North Delta Juvenile Salmon Survival Model
Rough Notes –

J. Burau and A. Blake
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-Model philosophy
-Regional conceptual model
-Model formulation/assumptions
-Description of extensions of the model extensions to include dead end sloughs and tidal dispersion

Introduction

Delta Cross Channel (DCC) gate operations significantly influence the flows in all of the channels in the north Delta (Burau et.al., 2006). These changes in flow likely affect the distribution of salmon outmigrants amongst the channels in the north Delta and, moreover, likely influence the survival within each channel segment by changing local flow regimes (e.g. shear) and by changing the travel (exposure) time in each reach. This suggests the current management strategy focused strictly on keeping juvenile salmon out of the Mokelumne system by closing the DCC gates should be expanded to include the effects of DCC gate closures on salmon migration through all of the north Delta junctions and channels. In particular, the current management strategy only considers reduction in losses of juvenile salmon outmigrants that would have been diverted into the DCC when the gates are closed. Using a regional approach would balance losses through the DCC against possible increased losses in Sutter, Steamboat and Georgiana Sloughs, because the flows, and presumably the numbers of juvenile salmon, in all of these channels increase when the DCC gates are closed. Therefore a regional strategy for protecting juvenile salmon outmigrants is needed that explicitly incorporates DCC gate operation impacts on salmon survival in all junctions and channels in the north Delta. As a first step towards this goal, this set of notes begins the process of developing a conceptual model of juvenile salmon survival in the north Delta. The purpose of this model is to: (1) establish critical knowledge gaps, (2) establish priorities for modeling and data gathering activities for future studies, and (3) to ultimately develop a management tool that can be used in a regulatory framework to optimize salmon outmigrant survival in the north Delta. The goal of this management tool would be to optimize operations to maximize the number of juvenile salmon passing Chipp's Island. One could argue that it is better to pass fewer heathier/stronger fish past Chipp's Island as a means of increasing the overall success of the population. This is beyond the scope of this effort and a simple metric of maximizing the total number of fish that pass Chipps Island is used, condition of the fish is not part of this analysis.

We hope this model evolves from its current state as a conceptual framework into a useful tool for estimating the distribution of juveniles within the north Delta channel network and their survival within each channel segment. To make this model actually useful beyond a conceptual framework: (1) entrainment models for each junction and (2) survival estimates for each channel must be developed. To a large extent we don't know what these models will look like. Nonetheless, we begin this process by making educated guesses as a first cut at system response so we can see what the model is REALLY sensitive to as a means of prioritizing future modeling exercises and field data collection activities. Initially, the entrainment and survival relations will be developed using multi-dimensional particle tracking models. Then studies using acoustically tagged juvenile salmon will be used to develop the entrainment and survival sub-models for each junction and channel segment, respectively. If nothing else, this conceptual model will help us define a research program for juvenile salmon outmigration in the north Delta by explicitly defining what we need to know and to what level of certainty we need to know it.

This approach may be a bit mechanistic for some, and justifiably so, since biological processes seem to defy mechanistic descriptions. Nonetheless, this approach does quantify what we know, what we don't know and, to some extent, prioritizes what we need to know. Many of the relations required may never be determined given the vagaries of biological processes and the difficulty and expense of obtaining the data necessary to fill in the details of these relations. Nonetheless, it is useful to try to explain things mechanistically as a starting point, at least to inform the less rigorous relations that may actually be possible.

Modeling Philosophy - Simplicity

Basic model description

The envisioned model must be simple to be useful to managers (the law of parsimony and Occam's razor notwithstanding) because it is simply not feasible to run sophisticated, time consuming, multi-dimensional particle tracking models, or conduct juvenile salmon outmigrant experiments every time a change in policy or management decision is needed. Yet, the movements of salmon outmigrants in the north Delta are complex, due, in part, to the diversity of possible outmigration pathways. A middle ground approach is needed that captures this complexity as simply as possible. This modeling exercise is an attempt to capture the essence of the detailed numerical model results and field experiments in a simple and useful decision-making tool. As a first step, this model simply accounts for, and distributes among the north Delta channels, an initial quantity of Sacramento River juvenile salmon, N_0, based on: (1) an entrainment function, α_j, at each junction, j, and (2) the survival rate, γ_i, within each channel, i. Both the entrainment function α_j and survival rate γ_i are functions that vary between 0 and 1 in the model, and, in the case of the entrainment function, can be thought of as a ratio or probability. Coming up with these relations is key to the success of this entire approach. The form of the entrainment relations are unknown, but they are likely to be junction specific (depending on approach channel curvature, specific junction geometry, etc.) and will likely depend on flow rate, degree of tidal forcing, salmon run, smoltification, etc. Survival rates will also likely depend on flow rate because flow rate, to a large degree, determines travel times (or exposure times) within individual channel segments. Flow rate may also influence the predation rate, by creating greater lateral shears that have the possibility of disorienting juvenile outmigrants favoring predators. The entrainment relations and survival rates will be determined through particle tracking experiments and through tracking of acoustically tagged juvenile salmon.

Temporal challenges

Fortunately, the distribution of flows among the north Delta channels at the tidally-averaged timescale is relatively straightforward, and, remarkably predictable and stable (Burau and others, 2006) even though the flow dynamics at tidal timescales are generally complex at individual channel junctions. Thus, we begin formulating the North Delta Juvenile Salmon Survival Model at the tidally-averaged timescale using net flow relations, even though we strongly suspect that the tidal timescale evolution of velocity structure within junctions controls the entrainment of juvenile salmon within individual junctions. Bridging the temporal divide between the tidally-averaged, or management timescale, and the tidal timescale, is one of the greatest challenges faced in this effort. However, the tidal timescale dynamics are intimately tied to the Sacramento River flows (Burau and others, 2006), so we hypothesize that a relation between the net flows and entrainment rate exists and is attainable using this approach. With the exception of tidal operation of the DCC gates, project operators only have control at the tidally-averaged timescale: through reservoir releases, changes in export rates (which have a limited effect on salmon survival in the north Delta) and by operating the DCC gates for periods of a day or longer. Hopefully, by releasing acoustically tagged juvenile salmon over 24 hour periods in synchrony with the tides, under a wide variety of Sacramento River flow rates and gate operations, we will be able to bridge the gap between the tidal and residual timescales. Essentially, we hope that the particle tracking experiments and field investigations of entrainment at the tidal timescale using acoustic tags will allow us to build sufficiently accurate entrainment and survival sub-models at the tidally averaged timescale for use in this management tool.

Model formulation – Accounting Methodology

A simple example

This model is really a glorified accounting scheme that keeps tract of where fish go and where they die. The heavy lifting is done by the entrainment and survival sub-models. Similar to the development of most numerical models, a channel network invariant numbering scheme, which at first blush looks unnecessarily complicated, is used that allows changes to the model network by changing the input files not the code (e.g. modification of the channel network does not require a change in the calculation routines) A simple example is used to fix ideas, then three different models of the north Delta are constructed: these begin simply and increase in complexity. The simplest model of the north Delta is applied first, because, at this point, we know very little regarding the entrainment relations at each junction and the channel specific survival rates. The accounting scheme used in the model assumes that: (1) fish are conserved in a junction (e.g. in = out and no mortality in junctions) and (2) reach specific mortality is dependent on the time spent in that reach, (3) fish, in a regional sense, move downstream with the net flows. We'll account for tidal exchanges later. To see how these assumptions are implemented consider figure 1, a simple network that includes all of the elements needed to model the north Delta, where a single channel is split into two channels, one of which has a dead-end slough attached. These channels then reconnect. For clarity, and to assure that fish are conserved in each junction, the network relations are derived and implemented on a channel junction basis (the order of the junction calculations is stored in variable jord(j) in the code). Two types of junctions are specified: (1) a "split" junction (jype=1), and a (2) "combine" junction (jtype=2)(Figure 2). For a "split" junction, k, the entrainment relation, α_k, (remember: $0 \le \alpha_k \le 1$) is specified for one of the two channels leaving the junction, call it the primary exit channel. Note that the junction designation, k, is the number of the primary exit channel, $k = j_{k,1}$. To conserve fish, the entrainment in the secondary channel, $J_{k,2}$, is simply $1-\alpha_k$. For example, if $\alpha_k = 1$ at a given junction, then all of the juvenile salmon would be diverted into the primary channel and none would be diverted into secondary channel. If $\alpha_k = 0.8$, then 80% of the fish entering this junction would go down the primary channel and 20% down the secondary channel. Thus, the relation between the entry channel and primary and secondary channels in each junction (connectivity) need to be mapped. So, for each "split" junction, k, the incoming channel is $J_{k,0}$, the primary exit channel is $J_{k,1}$ and the secondary exit channel is $J_{k,2}$ (Figure 2). In the case of junction 1 in figure 1 this connectivity is: $J_{1,0}=0$, $J_{1,1}=1$, $J_{1,2}=2$. For a “combine” junction an entrainment function isn’t needed and the junction number is specified as the exit channel number. So for junction 5 in figure 1, the connectivity is $J_{5,0}=5$, $J_{5,1}=1$, $J_{5,2}=4$. Finally, the survival rate, γ_i, (remember: $0 \le \gamma_i \le 1$) for each channel, i, must be specified or calculated. If the survival rate γ_i were 1.0, then all of the juvenile salmon in that reach would survive, if it were zero than none would survive. For a complete list of terms see appendix A.

