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14. ABSTRACT

Flows through networks of solid objects are ubiquitous in natural and engineered systems. Some common examples include flows through (i) vegetated areas in coastal wetlands, (ii) urban environments, (iii) biofilm reactors and (iv) natural and manufactured porous media. These all share common features and can range from slow laminar flows to fast highly turbulent flows. Understanding mean and turbulent flow structure and the detailed role of the presence of solids in the flow path in terms of flow resistance and streamline structure can be

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Report Title

Final Report: Numerical Upscaling of Flow and Transport Through Obstructed Regions over a Broad Range of Reynolds Numbers (3.4.1.2)

ABSTRACT

Flows through networks of solid objects are ubiquitous in natural and engineered systems. Some common examples include flows through (i) vegetated areas in coastal wetlands, (ii) urban environments, (iii) biofilm reactors and (iv) natural and manufactured porous media. These all share common features and can range from slow laminar flows to fast highly turbulent flows. Understanding mean and turbulent flow structure and the detailed role of the presence of solids in the flow path in terms of flow resistance and streamline structure can be critical if one wants to understand transport processes within these flows. The primary goal of this project is to advance computational methods and predictive capabilities of flow and transport over a diverse range of obstructed flow conditions. To this end we are developing a suite of numerical tools for modeling flow and transport at the micro-scale, which resolves fluid and solid to produce upscaled models and parameterizations for flow and transport at the macroscale, where the
influence of the solids is effectively modeled, but not resolved. These models will reproduce complex anomalous behaviors associated with flow and transport inherent to these flows.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received		Paper
08/10/2015	8.00	Steven A. Mattis, Clint N. Dawson, Christopher E. Kees, Matthew W. Farthing. An immersed structure approach for fluid-vegetation interaction, Advances in Water Resources, (06 2015): 0. doi: 10.1016/j.advwatres.2015.02.014
08/10/2015	9.00	Nicole Sund, Diogo Bolster, Steven Mattis, Clint Dawson. Pre-asymptotic Transport Upscaling in Inertial and Unsteady Flows Through Porous Media, Transport in Porous Media, (06 2015): 0. doi: 10.1007/s11242-015-0526-5
08/10/2015	10.00	T. Aquino, A. Paster, D. Bolster. Incomplete mixing and reactions in laminar shear flow, Physical Review E, (07 2015): 0. doi: 10.1103/PhysRevE.92.012922
08/27/2014	6.00	Amir Paster, Diogo Bolster, David Benson. Connecting the Dots: Semi-Analytical and Random2 Walk Numerical Solutions of the Diffusion-Reaction3 Equation with Stochastic Initial Conditions , Journal of Computational Physics, (01 2014): 91. doi:
08/27/2014	7.00	Diogo Bolster, Yves Meheust, Tanguy Le Borne, Jeremy Bouquain, Phillipe Davy. Modeling presasymptotic transport in flows with significant intertial and trapping effects--The importance of velocity correlations and a spatial Markov model, Advances in Water Resources, (05 2014): 89. doi:

TOTAL: **5**

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received Paper

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

N. Sund and D. Bolster, The Impact of Early Time Behavior of Solute Transport at High Peclet Number on Upscaled Markovian Transport Models, AGU Fall Meeting, 2015.

D. Bolster, The Spatial Markov Model for Preasymptotic and Anomalous Transport-To correlate or not to correlate?, The MADE Challenge for Groundwater Transport in Highly Heterogeneous Aquifers: Insights from 30 Years of Modeling and Characterization at the Field Scale and Promising Future Directions, 2015.

N. Sund, The Impact of Early Time Behavior of Solute Transport at High Peclet Numbers on Upscaled Markovian Transport Models, The MADE Challenge for Groundwater Transport in Highly Heterogeneous Aquifers: Insights from 30 Years of Modeling and Characterization at the Field Scale and Promising Future Directions, 2015.

