Chapter 4. DSM2-GTM

4.1 Introduction

DWR's Delta Modeling Section is developing a new DSM2 transport module, the General Transport Model (GTM). The mesh for GTM is fixed (Eulerian) rather than moving with flow (Lagrangian). This should make it easier to interact with other models, georeferenced data, and visualization, as well as to couple to Hydro. It is also based on a more flexible software framework that is easier to adapt to new groupings of constituents. Mercury and sediment are of particular interest. The algorithm is a second order upwind solver developed in a prior collaboration with UC Davis with low numerical diffusion and an elaborate verification framework covering tough problems. This chapter describes some of the practical issues of embedding such a model in a looped network or in a DSM2 grid with many intermediate junctions (nodes) along a single physical channel reach. We demonstrate the effect the DSM2-Qual schema can have on numerical diffusion, and make some preliminary comparisons with DSM2-Qual on advection problems in which GTM appears to be less diffusive in more complex flow fields or on more intricate grids.

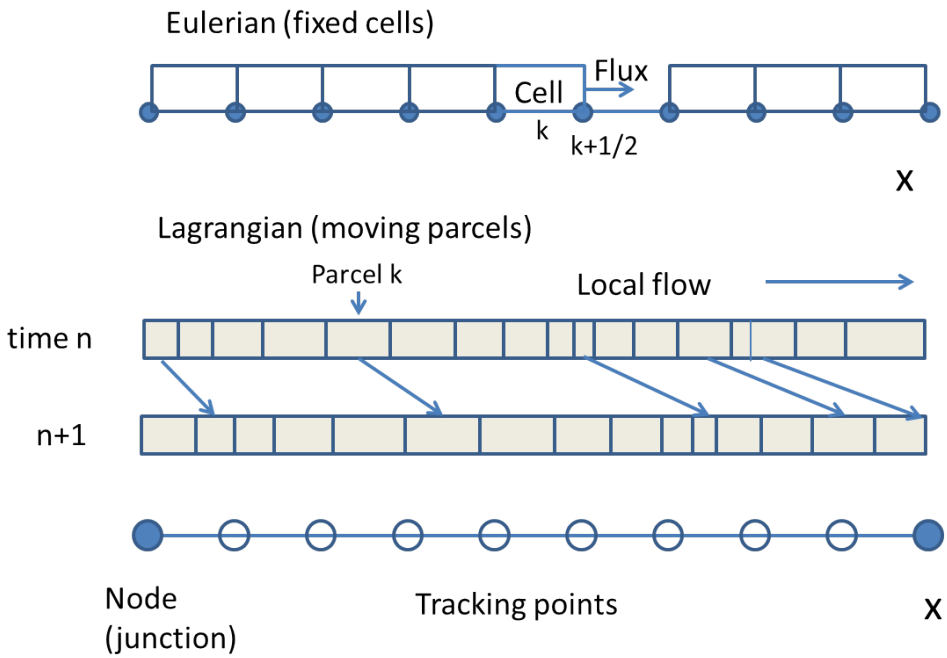
4.2 Eulerian versus Lagrangian Frames of Reference

Eulerian and Lagrangian frames of reference are two fundamental ways of thinking about and measuring transport processes, each with its advantages and disadvantages. The Eulerian frame of reference can be visualized as sitting on the bank of a river and watching the water passing that fixed location. A typical Eulerian transport model has a fixed spatial grid that is updated by defining fluxes between cells. The accuracy of the flux approximation usually drives the accuracy of the overall scheme. The simplest schemes are plagued by numerical diffusion (a tendency for a plume to spread out) and although this is a solved problem at this point, the better schemes have only become ubiquitous within the last 15 years. Multidimensional models often use Eulerian or hybrid approaches.

A Lagrangian frame of reference can be visualized as sitting in a boat and drifting down a river. In fluid dynamics, a Lagrangian model follows individual fluid parcels as they move through space and time. Figure 4-1, bottom, shows a "train" of particles moving from left to right with local flow. One parcel is created on the left and others exit on the right. The number of parcels in a channel depends on the length of the channel, local velocity, and tidal excursion. As few as one parcel can occupy a channel, but a more typical number is 30 to 50. In theory, Lagrangian schemes are immune to numerical diffusion, an advantage that has been known since the time of Fischer (1979), although, as we shall see, the practical implementation (junctions, output retrieval) leads to some inaccuracy.

Perhaps the greater issue with a Lagrangian model comes from trying to relate it to an Eulerian world – exporting data to a Geographical Information System (GIS), or creating an animation. It is possible to economically track parcels based on volumetric calculations by estimating when parcels pass tracking points and junctions. In Qual's predecessor, the Branched Lagrangian Transport Model (BLTM), tracking points were also used as locations to inject a more detailed flow field without triggering mixing (which occurs at junctions). Example tracking points are shown in the bottom of Figure 4-1. For reasons that hark back to computational and memory limitations, DSM2 does not exploit the idea of interior tracking points within a channel.

Figure 4-1 Illustration of Eulerian versus Lagrangian Frame of Reference



4.3 DSM2-Qual and the Branched Lagrangian Transport Model (BLTM)

DSM2-Qual is based on the BLTM. The original transport code was developed by Harvey Jobson (USGS) and adapted to the Delta by DWR staff (Annual Report, 1998). DSM2-Qual has been widely used to simulate water quality in the Sacramento-San Joaquin Delta. Besides conservative constituents (e.g. EC), DSM2-Qual models the dispersion and kinetics of a fixed selection of non-conservative constituents, including dissolved oxygen, carbonaceous biochemical oxygen demand, phytoplankton, organic nitrogen, ammonia nitrogen, nitrite nitrogen, organic phosphorus, dissolved phosphorus, total dissolved solids, and temperature. The conceptual and functional descriptions of the constituent reactions are based generally on QUAL2E (Brown and Barnwell, 1987). See Jobson and Scoellhamer (1987) for a description of the Lagrangian formulation which provides the basic framework for DSM2-Qual.

As its name implies, a key practical feature of the BLTM design is the accommodation of a branching or looping channel structure. This is an important feature when modeling the Delta. In BLTM, parcels entering a channel junction are blended before being sent on into outgoing channels. This blending is an appropriate treatment for nodes that represent real junctions and confluences, such as node 113 at the junction of Middle River and Victoria Canal in Figure 4-2.

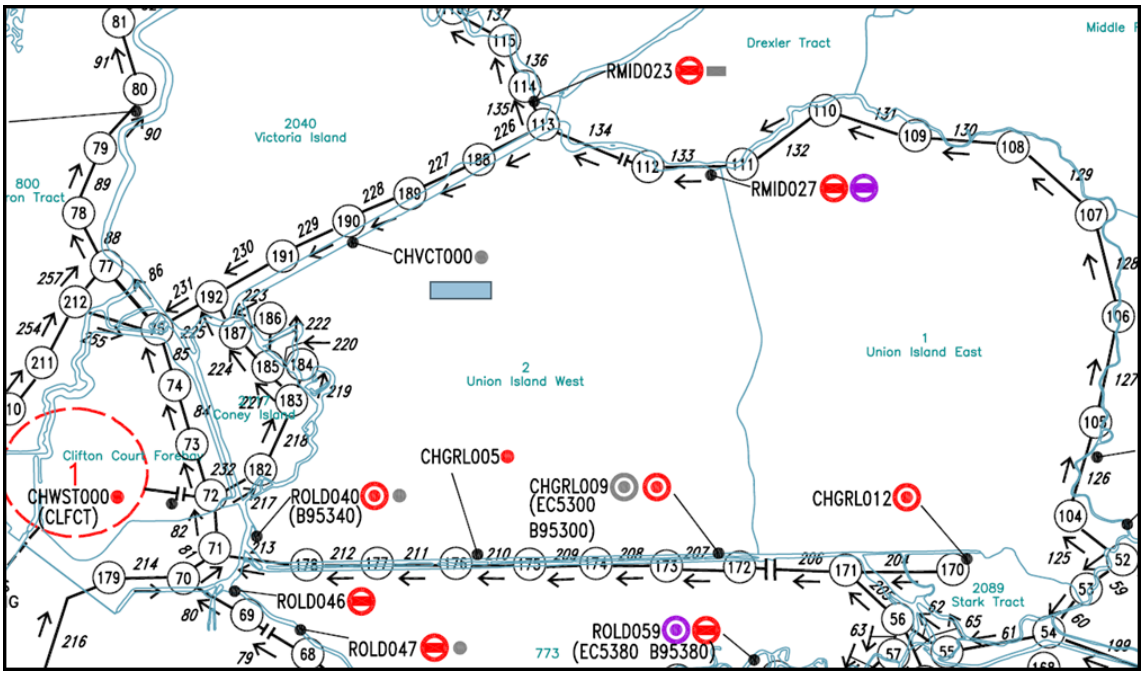
In DSM2-Qual, intermediate nodes along a single physical reach (such as nodes 104-112 on Middle River in Figure 4-2) are also treated as BLTM junctions, and parcels passing them are therefore mixed as well. The design imposes the following tradeoff between the accuracy of the flow field and the accuracy of the transport algorithm:

- Flows are delivered from Hydro to Qual only at the upstream and downstream end of each channel, next to map nodes. Thus, in order to deliver sufficient flow detail, more nodes are required.

