantly. Although the number of well points is limited, such large spikes characterized by the zero-dispersion case do not appear to be evident in the data, leading to the conclusion that dispersion is occurring in the aquifer.

It is useful at this point to define a "concentration factor" C_f as the concentration predicted by the model divided by the benchmark concentration representative of conditions measured in the Atlas sampling program (HLA, 1998), for which the average river flow was 5275 CFS. For example, under steady state conditions with a time step of 1/10 day the benchmark concentration would be 10 particles per day divided by a flow of 5275 CFS.

Table 3 shows the peak concentration factors and their quantiles for two different particle densities (5 per day and 10 per day), and three different longitudinal dispersivities (0, 1 and 10 ft). Also shown in this table are the results of robust smoothing (SUPSMU, MathSoft, 1993) of the particle concentrations. The smoothing calculations are an attempt to remove computational "noise" from the calculations which is an artifact of the calculation using too sparse a number of particles. The highest peak concentration factor of about 80 was predicted

[1]This method relies on the fact that the normal probability distribution function is a solution to Fick's law of diffusion.

for 5 particles/day, no dispersion and no smoothing. Increasing the number of particles to 10 per day increased the resolution and lowered the peak concentrations to about 50 times the nominal steady state concentration. Dispersion added to the calculations leads to a significant drop in peak C_f to about 18 and 15 for $\alpha = 1$ and 10 ft, respectively. As shown in Figure 13, applying robust smoothing to the result for $\alpha = 1$ ft with a 2 day or 5 day window reduced the peak concentrations to about 14 and 13, respectively.

Other, more qualitative arguments lead to a reduction in C_f:

- The current one-dimensional model might overestimate the peak release of ammonia because it would predict release at every point along the bank simultaneously. The length of the groundwater pathway varies from a minimum of about 1000 ft to over 3000 ft. At the least, the release of contaminated groundwater from the bank would be on different schedules, depending on the length of the flow path, so the net contribution of ammonia flux to the river would have a broader, lower amplitude peak than if the contributions all happened in synchronization.

- Retardation and matrix diffusion might lead to higher mixing of contaminated and uncontaminated water within the aquifer. There may be storage mechanisms in the aquifer that lead to mixing between the contaminated and uncontaminated waters. For example, ammonia may be sorbed to an extent on the alluvium, or diffuse into the matrix of the particles. Another possible mechanism would be the forcing of contaminated water into the lower-permeability layer above the aquifer. If the phreatic surface extends into this layer, then contaminated water might be held for a longer time than would be suggested by the properties of the coarse alluvial aquifer alone.

- The calculations performed assume that the concentration in the river is inversely proportional to the river flow rate. However the arguments made in section 3.1 about concentration effects at low river flow lead to a position that halving the flow rate of the river results in less than a doubling of concentration and extent of the mixing zone; i.e., C is proportional to Q^{-p} where p is a number less than 1. The effect of river flow rate on concentrations is therefore overestimated.

- The highest concentrations in the river would occur infrequently. Figure 14 shows the cumulative distribution function of C_f for $\alpha = 1$ ft. The peak C_f would be 18.5, but the 99th percentile results would be only 7.75. If something less than absolute highest concentration factor at any time is acceptable, the case could be made that the concentration would be considerably smaller than the peak. Note that this is a "frequency" argument rather than an "uncertainty" argument. Uncertain relates to the degree of belief in our model.

On the basis of the modeling results and the qualitative arguments, it is reasonable to predict that concentrations in the river might by amplified by a factor of 10 above nominal steady state concentrations as a result of variable river flow and bank storage.

3.2.5 Calculation of Peak and Chronic Concentrations

The highest measured shoreline concentration from the HLA study was 2.4 mg/L ammonia (HLA, 1998). Taking credit for a 10^{-8} cm/sec cover on the tailings pile would offer a reduction in concentration by a factor of 0.0114. Combining this with the C_f estimate of 10 would yield a concentration under remediated conditions of 2.4 x 0.0114 x 10 = 0.27 mg/L ammonia, which would be in compliance with the Fish and Wildlife Service criteria for acute releases of 1.93 mg/L. The same logic can be applied to the chronic concentration at the edge of the specified regulatory limit of 2500 downstream. The concentration measured by HLA at the shoreline was about 2.2 mg/L ammonia. The commensurate concentration after remediation would be 2.2 x 0.0114 x 10 = 0.25 mg/L ammonia, which is within the regulatory limit set for chronic releases by the Fish and Wildlife Service [this analysis is expanded in the addendum].

4. Conclusions

The PAHL staff performed an analysis of the discharge of ammonia from the Atlas tailings pile and its fate in the Colorado River. The staff conducted several calculations to determine the effectiveness of planned remediation of the Atlas site with regard to concentrations of ammonia in the Colorado River. The first set of calculations estimated the fluxes of ammonia leaving the tailings pile, entering the river and being transported down river. The staff estimated that there were approximately 900,000 grams of ammonia leaving the tailings pile per day during the time when the pile was in active operation and there was a wet pond on the surface. This estimate was based on an infiltration rate calculated from the measured decrease in water level in the pile, and on measured ammonia concentrations from wells in the pile. The estimate of ammonia release to the river was about 236,000 grams per day on the basis of concentrations and water levels in riverside well points. The estimate of ammonia being transported downstream in the Colorado River within 50 ft of the bank was about 263,000 grams per day.

The staff estimates that there was considerable uptake of water and transpiration by the Tamarix on the bank, and that this is likely to account for a significant loss of ammonia (more than half) before it reached the river. The staff believes that Tamarix or other phreatophytes such as willow and cottonwood will remain a major factor in the water and ammonia balance for the regulatory time of interest.

The staff also estimates that there will be a considerable fluctuation of contaminants into the Colorado River because of large-scale changes in river stage, especially during spring melt. These water level changes will cause reversals of the hydraulic gradient in the water table aquifer, which can lead to the buildup of contaminants in the bank and release at considerably greater rates once the water level falls. When these large rates of contaminated groundwater release coincide with low river flow rates, high concentrations could exist in the river. The staff estimates that peak concentrations could be a factor of up to 10 times greater than those

measured by the applicant in its 1997 field study (HLA, 1998), but that this would occur infrequently.

On the basis of its analysis, the staff has reached the following conclusions about the behavior of the Atlas system, and the likelihood that the site will comply with regulatory standards for discharge of ammonia into the Colorado River:

- On the basis of the good agreement among the fluxes of ammonia, including the likely loss through transpiration, the staff was able to estimate with confidence that the likely infiltration rate on the pile must have been on the order of 50 gallons per minute. The importance of this estimate is that a low-permeability clay cap would effectively remediate the site by reducing infiltration to low levels. A low permeability cap with 10^{-7} cm/sec permeability would reduce infiltration to 5.7 gpm, and a 10^{-8} cm/sec permeability cap would reduce infiltration to 0.57 gpm. These estimates assume that the infiltration of the site is equal to the cap permeability under a unit hydraulic gradient. Because flux is proportional to infiltration rate, the staff would expect up to a two order-of-magnitude decrease in flux for a 10^{-8} cm/sec cap. The staff also suggests that under present-day conditions without a pond on the surface, recharge on the site because of precipitation might be much smaller regardless of the type of cover imposed. Studies of infiltration through caps on tailings piles (DOE, 1991) and infiltration in thick alluvium at Yucca Mountain, Nevada (DOE, 1998), indicates that there is little or no net infiltration under dry desert conditions in soil or deep alluvium.

- The staff believes that the higher concentrations along the shoreline of the river observed by the State of Utah are inconsistent with calculations of mass flux of ammonia on land. A possible explanation of this discrepancy is that the measured ammonia concentrations were a result of transient releases resulting from the outflow of bank storage from higher river stage, and are not a true indication of the steady state releases to the river.

- The staff believes that if a 10^{-8} cm/sec cap were placed on the tailings pile, the site would comply with the accute ammonia standard within the mixing zone of 1.93 mg/L, and the chronic ammonia standard of 0.38 mg/L at the downstream extent of the mixing zone. The staff also believes that episodes of high ammonia concentration in the river will be infrequent, caused by periods of relatively high groundwater flux coinciding with relatively low river flow. If the standard could be restated to recognized the low frequency of these episodes (e.g., the concentration is less than the standard 95% of the time), the staff would have higher confidence in compliance.

5. Uncertainties in calculations and recommendations for improvement

Many of the calculations performed in this study were simplified, reflecting the relatively incomplete nature of the data set available and in some cases schedule limitations. Additional

refinements to the calculations might be able to improve the estimates of river concentration and the effectiveness of remediation. These improvements include:

- Improve the groundwater transport model. The one-dimensional model of transient groundwater flow did not include the possible infiltration from the surface during periods of significant overbank flooding, or the removal of water by transpiration from the Tamarix. Both these phenomena could be significant. Although the effects were taken into account empirically, it would be possible to modify the one-dimensional model to account for all the phenomena simultaneously, thereby reducing this modeling uncertainty. Another improvement to the groundwater model would be to represent the aquifer in two dimensions laterally. The current one-dimensional model might overestimate the peak release of ammonia because it would predict release at every point along the bank in synchronization. A model that was distributed laterally as well as longitudinally might spread out the releases, leading to smaller peak concentrations in the river.

- Improve river mixing model. The changes in concentration with distance and time because of changes in river flow rate were estimated empirically only and not quantitatively modeled. River dispersion models exist that could be used to estimate the expected nature of the pollutant plume with changing flow rates in the river. There are sufficient measurements of concentrations in the river to allow calibration of such a model, but additional data such as more accurate river cross-sections in the area of the mixing zone, tracer experiments and velocity transects would improve the predictions.