Number of Presentations: 3.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received		Paper
08/27/2014	1.00	Diogo Bolster, Yves Meheust, Tanguy Le Borgne, Jeremy Bouquain, Phillipe Davy. Modeling preasymptotic transport in flows with significant inertial andtrapping effects – The importance of velocity correlations and a spatialMarkov model, Advances in Water Resources (12 2013)
08/27/2014	2.00	Amir Paster, Diogo Bolster, David A. Benson. Connecting the dots: Semi-analytical and random walk numerical solutions of the diffusion-reaction equation with stochastic initial conditions, Journal of Computational Physics (04 2013)
08/27/2014	5.00	Steve Mattis, Clint Dawson, Christopher E. Kees, Matthew W. Farthing. An Immersed Structure Approach for Fluid Vegetation Interaction, Advances in Water Resources (08 2014)
09/21/2016	11.00	Nicole L. Sund, Diogo Bolster, Clint Dawson. Upscaling transport of a reactive solute through a periodically convergin-divering channel at pre-asymptotic times, Journal of Contaminant Hydrology (05 2015)
TOTAL:		**4**

Number of Manuscripts:

Books

Received	Book

TOTAL:

Received	Book Chapter

TOTAL:

Patents Submitted

Patents Awarded

Awards

Clint Dawson was elected a fellow of the Society for Industrial and Applied Mathematics in 2016.

Graduate Students

NAME	PERCENT_SUPPORTED	Discipline
Nicole Sund	0.67	
Maya Wei	0.38	
FTE Equivalent:	**1.05**	
Total Number:	**2**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
Steven Mattis	0.13
FTE Equivalent:	**0.13**
Total Number:	**1**

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Diogo Bolster	0.00	
Clint Dawson	0.00	
FTE Equivalent:	**0.00**	
Total Number:	**2**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period:	0.00
The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:......	0.00
The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:......	0.00
Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):......	0.00
Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:......	0.00
The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense	0.00
The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:......	0.00

Names of Personnel receiving masters degrees

NAME

Total Number:

Names of personnel receiving PHDs

NAME
Nicole Sund
Total Number: **1**

Names of other research staff

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

(4) Statement of Problem

Flows which pass by and flow through solid objects are ubiquitous in natural and engineered systems. Some common examples include (a) flow through vegetated areas in coastal and riverine wetlands [Vymazal, 2011], (b) flow through urban environments [Fernando, 2009 and 2010], (c) flow through biofilm reactors for clean water technology [Martin and Nerenberg, 2012] and (d) flows through natural and manufactured porous media [Bear, 1988]. These flows all share common features and can range from very slow laminar flows to very fast highly turbulent flows. Understanding mean and turbulent flow structure and the detailed role of the presence of solids in the flow path in terms of flow resistance and streamline structure can be critical if one wants to understand transport processes within these flows, which again can be very important for each and every one of the examples.
Solids in the path of the flow tend to have three main influences:

(i) Viscous interaction of the solid with the fluid exerts a net drag resistance on the flow, which dissipates energy and must be overcome for flow to continue. This effect can scale in quite a nonlinear manner that varies depending on low, intermediate or high flow speed conditions [Kundu, 2004].

(ii) The presence of the solids means that one has no-flow and no-slip boundaries within the flow domain. This can result in mean fast preferential flow channels through the solids as well as slow if not immobile/stagnant regions within the flow domain. The solid boundaries also act as a source for turbulent flow structures [Pope, 2000]. This in turn gives rise to a broad range of temporal, spatial and velocity scales in the system, which is known to complicate modeling matters significantly [Klafter et al., 2011] [Klages et al., 2008].

(iii) If the flow is sufficiently strong and the solid sufficiently flexible it may be necessary to account for fluid-solid interactions, which can significantly alter the flow field structure and effective resistance of the solids.

In many practical situations it is not desirable, nor even feasible, to fully resolve the flow field through such environments and it may be preferable to work within an upscaled framework that does not explicitly resolve the presence of the solids in the flow field, but accounts for their presence in an effective manner. This requires an upscaling technique, along the lines of homogenization [Hornung, 1997] or volume averaging [Whittaker, 1998], that is capable of capturing the necessary complexities.