- Nodes are treated by DSM2-Qual as BLTM junctions, therefore causing mixing of parcels at fairly regular Eulerian intervals and inducing numerical diffusion.

The dense spacing of map nodes was further cemented into practice by the way agricultural (DICU) mass sources and sinks are input, which is only allowed at map nodes. Although we will not pursue the idea further for DSM2-Qual, some of the design could be improved upon by eliminating the large number of intermediate nodes and treating them as tracking points, leaving longer uninterrupted reaches of Lagrangian transport.

Figure 4-2 DSM2 Map Showing Node and Channels for a Region near Clifton Court



4.4 GTM: An Eulerian One-Dimensional Transport Model

4.4.1 Project Introduction

In a collaborative project with UC Davis, Ateljevich et al. (2011) developed a second order upwind one dimensional Eulerian model of advection, dispersion and reactions or sources. The advective-diffusive part of model describes basic conservative transport, and the generalized reaction term can be tailored to non-conservative water quality kinetics including sediment transport.

In conservative form, the equations read:

$$\underbrace{\frac{\partial\big(A(x,t)C(x,t)\big)}{\partial t}}_{\text{Time evolution}} + \underbrace{\frac{\partial\big(A(x,t)C(x,t)u(x,t)\big)}{\partial x}}_{\text{Advection}} = \underbrace{\frac{\partial}{\partial x}\left(A(x,t)K(x,t)\frac{\partial C(x,t)}{\partial x}\right)}_{\text{Dispersion}} + \underbrace{R(x,t,C(x,t))}_{\text{Source/Reaction}} \qquad \text{Eq. 4-1}$$

where x is the distance, t is time, A is the wetted area, C is the scalar concentration, u is the mean flow velocity, K is the longitudinal dispersion coefficient, and R is the source term (deposition, erosion, lateral inflow, and other forms of sources and sinks). Eq. 4-1 describes the mass conservation of a pollutant in dissolved phase, or suspended sediment away from the streambed.

An operator splitting approach was adopted for the solution, meaning that the advection, dispersion, and reaction processes are integrated sequentially in a specially orchestrated predictor-corrector sequence. The nature of the problem and the importance of the conservation of mass strongly suggested employing a finite volume method (FVM). The algorithms employed for GTM include a second-order two-step unwinding method with van Leer flux limiter for advection.

A software testing framework was also developed for verifying the required accuracy of this solver over an incrementally more complex set of 1-D flows, geometry, spatially varying mixing parameters and combinations of operators. Our testing objective was to verify second-order (or close) accurate scheme in both time and space on nonlinear problems, allowing for some loss of accuracy for problems with more involved boundary conditions or over complex geometry.

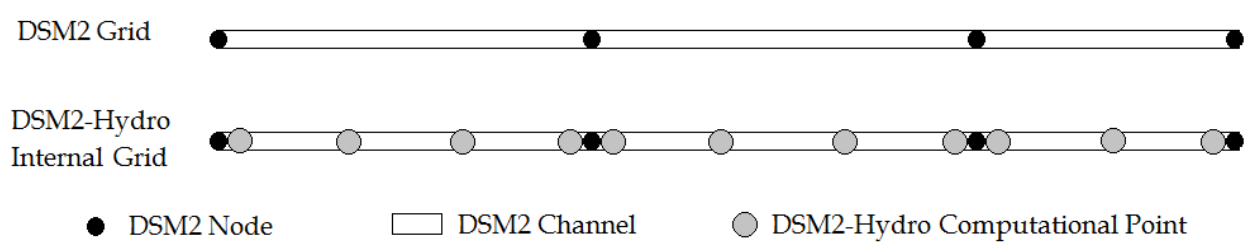
Prior work focused on a single-channel, with speculative software "hooks" where the algorithm had to be patched together for use in a network. Much additional work was needed to make the algorithm workable for production modeling in the Delta, including the provision of a flow field from DSM2-Hydro, specification of the behavior at junctions and connection to the DSM2 input system. These topics are sketched below.

4.4.2 Flow and Geometry Transfer from DSM2-Hydro

GTM was designed so that the provision of the flow field and geometry is a swappable role that is not connected to any particular model or input system. We had three different sources in mind:

- Tests, where the flow field can be written as a software function.
- Stored output from DMS2 Hydro using a *tidefile.*
- Direct connection (*in-line)* interaction with Hydro to facilitate longitudinal density effects on momentum and operating rules based on water quality.

Figure 4-3 Illustration of DSM2 Nodes and DSM2-Hydro Computational Points



DSM2-Hydro computes hydrodynamics at computational points spaced more densely than the nodes on a DSM2 map (Figure 4-3). By default, the model only writes out hydrodynamics results at the upstream and downstream end of each channel. We have already remarked this imposes an awkward tradeoff in DSM2-Qual between the accuracy of the flow field and that of the transport algorithm, so we now write out and utilize data at every DSM2-Hydro computation point.

In the present project, the tidefile is being expanded to allow a lossless representation in both time and space, without transformation. Tidefile flows in the current DSM2-Hydro are *theta averaged*, a sort of lopsided time average that is related to DSM2-Hydro's stability criterion and sense of mass conservation, but otherwise not particularly desirable or intuitive. These averaged flows cannot be inverted to recover the original instantaneous flows so the new hydro tidefile will only store ordinary instantaneous flow. In terms of memory use, the additional spatial detail represents a 30% to 50% increase in the amount of stored data. The extra space may be recouped to some extent by removing redundant information. For instance, DSM2-Hydro outputs both stage and flow area, but flow area and other geometric quantities can be calculated readily from stage or water surface elevation provided the relevant lookup tables are also included.

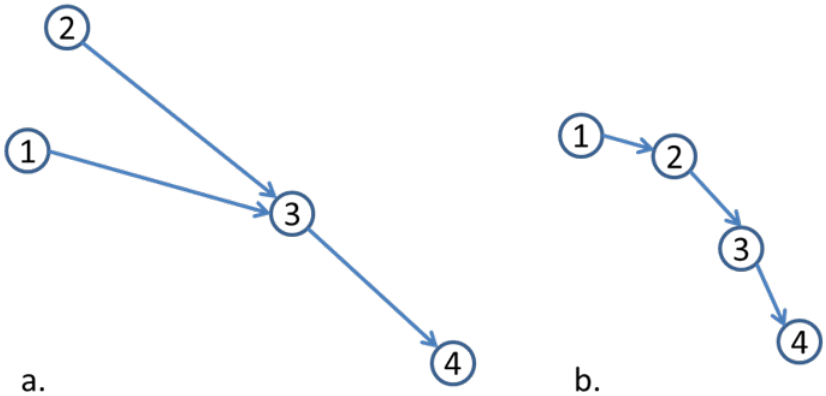
Finally, the spatial resolution of GTM is much finer (usually by a power of 2, such as 8 or 16) than that of DSM2-Hydro. Even with a lossless transfer the flow field provided by hydro is incompletely specified and requires interpolation. Our approach starts by interpolating water surface elevation. The area is then calculated based on geometry and water surface. Once area is determined for all grids, flow is obtained by satisfying conservation of mass marching forward in time. A small discrepancy can develop between the flows thus calculated and the value at the next hydro time step, and the residual is redistributed. The accuracy of the scheme is still being evaluated.

4.4.3 Network Considerations

As in the case of DSM2-Qual, an important implementation detail for GTM in the Sacramento-San Joaquin Delta is the method to treat junctions and flow over a network.

Our compatibility conditions at nodes differentiate between true junctions at the confluence of two or more channels (Figure 4-4a) and intermediate nodes along channels (4-4b). Both the advection and dispersion schemes span intermediate nodes without interruption except for the introduction of lateral agricultural sources. Because adjoining channels do not have exactly the same mesh spacing (dx), some modification was required to accommodate discrete changes in the discretization that occur across nodes. The model does not attempt to calculate concentration gradients (ie, it drops from second to first order accuracy) near multi-channel junctions. Incoming water to the junction is completely mixed before being sent on to outgoing channels.

Figure 4-4 Representation of (a) "True Junction" (Node 3) and (b) a String of Intermediate Nodes along a Single Reach



All these treatments are simple. We found it difficult to engineer simple compatibility conditions at these junctions that would work over a broad class of flows, salinity gradients, channel sizes and configurations. We also wished to avoid additional inputs and ad hoc decision making (e.g. to specify the "main channel").

4.5 Other GTM Code Design and DSM2 Integration Considerations

In connecting GTM to DSM2-Hydro, much of the effort has been spent on input and output (I/O) system design, temporal and spatial interpolation, testing, modifications for boundaries, junctions, and reservoirs. A few items are mentioned here that we believe are of interest even in the prototype stage.