Now, for each channel reach, j: (1) the number of fish entering the reach, $N_{j,1}$, is computed, (2) the number of fish leaving the reach, $N_{j,2}$, is computed (e.g. survival), and finally (3) the mortality, M_j is computed. Thus, to be clear: for $N_{j,k}$, k=1 are fish entering the j’th reach, k=2 are fish leaving the reach, which, incidentally, is consistent with the way in which data will be collected in the field to develop these relations (e.g. an array of acoustic tag listening stations). The relations for the first junction in figure 1 are given in example 1 below, where the number of fish entering channel 1, $N_{1,1}$, is simply the product of the number of fish entering the junction, N_0, and the entrainment relation, α_1, for junction 1. To conserve fish in the junction, the number of fish entering channel 2, the secondary channel, is simply the product of $(1-\alpha_1)$ and the number of fish entering the junction, N_0. The survival and mortality in the reach are computed in a manner identical to reach 1.

Dead-end channels

Other types of accounting elements are needed to complete a salmon outmigration model. For example, Places like Elk Slough, Snodgrass Slough and the Liberty Island complex (Liberty Island, Lindsey Slough and the Sacramento Deep water ship channel), exist, which are, most of the year, dead-end channels. They are characterized by very low net flows, yet juvenile salmon are thought to utilize these environments, either through tidal exchange processes, or through behavioral responses. The entrainment relation in these dead-end sloughs may depend on the tidal flows or tidal excursion (for example, we think juvenile salmon exchange into the Liberty Island area tidally) or on behavioral cues. These regions, shown schematically in figure 1 as a side channel, must somehow be taken into account in the model. Some of these areas may actually be good rearing areas, where juvenile salmon increase their ability to survive. Yet in this model, based strictly on numbers of fish, these areas can only be modeled in terms of their impact on mortality. Moreover, there may be channels that exit the modeled domain, for example, channels that exit the modeled system into the central Delta, that must be accounted for. Those fish that enter these regions are assumed not to make it out (e.g. $\gamma_i = 0$) and thus the entrainment function, $\alpha_j = 0$, actually determines the mortality rate in dead end sloughs. For the example in figure 1, the relations are as follows:

Example 1 (Figure 1)

Junction 1 (split)

$N_{1,1} = \alpha_1 N_0$, $\quad N_{1,2} = \gamma_1 N_{1,1}$, $\quad M_1 = \beta_1 N_{1,1}$

$N_{2,1} = (1-\alpha_1) N_0$, $\quad N_{2,2} = \gamma_2 N_{2,1}$, $\quad M_2 = \beta_2 N_{2,1}$

Junction 3 (split)

$N_{3,1} = \alpha_3 N_{2,2}$, $\quad N_{3,2} = \gamma_3 N_{3,1}$, $\quad M_3 = \beta_3 N_{3,1}$ (Dead end: α_3 is mort rate, $\gamma_3 = 0, \beta_3 = 1$)

$N_{4,1} = (1-\alpha_3) N_{2,2}$, $\quad N_{4,2} = \gamma_4 N_{4,1}$, $\quad M_4 = \beta_4 N_{4,1}$

Junction 5(combine)

$N_{5,1} = N_{1,2} + N_{4,2}$

Generalized relations

Based on the simple schematic in figure 1 we can generalize the relations for each junction type if we use the numbering templates shown in figure 2:

(1) Split junction, k

$$N_{j_{k,1},1} = \alpha_{j_{k,1}} N_{j_{k,0},2}, \quad N_{j_{k,1},2} = \gamma_{j_{k,1}} N_{j_{k,1},1}, \quad M_{j_{k,1}} = \beta_{j_{k,1}} N_{j_{k,1},1} \tag{1}$$

$$N_{j_{k,2},1} = (1-\alpha_{j_{k,1}}) N_{j_{k,0},2}, \quad N_{j_{k,2},2} = \gamma_{j_{k,2}} N_{j_{k,2},1}, \quad M_{j_{k,2}} = \beta_{j_{k,2}} N_{j_{k,2},1} \tag{2}$$

(2) Combine junction, k

$$N_{j_{k,0},1} = N_{j_{k,1},2} + N_{j_{k,2},2}, \quad N_{j_{k,0},2} = \gamma_{j_{k,0}} N_{j_{k,0},1}, \quad M_{j_{k,0}} = \beta_{j_{k,0}} N_{j_{k,0},1} \tag{3}$$

For the simple example given in figure 1, we simply need to define the $\alpha_{j_{k,1}}$'s for each junction and the $\gamma_{j_{k,1}}$'s for each channel, communicate the connectivity to the model by specifying the junction relations shown in figure 2 as:

Junction k=1 (split: jtype=1)
$j_{1,0} = 0$, $j_{1,1} = 1$, $j_{1,2} = 2$

Junction k=3 (split: jtype=1)
$j_{3,0} = 2$, $j_{3,1} = 3$, $j_{3,2} = 4$

Junction k=5 (combine: jtype=2)
$j_{5,0} = 5$, $j_{5,1} = 1$, $j_{5,2} = 4$

And then apply the junction relations using equations 1-3. For the example given in figure 1, the following input geometry file is used, which specifies the junction connectivity.

In the program, algorithm above is used, however the array configuration is slightly changed. In my notation, if you have a 2d Array N, the value at the i,j location in that array is given as N(i,j).

I have a node array (can be changed), which is nx4, where n is the number of nodes.
For a split node:
N(i,:)=[input branch #, primary branch #, secondary branch #, node type]

For a combine node:
N(i,:)=[primary branch #,input branch #1, input branch #2, node type]

I then create a flow array, Q (bx1), time of travel array, TT (bx1), and a fish array, F (bx3), where b is the number of branches.

The computation algorithm is the same as above, generaly: (index from 1)(g=predation)
Looping for n=1:number of nodes

If node type is split:

F(N(n,2),1)=F(N(n,1))*e
F(N(n,2),2)= F(N(n,1))*e*g
F(N(n,2),3)= F(N(n,1))*e -F(N(n,1))*e*g
F(N(n,3),1)=F(N(n,1))*(1-e)
F(N(n,3),2)= F(N(n,1))*(1-e)*g
F(N(n,3),3)= F(N(n,1))*(1-e) -F(N(n,1))*(1-e)*g

If node type is join

F(N(n,1),1)=F(N(n,2),2)+F(N(n3),2)
F(N(n,1),1)=(F(N(n,2),2)+F(N(n3),2))*(1-g)
F(N(n,1),1)= F(N(n,2),2)+F(N(n3),2)-((F(N(n,2),2)+F(N(n3),2))*(1-g))

Geometry input file

```
c
c-------------North Delta Salmon Survival Model input file - Example Stencil
c
----im----jm
    5    3
-----j-jtype-----0-----1-----2-------a
    1    1    0    1    2   0.75
    3    1    2    3    4   0.75
    5    2    5    1    4   0.75
-----i-------g
    1    0.9
    2    0.9
    3    0.9
    4    0.9
    5    1.0
```

Development of a Delta Network

Three different geometric models of the north Delta are initially envisioned: these are likely to change as our understanding of juvenile salmon movements through the north Delta improves and as data become available to quantify the entrainment and survival relations. Losses to the central Delta are modeled in reach 7 in figure 3 by specifying zero for the survival rate and adjusting the entrainment function to account for mortality to fish that leave the modeled portion of the system (e.g. are lost in the central delta due to indirect affects (high central delta water temperatures, longer travel times to the bay) and direct losses at the pumps.

North Delta Model 1 – Three migration pathways

We begin the process of developing a conceptual model of the north Delta by simplifying the channel network down to three conveyance corridors (Figure 3): more detail can be (and is) added later as the information to warrant the additional complexity is obtained. The conveyance corridors include: (1) Sutter and Steamboat Sloughs, (2) the Sacramento River, (3) the Mokelumne River corridor which includes Georgiana Slough – based on the so-called Delta transfer flow.

For the simplified north Delta network shown in figure 3, the model geometry input file is simply:

```
c
c-------------North Delta Salmon Survival Model input file - Model 1
c
----im----jm
    8    5
-----j-jtype-----0-----1-----2-------a
    1    1    0    1    4   0.75
    2    1    1    2    5   0.75
    3    2    3    4    2   0.75
    6    1    5    6    7   0.75
    8    2    8    3    6   0.75
-----i-------g
```

1	0.9
2	0.9
3	0.9
4	0.9
5	0.9
6	0.9
7	0.0
8	1.0

For the implementation in the simple model example, junction 6 is defined differently, with the primary node given as node 7, and the secondary node is given as node 6. This is because the example model uses flow splits to define junction entrainment coefficients, and the model introduces a user defined flow into branch 7 to represent flow into the central delta (exports?), but doesn't subtract this flow from branch 6, as branch 6's flow is defined by a relationship with the Freeport flow, and is always the same as the flow in branch 5. Hence, using branch 6 as the primary branch would give branch 6 an entrainment coefficient of 1 based on flow split.

