New York State Water Resources Institute Annual Technical Report FY 2013

Introduction

The Mission of the New York State Water Resources Institute (WRI) is to improve the management of water resources in New York State and the nation. As a federally and state mandated institution located at Cornell University, WRI is uniquely situated to access scientific and technical resources that are relevant to New York State's and the nation's water management needs. WRI collaborates with regional, state, and national partners to increase awareness of emerging water resources issues and to develop and assess new water management technologies and policies. WRI connects the water research and water management communities. Collaboration with New York partners is undertaken in order to: 1) Build and maintain a broad, active network of water resources researchers and managers, 2) Bring together water researchers and water resources managers to address critical water resource problems, and 3) Identify, adopt, develop and make available resources to improve information transfer on water resources management and technologies to educators, managers, policy makers, and the public.

Research Program Introduction

The NYS WRI's FY2013 competitive grants research program was conducted in partnership with the NYS Department of Environmental Conservation (DEC) Hudson River Estuary Program (HREP). The overall objective of this program is to bring innovative science to watershed planning and management. In FY2013 research was sought that fit within the context of New York State's growing concerns about aging public infrastructure, economic constraints on public investment, and the recent requirement for State planning agencies to incorporate principals of "smart growth" as promulgated in the 2010 Smart Growth Public Infrastructure Policy Act (http://smartgrowthny.org/index.asp). The specific areas of interest for the FY2013 grants program solicitation were: 1) Water-related infrastructure including water supply and wastewater treatment facilities, distribution networks, decentralized treatment installations, dams, constructed wetlands, "green" infrastructure, etc., and their current state and effectiveness at providing water and ecosystem services regionally at reasonable cost; 2) Regional economic vitality with respect to water infrastructure and its effect on private and public investment and industrial development; 3) Integration of scientific, economic, planning/governmental and/or social expertise to build comprehensive strategies for public asset and watershed management; 4) Smart growth and its implications for water related infrastructure development, regional water quality, and regional economy; 5) Novel outreach methods that enhance the communication and impact of science-based innovation to water resource managers, policy makers, and the public; 6) The economics and benefits of source watershed protection strategies and the use of ecological services to meet water supply and quality needs, as opposed to treatment at point of delivery. Projects were evaluated by a panel consisting of representatives of the US Geological Survey, the NYS DEC, and faculty from Cornell University. Several research projects were initiated, but were funded through DEC sources that WRI leverages with its base federal grant. For FY2013, the NYS WRI conducted one research product using federal funds:

1. Assessment of extreme weather impacts on water infrastructure PI: Susan Riha, Cornell University

We also report on an on-going 104G project:

1. The remote monitoring of surface velocity, bathymetry, and discharge PI: Edwin A Cowen, Cornell University

Additionally, WRI staff funded in part by the 104b program engaged in ad hoc research activities which are also reported on here.

The Remote Monitoring of Surface Velocity, Bathymetry, and Discharge

Basic Information

Title:	The Remote Monitoring of Surface Velocity, Bathymetry, and Discharge
Project Number:	2012NY189G
Start Date:	9/1/2012
End Date:	8/21/2014
Funding Source:	104G
Congressional District:	22
Research Category:	Engineering
Focus Category:	Methods, Water Quantity, Hydrology
Descriptors:	None
Principal Investigators:	Edwin A. Cowen

Publications

There are no publications.

Remote monitoring of volumetric discharge based on surface mean and turbulent metrics

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ABSTRACT: Traditional methods of directly measuring volumetric discharge are expensive, manpower intensive, and often require technicians to work in hazardous conditions. Here we have developed a reliable, continuous and efficient method of remotely monitoring volumetric flow rate. A series of Large-scale Particle Image Velocimetry (LSPIV) and Acoustic Doppler Velocimetry (ADV) measurements are made in a wide-open channel. The experiments are conducted for a wide range of aspect ratios, Reynolds numbers and Froude numbers. The results indicate that the mean surface velocity is related to the depth-averaged velocity and the surface integral length scale varies predictably with the flow depth, thus calculation of the flow rate is enabled. Our primary objective is to develop a non-contact discharge monitoring approach that will reduce stream-gaging costs at potentially better accuracy relative to current methods, while reducing hazards to USGS personnel.

1 INTRODUCTION

The United States Geological Survey (USGS) has been tasked with monitoring volumetric discharge (total volume of water flowing through a river cross section per unit time) in all of our nations' rivers and streams. Accurate determination of this fundamental hydrological parameter is essential in the design and operation of hydrologic engineering projects, the minimization of drought, the monitoring of water quality and the prediction of transport of environmental contaminants. Moreover, these data are used in the forecasting of public water supplies, in assessing environmental regulations and in flood control and damage mitigation. Simply put, accurate measurements of discharge are vital in the management of water as a national resource.