- Uptake of water and dissolved chemicals by the Tamarix has been predicted to play an important role in the ultimate release to the Colorado River. Quantitative measurements of chemical contaminants in the leaves and wood of the Tamarix would serve to validate this presumption.

- Because release of contaminated water from bank storage may play a role in causing periods of high concentration in the river, it would be useful to institute a testing program to capture this effect. For example, concentration in the river could be measured at a single point, either continuously or at close time intervals, along with head and concentration at well points on shore near the river measurement station. Collecting these data over a few months, especially when large fluctuations in the river stage were expected, would serve to validate this model.

6. References

Atlas Corporation Moab Mill, Moab, Utah, prepared for the U.S. Fish and Wildlife Service, Salt Lake City, UT.

Chow, V.T., *Open Channel Hydraulics,* McGraw Hill, New York, 1959

Codell, R.B., K.T. Key, and G. Whelan, "A collection of mathematical models for dispersion in surface water and groundwater", NUREG-0868, U.S. Nuclear Regulatory Commission, 1982.

DOE, 1991, "Analysis of infiltration through a clay radon barrier at an UMTRA disposal cell", U.S. Department of Energy, UMTRA Project Office, Albuquerque Operations Office, January 1991.

DOE, 1998, "Viability Assessment of a Repository at Yucca Mountain", Department of Energy, Las Vegas Nevada.

Gay, L.W., and L.H. Fritschen, "An energy budget analysis of water use by saltcedar", Water Resources Research, Vol 15, no 6, December 1979

Harding Lawson Associates (HLA), 1998, Colorado River Sampling Report Atlas Uranium Mill and Tailings Site, Moab, Utah, prepared for Atlas Corporation, Jan 23, 1998

Oak Ridge National Laboratory, (ORNL/GJ), 1998. "Limited Groundwater Investigation of the Atlas Corporation Moab Mill, Moab, Utah" , Oak Ridge National Laboratory, Grand Junction, Colorado, January 9, 1998.

MathSoft, 1993 *S-Plus Reference Manual*, routine SUPSMU, MathSoft, Inc., Seattle WA, 1993

McWhorter, D. and D.K. Sunada, *Ground-Water Hydrology and Hydraulics*, Water Resources Publications, Fort Collins CO, 1979

Mussetter, R.A., M.D. Harvey, "Geomorphic, Hydraulics and Lateral migration characteristics of the Colorado River, Moab", Mussetter Engineering Inc, Fort Collins, May, 1994

Sinclair, W. memorandum from William Sinclair to Don Ostler, State of Utah, May 3, 1995.

Smith, S. University Nevada Las Vegas, personal communication, Jan 27, 1999.

Utah Division of Radiation Control, 1996, State Update Report for Intensive Ammonia Sampling of Colorado River and Request for Additional Studies: Atlas Uranium Tailings Near Moab, Utah, Letter Report, Utah Division of Radiation Control, Salt Lake City, Utah, December 11, 1996

Utah Division of Radiation Control, 1997, Atlas Uranium Mill Tailings near Moab, Utah: January y, 1997, Utah DEQ Intensive Colorado River Water Quality Sampling Results, Need for Additional Studies, Letter Report, Utah Division of Radiation Control, Salt Lake City, Utah (June 20, 1997)

Weisborn, D. , "Saltcedar impacts on salinity, water, fire frequency and flooding", *The Saltcedar Management Workshop,* June 12, 1996, University of California, Rancho Mirage California

Addendum to Atlas Ammonia Report

by Richard Codell

A.1 Introduction

This addendum amplifies the discussion about the concentration at the downstream edge of the mixing zone and how it responds to changes in flow. This topic was discussed in section 3.1.4 of the report "Analysis of Release and Transport of Ammonia from the Atlas Tailings Pile and its Fate in the Colorado River" by the same author. The previous analysis discussed the belief that the dilution in the river would be less than proportional to the flow rate in the river, however this factor was not incorporated into the calculations of peak concentration. The present analysis treats the relationship between the river flow rate and concentration explicitly, especially for the concentration at the downstream extent of the specified mixing zone. This analysis should also apply, at least partially, to the determination of the maximum concentration.

A.2 Concentration at Edge of Mixing Zone

The downstream extent of the mixing zone is defined as the point at which the maximum plume concentration drops below 0.38 mg/L ammonia. To estimate how the mixing zone will change with changes in river flow rate, consider the concentration measured in the river at the regulatory limit of 2500 ft downstream of the upper extent of the pile, and determine how concentration will respond to shifts in the flow rate alone.

A.2.2 Assumptions of analysis

The analysis makes the following assumptions, which are reasonably well founded at this site and location:

- The system is at steady state.

  Rationale: At the time scale of interest, the transients in the river are much faster than the groundwater transients, so we can reasonably assume that the system is at steady state.

- The releases to the river emanate from a point source on shore.

  Rationale: Since we are calculating the concentration at a large distance from the point of release, it is reasonable to assume a point source release at the bank. The distance over which the groundwater plume is spread would be small compared to the distance of the downstream extent of the mixing zone.

- The river channel near shore has a constant slope.

  Rationale: The measurements out to 50 ft indicate that the river is shallow, and approximately constant slope. Since we are most concerned with the plume at $y = 0$ (near shore), deviations from this approximation further from shore should not affect the solution adversely. This assumptions allows us to conclude that the plume will remain approximately the same shape at lower river stage, only translated further away from the shoreline.

For the distances that the plume extends downriver, the effect of the opposite shore can be treated as insignificant. In this case, the dilution of the plume in the river at steady state will be proportional to the square root of distance from the point of release. In terms of Figure 2 in Codell et al (1982), the dilution immediately next to the shoreline can be expressed as:

$$\frac{C}{W/Q} = \gamma\sqrt{\frac{Q^2}{Dx}} \qquad (1)$$

where C = the concentration in the river next to the shore, W = the release rate of ammonia, Q = the river flow, x = downstream distance and D = the dispersion coefficient:

$$D = \overline{E_y u d^2} \qquad (2)$$

where E_y = the dispersion coefficient across the river, u = velocity in river, d = depth, and the overbar signifies arithmetic mean.

As noted in Section 3.1.3 of the main report, for a flow rate of 2550 CFS representing the 10th percentile low flow, the velocity u would decrease to 76% of the velocity for the benchmark flow rate of 5275 CFS corresponding the the HLA (1998) sampling conditions. At a fixed location x downstream of the point of releases, the relative concentration under conditions of lower flow can be calculated as the ratio of Equation 1 evaluated for the two conditions. In this case, most of the terms would cancel, leading to the result:

$$\frac{C}{C_0} = \sqrt{\frac{D_0}{D}} = \sqrt{\frac{E_{y,0}u_0}{E_y u}} \qquad (3)$$

where the zero subscript refers to the benchmark values. If E_y is independent of velocity, then the concentration at the lower flow rate would be:

$$C = C_0 \times \sqrt{\frac{1}{0.76}} = 1.147 C_0 \tag{4}$$

Sayre et al (1973), however suggest that the dispersion factor is approximately proportional to the velocity. If this is the case, then the concentration will be inversely proportional to the velocity:

$$C = C_0 \left(\frac{1}{0.76}\right) = 1.316 C_0 \tag{5}$$

In either case, the concentration is not directly proportional to flow rate, but rather to a reduced power of flowrate. For the latter case, the concentration would be proportional to the flow rate raised to the power n = 0.378, i.e.,

$$\frac{C}{C_0} = \left(\frac{Q_0}{Q}\right)^{0.378} \tag{6}$$

Considering other factors that would tend to increase concentration in the river, such as the compression of streamlines of groundwater flow at lower stages, it would be conservative to use a power of n = 0.5. The concentration factor calculations discussed in Section 3.2.4 were revised by inserting a square root dependency (i.e., n = 0.5) on flow rate into the dilution calculations. The results of this revision were as expected, showing a smaller concentration factor resulting from changes in river flow coupled to bank storage. For α = 1 ft, 10 particles per day, and no smoothing, the peak C_f was about 11 as opposed to C_f = 15.46 for the case of n = 1.0. The 99th percentile values were 5.08 versus 6.38 for n=0.5 and n=1.0, respectively.

Taking into consideration the factors tending to reduce C_f discussed in Section 3.2.4, a reasonable estimate that can be applied to the concentration at the edge of the mixing zone would be C_f = 5.

A.2.2 Calculation of concentration at edge of mixing zone

If we consider the end of the mixing zone to be 2500 ft downstream of the upper reaches of the tailings pile, the measured shoreline concentration from the HLA study was 2.2 mg/L ammonia (HLA, 1998). Taking credit for a 10^{-8} cm/sec cover on the tailings pile would offer a reduction in concentration by a factor of 0.0114. Combining this with the C_f estimate of 5 would yield a concentration under remediated conditions of 2.2 x 0.0114 x 5 = 0.125 mg/L ammonia, which would be in compliance with the Fish and Wildlife Service criteria for

chronic releases.

A.3 Calculation of acute concentration

If this analysis also applies to the calculation of the acute concentration, the acute concentration would be reduced from 0.27 to 0.135 mg/L. The biggest uncertainty in this case is that the assumption about the release occurring from a point source would no longer apply, since the maximum concentration would occur near the area of groundwater discharge to the river. However peak concentration is less of a problem in the Atlas case than is the concentration at the downstream extent of the mixing zone.

A.4 Additional Reference

Sayre, W.W., and T.P. Yeh, "Transverse mixing characteristics of the Missouri River downstream from the Cooper Nuclear Stations", IIHR Report no. 145, Iowa Institute of Hydraulic Research, April 1973.