Additionally, if one is interested in upscaling transport it is not always sufficient to upscale flow and then account for transport with some effective Fickian dispersion coefficient as is often done within upscaled flow frameworks. The presence of broad distributions in temporal, spatial and velocity scales is known to give rise to anomalous (non-Fickian) transport in a large number of physical systems [Klages et al., 2008], which Fickian parameterizations have no hope of capturing properly. A variety of anomalous transport modeling frameworks have emerged to deal with these shortcomings including moment methods [Neuman, 1993], projector formalisms [Cushman et al., 1994], continuous time random walks (CTRW) [Berkowitz et al., 2006] [Lawler and Limic, 2010], multi-rate mass transfer models [Haggerty and Gorelick, 1995] [Carrera et al., 1998] and fractional advection dispersion equations [Meerschaert and Sikorski, 2012] [Metzler and Klafter, 2000]. While conceptually distinct, all of these models are rooted in the same principle that modeling transport in systems with broad spatial and temporal distributions requires modeling frameworks that are mathematically nonlocal in space and/or time, a feature that traditional Fickian models do not have.

While each of these models is capable of capturing certain forms of anomalous transport, most of them are still limited, because their derivation relies on some generalized central limit process, whereby random increments in time and space converge to stable distributions [Meerschaert and Scheffler, 2001]. This requires the assumption of identically distributed independent variables (iid). A series of recent papers [LeBorgne et al., 2008] [LeBorgne et al., 2012] [Kang et al., 2011] [Magdziarz et al., 2012] [Tejedor et al., 2010] have demonstrated that for many systems of interest that the iid assumption is not valid. In fact there can be strong correlation between successive temporal and spatial jumps. These papers have demonstrated that one can resolve this concern with the framework of the correlated CTRW (cCTRW). These studies were predominantly for low Reynolds number or Darcy type flow.

The primary goal of the work here is to advance computational methods and predictive capabilities of flow and transport over a diverse range of obstructed flow conditions. To this end we are developing a suite of numerical tools for modeling flow and transport at the micro-scale, which resolves fluid and solid to produce upscaled models and parameterizations for flow and transport at the macroscale where the influence of the solids is effectively modeled, but not resolved; these models will reproduce complex anomalous behaviors associated with flow and transport inherent to these flows. They will be able to model a broad range of conditions, from low Reynolds number laminar flows to high Reynolds number turbulent flows. Broadly speaking the project can be broken into three components

(i) Upscaling flow from micro to macro-scale: Flow at the micro-scale is studied via Large Eddy Simulation (LES) to capture turbulent flow effects in a reliable manner.

(ii) Accounting for fluid-solid interactions at the micro-scale: Fluid-solid interaction is modeled using immersed boundary (IB) and Arbitrary Lagrangian-Eulerian (ALE) methods.

(iii) Upscaling transport from micro to macro-scale: At the micro-scale transport is simulated using a particle based Brownian motion random walk method (RW). This is upscaled to a correlated Continuous Time Random Walk.

Combining (i) and (ii) the model produces effective drag coefficients that can be incorporated into a macro-scale flow model of choice to reliably predict flow speeds; (iii) provides a macroscale transport model capable of capturing anomalous transport over broad temporal scales and not just at asymptotic times as for conventional models.

(5) Summary of results (Figures are attached.)

(I) Modeling and Upscaling Transport

In years 1 & 2 for modeling and upscaling of transport, we considered three important geometries: (i) flow through a wavy channel, which has historically been an idealized model of flow through a porous system, (ii) flow through a two dimensional porous medium and (iii) a simple d-dimensional hyper-cube domain where solutes can diffuse and also react, a process not included in models (i) and (ii), but of fundamental importance in many environmental flows.

Each of these geometries was chosen to address a different issue, (i) to study the importance of including correlation effects in upscaled particle tracking models, (ii) to explore the effect of unsteady and turbulent flow on upscaling of transport and (iii) how best to incorporate chemical reaction processes in diffusive systems.