North Delta Model 2 – Five migration pathways

The second network considered is the “five conveyance corridor”. This example, shown in figure 4, is a step up in complexity from the first example, yet does not include dead-end channels, or the possibility of tidal influences. Using this network, Sutter and Steamboat Sloughs are modeled independently and the Mokelumne River is separated from Georgiana Slough, although the North and South Fork Mokelumne have been combined. Once again, losses to the central Delta are modeled by adjusting the entrainment rate and setting the survival rate to zero.

For the simplified north Delta network shown in figure 4, the model geometry input file is simply:

```
c
c-------------North Delta Salmon Survival Model input file - Model 2
c
----im----jm
   14    9
-----j-jtype-----0-----1-----2-------a
    1    1    0    1    6   0.75
    2    1    1    2    7   0.75
    3    1    2    3   10   0.75
    4    1    3    4    9   0.75
    8    2    8    6    7   0.75
    5    2    5    8    4   0.75
   11    2   11    9   10   0.75
   12    1   11   12   13   0.75
   14    2   14   12    5   0.75
-----i-------g
    1    0.9
    2    0.9
    3    0.9
    4    0.9
    5    0.9
    6    0.9
    7    0.9
    8    0.9
    9    0.9
   10    0.9
   11    0.9
```

12	0.9
13	0.0
14	1.0

North Delta Model 3 – Complete system

A first cut at a relatively complete model of the system is given in figure 5 where: (1) all of the channel segments are represented; (3) dead-end sloughs, (4) tidal exchanges and (5) losses to the central Delta are modeled.

Beginning in the north, Sutter Slough will likely include mortality in Elk Slough. We know very little regarding the hydrodynamics of Elk Slough (tidal prism, the phase of the tidal flows in Elk Slough with respect to Sutter Slough, and the net flow due to agricultural withdrawals and returns, etc.), except that it does tidally exchange with Sutter Slough. And, we don't know whether this is a good or bad place for juvenile salmon even though it is probably one of the best purely riparian corridors in the Delta. Mortality in Liberty Island, Lindsey Slough and the Sacramento Deep Water ship channel area is treated as a single entity in this conceptual model. If predation in this region is particularly large, as some suspect, then we'll have to untangle which of these regions is the culprit, so we can presumably try to do something about it. The Liberty Island area may be a place where some relatively simple changes in geometry could reduce mortality; for example, increasing the size of the openings in Liberty Island could reduce velocity shears and thus predation there. Elk Slough, Snodgrass Slough and Liberty Island are all modeled as dead-end sloughs. The entrainment relations will change in these areas as the Sacramento River flows increase because increases in the Sacramento River flows locally decreases the tidal exchange. Also, during "high water", Snodgrass Slough can have a significant net discharge from the Mokelumne system and Cache Slough conveys water from the Yolo bypass when it floods.

Including tidal effects

Throughout the north Delta, the net flows can be fairly well estimated based on the Sacramento River flows measured at Freeport and DCC gate position. However, as one moves into the more strongly tidally affected areas near the confluence of Cache Slough and the Sacramento River, other forcing factors begin to influence the movements of juvenile salmon, such as tidal dispersion (mixing due to tidal exchanges) the spring neap cycle, export pumping rates, San Joaquin River flows, and meteorological influences (wind and atmospheric pressure changes). For example, we know, based on radio tracking experiments that juvenile salmon traversing the Sacramento River can be tidally exchanged up Cache Slough into the Liberty Island area (Vogel, 200x). This exchange is in opposition to the to the net flow in Cache Slough. So how and where do we account for mortality that occurs due strictly to tidal exchanges in this model? One could argue, that these losses should be accounted for in the mortality in the Sacramento River since this is the migration pathway that was used in reaching Liberty Island. Indeed, as a first cut, loss terms have been added to both lower Steamboat Slough and the lower Sacramento River, as is shown in figure 5. If Liberty Island actually has significant tide induced mortality, then the mortality for each of these loss terms may be a step function (i.e. the mortality falls off dramatically when the tidal excursion is less than the along-channel distance from either of these channels to Liberty Island). The tidal excursion in this area will be a function of the Sacramento River flow at Freeport and DCC gate position.

In the end, it may not be possible to represent the net flows in the southwest portions of the network shown in figure 5. And, one could argue that survival in these areas is not strongly correlated with either the Sacramento River flow or DCC gate operations anyway. These flows are shown on figure 5 as a conceptual placeholder, and may not be relevant as the model evolves. Nonetheless, from a management perspective, it is important to know where such things as the Sacramento River flows and DCC gate operations are important and where they are not. Still, in terms of a salmon survival model, we'll need survival estimates for these reaches and hopefully some idea what they depend upon. This is particularly important in the western Delta where outmigrants are likely to spend a significant period of time. For example, radio tag experiments have shown that juvenile salmon move through the Mokelumne system within hours, yet take a couple weeks to reach Chipps Island (Vogel, 20xx). Based on time alone it is probably important to know what is happening to outmigrants in this region. The difference in travel times speaks to the strong influence the Sacramento River has on the north/east portion of the north Delta, including the Mokelumne River system and Georgiana Slough and the strong influence the tides have on the San Joaquin River north of Franks Tract which weakens the influence of the rivers there.

Input data set for the network shown in figure 5

```
c
c-------------North Delta Salmon Survival Model input file - Model - 3
c
----im----jm
   35   21
-----j-jtype-----0-----1-----2-------a
    1    1    0    1    9   0.75
    2    1    1    2   12   0.75
    3    1    2    3   21   0.75
    4    1    3    4   24   0.75
    8    1    4    8    5   0.75
   10    1    9   10   11   0.75
   14    1   11   14   13   0.75
   18    1   13   18   19   0.75
   15    2   15   12   14   0.75
   17    1   15   17   16   0.75
   20    2   20   16   19   0.75
    6    2    6    5   20   0.75
    7    1    6    7   31   0.75
   22    1   21   22   23   0.75
   25    1   23   25   26   0.75
   27    2   27   25   26   0.75
   28    2   28   24   27   0.75
   30    1   28   30   29   0.75
   32    2   32   31   30   0.75
   33    1   32   33   34   0.75
   35    2   35   34    7   0.75
-----i-------g
    1    0.9
    2    0.9
```

3	0.9
4	0.9
5	0.9
6	0.9
7	0.9
8	0.0
9	0.9
10	0.0
11	0.9
12	0.9
13	0.9
14	0.9
15	0.9
16	0.9
17	0.0
18	0.0
19	0.9
20	0.9
21	0.9
22	0.0
23	0.9
24	0.9
25	0.9
26	0.9
27	0.9
28	0.9
29	0.0
30	0.9
31	0.9
32	0.9
33	0.0
34	0.9
35	1.0

Discharge Ratio model

A simple model of entrainment is developed based on the ratio of the discharges at a junction and survival rate is inversely proportional to the travel time (e.g. as travel time (exposure) increases, survival decreases).

Discharge Calculations

Statistical relations have been derived for each of the flows for the channels shown in figure 3 based on the Sacramento River flow rate measured at Freeport, Q_{fpt} and Delta Cross Channel gate position – open or closed (appendix B). These relations take on the form:

$$Q_i^o = \frac{1}{a_i^o + b_i^o / Q_{fpt}}$$ for DCC gate open discharges (superscript "o" for open)

And

$$Q_i^c = \frac{1}{a_i^c + b_i^c / Q_{fpt}}$$ for DCC gate closed discharges (superscript "c" for closed)

The fits to data and the a's and b's are given in appendix B.

Survival as a function of travel time

Travel time probably should eventually be estimated on the basis of particle tracking experiments – e.g. the tidally-averaged travel time for a whole bunch of numerical particles (with and without behavior). This will require a multi-dimensional model of the entire northern reach and a full 3D formulation in the split junctions. Nonetheless as a first estimate we have

$$v_i = \frac{Q_i}{A_i}$$

Where $v_i = \frac{Q_i}{A_i}$ is channel segment average velocity, where Q is based on the statistical relations and the cross sectional area is obtained from the cross sections at out measuring stations – a more accurate cross sectional area for a given reach could be determined using GIS on a bathymetry file. However, we could also get an estimate by regressing the cross sectionally averaged velocity at our flow stations with the discharge at Freeport directly. The area in this incarnation of the model is a constant not a function of water level which obviously varies with Sacramento River discharge.

The travel time, Δt_i, for the i'th channel segment is computed based on the length, L_i, of the channel segment (measured in topo), divided by the average velocity, v_i.

$$\Delta t_i = L_i / v_i$$

Actual travel times are likely to be much faster then this since juvenile salmon usually travel in the upper portion of the water column. Although they do "travel" downstream with an upstream orientation (weak, positive rheotaxis orientation, on the order of .1-1 bl/s [bl=body length]), which will somewhat reduce this affect. In addition, one should consider the tendency of salmon to move in a temporal migratory spiral, where they spend part of the day holding and/or feeding, and part of the day moving downstream. This spiral changes depending on the type of fish, its run, its life history strategy (stream type fish could have ½ the residency time of the classic ocean type fish with a 50% spiral), and the fishes degree of smoltification. This should be formally considered and included, as a fish that spends ½ of its time holding will have a much greater residence time.