The current system used by the USGS to directly measure volumetric flow rate involves partitioning the river into a transverse series of finite segments and measuring vertical profiles of streamwise velocity in each segment. The volumetric discharge is then calculated using the velocity-area method formula,

$$Q = \sum \left(V_{avg} b H_{local} \right) \quad (1)$$

where Q represents the total volumetric discharge [m^3/s] and is equal to the summation of each segment's depth-averaged velocity, V_{avg} [m/s] times its width, b [m] and depth, H_{local} [m] (Rantz 1982). Traditionally, discharge measurements have been accomplished through traversing the river in a boat or through wading. Devices such as current meters or an Acoustic Doppler Current Profilers (ADCP) are typically used to measure the current velocity.

Because of the significant effort involved in measuring discharge, generally once a discharge measurement is made, it is related to the river stage (the elevation of the river surface above some arbitrary datum) occurring at the same time as the discharge measurement. Over time, the USGS has amassed a sizeable database of concurrent stage and discharge measurements for each of its ~ 7,300 gaging stations and has developed rating curves that express this functional relationship. The use of rating curves makes it possible for the USGS to continually estimate discharge by monitoring a river's stage, a measurement that is far easier to make on a continual basis.

Under ideal conditions, discharge determined from rating curves can be accurate to within 5% of the true value (Sauer & Meyer 1992). However, if the river is unstable or if the cross-section of the river varies widely an existing stage-discharge relation can become inaccurate. Flood conditions, releases from a dam, excess vegetation growth, a moving or soft erodible bed can all significantly influence a river's stage-discharge relationship. Figure 4 of Mason & Weiger (1995) provides such an example, where it can be observed that the discharge for a river stage of three feet changed by two orders of magnitude after a flood.

It is desirable to have accurate discharge data for all river flow conditions but the need is more urgent during floods. Discharge data is a key input into the river models developed by the National Weather Service (NWS), from which flood warnings and evacuation notices are made to the general public when dangerous conditions threaten. Without accurate discharge measurements it is difficult to predict precisely when a river will crest and when evacuations of local residents need to take place. Timely and accurate flood forecasts minimize economic damage and save human lives. A potential solution to this problem would be to make periodic measurements of discharge during floods. However, it is often the case that conditions are not safe and the risk to equipment and USGS personnel life are unacceptable.

Since direct measurements of discharge for all river conditions are time consuming and often hazardous to obtain, there have been many attempts at introducing remote sensing techniques to the process of stream gaging. Several attempts at incorporating radar technology have been made and were the primary focus of previous USGS task committees (e.g. Hydro 21). Several other investigations (Nicolas et al. 1997, Lee et al. 2002a, b, Mason et al. 2002, Costa et al. 2000, Melcher et al. 2002) have demonstrated the capacity of radar to make accurate velocity measurements of the water surface. However, in each of these studies the radar system used to measure the surface velocity could not simultaneously provide information about the bathymetry or the river depth. An additional measurement system that had to be, in all cases, traversed across the river was required to determine the river cross-sectional area and facilitate calculation of discharge.

Several investigations have focused on incorporating LSPIV and other optically based techniques into the process of stream gaging (Weitbrecht et al. 2002, Creutin et al. 2003, Creutin et al 2002, Fujita & Tsubaki 2002, Fujita et al. 1998). While LSPIV is capable of capturing instantaneous and accurate profiles of streamwise velocity across an entire field of view, here again, each of these studies relied on an additional measurement system to determine the river bathymetric information.

The technique that is proposed herein seeks to leverage the strengths of traditional PIV in the process of river gaging and further seeks to streamline the process by eliminating the need for a second measurement system to capture bathymetric information that is necessary to determine volumetric discharge. The required bathymetric information is extracted from the captured images through application of turbulence theory. Hence, the captured images of the water surface not only provide information about the mean surface flow but they simultaneously permit investigation of local bathymetric conditions. This is accomplished through the calculation of the integral length scale at the water surface, which we demonstrate to be correlated predictably to flow depth.

2 EXPERIMENTAL METHODOLOGY

2.1 *Wide-open Channel Flume*

A series of experiments were conducted in a recirculating, wide-open channel flume, described in detail in Liao & Cowen 2010, housed in the DeFrees Hydraulics Laboratory at Cornell University. The test section of the channel is 15 m long, 2 m wide and 0.64 m deep. The measurements conducted as part of this investigation were made ~9 m downstream from the inlet of the test section to allow sufficient distance for the boundary layer to fully develop. As illustrated in Figure 1, the origin of the coordinate system is located at the beginning of the test section, along the channel centerline, at the channel bed. The x coordinate indicates the streamwise direction, the y coordinate indicates the transverse and the z coordinate indicates the vertical direction.