In our last year we focused on two main efforts

a. In years 1 and 2 we showed that the Spatial Markov model can outperform many classical, as well as so called non-classical, upscaling procedures, particularly in capturing preasymptotic behaviors. However, as with any upscaled model it must have its limits, particularly a smallest scale at which it can be applied. Knowledge of this is critical to accurate implementation of the model. We set out to answer this specific question: what is the smallest time/spatial scale at which the Spatial Markov model can reliably be applied without violating any implicit and explicit assumptions?

b. While we have shown that the Spatial Markov model can model simple linear reactions, nonlinear mixing driving reactions have still not been implemented adequately. In approach (iii) above we have successfully shown that particle tracking methods can be used to model mixing limited reactive systems at small scales, but not yet in a fully upscaled framework. Thus our goal here was to combine efforts (ii) and (iii) to upscale mixing driven bimolecular reactions using the Spatial Markov framework. Specifically we set out to extend the Spatial Markov model in such a way that it can faithfully upscale mixing processes, an essential first ingredient to any mixing driven reactive upscaling procedure.

Key outcomes from these distinct efforts are

Outcomes for Goal (a)

Classical Taylor dispersion models, while incredibly powerful can typically only be applied after a characteristic Taylor diffusion time L^2/D has passed (L is a characteristic length of the system under consideration and D is the diffusion coefficient). Correspondingly this means that the model can be applied after some length scale vL^2/D where v is a characteristic velocity of the system. In many cases this can be prohibitively large to make predictions of practical interest. We know that the Spatial Markov model works for much smaller scales, but what are they?

We chose to begin by focusing on some classical flows (Poiseuille and Couette flow), where Taylor and classical dispersion theories are completely characterized and understood so as to enable a clear comparison. We then rigorously calculated the smallest scales over which the Spatial Markov model can be applied for these flows. Specifically, we showed that the smallest timescale, where the assumptions of the Spatial Markov model hold, is given by the geometric average of two other critical time scales, the onset of correlation time scale and the diffusion time scale. The onset of correlation time scale is the characteristic time it takes for advection effects to dominate over microscale diffusion (~D/v^2). Typically for advection dominated systems this time scale is order of magnitudes smaller than the diffusion time scale and given that taking the geometric mean favors lower values, this smaller scale dominates. For systems where diffusion is isotropic this results in a time scale L/v, which is the characteristic advection time. Thus, the Spatial Markov model can be reliably applied for times larger than the characteristic advection time. The ratio of the advection time scale to the diffusion time scale is the Peclet number. For many systems of practical interest the Peclet number is O(100-1000) or greater meaning that the Spatial Markov model can be reliably be applied at scales 100-1000 times smaller than classical Taylor dispersion models.

This theoretical estimate was then validated by applying the model using scales on the range ten times smaller to ten times bigger than our predicted scale. In all instances when the Spatial Markov model was applied at scales smaller than that we predicted it failed to match observation from microscale simulations. On the other hand, for all cases where it was applied at a scale equal to or larger than that which we predicted, the model worked excellently. Figure 1 below demonstrates an example where the Spatial Markov model was used to try and predict large scale spreading of a plume. The models applied at scales below our theoretical prediction, underpredict this spreading, while those applied above it appear to work very well.

Goal (b)

We successfully developed a first prototype of a model that we term Lagrangian Transport Eulerian Reaction Spatial Markov model, or the LATERS Markov model. It is a hybrid approach that takes advantage of the strengths of both the Lagrangian and Eulerian modeling approaches to both accurately account for subscale mixing and ultimately efficiently upscale reactive transport.

The model uses the Spatial Markov model, which we developed in detail in years 1 and 2, to predict large-scale transport. This provides us with a macroscopic estimate of mean concentration. However, in order to accurately predict chemical reactions, knowledge of subscale fluctuations is required. This necessitates a closure model, but as we have shown in years 1 and 2, other than for very simple setups, such closure models are difficult to obtain analytically. We thus rely on a numerical approach that downscales the mean concentration field obtained with the Spatial Markov model – where we use the Eulerian small-scale velocity field to do so. Specifically we assume that the downscaling can be done by mapping a particle's macroscopic location to a location in the microscale by combining information on streamlines and local velocity fluxes at the microscale (i.e. particles spend less time in fast regions and so have a lower probability of being there).