Example:

tt~[L/(V-.5bl/s)]*(1+(1-%time spent migrating))

Tt = travel time,
L = Length of channel
V= cross-sectionally averaged water velocity

The survival rate is based on a linear function of the normalized travel time, where the normalized travel time is the travel time, Δt_i, divided by the maximum travel time, $T_{\max}$

in the reach for a Freeport discharge of 5,000 cfs (approximate lowest measured discharge at Freeport).

$$\gamma_i = c_0 - c_1 \frac{\Delta t}{T_{\max}} \qquad 0 \le \gamma_i \le 1$$

And the mortality rate is $\beta_i = 1 - \gamma_i$

Two predation functions have been included in the model, a constant predation rate model, and a simple Lotka-Volterra model solution.

The linear model is a solution to the simple conceptual case where predators can eat a constant number of fish in a given amount of time, for example, each bass can eat 10 salmon an hour. Expressed as a differential equation, where S=salmon population, P=number of predators, and r=feeding rate (S/t):

$$\frac{\partial S}{\partial t} = -Pr$$

S(t)=S-Prt

The user specifies a predator density to be used as P (User is prompted in units of fish/mile, it should be something like predators/predation control volume, but right now the values are arbitrary.). The user also specifies a constant for r

The Lotka-Volterra preditor prey model has the general form of :

$$\frac{\partial S}{\partial t} = rS-aSP$$

and

$$\frac{\partial P}{\partial t} = bSP-mP$$

Where:

r= rate of prey (salmon) population increase

a= predation rate

b= predation dependent predator population increase

m= predator mortality

The simplest solution to this relationship is used, with no prey population increase (good assumption), and no change in predator population over time (probably poorish assumption). We should consider looking at research into predator densities in the north Delta, and, if this is lacking, research regarding predator populations establishing themselves below dams and juvenile bypass structures.

$$\frac{\partial S}{\partial t} = \text{-aSP}$$

S(t)=Se^(-aP)

Again, the user specified predator density is used for P, and the predation rate control is used for a. Note that the "a" required for realistic predation with the LV model is much smaller than the a required for the linear model, so the control has a logarithmic scale.

To actually determine these parameters in the field, we need to measure survival through a reach at multiple Q's (to get different travel times), and electro fish for predators to determine predator densities. With these two quantities, one can make a stab at determining the general nature of the predation relationship, and its parameterization. Of course, all of these parameters are probably a function of Q, S, T, etc. but this would give you a first pass, and represents the minimum requirements for field data.

References

Lotka, A. J. 1925. Elements of physical biology. Baltimore: Williams & Wilkins Co.

Volterra, V. 1926. Variazioni e fluttuazioni del numero d'individui in specie animali conviventi. Mem. R. Accad. Naz. dei Lincei. Ser. VI, vol. 2

Entrainment function

The entrainment function at a junction is based on the ratio of the discharges multiplied by an "efficiency" factor, e_k

$$
\begin{Bmatrix}
\varepsilon \geq 0 & \alpha_k = \dfrac{Q_{j_{k,1}}}{Q_{j_{k,0}}} + \left(1 - \dfrac{Q_{j_{k,1}}}{Q_{j_{k,0}}}\right) * \varepsilon \\
 & \\
\varepsilon < 0 & \alpha_k = \dfrac{Q_{j_{k,1}}}{Q_{j_{k,0}}} * (1 - abs(\varepsilon))
\end{Bmatrix}
$$

This equation has been updated to reflect the implementation in the model, so that E always ranges from -1 to 1, and that it always scales a branches entrainment from 0 to 1.

Where the efficiency factor is $e_k > 1$ for primary exit channels on the outside of a bend, for example. At some point we will need to develop entrainment relations for each junction based on long term averages of multidimensional model particle tracking experiments and finally, based on field data such as acoustically tagged juvenile salmon, hydroacoustics, etc.

Random thoughts:

(1) With the DCC gates closed Geogiana Slough travel time goes up but exposure may actually increase due to a reduction in net flow through the Mokelumne which creates a lot of tidal sloshing in the lower mokelumne, possible entrainment in South Mokelumne even though Geogianna Slough is unitdirectional – the lower Mokelumne becomes very tidal when the gates are closed.

(2) Losses to central delta depend upon the discharge out of Mokelumne, the San Joaquin River flows and the export rate and water temperature.

(3) When Freeport flows go up tidal sloshing and dispersion goes down decreasing exposure for two reasons (1) increase in net flows and net travel time and (2) reduction of dispersion and exposure to hot spots… For example, when net flow is low and tidal currents high juvenile salmon may be exposed to a particular bad spot multiple times before the net discharge moves them past it. Also, I expect the average travel time to go up in the tidally affected areas because a number of the particles will be advected into higher residence times areas such as Snodgrass

Slough, Elk Slough, Liberty Island etc. Also, the standard deviation on the travel time estimates will go up – e.g. a wider variety of travel times due to tidal mixing putting the particles in distinctly different environments.

(4) There is a hydrodynamic residence time break where the flows change from uni- to bi-directional (which changes with Qfpt) and a geomorphologic break where there are large expansions in cross sectional area. This happens in two fundamental areas (a) Where Cache Slough meets the Sacramento River and Steamboat Slough and (2) where the Mokelumne meets the San Joaquin. We have a step function change in net outward movement and exposures proportional to the very long tidal excursions in these areas.

(5) The entrainment function approach is based on implicit assumptions regarding the ability to characterize interactions between processes with different characteristic time scales, and apply these characterizations at the residual (net) time scale. We have made the following attempt to rigorously state these assumptions in the below equation. Bridging this time-scale divide is critical and needs to be rigorously investigated in the future.

$$\frac{\int_{t_a}^{t_b} E_1\left(v(t), q(t), l(t), m(t), \ldots\right) \otimes N\left(t\right)}{\int_{t_a}^{t_b} E_2\left(v(t), q(t), l(t), m(t), \ldots\right) \otimes N\left(t\right)} = \left(\int_{t_c}^{t_d} N(t)\right) * \left(\frac{\varepsilon_1}{\varepsilon_2}\right)$$

Usually,

$$t_b - t_a >> t_d - t_c$$

Appendix A

Definition of terms

$N_0 =$ Initial number of juvenile salmon released in the upper reach of the Sacramento River.

$N_{j,k} =$ Number of juvenile salmon: j is the channel number; k=1 is the head of the channel, k=2 is the tail of the channel

$\alpha_i =$ Entrainment function for the ith junction – "i" is referenced to the primary channel, $0 \le \alpha_i \le 1$

$M_j =$ Mortality, number of fish lost in a given reach.

$\gamma_j =$ Survival in the jth channel – $0 \le \gamma_j \le 1$

$\beta_j =$ Mortality in the jth channel – $0 \le \beta_j \le 1$

$\gamma_j = 1 - \beta_j$

$Q_j =$ Discharge, in cfs, in the jth channel

$A_j =$ Average cross sectional area in the jth channel

$V_j =$ Reach-averaged velocity for the jth channel

$t_j =$ Time of travel in the j'th reach

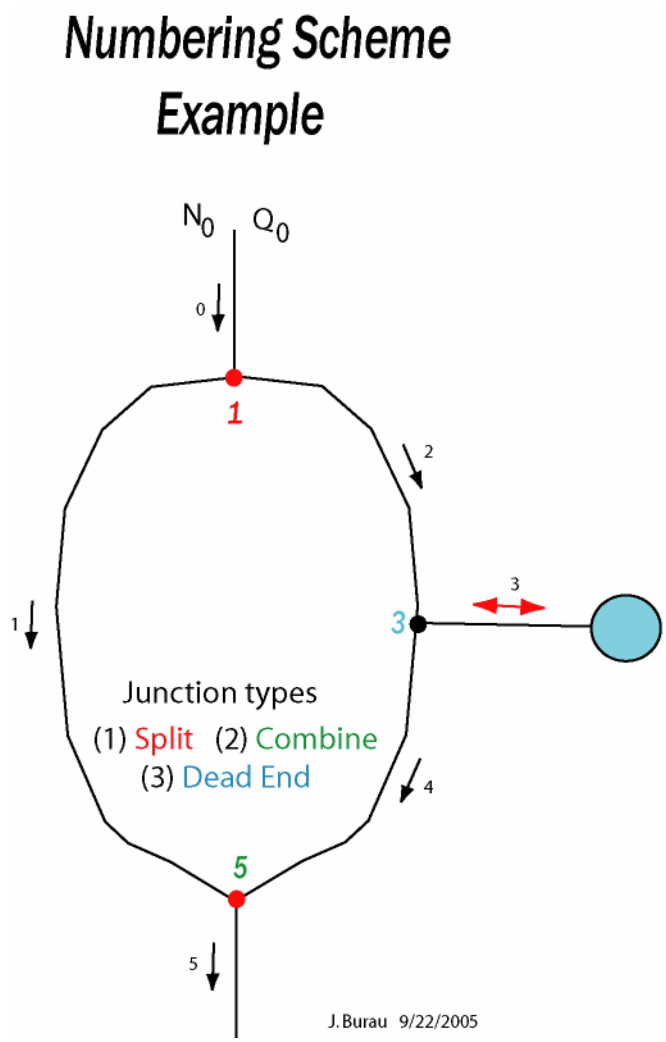

Figure 1 – Schematic of archetypal network of channel and junction elements.