2.2 *Experimental Cases*

Eight experimental cases were run, in which the flow depth was varied from 10.2 to 30.5 cm and flow speed was varied from 10.9 to 27.8 cm/s (Table 1). Of the dimensionless variables studied in these experiments and listed in Table 1, two that are of considerable interest here are the aspect ratio, B/H (where B is the channel width and H is the flow depth) and the ratio of boundary layer thickness to the flow depth, δ/H. The aspect ratio of the flow ranged from 6.6 – 19.7 across all the experiments. It has been noted by several investigators (Nezu et al. 1985, Albayrak & Lemmin 2011) and confirmed in this work that the aspect ratio sets the number of streamwise counter-rotating vortices in wide-open channels. The ratio of the boundary layer thickness

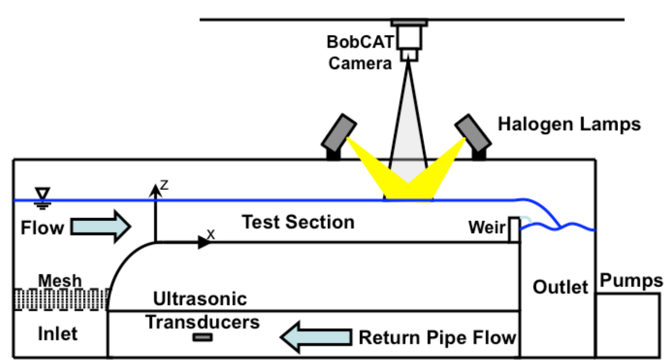


Figure 1. Schematic of the recirculating wide-open channel flume.

Table 1. Experimental Flow Cases

H [cm]	U_C [cm/s]	B/H	Re_H	Fr	δ/H	u*[cm/s]
10.7	11.3	18.7	10,680	0.10	2.03	0.50
10.2	24.6	19.7	25,400	0.25	1.87	1.17
15.2	11.0	13.1	15,210	0.08	1.42	0.51
15.3	27.8	13.1	38,275	0.20	1.24	1.12
20.6	11.0	9.7	20,550	0.07	1.05	0.49
20.3	27.5	9.9	50,725	0.18	0.94	1.12
30.5	10.9	6.6	30,460	0.06	0.71	0.48
30.5	25.0	6.6	76,175	0.14	0.62	1.10

U_C indicates the free surface centerline velocity. The Reynolds number, Re_H is based on the centerline velocity and flow depth. Fr is the Froude number. u* is the friction velocity.

to the flow depth, δ/H=0.62 – 2.03, is a critical parameter in these experiments that details what portion of the water column is comprised of the growing boundary layer. In other words, this parameter indicates how well developed the free surface flow is and how strongly it is influenced by the bed generated turbulence. In these experiments the boundary layer thickness, δ, has been estimated using Prandtl's 1/7th power law and the flow depth was set to achieve the desired range of δ/H values.

2.3 *Large-scale PIV Measurements*

Surface PIV experiments were conducted for each experimental case listed in Table 1 above. PIV is a well-established technique of fluid velocity measurement that is capable of characterizing an entire velocity field (Cowen & Monismith 1997). The technique employed here involves capturing images in rapid succession of the free surface of an open channel flow that has been artificially seeded with small buoyant particles. The average displacement of a small cloud of tracer particles is the same as the average displacement of that small region of surface fluid and when divided by the elapse time between images, yields an instantaneous surface velocity vector. The instantaneous velocity fields captured in successive images can be averaged in time to determine the mean velocity field. Subtracting the mean field from each instantaneous velocity field produces the instantaneous turbulent velocity field.

The experimental set-up for the LSPIV measurements includes a 12-bit IMPERX IGV-B2020 CCD camera that was suspended from the laboratory ceiling, approximately 3 m above the bed of the test section. This camera is capable of acquiring 123 fps and has a 2060 x 2056 pixel array. The camera was fitted with a 20 mm wide-angle lens with an aperture setting f/2.8. The field of view (FOV) of the camera is approximately 203 x 193 cm. The images cover the entire width of the channel in the spanwise direction (y = -100 to 100 cm) and x = 887 to 1091 cm in the streamwise direction. The spatial resolution in both directions was on average 0.105 cm/pixel. Great care was taken to ensure that the camera was mounted such that the imager plane was parallel to the flume bed.