4.5.1 User Input and Output

GTM uses the same common DSM2 code for reading and processing data such as the channel network and boundary data. The input system is based on a text reader using keywords that will seem familiar to users of DSM2-Qual. GTM reads in time-varying data from HDF5[4] and HEC-DSS[5]. A few minor additions and modifications have been made, for instance to specify the nominal cell size of the transport model (dx).

GTM will use HDF5 for model output to write the model state at specified intervals in space and time. There will be separate post-processing tools to take care of requests for output in other formats (HEC-DSS or text) at specific locations and for the creation of restart files.

4.5.2 Multiple Interactive Constituents

This transport model has been designed to allow multiple constituents moving at the same time. GTM simulates advection-diffusion, relegating the reactions between constituents to external modules using a design that facilitates synergy between components. The external modules in development include a sediment, dissolved oxygen, temperature, and mercury cycling module.

4.5.3 Courant-Friedrichs-Lewy (CFL) Condition and Subcycling

In transport problems, the CFL condition describes the time step required for stability while solving for advection. For a one-dimensional problem, the CFL condition has the following form:

$$CFL = \frac{u\Delta t}{\Delta x} \leq C_{max} \qquad \text{Eq. 4-2}$$

where u is the magnitude of the velocity, Δt is the time step, Δx is the space interval and C_{max} depends on the method used to solve the discretized equation, such as whether the method is explicit or implicit. Typically C_{max}=1 for an explicit solver, which amounts to a fairly mild restriction.

In intuitive terms, the CFL condition for our algorithm says that fluid may not be transported by the mean velocity more than one GTM computational cell in one time step. Since the possibility of this happening somewhere over a large channel network is common and hard to anticipate, most practical models that use explicit time stepping (including the community multidimensional models such as UnTRIM, RMA, SUNTANS, and SELFE) generally use subcycling or sub-time steps: the model is specified in terms of a

[4] HDF5 is a portable file format with no limit on the number and size of data objects
[5] HEC-DSS is a data storage system developed by the U.S. Army Corps of Engineers Hydrologic Data Center

nominal (usually coarse) step size that is subdivided adaptively in integer fractions to respond to faster flows.

4.5.4 Unit Testing

Ateljevich et al. (2011) already incorporated software quality and algorithm testing for the solver, both to test components of their algorithm and to verify formal convergence properties of GTM. The testing was done with uniform and reversing flow, and synthetic (analytical) tidal flow for single channel problems of increasing complexity in terms of nonlinearity and spatial variation of parameters. For the integration within DSM2, we are introducing tests both of the I/O system and of the solver at the scale of a full channel network, which may have multiple boundaries, junctions, and reservoirs. Many of these tests are practical in nature, for instance, to validate that the algorithm works symmetrically at a flow split. The only test we have added of a numerical nature is one that verifies the advection component of the algorithm for a channel with a transition in spatial step (dx) near the source of a contaminant plume. The original form of the GTM solver did not include variable spatial steps and it is essential for the way we implemented flow on the DSM2 network.

4.6 DSM2-GTM Test Cases and Results Comparison to DSM2-Qual

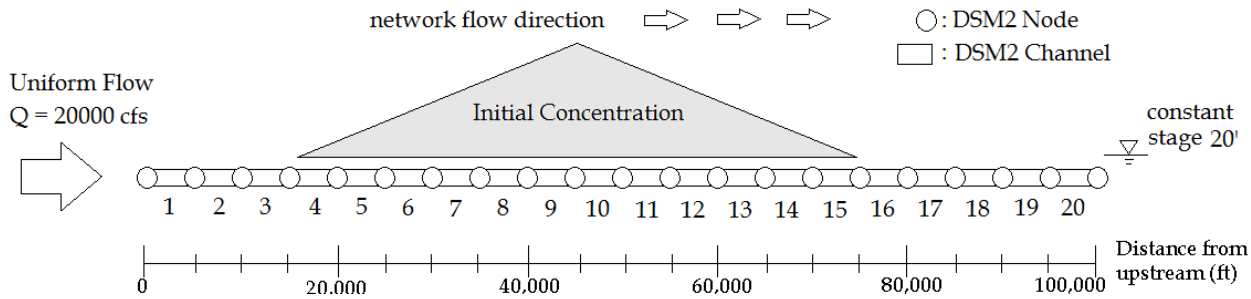
We designed a number of simple test cases to evaluate the behavior of GTM over a network and code correctness. In addition, a comparison with DSM2-Qual was of great interest. The hydrodynamics state for these cases are obtained from a DSM2-Hydro tidefile, appropriately formatted for each of the two transport models.

4.6.1 Advection in Uniform Flow along a Reach

The first case is steady, uniform, frictionless flow on a single reach with intermediate nodes. The mesh in this case is a straight long reach with 21 intermediate nodes from the beginning to the end (Figure 4-5). The spacing for those nodes is 5,000 ft. The upstream boundary condition is a uniform flow of 20,000 cfs and the downstream boundary condition is a fixed water elevation 20 ft. The channel area is 20,000 ft^2 over the full reach, yielding a uniform velocity of 1 ft/s. The hydrodynamics were simulated with DSM2-Hydro and verified to reach a steady state. The output was stored in Hydro tidefile, which contains 15-minute flows, water surface time series data and channel geometries.

A triangle shape of initial concentration with a peak of 500 (nominal units) was specified in the middle of the entire network. One ancillary reason for specifying intermediate nodes (besides our interest in their influence) is that DSM2-Qual only allows users to specify constant initial conditions for each channel – there is no control at the parcel level. This means that when we specify an initial condition, it is only correct up to a step-wise representation – a significant impediment to verification work.

Figure 4-5 Test Case for a Single Reach with Intermediate Nodes with Upstream Uniform Flow and Given Initial Concentration in the Middle of Reach



The result from DSM2-Qual is shown in Figure 4-6. The abrupt transitions come from the coarse assignment of initial concentration. Otherwise, the model exhibits the diffusion-free behavior expected of a Lagrangian model in simple flow – the plume keeps its amplitude and shape as it moves down the channel. The result from DSM2-GTM is shown in Figure 4-7 with dx=625 ft, and Figure 4-8 with the number of cells doubled so dx=312.5 ft. There is about a 4% peak reduction when dx=625 ft and the shape is preserved nearly perfectly when dx=312.5 ft. The time steps for the cases of dx=625 ft and dx=312.5 ft are 450 seconds and 225 seconds, respectively, and that makes CFL number 0.72.

Figure 4-6 Results of DSM2-Qual for Advection in Uniform Flow along a Single Reach with Given Initial Concentration in the Middle of Reach