Table 1 - Work Sheet for Groundwater Flux of Ammonia into Colorado River

Well Location	Gradient to river i	<I>	C NH_3 mg/L	Δx, ft	iC	<iC>	<iC>Δx	Cum <iC>Δx
TP-11	0.0033		1.5		0.0049			
		0.005		600		**0.00385**	2.31	2.31
TP-01	0.0067		0.41		0.0028			
		0.0084		600		**0.021**	12.6	14.91
TP-02	0.01		4		0.04			
		0.01		750		**0.053**	39.75	54.66
TP-03	0.01		6.5		0.065			
		0.0075		600		**1.2**	720	774.61
TP-12	0.0035		382		1.34			
		0.003		500		**1.54**	770	2429.86
TP-13	0.00244		710		1.73			
		0.0056		480		**6.52**	3129.6	5557.46
TP-14	0.00876		1285		11.3			
		0.0067		500		**6.65**	3325	8882.46
TP-15	0.00465		430		2.0			
		0.0047		480		**1.02**	489.6	9372.01
TP-16	0.0048		7.1		0.034			

Well Location	Gradient to river i	<I>	C NH_3 mg/L	Δx, ft	iC	<iC>	<iC>Δx	Cum <iC>Δx
		0.003		650		**0.021**	13.65	9385.21
TP-17	0.0011		7.3		0.008			
		0.0011		700		**0.008**	5.6	9391.31
T24-18	0.001		8.4		0.008			

Interpolating to TP-15.2 Sum of <iCΔx>

Discharge = Sum of <iCΔx> x aquifer thickness x permeability

= 9225.18 mg/L ft x 40 ft x 22 ft/day x 28.3 L/ft^3 x g/1000 mg

Total ammonia discharge = 230,000 grams/day

Table 2 - Flux of Ammonia in River

y (ft) = dist from shore	0		10		25		50
Δy (ft) = difference between stations		10		15		25	
C (mg/L) = vertically averaged C	2.4		1.25		0.35		0.145
Q dy ft^3/sec = cumulative flow in direction across river	0		11.34		84.4		205.7
ΔQ ft^3/sec = flow in segment		11.34		73.06		121.3	
C (mg/L) = average flow in segment		1.633		0.8		0.247	
C ΔQ = flux of ammonia in segment		18.52		58.45		29.96	

Sum of flux in all segments = 106.93 mg/L ft^3/sec x 28.3 L/ft^3 x g/1000 mg x 86400 sec/day = 262,000 g ammonia/day

Table 3 - Effect of Diffusion, Particle Density, and Smoothing on Concentration Factor, C_f[2]

Case	C_f - mean	C_f - median	C_f - 90th%	C_f - 95th %	C_f - 99th %	C_f - max
5 particles/day, no dispersion	1.183	0	3.44	5.94	12.66	82.07
10 particles/day, no dispersion	1.173	0	3.37	5.59	13.03	52.75
10 particles/day, α = 1 ft	1.14	0.3	3.38	4.49	7.7	18.25
10 particles/day, α = 10 ft	1.06	0.37	3.09	4.02	6.38	15.46
10 particles/day, α = 10,ft, smoothing window = 2 days						14
10 particles/day, α = 10,ft, smoothing window = 5 days						13

[2]Concentration factor defined as maximum concentration in river relative to concentration for mean groundwater discharge and mean river flow