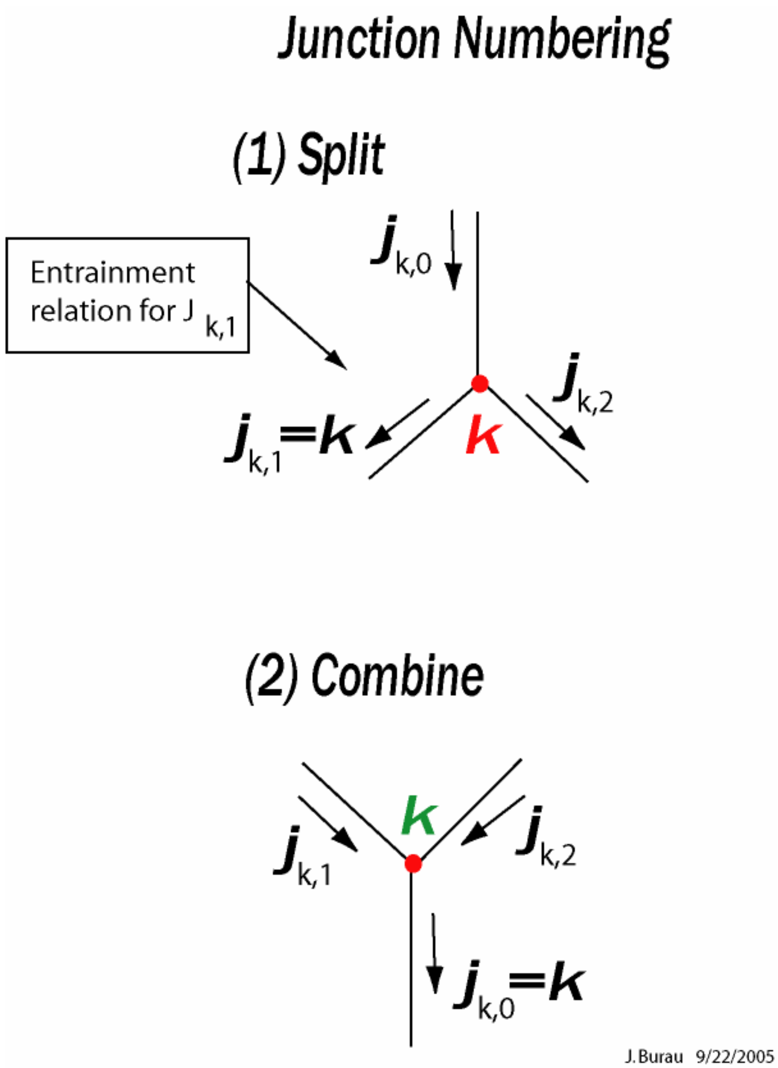

Figure 2 –Schematic of junction numbering schemes. Two types of junctions are specified: (1) split, (2) combine.

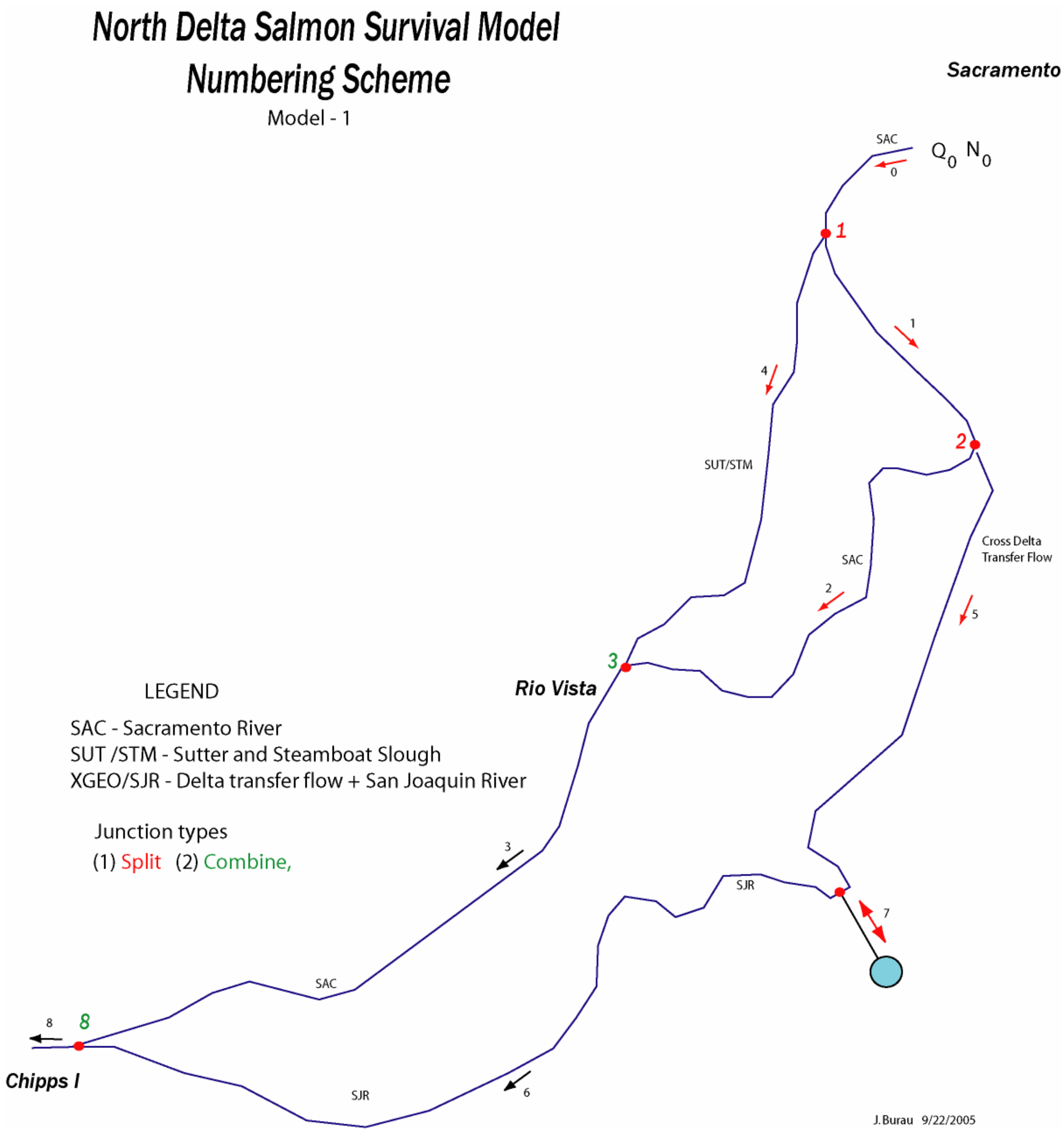

Figure 3 – Simple first-order salmon survival model of north Delta. This model includes three basic migration pathways: (1) Sutter/Steamboat, (2) mainstem Sacramento River, (3) Mokelumne/Georgiana.