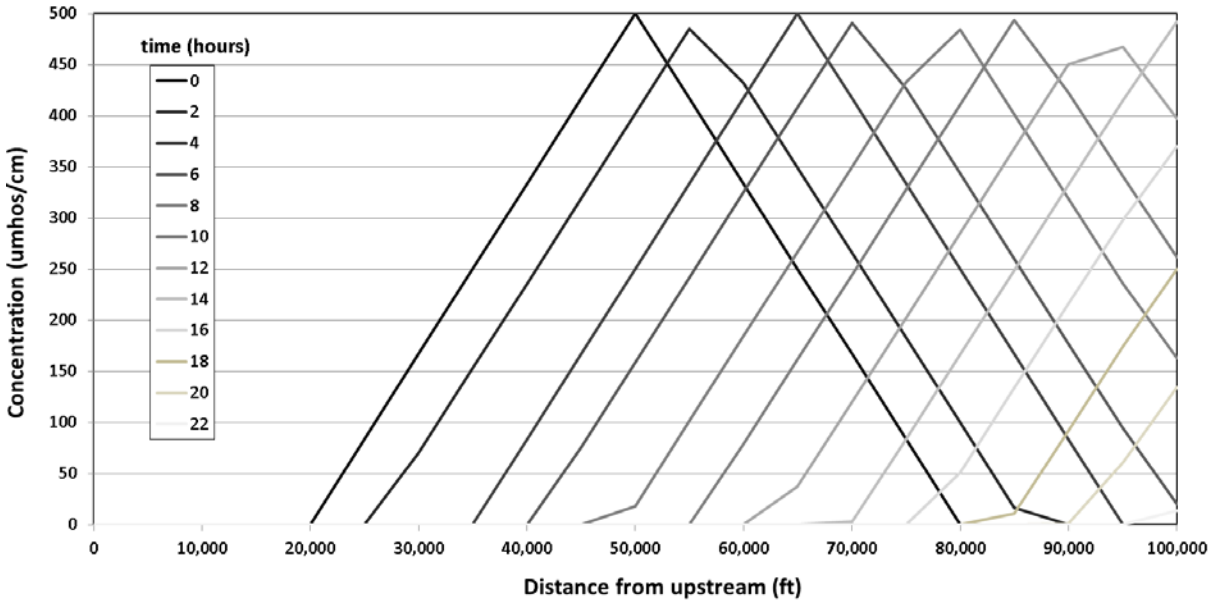
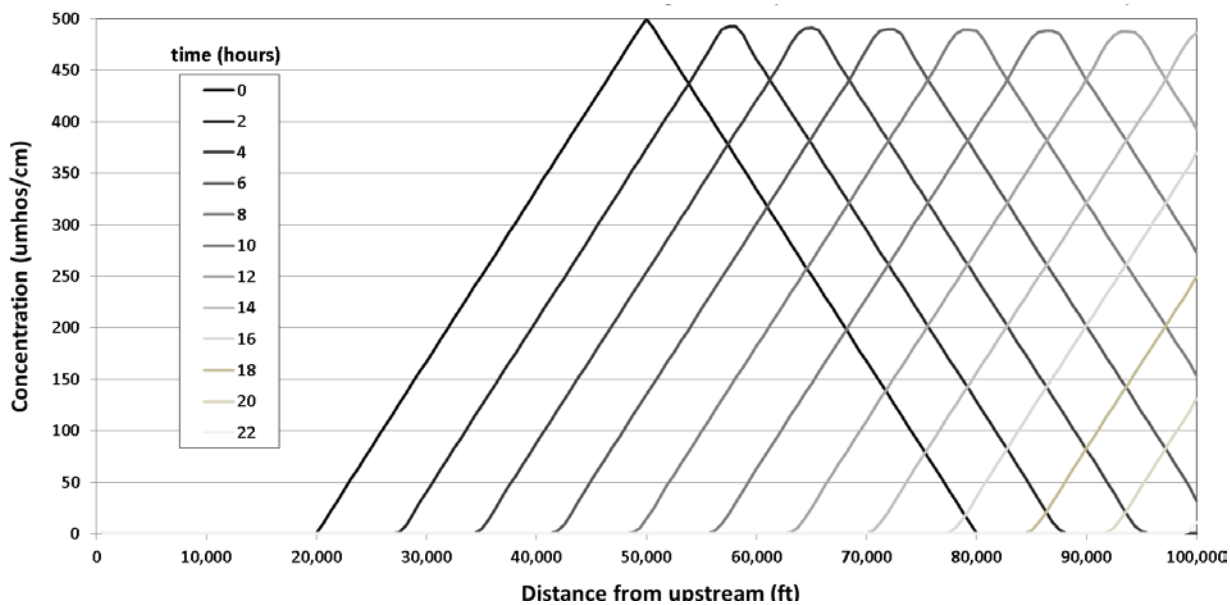
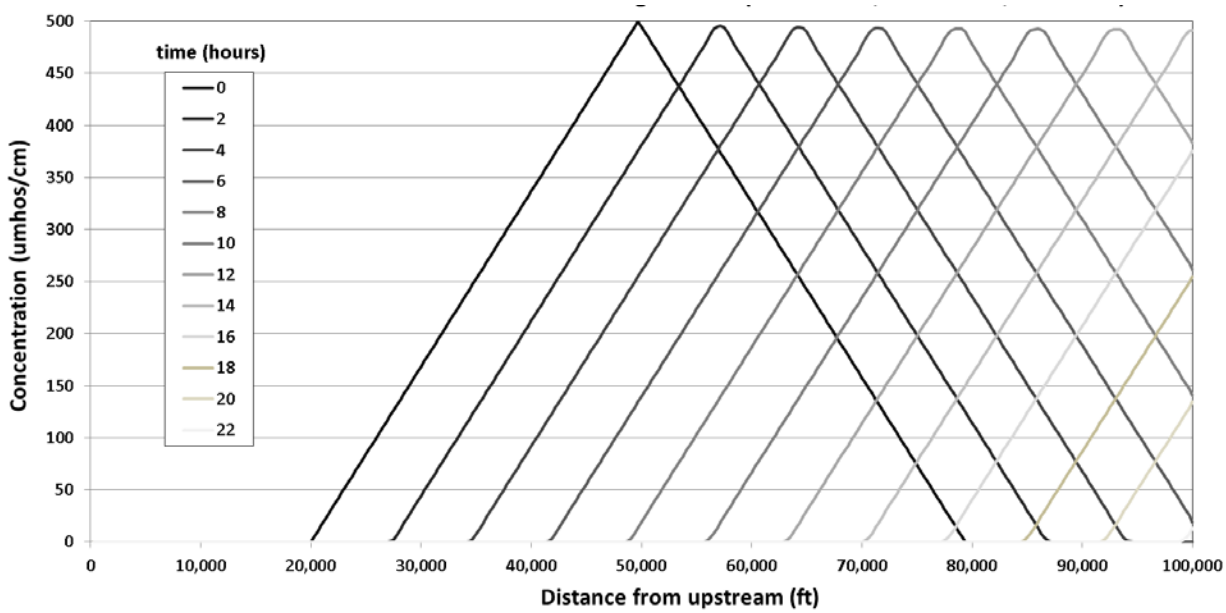


Figure 4-7 Results of DSM2-GTM for Advection in Uniform Flow along a Single Reach with Given Initial Concentration in the Middle of Reach (dx=625 ft)



Note: dx=625 ft., dt=450 sec., CFL=0.72

Figure 4-8 Results of DSM2-GTM for Advection in Uniform Flow along a Single Reach with Given Initial Concentration in the Middle of Reach (dx=312.5 ft)

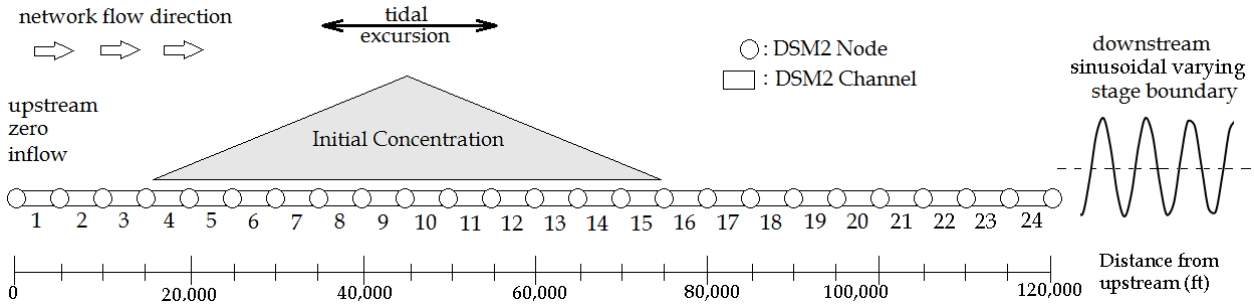


Note: dx=312.5 ft., de=225 sec., CFL=0.72

4.6.2 Advection in Oscillating Flow along a Reach

Our second test investigates the response to a sloshing tidal-like flow in the same channel system as the previous test. We assign zero inflow from upstream and 12-hour sinusoidal oscillation as the downstream stage boundary (Figure 4-9). The hydrodynamics is simulated with DSM2-Hydro until a periodic steady state is observed and the output is stored in Hydro tidefile at a 15-minutes time interval for input to DSM2-Qual and DSM2-GTM. The initial condition is as before but located slightly farther away from the downstream boundary.

Figure 4-9 Test Case for Advection in Oscillating Flow along a Reach with Given Initial Condition



The tidal excursion in this problem is approximately 20,000 feet. Solutions to closed basin problems are usually standing waves with uniform phase over the whole channel, so that after each 12-hour semidiurnal cycle, we expect the plume will return to its initial location. The result from DSM2-Qual is shown in Figure 4-10. After 12 days, the plume still centers on initial location but the peak is reduced by around 9%, which is still a remarkable achievement in this tough test. After one year (Figure 4-11), the amplitude of the plume is deteriorated to half and the location is shifted quite a bit.

The result from DSM2-GTM using the same tidal forcing is shown in Figure 4-12 and Figure 4-13. The peak of the plume reduces around 6% after 12 days of simulation. After one year of simulation, the amplitude remains at 75% value with no significant spatial shift and a slowdown in numerical diffusion.