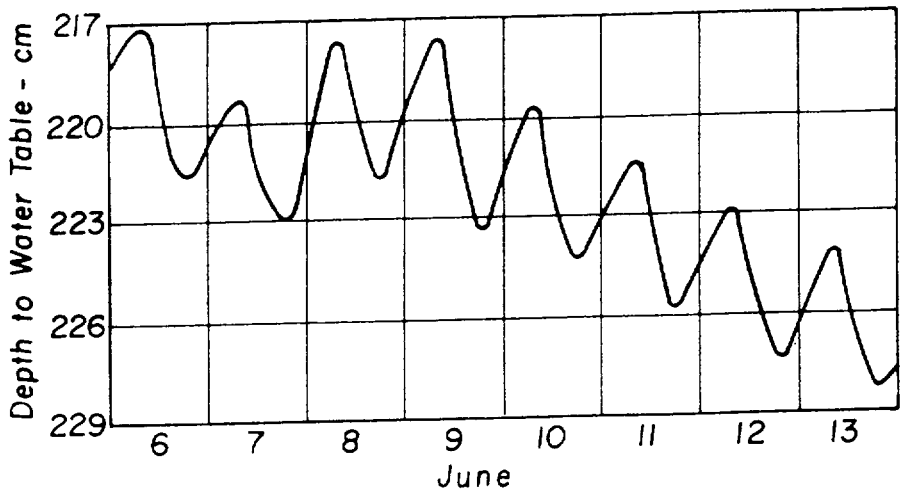


Figure 1 Water level fluctuation due to phreatophyte transpiration

Figure 2 - Cumulative Distribution Function, Cisco, Utah gage, 1965-1977

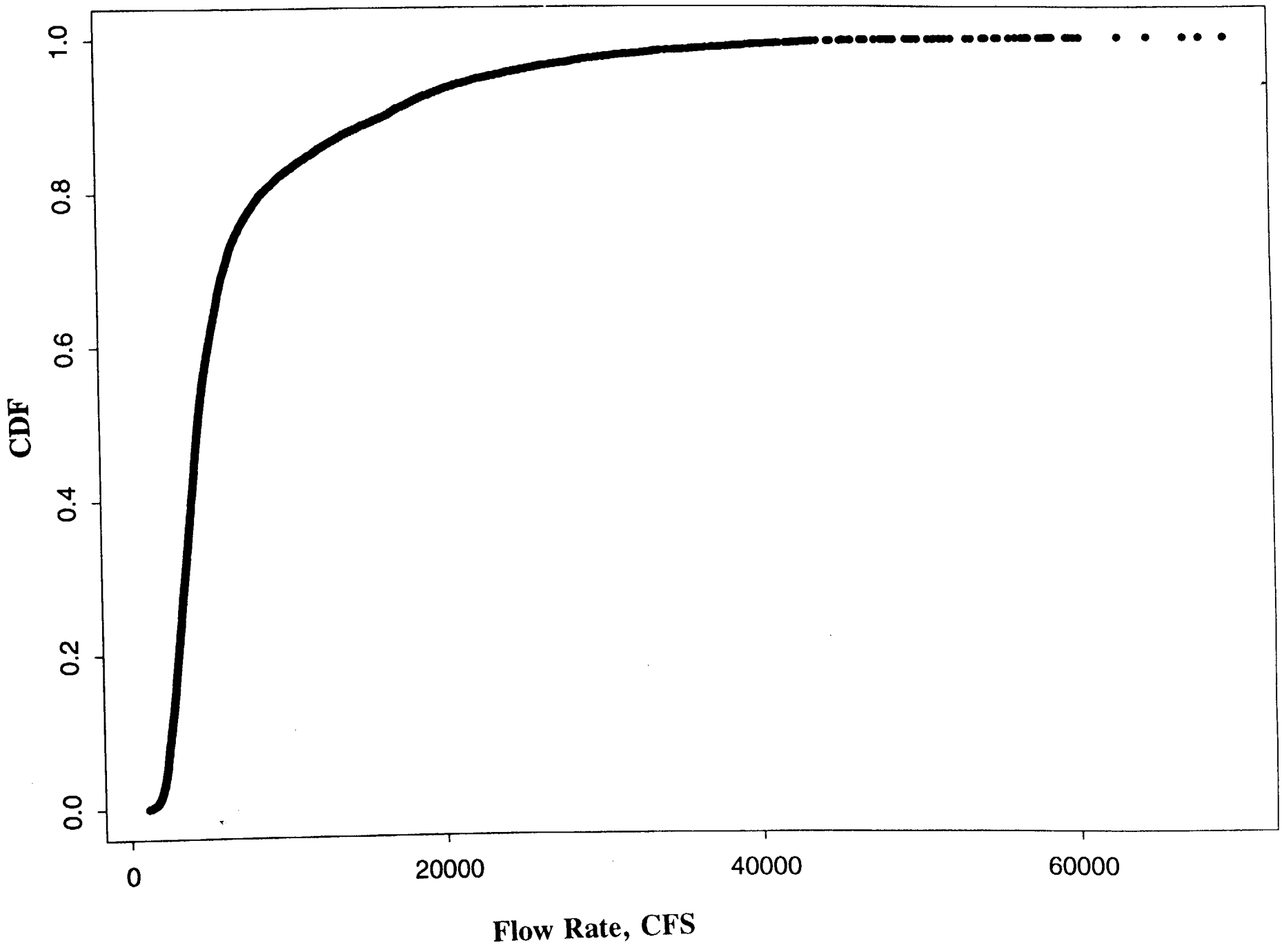


Figure 3

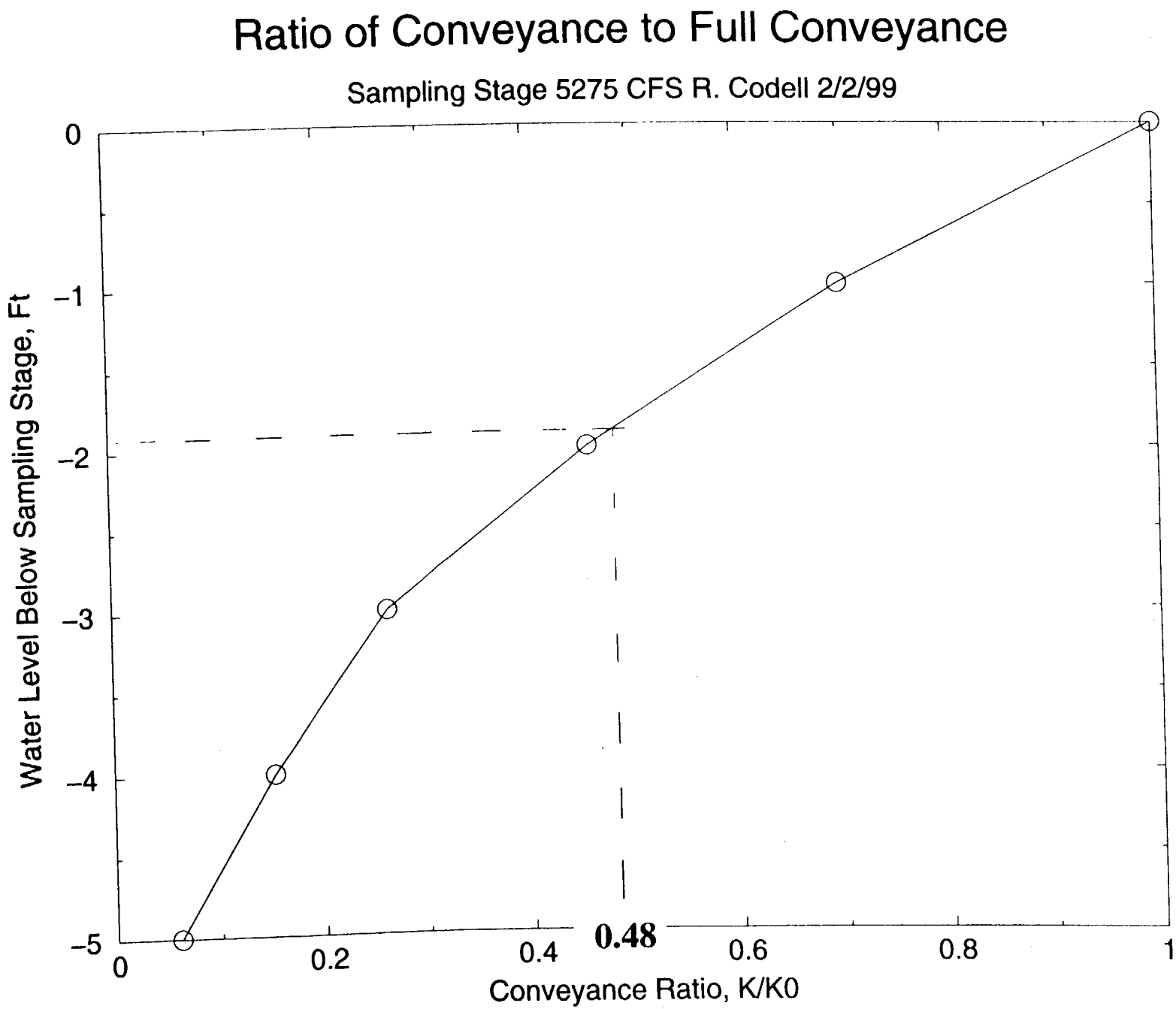
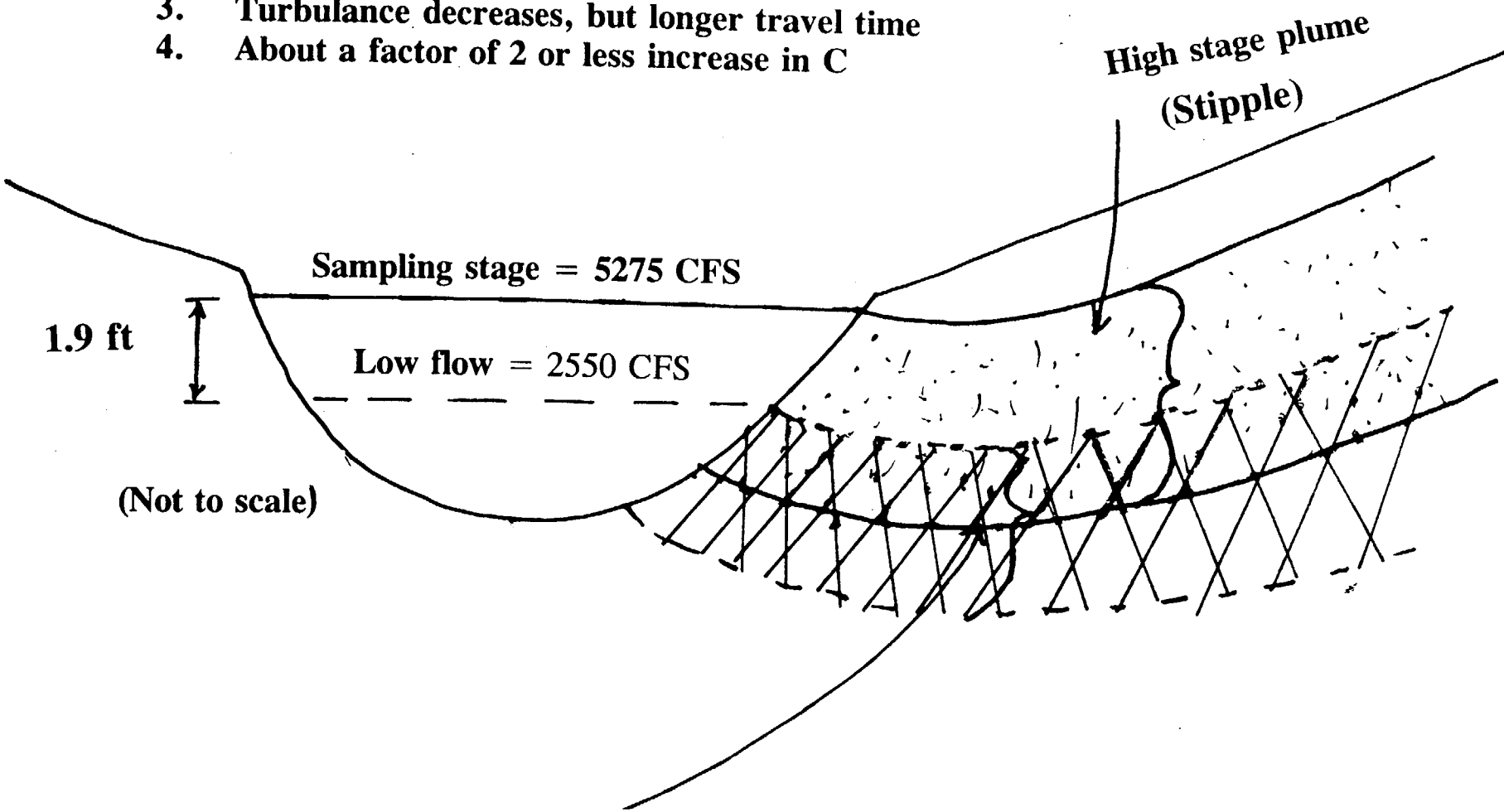

Ratio of Conveyance to Full Conveyance
Sampling Stage 5275 CFS R. Codell 2/2/99
Water Level Below Sampling Stage, Ft
0
−1
−2
−3
−4
−5
0
0.2
0.4
0.48
0.6
0.8
1
Conveyance Ratio, K/K0

Figure 4

Effect of Low Flow on Dilution in River

1. Plume of groundwater compressed
2. River slows to 76% velocity
3. Turbulance decreases, but longer travel time
4. About a factor of 2 or less increase in C

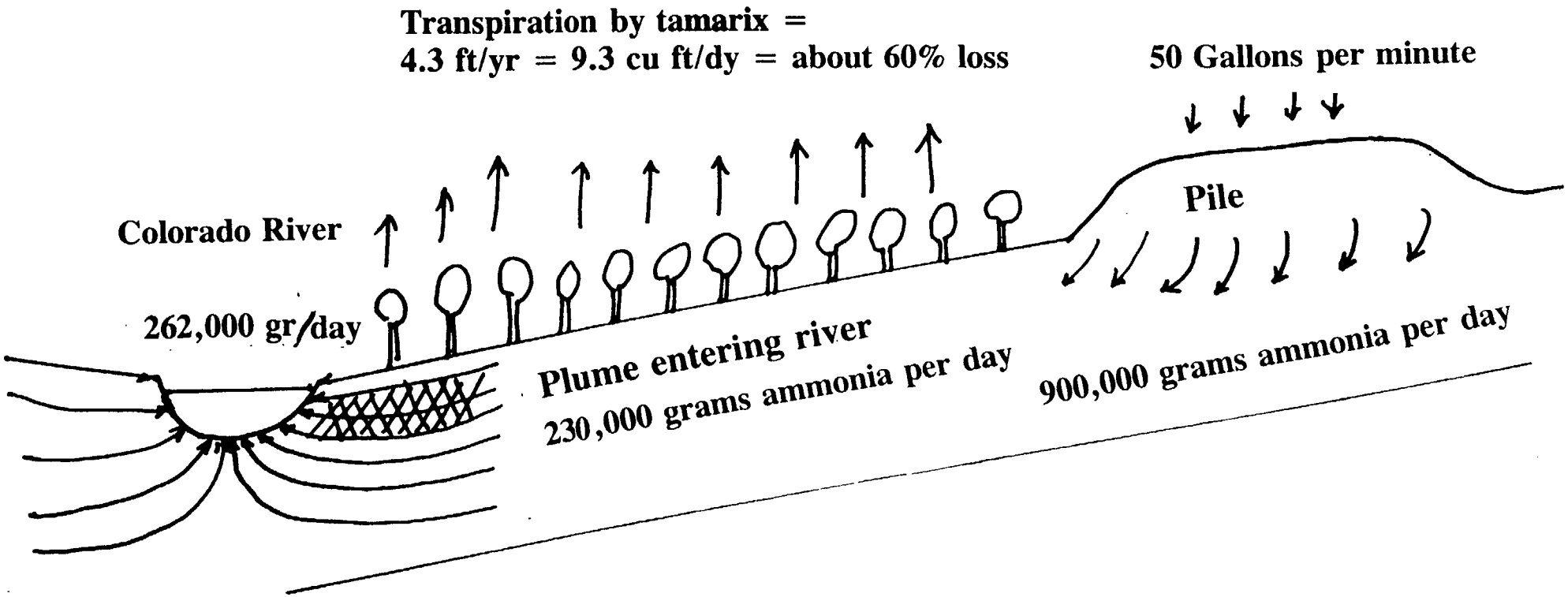
Atlas →



Low stage Plume (Cross-hatched)