The triggering of the camera and the timing of the image pairs was controlled through a computer running a MATLAB data acquisition code. The elapse time between two successive image pairs was varied according to the mean flow speed from Δt = 75 - 400 ms. A total of 4000 image pairs were captured at a sampling frequency of 1 Hz for each data set. The images were collected using the camera's software and saved on an external hard drive. A constant light source was provided through eight 500 W halogen lamps (four on the upstream side of the FOV and four on the downstream side).

The particles that are imaged in these experiments are Pliolite VTAC-L particles manufactured by OMNOVA. While these particles have a mean specific gravity of 1.03, there is a distribution of individual particle density, as evidence by their behaviour in water. The particles that float were preferentially selected for use in the experiments. The particles were sifted between a series of sieves and only particles in the range 420 - 600 microns (0.42 – 0.6 mm) were used in this study. The Stokes number for the particles is 0.003, indicating that the particles have ample time to adjust to the fluid flow.

All of the images were preprocessed prior to being analyzed. The stationary background of each image was removed applying the technique used by Mejia-Alvarez & Christensen (2013) and Honkanen & Nobach (2005). Following preprocessing, the images are processed via a FORTRAN algorithm that is an improved derivative of the algorithm described in Cowen & Monismith (1997).

2.4 *ADV Measurements*

Vertical profiles of velocity were made in the channel to characterize the properties of the flow throughout the water column using a Nortek Vectrino ADV. The ADV was moved vertically through the water column and measurements were taken at the approximate midpoint of the streamwise extent of the SPIV images (x = 981 cm). Five minutes of data were taken at each vertical position at a sample rate of 200 Hz. During post-processing the data was passed though a threshold filter and an adaptive Gaussian filter. The signal-to-noise ratio of these measurements was on average 16 dB and the correlation values were all high (> 93%).

2.5 *Ultrasonic Flowmeter*

An independent measure of volumetric flow rate was provided by a FLUXUS ADM 7407 ultrasonic flowmeter. Ultrasonic transducers were secured to both pipes that recirculate water to the test section and measurements were made for the duration of the

LSPIV tests. Volumetric flow rate was determined by summing the total amount of fluid flowing through both pipes. High quality flowmeter data (accuracy ± 3%) was ensured for all experiments and was judged through high values of signal quality (> 8) and signal-to-noise ratio (> 3) and accurate values of the sound speed of water in accordance with manufacturer specified recommendations.

3 RESULTS

Determination of volumetric flow rate using the velocity area method in Equation 1, requires knowledge of the depth-averaged velocity and the local flow depth across the entire width of the river. This section details how both the depth-averaged velocity and local flow depth can be determined solely from measurements of the surface velocity field. The section then concludes with a comparison of the volumetric flow rate calculated from the LSPIV imagery and from the ultrasonic flowmeter.

3.1 *Depth-averaged velocity*

Vertical profiles of streamwise velocity when normalized by the inner wall variables are observed to follow the logarithmic law with the von Kármán and the integral constants chosen consistent with the Nezu & Rodi (1986) and Nezu & Nakagawa (1993), $\kappa = 0.41$ and $B = 5.29$ (Figure 2). Because the ADV does not capture data in the viscous sublayer, the vertical profiles are extrapolated to the wall using the log-law. Prior measurements closer to the bed and not included here indicate that this is an appropriate course of action.

Depth-averaged velocity is determined simply by taking the weighted average of the streamwise velocity over the depth as indicated by Equation 2 below,

$$U_b = \frac{1}{H}\int_0^H U dh. \tag{2}$$

Depth-averaged velocity is determined for each experimental case and compared with the mean surface

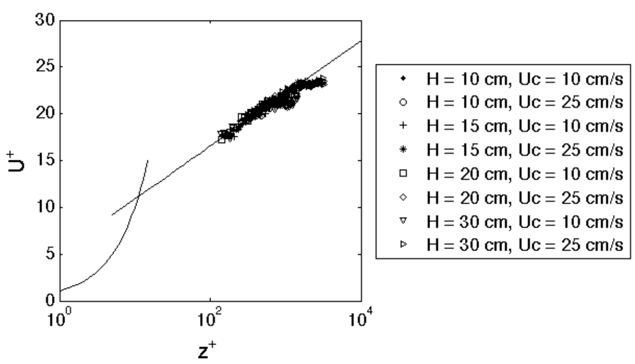


Figure 2. Mean streamwise velocity normalized by inner wall variables.