Figure 4-10 Results of DSM2-Qual for Advection in Oscillating Flow along a Reach after 12 Days of Simulation

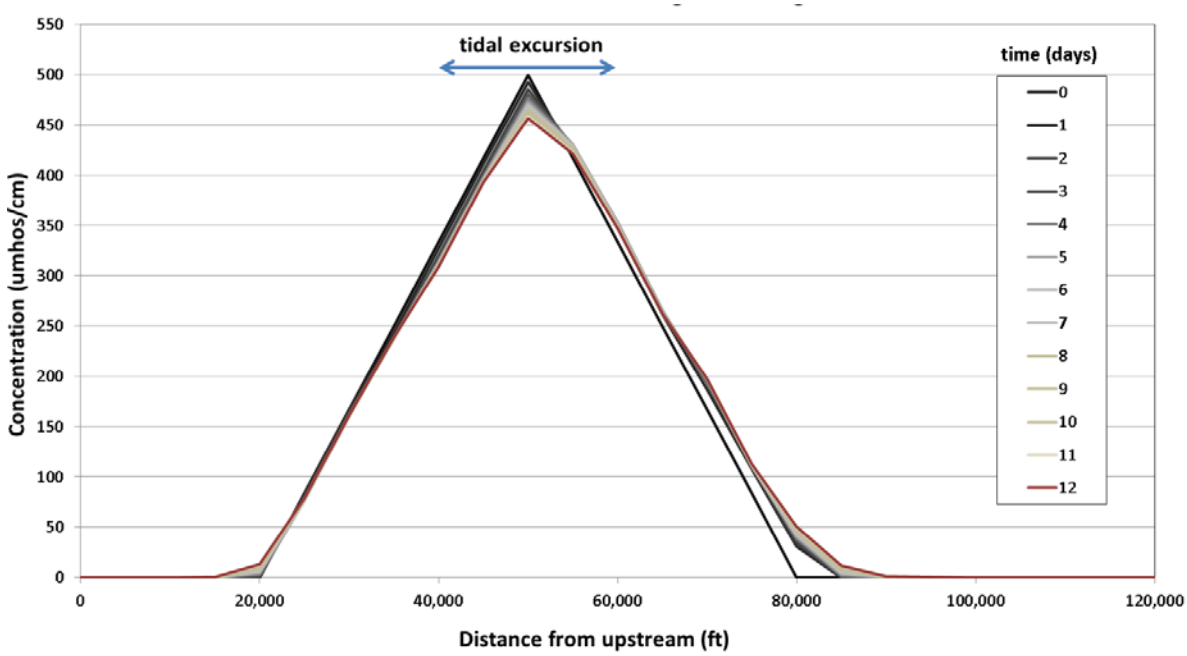


Figure 4-11 Results of DSM2-Qual for Advection in Oscillating Flow along a Reach after One Year of Simulation

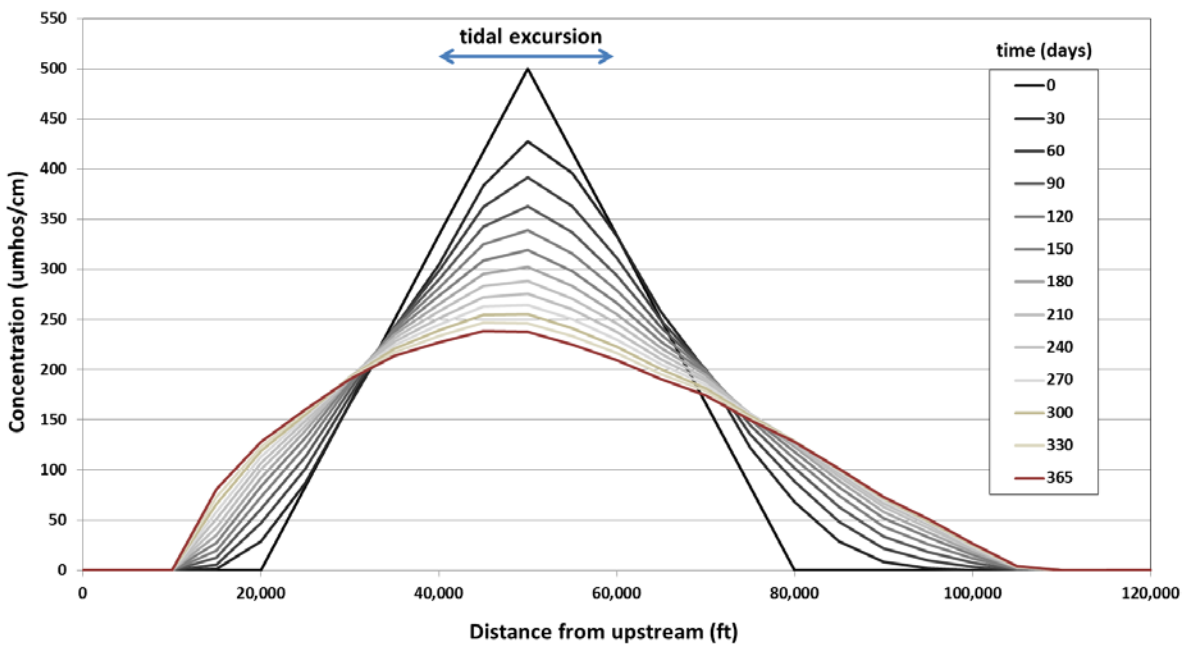
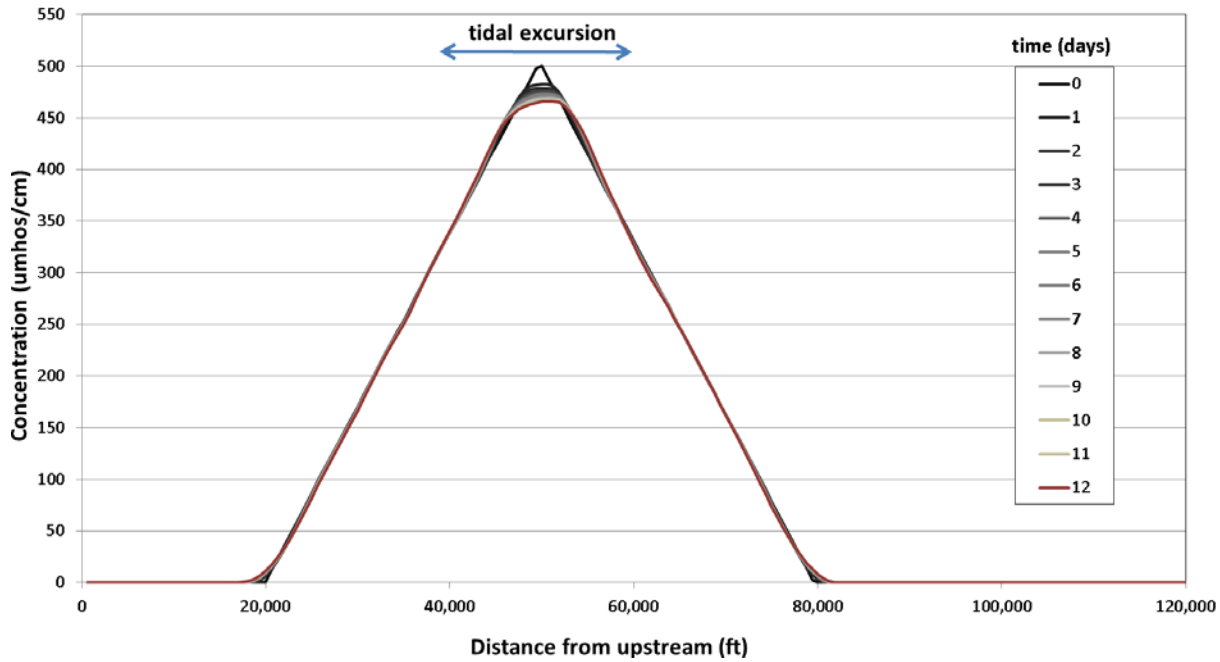
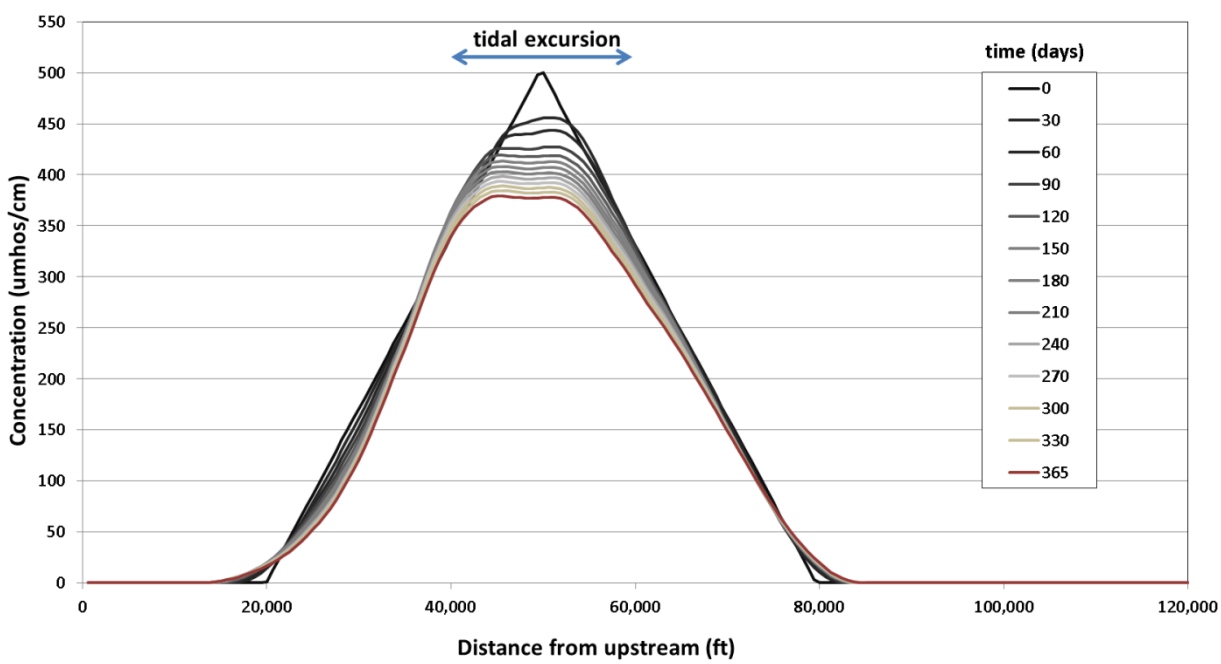