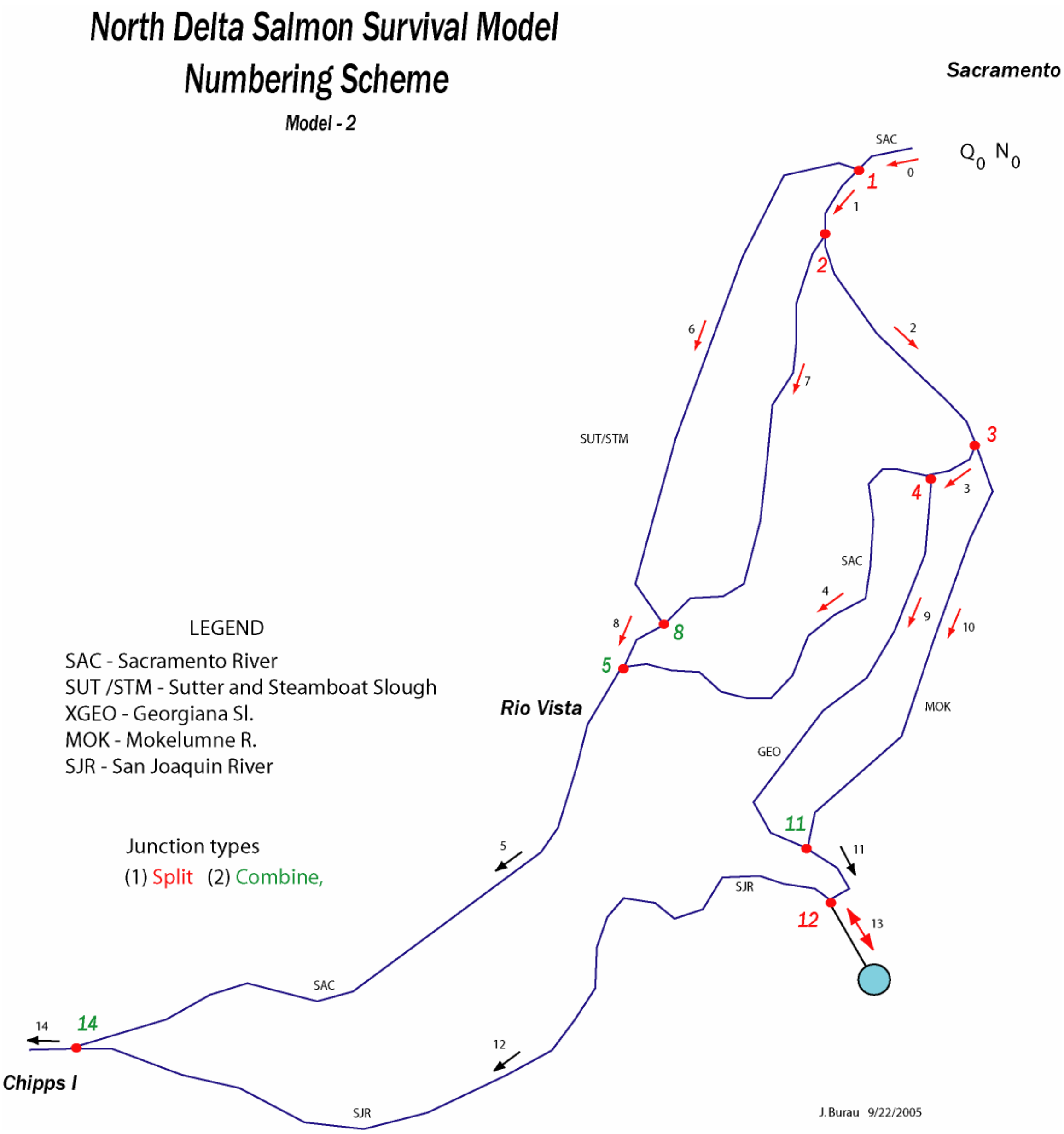

Figure 4 – Model 2 includes explicit separation of Sutter and Steamboat Sloughs and Georgiana Slough and Mokelumne River system.

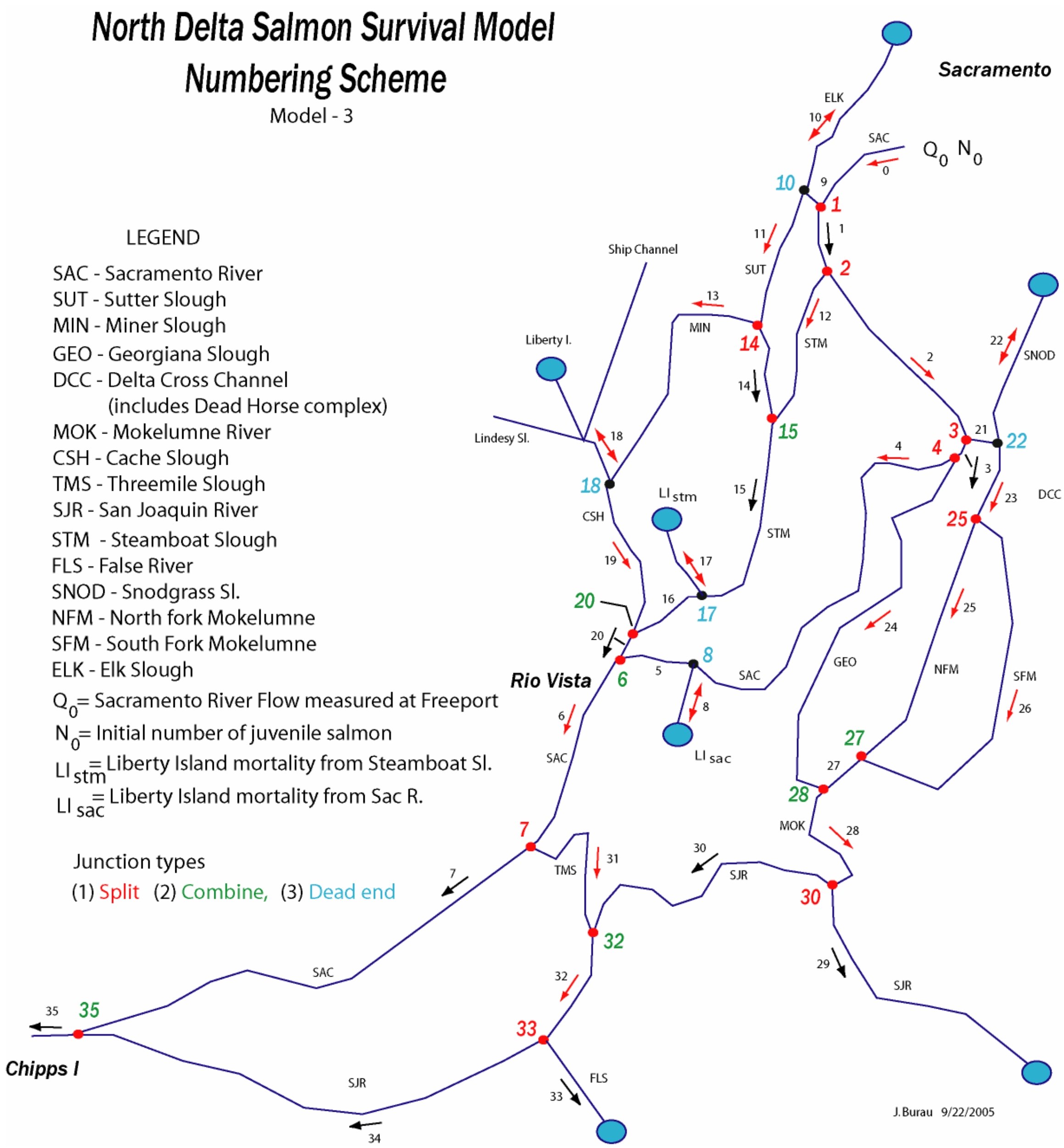

Figure 5 – Conceptualization of a model that includes simple representations of all of the major north Delta geometric elements, including losses in dead-end sloughs, losses to tidal dispersion, losses to central Delta separated into losses in False River and on the San Joaquin River.

Appendix B – Discharge Relations

Statistical relations were developed for each net flow in the channels shown in figure 3 based on the Sacramento River flow rate measured at Freeport, Q_{fpt} and Delta Cross Channel gate position – open or closed. These relations take on the form:

$$Q_i^o = \frac{1}{a_i^o + b_i^o / Q_{fpt}} \quad \text{for DCC gate open discharges (superscript “o” for open)} \qquad (1o)$$

And

$$Q_i^c = \frac{1}{a_i^c + b_i^c / Q_{fpt}} \quad \text{for DCC gate closed discharges (superscript “c” for closed)} \qquad (1c)$$

Where Q_{fpt} is the net flow measured in the Sacramento River at Freeport. For the channels shown in figure 3, the following constants (a,b) are used (for details see Burau and others, 2006)

Station	Open nonlinear a	Open nonlinear b	Open nonlinear Rsq	Closed nonlinear a	Closed nonlinear b	Closed nonlinear Rsq
RIO	-2.0748E-05	2.12408	0.98318	-7.64E-07	1.24	0.999416
SS	-4.4815E-05	3.65423	0.979567	-4.38E-06	2.46718	0.9984
WGA	1.4614E-05	1.27689	0.989449	3.04E-06	1.64879	0.998624
WGB	-2.3147E-05	4.86944	0.9248	2.84E-06	2.438109	0.99763
XGEO	4.1552E-05	1.570164	0.93335	2.26E-05	4.7498	0.980995

Table 1 – Nonlinear constants used in computing the flows for the network in figure 3 where the following mnemonics represent the flows in the following channels: RIO = calculated discharge in the Sacramento River at Rio Vista (computed based on the sum of SS and WGB: SS – Discharge in Sutter and Steamboat Sloughs based on the difference between the net flows measured at FPT and WGA; WGA = net flows measured in the Sacramento River above Walnut Grove; WGB = net flows measured in the Sacramento River below Walnut Grove (e.g. below Georgiana Slough); XGEO – Delta transfer flow computed based on the difference between the flows at WGA and WGB – represents the combined flow down DCC and Georgiana Slough.