So far LATERS has been successfully applied to model mixing in a flow through the geometry depicted in Figure 2. An example showing the good agreement between the upscaled model prediction and measurements from a high-resolution numerical benchmark is shown in Figure 3. The figure shows concentration variance, a well-known measure of mixing, against distance at a specific snapshot in time. Other than at the inlet and right at the leading edge, the match between model and benchmark is excellent, again suggesting the strength of the Spatial Markov modeling framework. The inlet and front conditions are boundary artifacts that we know how to fix and are doing so currently. While promising, this figure is also slightly misleading, as the presented metric is a global measure of mixing. Figure 4 shows more local measures of mixing. In the top are the results from the benchmark that our upscaled model is meant to reproduce, while on the bottom are the predictions with the LATERS model. Clearly, while the macroscopic mixing is well captured, small scale mixing is not as it predicts hotspots not apparent in the benchmark; this may pose a problem when it comes to accurately modeling chemical reactions within an upscaled framework. Nonetheless results are promising and suggest that the LATERS model will with some further effort provide an excellent framework for upscaling mixing and reaction nonlinear processes. We continue to work on refining this model.

(II) Modeling and upscaling flow

We have developed several methods for modeling incompressible flow through obstructed domains. These methods were implemented using the Proteus Computational Methods and Simulation Toolkit, a finite element package developed by Christopher Kees and Matthew Farthing at the USACE Engineer Research and Development Center Coastal and Hydraulics Laboratory. Drs. Kees and Farthing were also involved in the development of these methods.

The most common method of quantifying the upscaled drag due to a packing of obstructions is through bulk drag. The bulk drag is the drag due to the bulk effect of several obstructions that are too small to be directly resolved in a model. For a densely-packed obstructed channel, the amount of drag depends on many factors, including free-surface effects, turbulence, and complex velocity profiles. Also, the presence of nearby vegetative obstacles affects the drag. As described by [Nepf, 1999], for a vegetated channel, drag force per unit fluid volume is defined by the bulk drag equation. The drag force depends on a non-dimensional bulk drag coefficient, the fluid density, the mean velocity, the projected plant area per unit volume, and the so-called vegetation population density. Whereas for a single obstacle element, the drag coefficient is only a function of obstacle shape and Reynolds number, the bulk drag coefficient is also a function of population density, the density of the backing of obstacles.

We are have designed flow methods for obstructed flow that handle large-scale and complicated 3D domains containing rigid and/or flexible obstructions over which bulk drag characteristics can be quantified. We model flow-obstruction interaction in two main ways:

(i) Single-mesh approach

One approach involves incorporating obstacle-scale resolution of the flow domain on a single mesh with the direct imposition of a no-slip boundary condition on obstacles. Such a method requires extremely expensive and complicated meshing algorithms and is prone to numerical instability. To allow for flexible obstructions a moving mesh must be used, which introduces a level of computational complexity that is extremely difficult to handle, even at the small scale. For these reasons, we only use this approach for relatively simple geometries. We studied beds of rigid obstructions with this approach in [Mattis et al., 2012]. This method was also implemented for the one-way coupling of flow and transport to study the upscaling of transport in years 1 and 2 as described above.

(ii) Immersed boundary approach

The immersed structure approach that we have developed works for larger-scale, more complicated obstructed domains. Rather than fully resolving the obstacles on one fluid finite element mesh and imposing a no-slip condition to induce the drag, an immersed boundary approach is used. Separate fluid and structure meshes are used in their natural Eulerian and Lagrangian frameworks, respectively. The obstacles are modeled as long, thin inextensible flexible cantilever beams. Classical

Euler-Bernoulli beam theory is used in the beam model. The numerical method used is a fully nonlinear finite element method that uses Newton's method. We found that combined with incremental loading that the method is incredibly robust for finding stable equilibria for beam systems under loads that cause large deflections. The standard drag equation is used to calculate the drag force on the fluid by the immersed structures. As is the standard with immersed boundary methods, integral transforms involving approximations to the Dirac delta are used to map between the fluid and structure domains. In a method that conserves momentum, the momentum loss due to this drag force enters the fluid model as a local sink term. The fluid flow is modeled with the Navier-Stokes Equations with the dynamic Smagorinsky large eddy simulation (LES) turbulence model. This model has been shown to work well for laminar, turbulent, and transitional flow. This is implemented within the Proteus finite element toolkit. The method is described in detail in [Mattis et al., 2015]. The development of the methods, numerical software, and implementation was performed in years 1 and 2.