Figure 4-12 Results of DSM2-GTM for Advection in Oscillating Flow along a Reach after 12 Days of Simulation



Note: dx=625 ft., dt=180 sec., CFL<0.9

Figure 4-13 Results of DSM2-GTM for Advection in Oscillating Flow along a Reach after One Year of Simulation



Note: dx=625 ft., dt=180 sec., CFL<0.9

Figure 4-14 Results of DSM2-Qual for Advection in Uniform Flow along a Reach with Given Concentration Boundary Condition

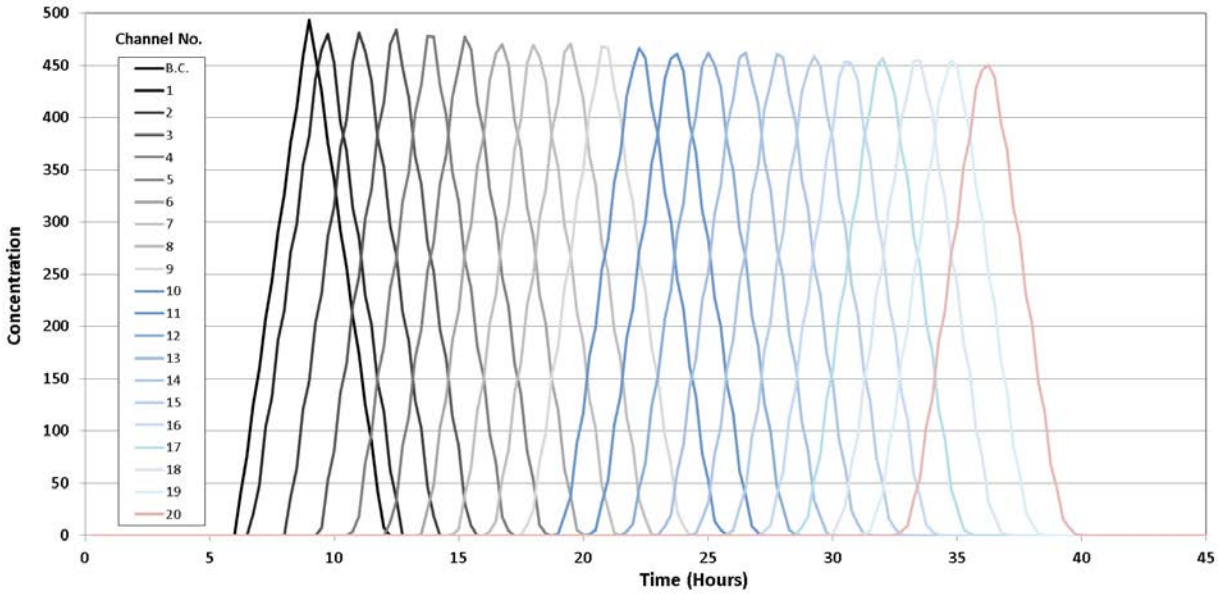
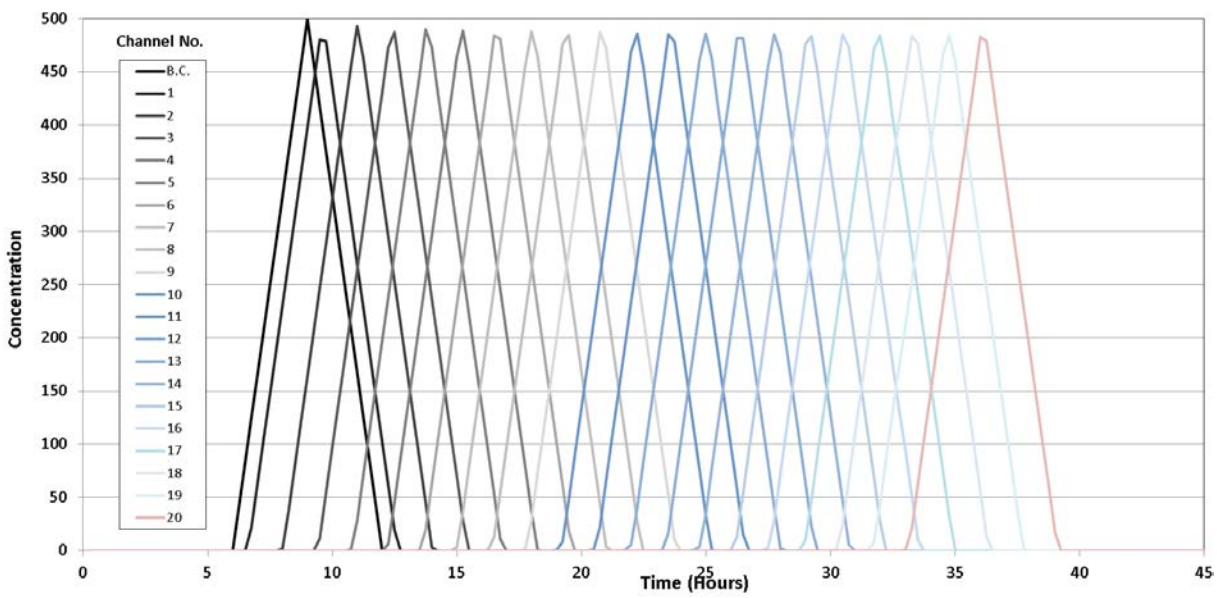


Figure 4-15 Results of DSM2-GTM for Advection in Uniform Flow along a Reach with Given Concentration Boundary Condition



Note: dx=312.5 ft., dt=5 min., CFL=0.96

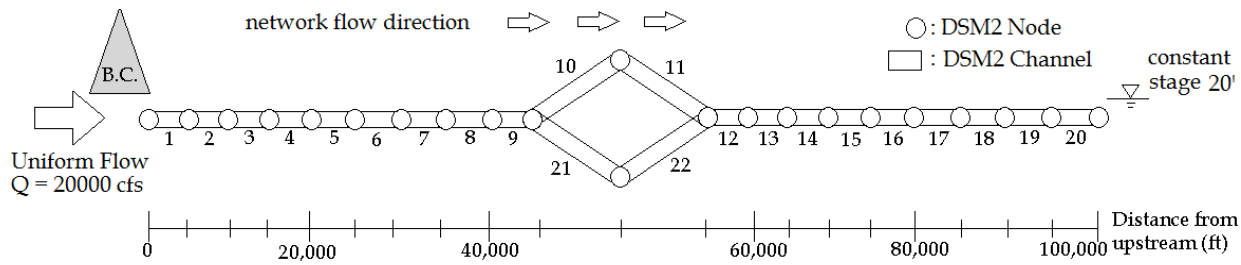
4.6.3 Advection in Uniform Flow along a Reach with Junctions

In the next test, we compare flow in a single channel to an equivalent problem around a flow split involving several junctions. For the single channel base case, the network is the same as we have used

before (Figure 4-5). Instead of using an initial concentration, we assign zero initial concentration and a time varying boundary condition that produces the same triangular shaped plume with a peak of 500 (nominal units) entering at the upstream boundary. The concentration at each channel over time is shown in Figure 4-14 and Figure 4-15. This gives us a baseline to see the impacts that are introduced by junctions.

Next, we insert a diamond shaped flow divide into the middle of the long channel, creating two divergent and two convergent junctions (Figure 4-16). The problem is otherwise the same as before, with the plume traversing from left to right.

Figure 4-16 Test Case Design for Junctions with Upstream Uniform Flow and Concentration Boundary Condition



The results from DSM2-Qual and DSM2-GTM are shown in Figure 4-17 and Figure 4-18, respectively. Both of them exhibit good symmetry of transport around the flow divide, with similar concentration for Channels 10 and 21 and for Channels 11 and 22. The large number of nodes introduces visible numerical diffusion into both models, but in different ways. In DSM2-Qual, the attenuation is gradual, reaching 10% by the time flow exits the flow split. The reason for this is that all nodes and junctions are detrimental in Qual, so the flow split is not really a novel feature in terms of error. In DSM2-GTM, we have eliminated a lot of the numerical error at intermediate nodes, so extra attenuation is attributable specifically to the flow splits. The peak drops by 8% which is 3% more than the case without junctions.