velocity measured by the LSPIV system in the same location that the ADV measurement was made. The ratio between these two velocities is found to vary with the ratio of boundary layer thickness to the flow depth, δ/H (Figure 3). As mentioned earlier, δ/H represents how well developed the free surface flow is. The range of values spanned in Figure 3, $U_b/U_{Surf} = 0.82 – 0.93$, is consistent with the range of values noted in other investigations. Harpold et al. (2006) measured a value of 0.95 in a laboratory channel. Rantz (1982) suggests that the ratio of depth-averaged velocity to surface velocity should fall between 0.84-0.92, with the lower values being more consistent with naturally occurring rivers and the higher values for laboratory flows. The range of values shown in Figure 3 plotted against δ/H corroborates the findings of Rantz (1982) and further reveal that lower values ($U_b/U_{Surf} \sim 0.85$) of this ratio correspond to free surface flows that are more fully developed such as the shallow flow cases in this study and naturally occurring rivers. With knowledge of this ratio one can predict depth-averaged velocities from corresponding measurements of surface velocities. For field applications of this methodology, given that a typical rivers' length much exceeds its depth, it is expected that the free surface will be quite well developed. The value 0.85, which is consistent with other studies, will be used.

3.2 *Local flow depth*

To determine local flow depth, we exploit the presence of streamwise counter-rotating vortices that occur in shallow open channel flows. These vortices have been well documented in several investigations (Shvidchenko & Pender 2001, Nezu 1993) and have been found to scale with the flow depth. Evidence that these structures exist in our channel can be seen in Figure 4. Instantaneous streamwise velocity fields as measured by our LSPIV system on the free surface for two flow cases (H=6.3 cm, U_c=26.2 cm/s H=20.3 cm, U_c=25 cm/s) are depicted in Figure 4. The horizontal striations that are present are alternating bands of high momentum (converging) and low momentum (diverging) fluid that are indicative of secondary flows influencing the free surface.

To quantify the size of these vortices, we calculate the integral length scale on the free surface. The integral length scale is the integral of the normalized autocorrelation function of the turbulent velocity fluctuations as seen in Equation 3. Because PIV yields a highly resolved spatial data set, a spatial correlation is performed as opposed to a temporal one. Both streamwise and transverse velocity fluctuations are considered, however because river bathymetry changes most rapidly in the lateral di-

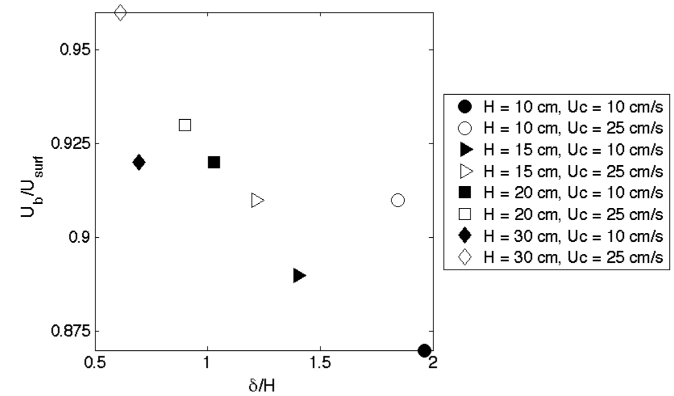
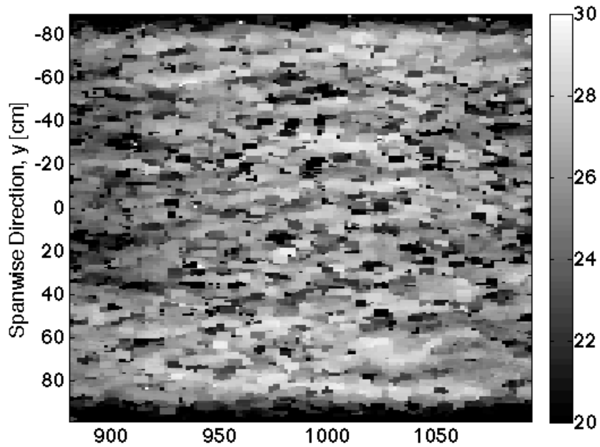
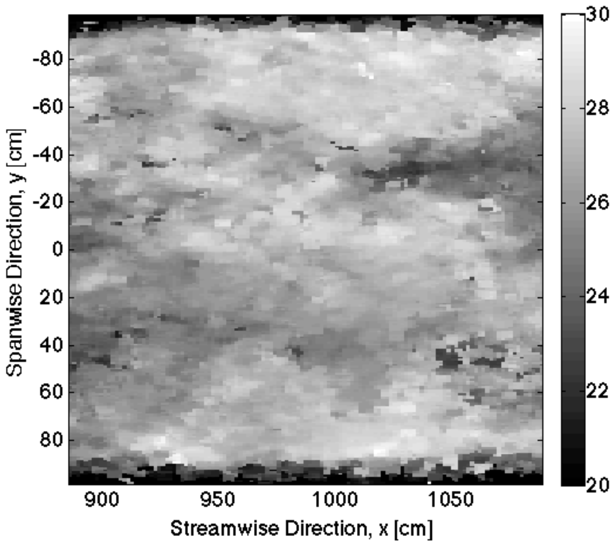


Figure 3. Depth-averaged velocity normalized by the mean surface velocity measured by the LSPIV system vs. boundary layer thickness normalized by the flow depth.



a.)



b.)