Our fluid-structure interaction models have been used to study several complex flow scenarios. One is channel flow containing many rigid or flexible obstacles using the the immersed boundary approach. The results from computational experiments were validated against well-respected experimental data [Nepf, 1999] as shown in [Mattis et al., 2015] . We captured trends that were noticed from experimental results. The tendency of bulk drag to decrease with increased population density is a very important result and is shown in Figure 5. While this is observed through experiments, most computational models ignore this trend for simplicity. Our method is able to capture the effect. We also see that flexible obstacles cause less bulk drag than rigid vegetative obstacles of the same dimension. Also, we found that the obstacle thickness and length have no major effect on the bulk drag coefficient, which was also found by experiments. We have shown that the immersed structure approach is effective at reproducing trends in upscaled parameters while still being computationally viable and considering the important factors of obstacle flexibility and bulk effects.

Another important flow scenario studied is the effects of obstructions on gravity waves. Using a two-phase flow method with a conservative level set method for tracking a water-air interface, we computationally modeled a wavemaker that generates gravity waves and allows them to propagate through a flume. The waves can be regular or be generated randomly based on some known wave spectrum.

We have studied a bed of long, thin obstacles using the immersed structure technique. Inside the flume, we placed rigid obstacles, flexible obstacles made of foam rubber with known parameters, and approximations of real vegetation. Early results for rigid obstacles were obtained in year one as shown in [Mattis, 2013]. Developing methods that reproduce results from wave tank experiments performed at ERDC has been a main focus in year 3. In the ERDC experiments [Anderson, 2014] , random wave series with spectra that are realistic for near-shore flow scenarios were driven through beds of synthetic vegetation. We have reproduced this wave tank set up numerically with the two-phase flow, immersed boundary, and wavemaker codes. The model was run for a variety of wave spectra and tank setups, as was done in the experiments. Control setups where there were no obstacles were also used. Several upscaled results were calculated to study the effect of obstacles on flow including downstream wave spectra, drag coefficients, and wave decay coefficients. We are looking at how these upscaled values vary with non-dimensional flow parameters such as Reynolds number, submergence ratio, relative wave height, and relative depth. Figure 6 shows the change in drag coefficient with respect to Reynolds number. In Figure 7, we show that the wave decay coefficient increases as the submergence ratio increases. This matches well with the experimental results. Figure 8 shows the decay of the downstream wave spectra for a given tank and wave series. Once again, the numerical and experimental results match quite well. There are many more values that we have compared, and in general we are doing a good job of reproducing upscaled values from experiments. This should be extremely useful as our numerical simulations come at a much smaller monetary, time, and energy expense than large experiments. These results are being compiled in a manuscript which will be submitted for journal publication soon.

(6) The bibliography is attached.

Technology Transfer

The project involved collaboration with Matthew Farthing, Chris Kees and Jane Smith at the US Army Corps of Engineers Engineer Research and Development Center. We worked with Farthing and Kees on the development of the Proteus software framework, and worked with Jane Smith on the application of Proteus to wave tank experiments with various types of vegetation.

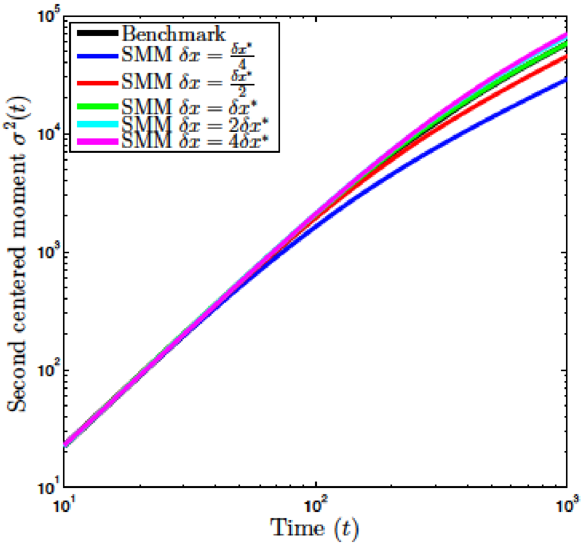

Figure 1: Comparison of Benchmark to Spatial Markov model predictions, parameterized at various scales, of the second centered spatial moment of a plume.