(Thinner)

Figure 5 - Coupled surface water/groundwater system



1. Reduction of NH_3 flux by 10^{-7} cm./sec cap = 0.114

2. Reduction of NH_3 flux by 10^{-8} cm./sec cap = 0.0114

3. Increase C in river because of release from bank storage by a factor of 10

Figure 6

Approximate Cross Section of Colorado River

Section 3–3a, R. Codell 2/1/99

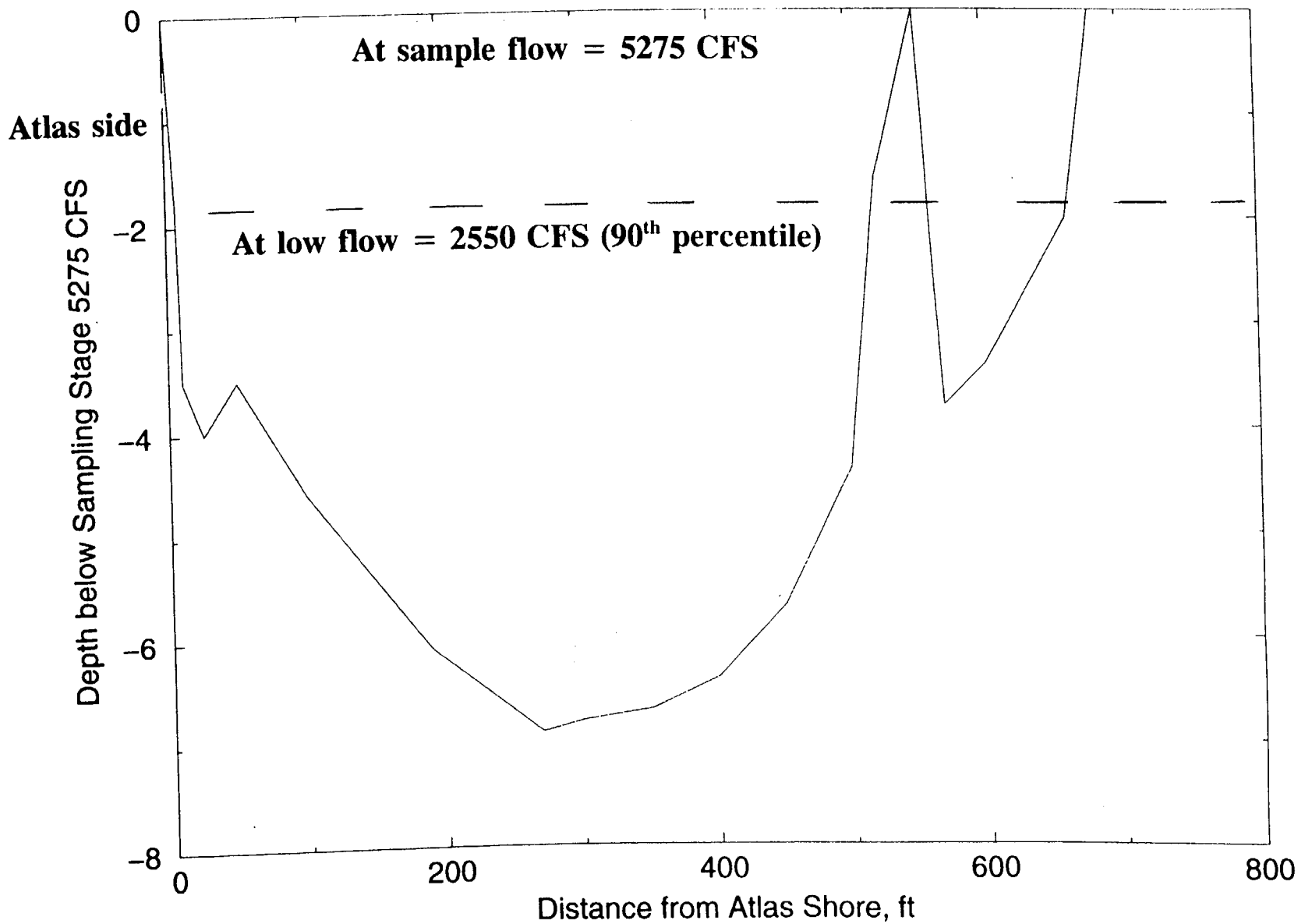


Figure 7 - Hydrograph of Stage versus Flow

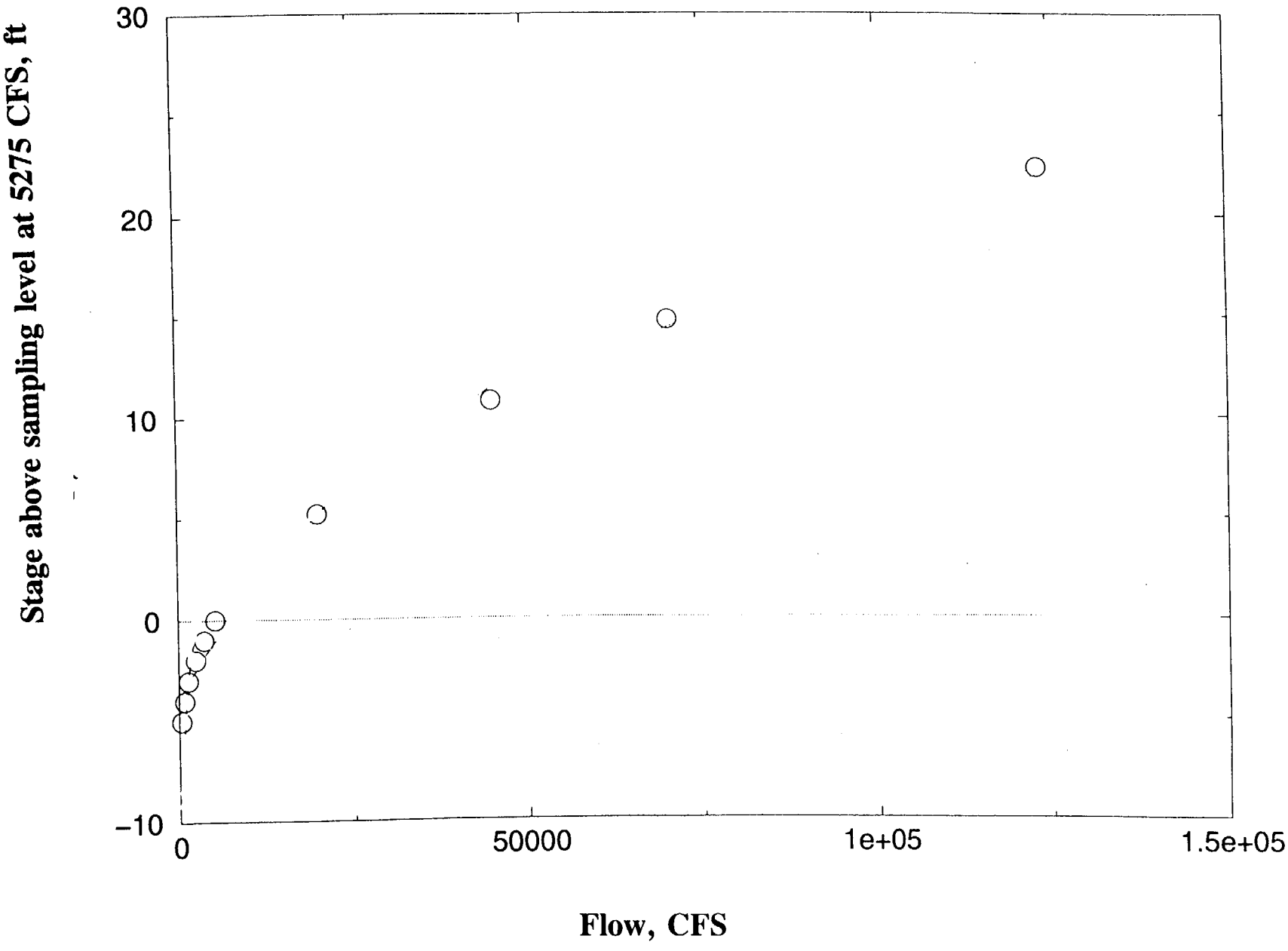
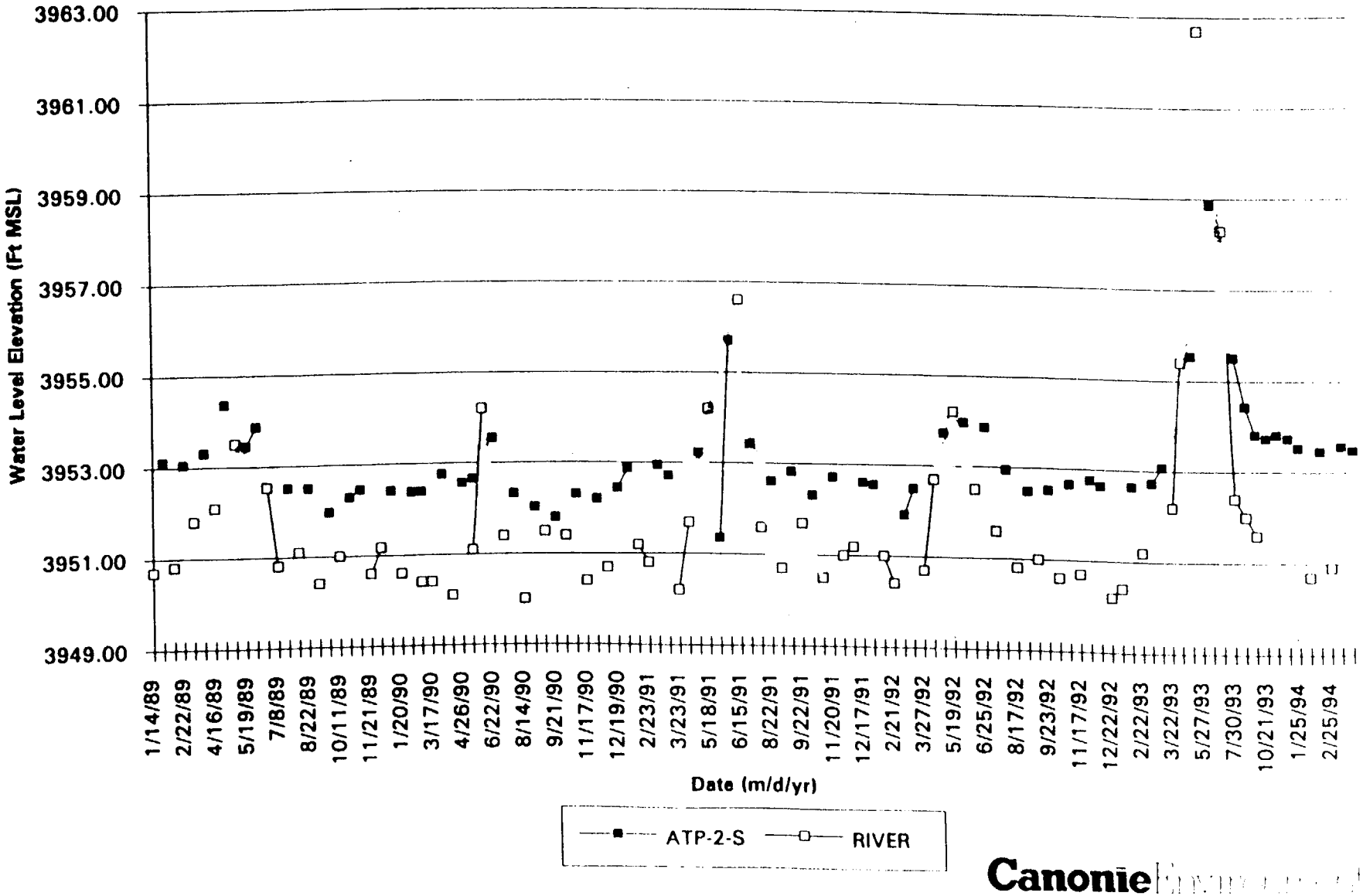