Figure 4. Instantaneous streamwise velocity. Contours are instantaneous streamwise velocity in cm/s. a.) Experimental case H=6.3 cm, U_C =26.2 cm/s. b.) Experimental case H=20.3 cm, U_C =25 cm/s.

rection, only correlations performed in the streamwise direction lead to unambiguous determination of flow depth.

In Equation 2 below, $a_{ij,k}$ is the normalized autocorrelation function and r is the separation vector. The subscripts *i, j,* and *k* are replaced with a 1 to indicate the streamwise direction and a 2 to indicate the transverse direction.

$$L_{ij,k} = \int a_{ij,k}(r)dr$$

$$\text{where, } a_{ij,k}(r) = \frac{\overline{u_i\left(x_c - \frac{1}{2}r_k\right)u_j\left(x_c + \frac{1}{2}r_k\right)}}{\left[\overline{u_i\left(x_c - \frac{1}{2}r_k\right)^2}\,\overline{u_j\left(x_c + \frac{1}{2}r_k\right)^2}\right]^{1/2}} \quad (3)$$

$L_{11,1}$ captures the streamwise distance over which the streamwise velocity fluctuations are correlated. It is calculated at every transverse location in the LSPIV field of view and depicted in Figure 5. With the exception of the 30 cm case, it is readily apparent that $L_{11,1}$ scales with the flow depth. The aberrant behavior of the 30 cm flow case is attributed to its low value of $\delta/H=0.62$, indicating a less developed free surface. Neglecting the influence of the corner vortices that occur near the sidewalls, the average across the central core of the flow is plotted in Figure 6. It is clear that $L_{11,1}$ is strongly correlated with the flow depth. For each flow case, $L_{11,1}$ is ~2.5 times the flow depth. The results further suggest a Reynolds number dependence.

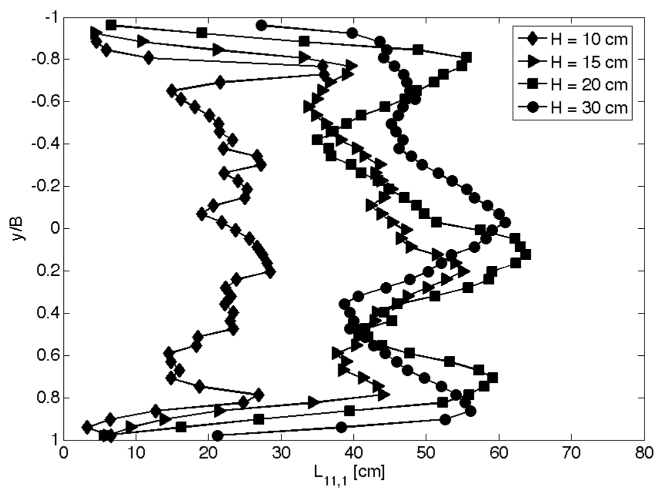


Figure 5. Streamwise integral length scale, $L_{11,1}$ vs. nondimensional channel width. The centerline velocity for all cases shown is ~25 cm/s.

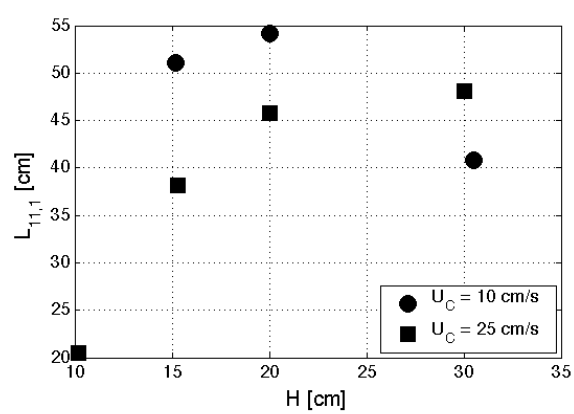


Figure 6. Mean streamwise integral length scale plotted against flow depth.