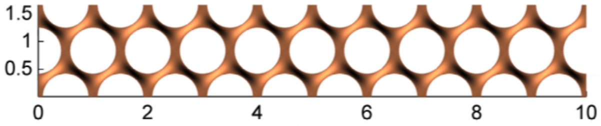

Figure 2: Flow Geometry on which the LATERS model is developed and tested. Flow is from left to right.

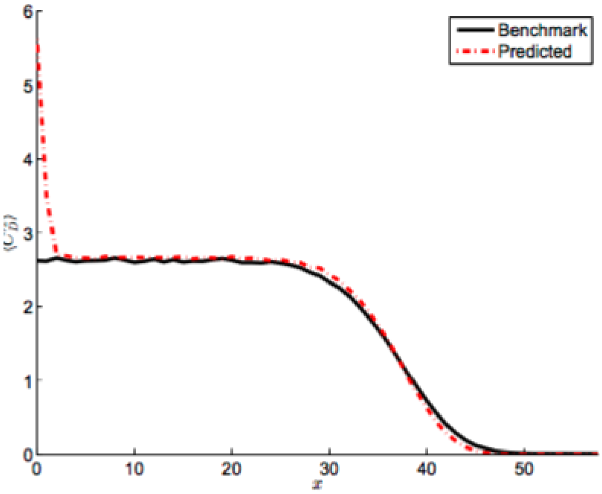

Figure 3: Comparison of benchmark and LATERS model prediction of concentration variance, a measure of mixing, at a specific snapshot in time.

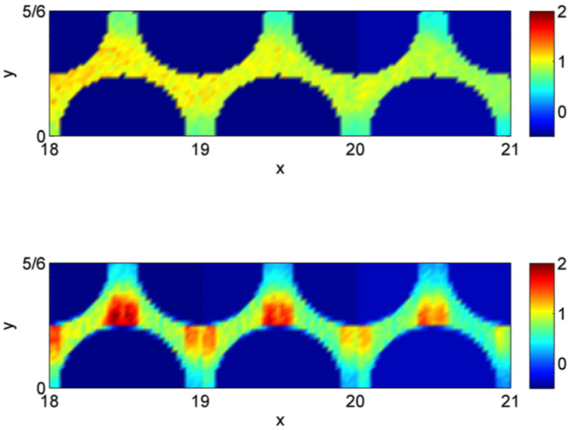

Figure 4: Comparison between benchmark (top) and LATERS prediction (bottom) of small scale mixing. Clearly LATERS model predicts hotspots not seen in benchmark even though macroscopic mixing is well modeled.

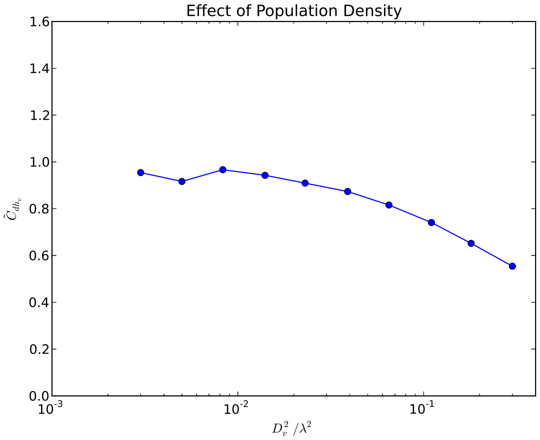

Figure 5: The relationship between population density of obstacles and the bulk drag coefficient.