Figure 8

Water Level Comparison Between Piezometer ATP-2-S and Colorado River



Canonie

XSECTA XLS Chart 16 [6/29/94]

Figure 9

Water level at river, 500 ft and 1000 ft from shore,
1/14/89 to 2/20/94

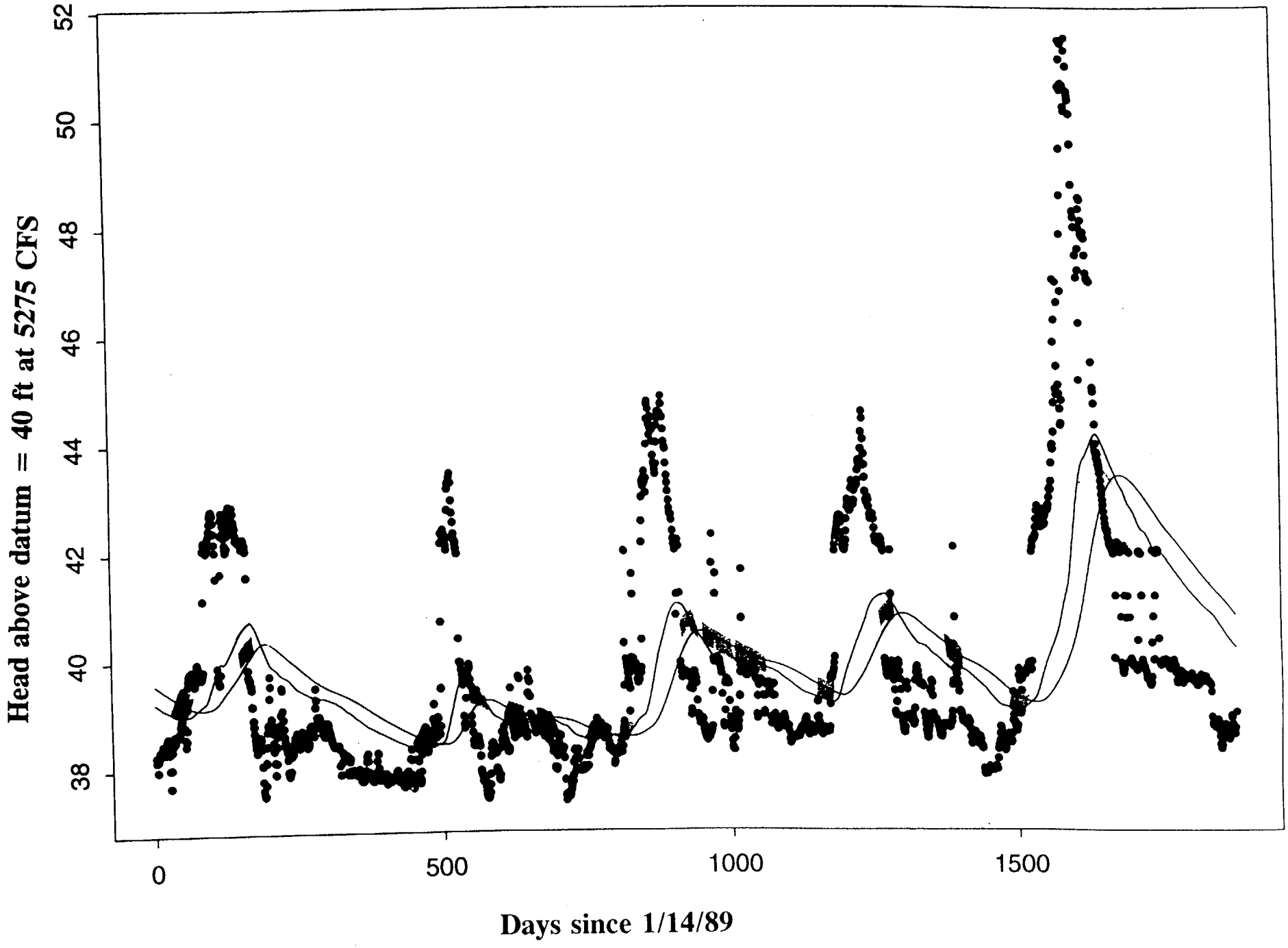


Figure 10 - Gain and release from bank