$L_{22,1}$ captures the streamwise distance over which the transverse velocity fluctuations are correlated. It is also calculated at every transverse location in the

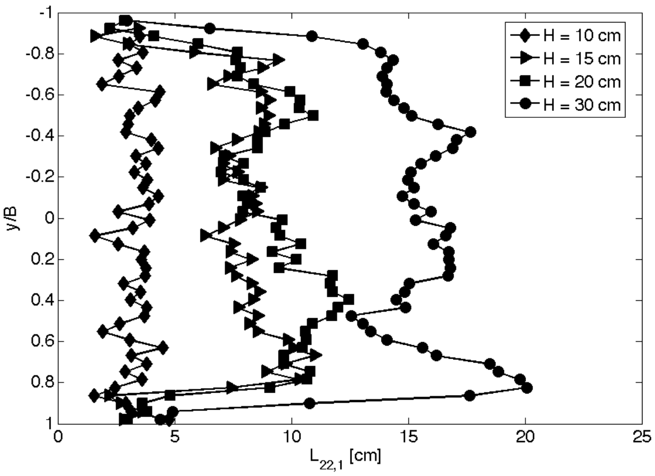


Figure 7. Transverse integral length scale, $L_{22,1}$ vs. non-dimensional channel width.

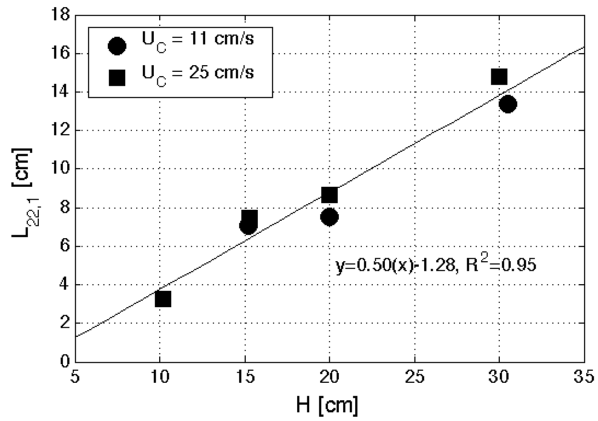


Figure 8. Mean transverse integral length scale plotted against flow depth.

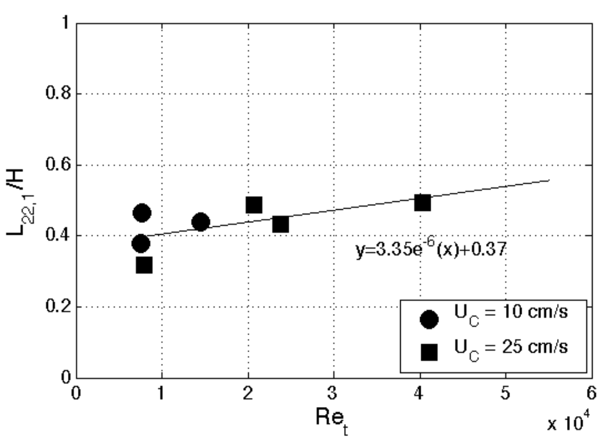


Figure 9. Turbulent Reynolds number versus normalized transvers integral length scale.

LSPIV field of view and depicted below in Figure 7 and Figure 8. $L_{22,1}$ is ~0.5 times the flow depth. The correlation between $L_{22,1}$ and the flow depth is even stronger.

Because free surface vortices will be larger in the field as compared with laboratory results, considering potential limitations of a camera's field of view $L_{22,1}$ is chosen over $L_{11,1}$, for estimating volumetric discharge. Our results are fully characterized when $L_{22,1}$ is normalized by the flow depth and plotted against the turbulent Reynolds number, Re_t, as in Figure 9. Because free surface vortices advect with the mean flow, the turbulent Reynolds number is formed with the mean local fluid velocity and $L_{22,1}$. As expected, $L_{22,1}/H$ shows a linear dependence on Re_t. It is trivial then to determine local flow depth using the relation given in Figure 9 and the known local values of surface velocity and integral length scale.

3.3 *Volumetric Discharge*

An estimate of the volumetric flow rate is thus enabled through knowledge of the relationship between the surface mean velocity and the depth-averaged velocity and the linear relation given in Figure 9. Predictions for volumetric discharge are compared with an independent measurement provided by the ultrasonic flowmeter and are shown in Table 2. The agreement between the measured and predicted flow rates is excellent.

Table 2. Measured and predicted volumetric discharge for experimental cases.