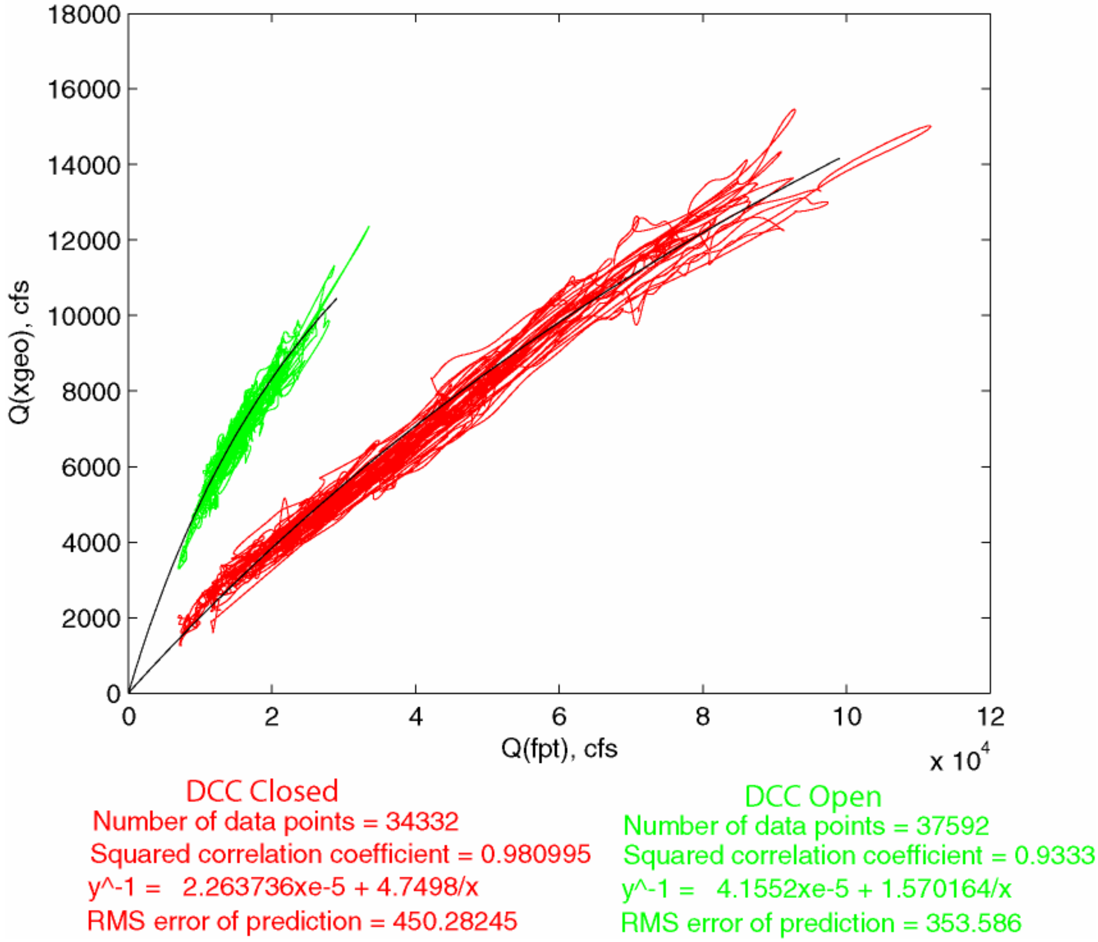

Figure 6 – Scatter plot of the so called "Delta Transfer Flow", XGEO, computed as the difference between the net flows measured at WGA and WGB versus the net flow measured in the Sacramento River at Freeport, Q(fpt). Period of record: 1993-2004, ~11 years of data. Hourly data plotted. Data collected when the DCC gates were open in green and closed in red. Black lines represent fits to the data using equations (1o), (1c) above.

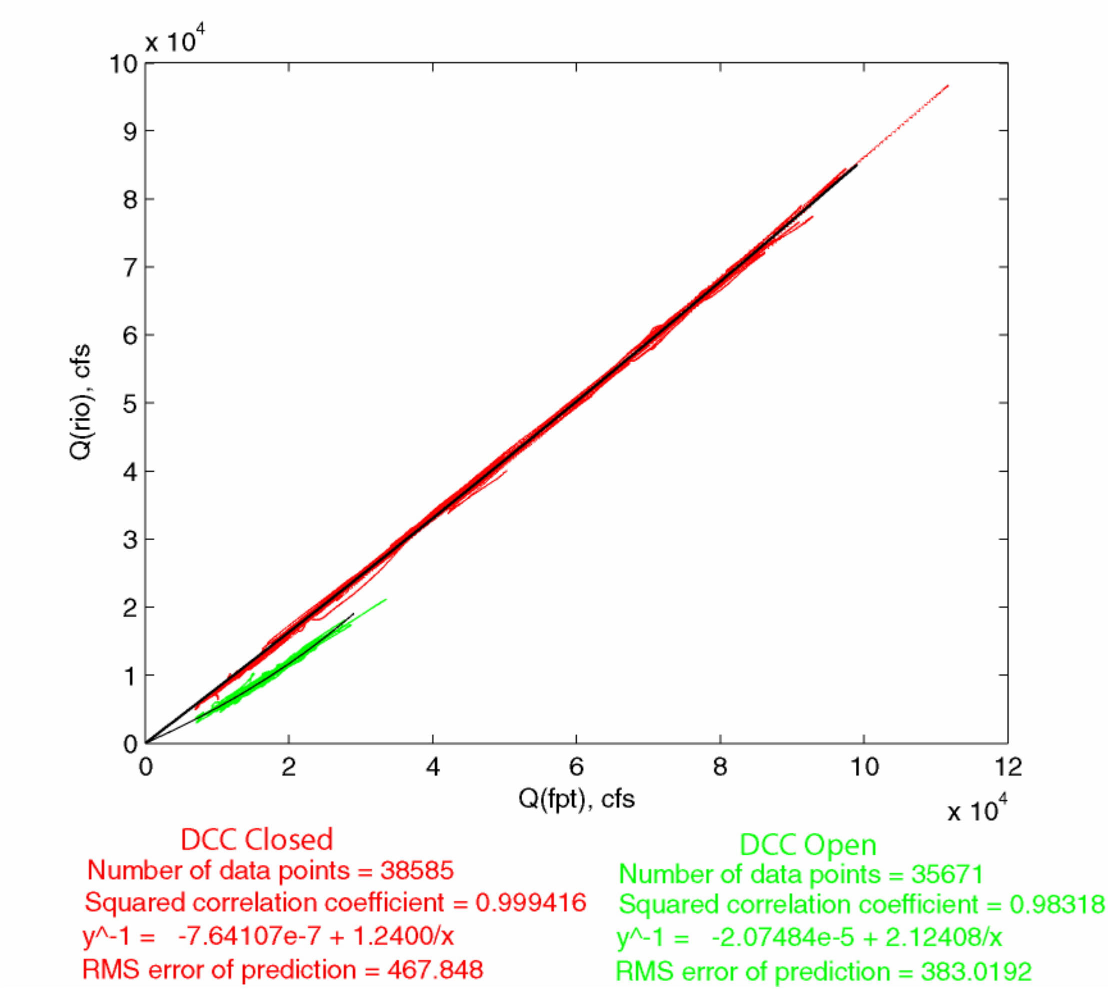

Figure 7 – Scatter plot of the computed net flow in the Sacramento River at Rio Vista, RIO, computed as the sum of the net flows in SS and WGB versus the net flow measured in the Sacramento River at Freeport, Q(fpt). Period of record: 1993-2004, ~11 years of data. Hourly data plotted. Data collected when the DCC gates were open in green and closed in red. Black lines represent fits to the data using equations (1o), (1c) above.