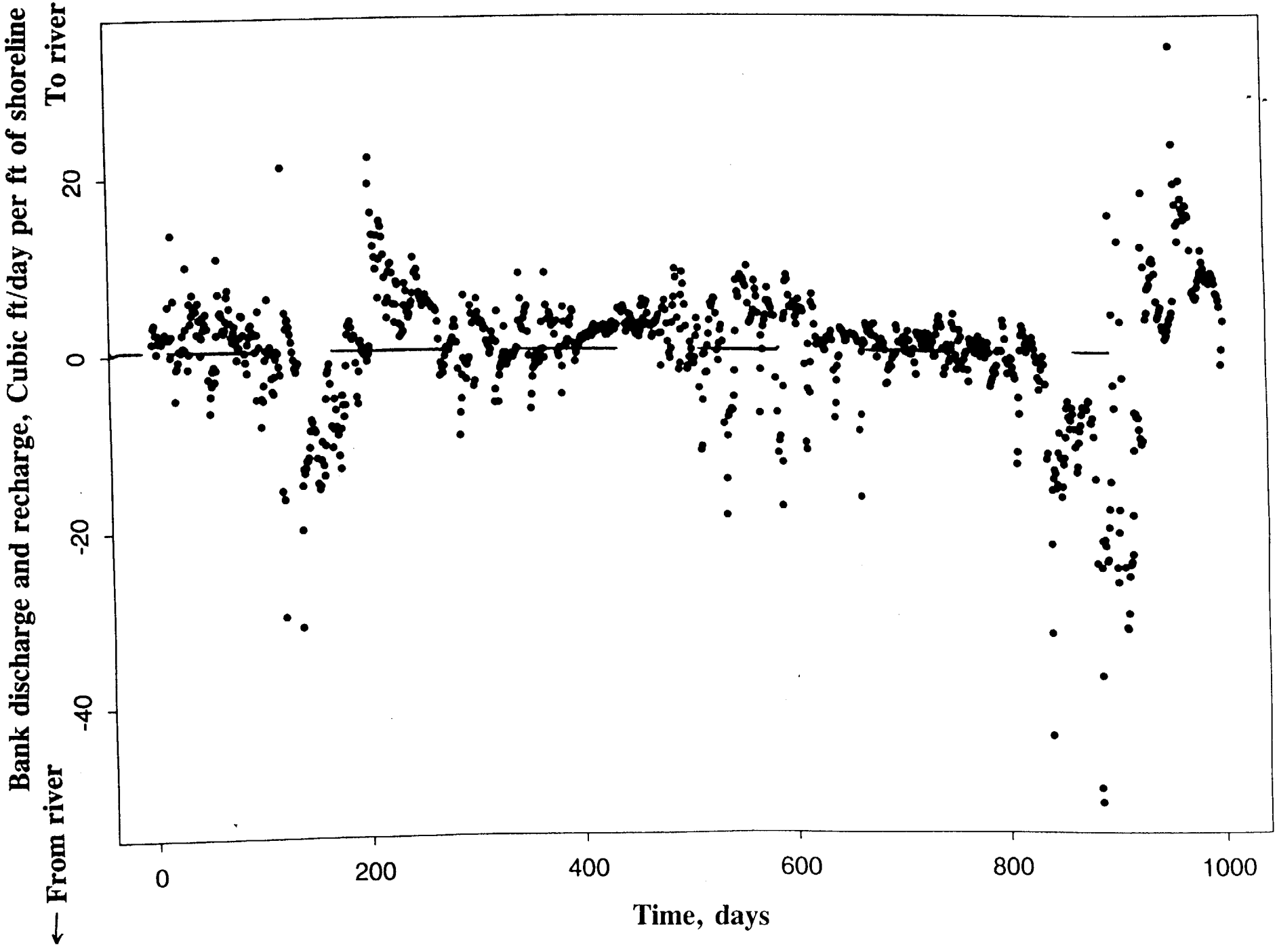


Figure 11

Concentration factors, no dispersion (•) and 1 ft dispersion (solid line)

R. Codell 2/16/1999

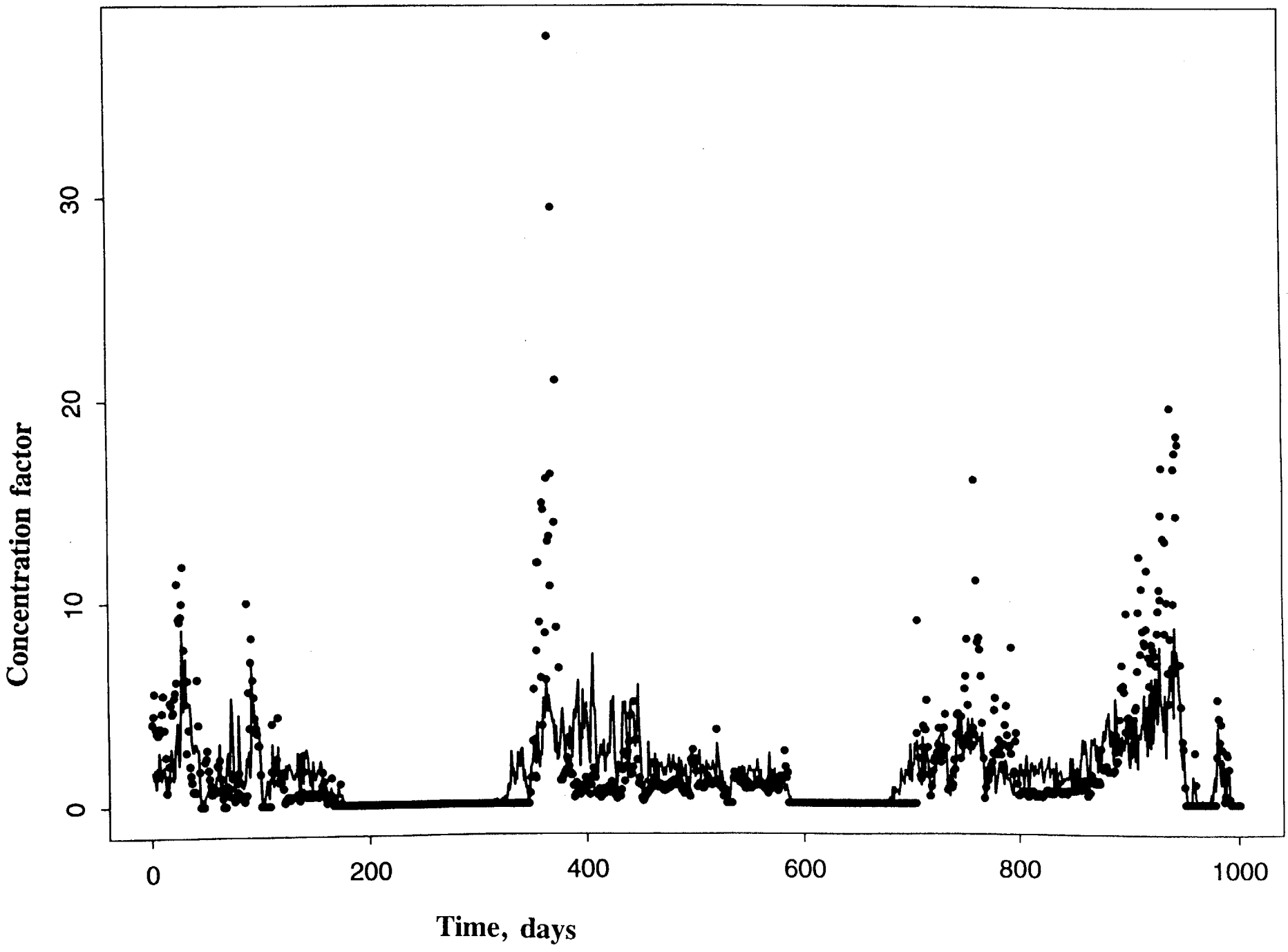


Figure 12

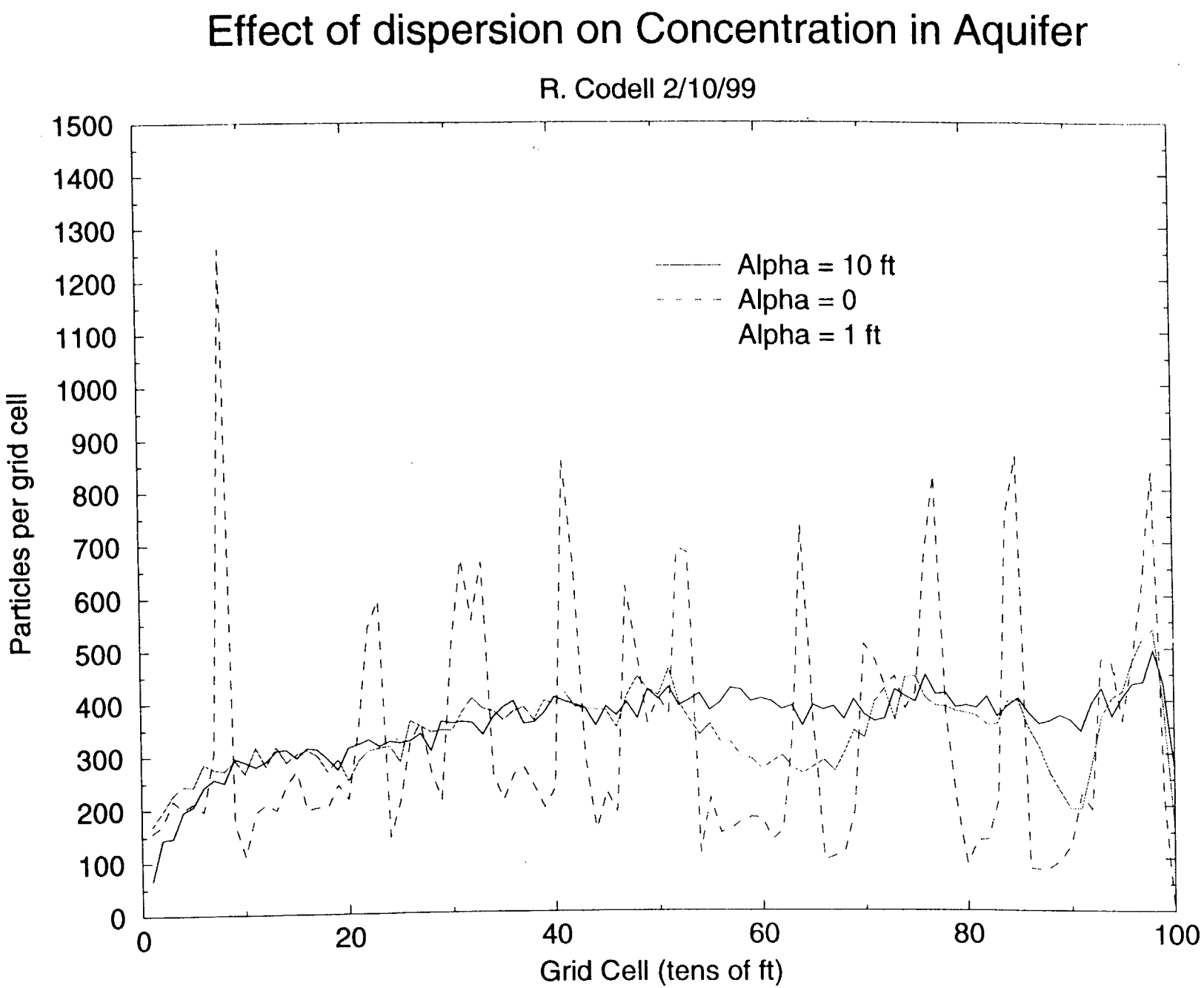
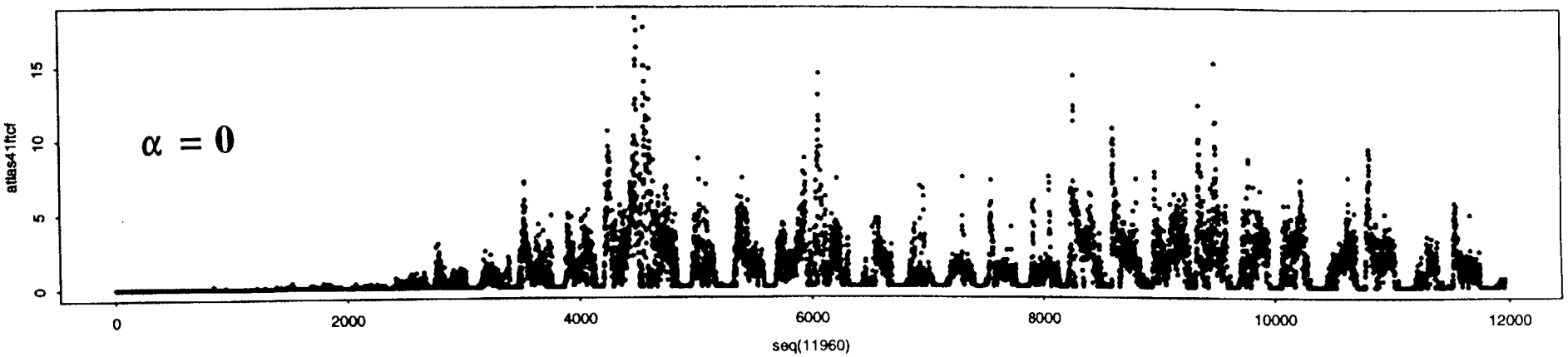
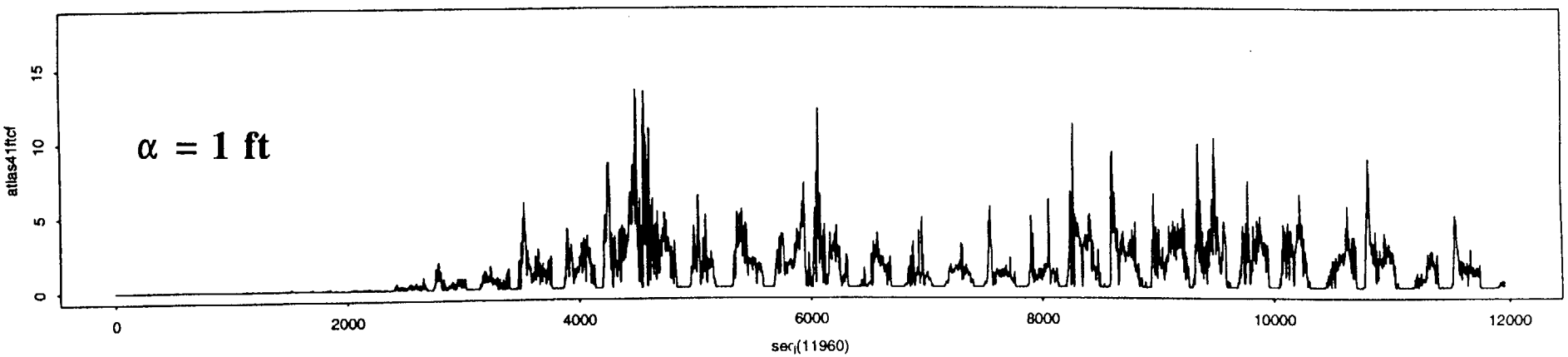