Figure 4-17 Results of DSM2-Qual for Advection in Uniform Flow along a Reach with Junctions

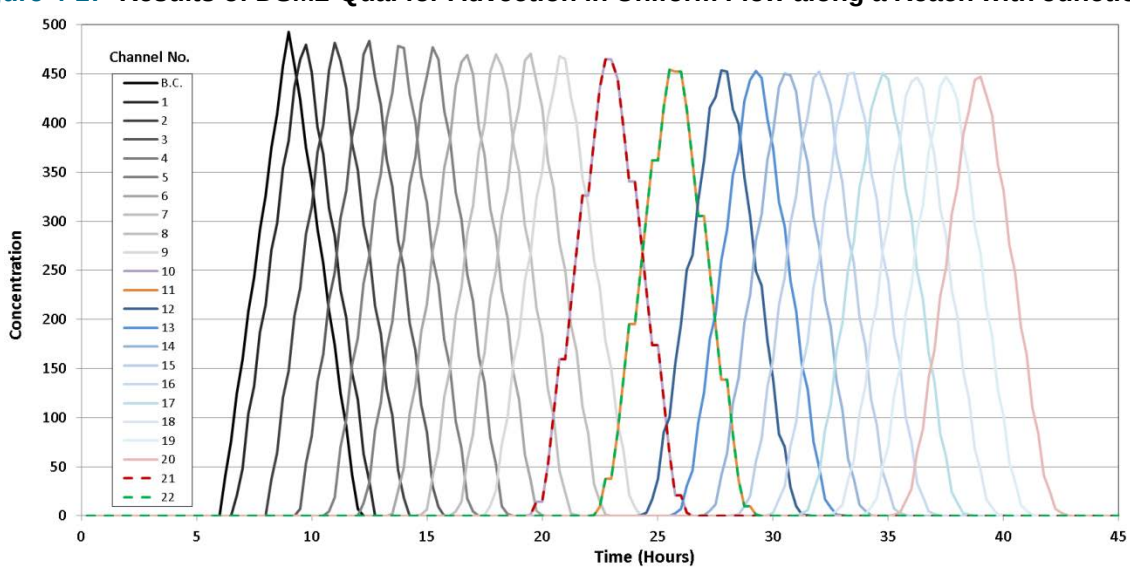
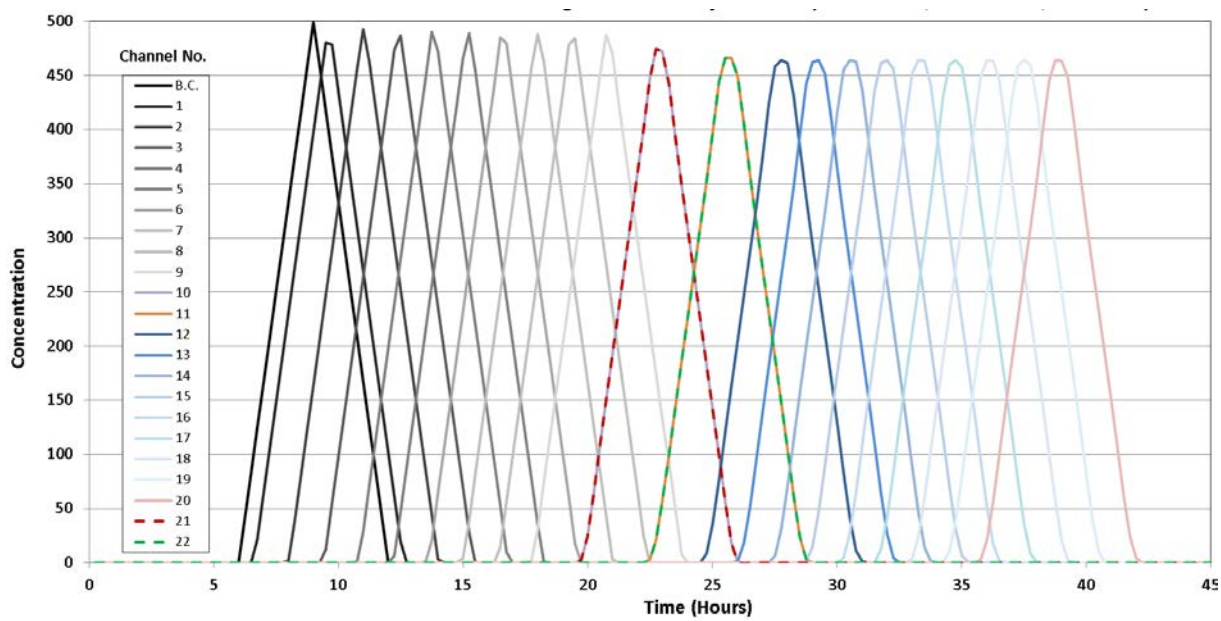


Figure 4-18 Results of DSM2-GTM for Advection in Uniform Flow along a Reach with Junctions



4.6.4 Diffusion and Reaction Tests

The diffusion and reaction components were developed collaboratively with UC Davis and unit tested by Ateljevich et al. (2011) on single channel cases including interaction with advection with time-varying boundaries (which tend to be difficult problems to solve accurately with operator splitting). We have implemented diffusion in the context of DSM2 and network flow, but verified only qualitatively that diffusion works as intended. We are still actively working on compatibility conditions at nodes.

The reaction component solver has also been tested in prior work on complex cases, including stiff reactions and interaction with advection and boundaries. The solver has been connected to GTM, but again like diffusion it has not been extensively tested in the context of a channel network.

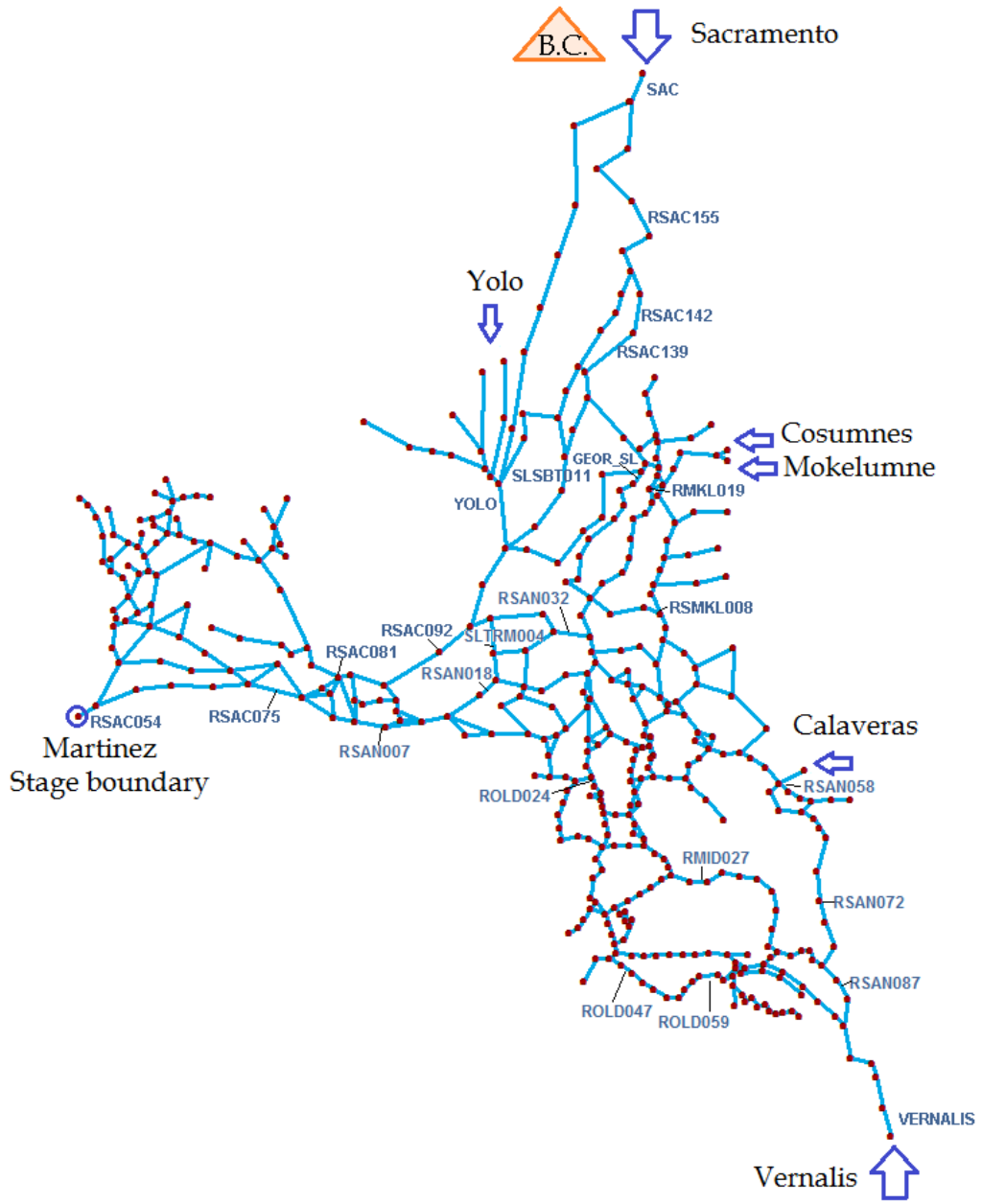
4.7 DSM2-GTM Advection Test for a Delta-like Network and Comparison to DSM2-Qual

As a larger scale system test including network geometry, input time series and the Eulerian scheme over the network, we use a simplified synthetic hydrodynamic forcing over the entire Delta.