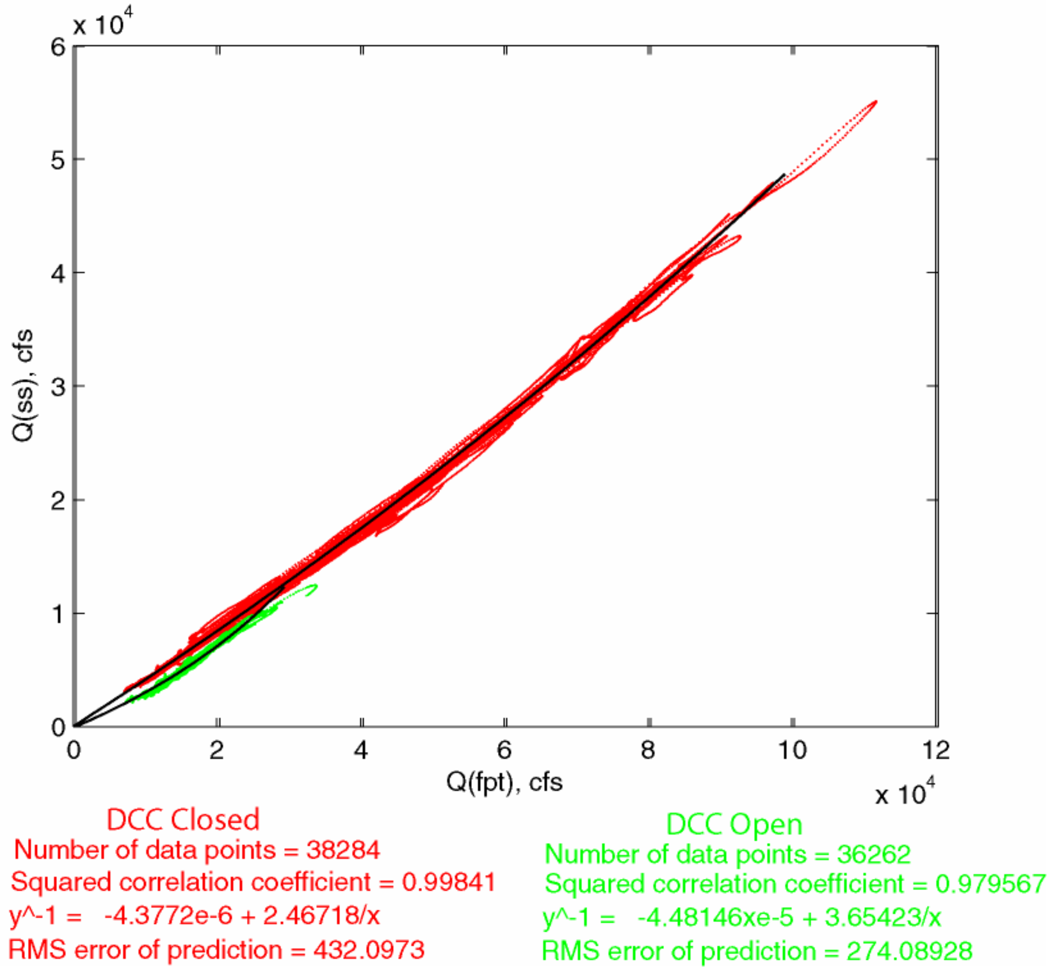

Figure 8 — Scatter plot of the computed net flow in a combination of Sutter and Steamboat Sloughs, SS, computed as the difference of the flows at Station WGA and FPT versus the net flow measured in the Sacramento River at Freeport, Q(fpt). Period of record: 1993-2004, ~11 years of data. Hourly data plotted. Data collected when the DCC gates were open in green and closed in red. Black lines represent fits to the data using equations (1o), (1c) above.

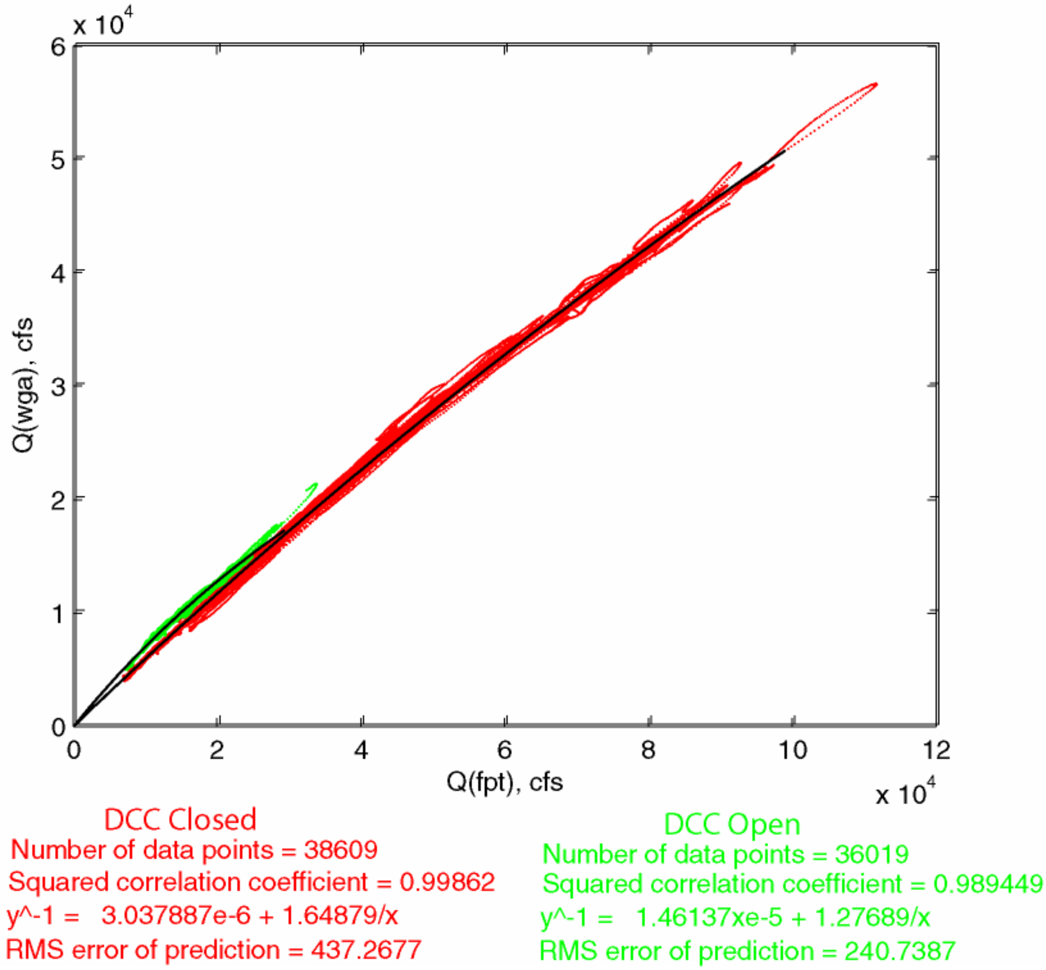

Figure 9 – Scatter plot of the measured net flow in the Sacramento River at station WGA (measured above Walnut Grove) versus the net flow measured in the Sacramento River at Freeport, Q(fpt). Period of record: 1993-2004, ~11 years of data. Hourly data plotted. Data collected when the DCC gates were open in green and closed in red. Black lines represent fits to the data using equations (1o), (1c) above.

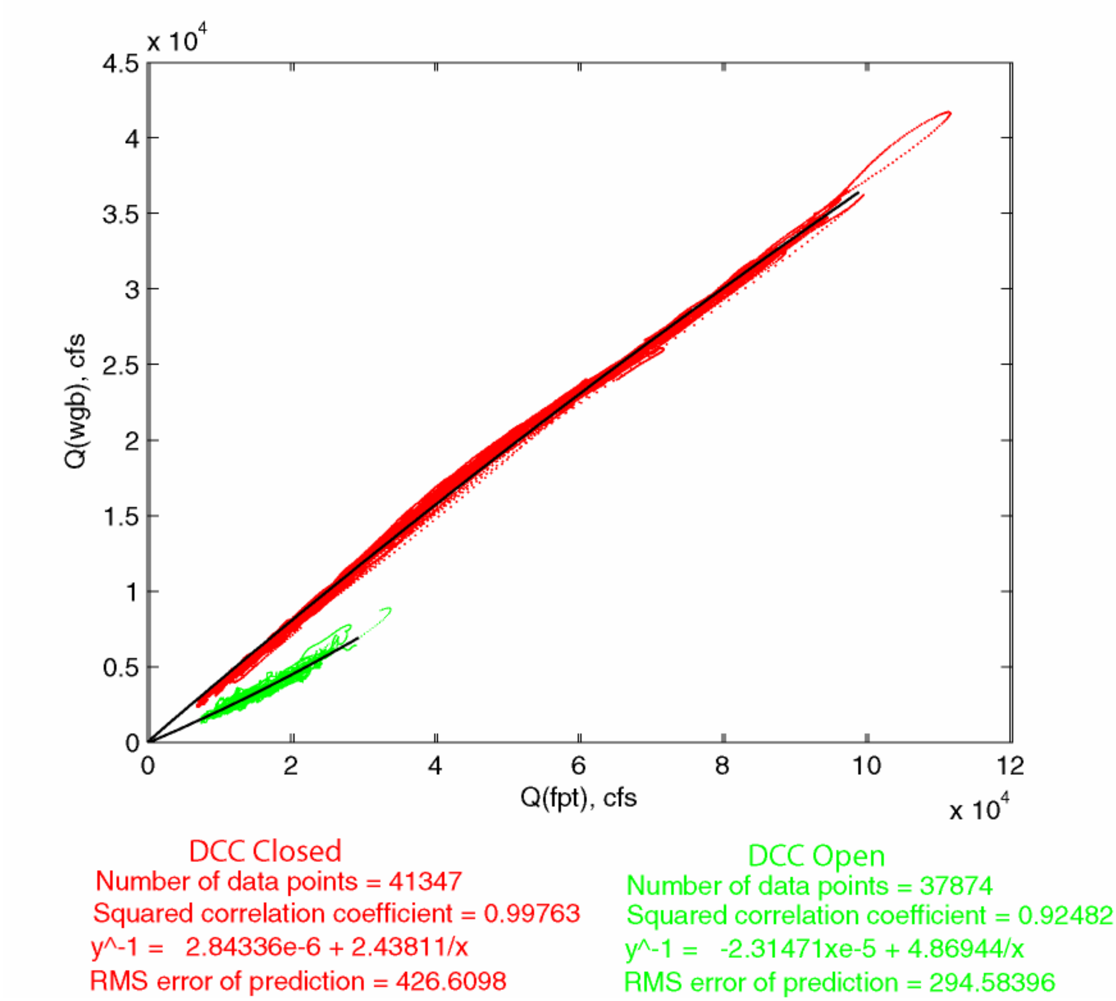

Figure 10 – Scatter plot of the measured net flow in the Sacramento River at station WGB (measured below Walnut Grove – below Georgiana Slough) versus the net flow measured in the Sacramento River at Freeport, Q(fpt). Period of record: 1993-2004, ~11 years of data. Hourly data plotted. Data collected when the DCC gates were open in green and closed in red. Black lines represent fits to the data using equations (1o), (1c) above.