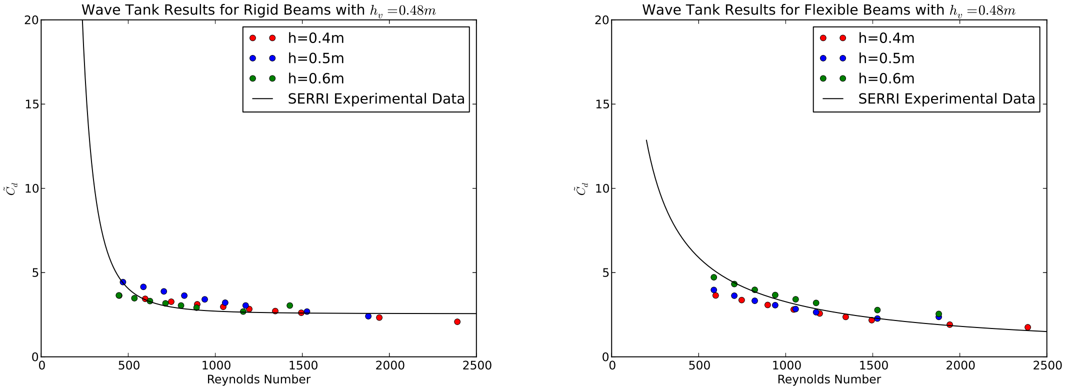

Figure 6: Bulk drag coefficient values for a wave tank setup for rigid obstacles (left) and flexible obstacles (right) compared to experimental results.

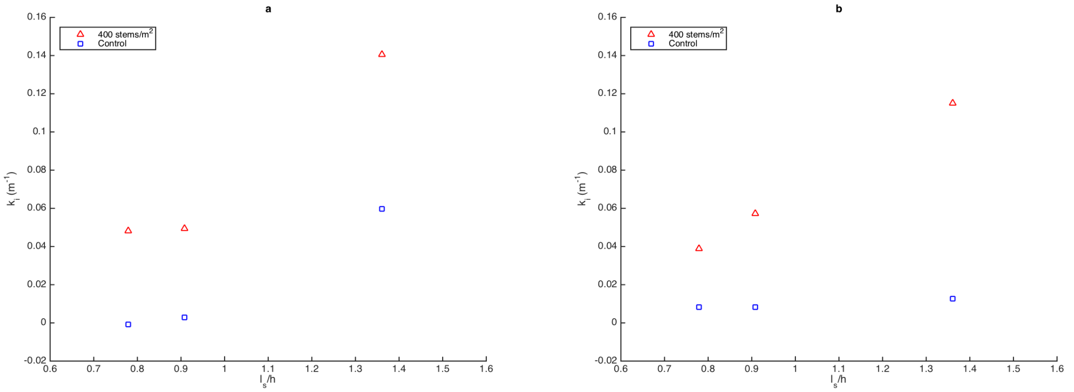

Figure 7: Wave decay coefficient with respect to submergence ratio calculated by (a) numerical simulations and (b) experiments.

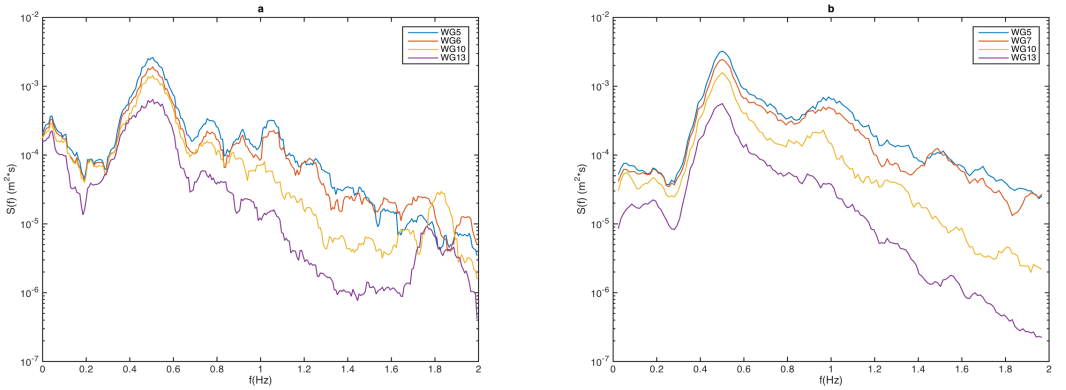

Figure 8: Downstream wave spectrum calculated by (a) numerical simulations and (b) experiments.

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