The DSM2 grid for the Sacramento-San Joaquin Delta is shown in Figure 4-19. The red dots represent DSM2 nodes; blue lines in between are DSM2 channels. Observed 15 minutes historical inflows from February 1, 1998, to March 30, 1998, are imposed at Sacramento, Yolo, Cosumnes, Mokelumne, Calaveras, and Vernalis. Historical water levels are imposed at Martinez. A triangle-shaped boundary concentration with a peak of 500 umhos/cm and 6-hour span is specified at Sacramento and zero initial concentration is specified across the entire grid. Hence, the problem has tidal character as far as the flow field but the tracer being modeled is not similar to salt in that it propagates from the upstream boundary.

The results from DSM2-Qual and DSM2-GTM are shown in Figure 4-20 and Figure 4-12, respectively. In both cases the plume is considerably diluted as it makes its way downstream, a phenomenon that is certainly influenced both by tidal mixing and numerical diffusion. Travel time and the modes of the plumes coincide reasonably well at many stations, with disagreement growing with travel time. Overall, the GTM result is the less attenuated one at most sites, but this generalization is not universal.

Figure 4-19 Test Case for Delta-like Grid with Observed Inflows and Tidal Stage at Martinez



name	location	name	location
SAC	Sacrmaneto River upstream	SLTRM004	San Joaquin River at Three Mile Slough
RSAC155	Sacramento River at Freeport	RSAC092	Emmaton
RSAC142	Sacramento River at Hood	RSAC081	Collinsville
RSAC139	Sacramento River at Green's Landing	RSAC075	Mallard Island
SLSBT011	Steamboat Slough	RSAC054	Martinez
GEORG_SL	Georgiana Slough	RSAN032	San Andreas Landing
RMKL019	North Fork Mokelumne River	RSAN018	Jersey Point
YOLO	Yolo Bypass	RSAN007	San Joaquin River at Antioch
RSMKL008	South Fork Mokelumne at Staten Island		

Figure 4-20 Results of DSM2-Qual for Entire Delta with Observed Inflows and Stage at Martinez

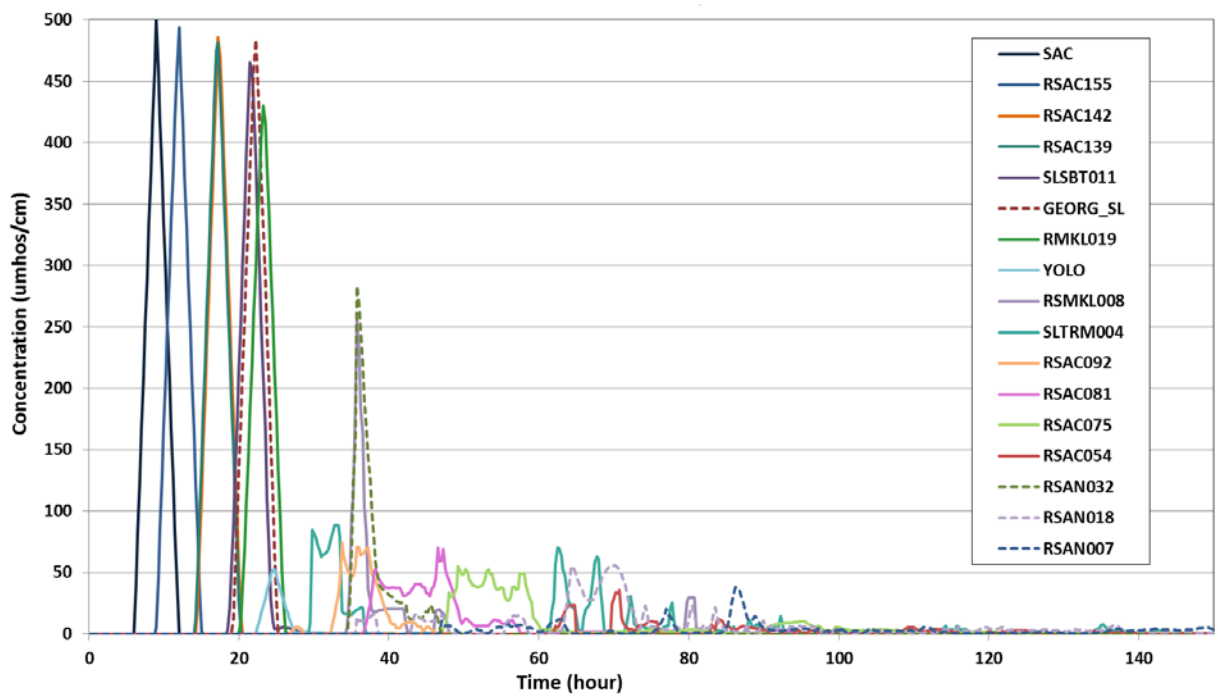
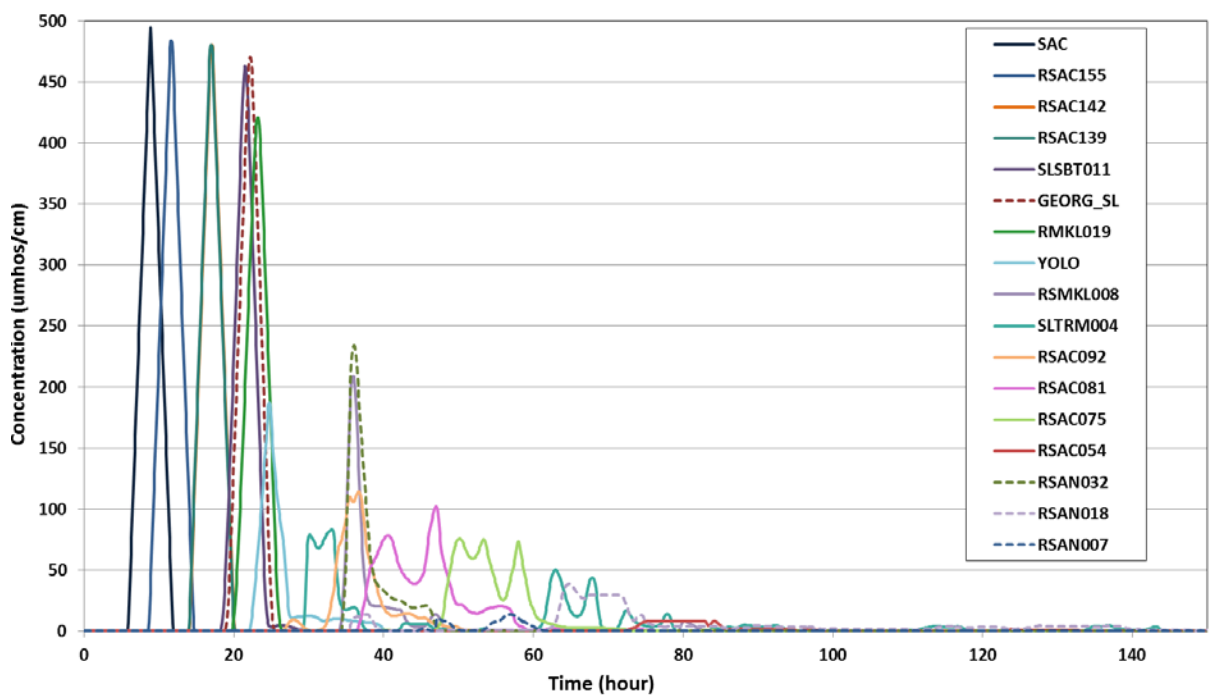


Figure 4-21 Results of DSM2-GTM for Entire Delta with Observed Inflows and Stage at Martinez



4.8 Summary

1. DSM2-GTM accomplishments thus far include integration of GTM into DSM2, accommodating special features (boundaries, junctions, etc.), and successful simulation of advection over a full Delta using a full cycle of DSM2-Hydro and DSM2-GTM.
2. Test results indicate GTM simulates transport well for either uniform or tidal flow. Eulerian spatial referencing offers convenience and extensibility.
3. The computational code in GTM has been verified rigorously in a repeatable framework.
4. Tests indicate DSM2-Qual exhibits significant numerical dispersion when a plume travels through a reach with many intermediate nodes, yet an artificial tradeoff exists whereby such intermediate nodes are required for flow field accuracy. DSM2-GTM is less impacted by such nodes.
5. We have implemented diffusion and generic reactions in GTM. These processes have been thoroughly tested in prior work, including some thorny operator splitting issues associated with boundaries.
6. Preliminary results for a Delta-scale problem without reservoirs indicate GTM is comparable to DSM2-Qual in performance and gives reasonable results.
7. Simultaneous, ongoing work is being conducted on coupled mercury and sediment interaction.

4.9 Acknowledgements

We want to acknowledge Fabian Bombardelli and Kaveh Zamani from UC Davis for their roles in the initial development of the GTM solver and testing system. We thank Ralph Finch and Lianwu Liu for their helpful descriptions of aspects of DSM2-Hydro and DSM2-Qual.

4.10 References

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