Effect of dispersion on Concentration in Aquifer
R. Codell 2/10/99
Alpha = 10 ft
Alpha = 0
Alpha = 1 ft
Particles per grid cell
Grid Cell (tens of ft)
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
0
20
40
60
80
100

Figure 13





Concentration factor for alpha = 1 ft, with 0, 2 and 5 ft smoothing windows

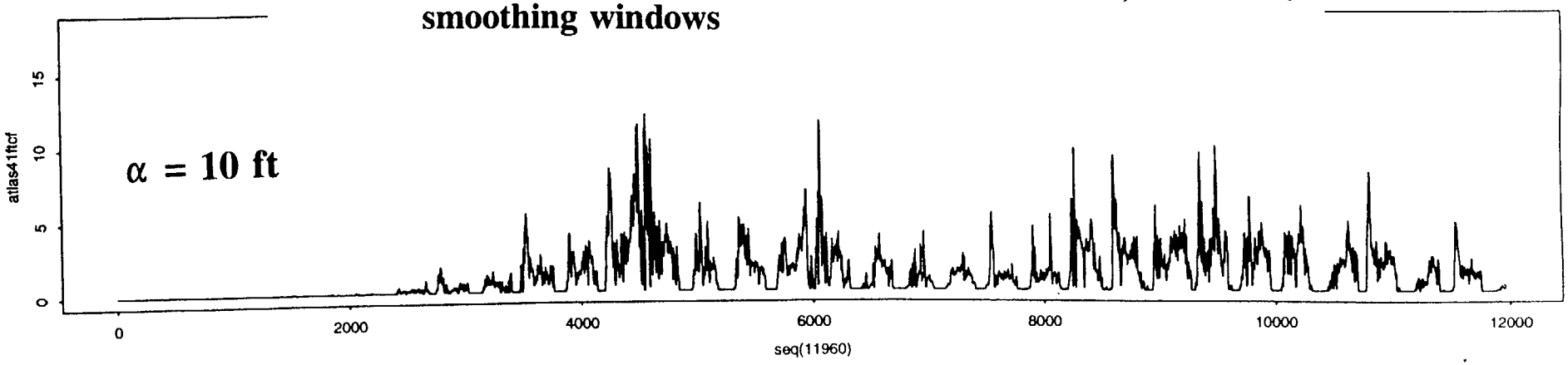
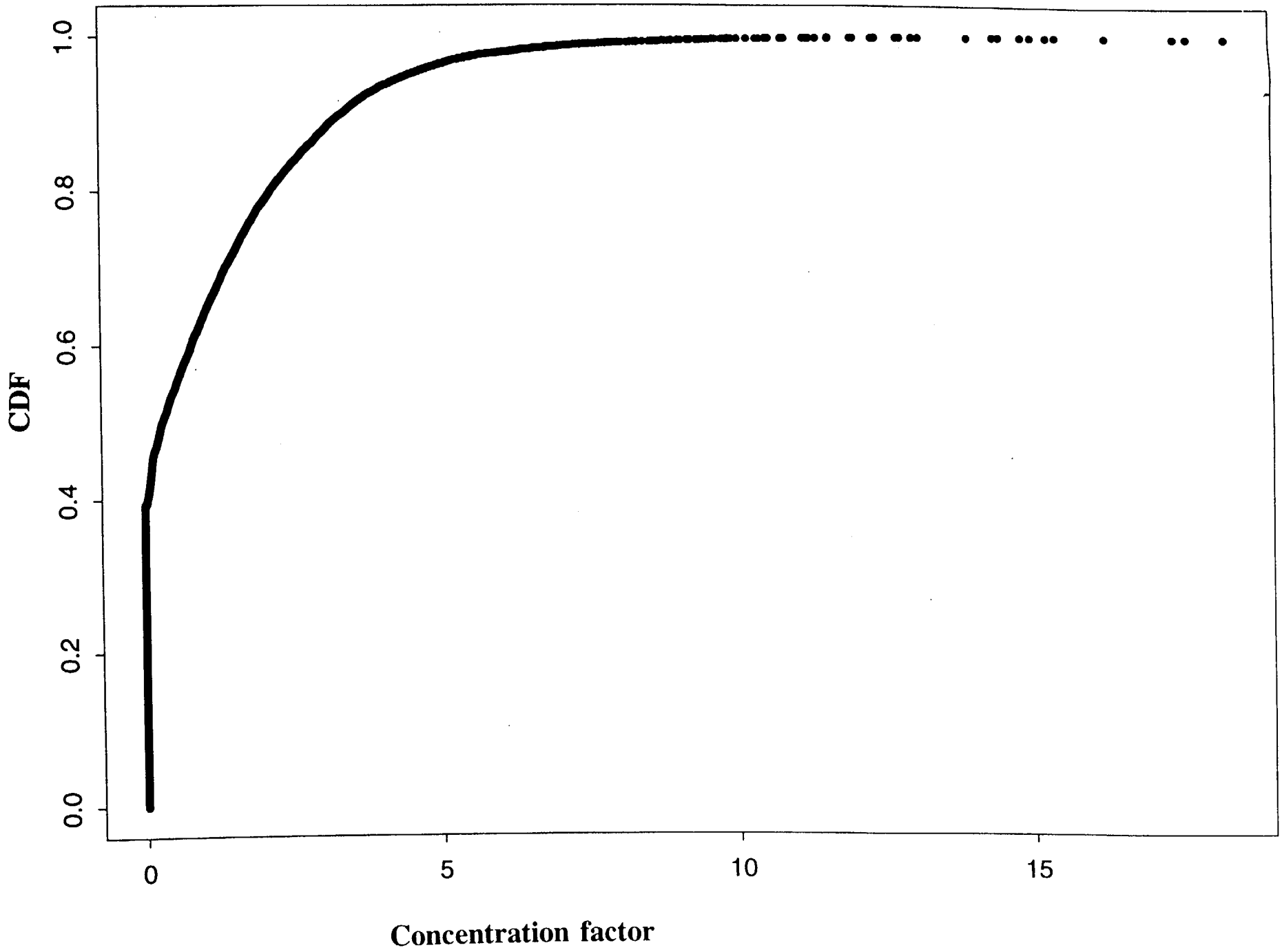


Figure 14

CDF of concentration mult factor in river for alpha = 1 ft
R. Codell 2/10/99