H [cm]	U_C [cm/s]	Q_{LSPIV} [m^3/hr]	$Q_{flowmeter}$ [m^3/hr]
10.2	24.6	150.93	143.85 ± 0.1
15.2	11.0	105.40	94.8 ± 0.2
20.6	11.0	137.08	138.14 ± 0.2
20.3	27.5	317.57	307.8 ± 0.3
30.5	10.9	214.16	204.54 ± 0.2
30.5	25.0	518.14	504.53 ± 0.4

Q_{LSPIV} designates discharge values calculated from LSPIV data. $Q_{flowmeter}$ designates discharge values measured with ultrasonic flowmeter.

4 CONCLUSIONS/FUTURE WORK

We have demonstrated that the surface velocity can be used as an accurate predictor of the local depth-averaged velocity. Our findings regarding this relationship are consistent with the work of many other researchers in both open channel and river flows. We have also demonstrated that the integral length scale, in particular $L_{22,1}$, is a reliable and powerful indicator of the local flow depth. Use of these two parameters has led to accurate predictions of volumetric flow rate.

Additional experiments have been completed to the effect that bed roughness will have on the free surface turbulent signatures and on the ratio of depth-averaged velocity to the mean surface velocity. Experiments in a channel with a trapezoidal cross-section and flood plain have also been conducted and are currently under analysis with the objective of studying how the surface integral length scale changes in regions of gradually changing local bathymetry. Validation of this methodology will also be carried out in two local rivers in conjunction with USGS personnel.

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Assessment of extreme weather impacts on water infrastructure

Basic Information

Title:	Assessment of extreme weather impacts on water infrastructure
Project Number:	2013NY203B
Start Date:	3/1/2013
End Date:	2/28/2014
Funding Source:	104B
Congressional District:	23
Research Category:	Climate and Hydrologic Processes
Focus Category:	Management and Planning, Floods, Climatological Processes
Descriptors:	None
Principal Investigators:	Susan Riha

Publications

1. Vedachalam, S., John, M.E.; Riha, S.J., 2014, Spatial analysis of boil water advisories issued during an extreme weather event in the Hudson River Watershed, USA, Applied Geography, 48:112-121
2. Vedachalam, S.; John, M.E.; Riha, S.J., 2014, Spatial Analysis of Boil Water Advisories Issued During an Extreme Weather Event in the Mohawk-Hudson Watershed, in Proceedings of the Mohawk Watershed Symposium, Union College, Schenectady, NY, 43.

Spatial Analysis of Boil Water Advisories Issued during an Extreme Weather Event in the Hudson River Watershed, USA

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Abstract

Water infrastructure in the United States is aging and vulnerable to extreme weather. In August 2011, Tropical Storm Irene hit the eastern part of New York and surrounding states, causing great damage to public drinking water systems. Several water supply districts issued boil water advisories (BWAs) to their customers as a result of the storm. This study seeks to identify the major factors that lead water supply systems to issue BWAs by assessing watershed characteristics, water supply system characteristics and treatment plant parameters of water districts in the Mohawk-Hudson River watershed in New York. Logistic regression model suggests that the probability of a BWA being issued by a water supply district is enhanced by higher precipitation during the storm, high density of septic systems, lack of recent maintenance and low population density. Interviews with water treatment plant operators suggested physical damage to water distribution systems were the main causes of boil water advisories during storms. BWAs result in additional costs to residents and communities, and the public compliance of the advisory instructions is low, so efforts must be made to minimize their occurrence. Prior investments in infrastructure management can proactively address municipal water supply and quality issues.

Keywords

Boil water advisory; Tropical Storm Irene; Mohawk-Hudson watershed; extreme weather; water infrastructure; water main break

Citation

Vedachalam, S., John, M.E., & Riha, S.J. 2014. Spatial Analysis of Boil Water Advisories Issued During an Extreme Weather Event in the Hudson River Watershed, USA. *Applied Geography,* **48**:112-121. Available at: http://dx.doi.org/10.1016/j.apgeog.2014.02.001

1. Introduction

Water infrastructure in the United States is aging and vulnerable to extreme weather. Recent events demonstrated the importance and vulnerability of this critical infrastructure. During late August 2011, the eastern part of New York State, USA experienced unprecedented precipitation from Tropical Storm Irene. The storm caused great damage to infrastructure, taking out power and phone lines, and washing out roads and bridges. In the case of water infrastructure, 29 dams, including six high hazard dams were damaged across New York, and 31 wastewater treatment plants were inundated or unable to operate throughout eastern New York (Meyer et al., 2012a; Vedachalam and Riha, 2013). Further, boil water advisories affecting nearly half a million customers were issued by local water districts in counties along the lower Hudson River (Meyer et al. 2012b). Boil water advisories require residents to boil their tap water before coming in active contact through drinking, brushing teeth, washing dishes, etc. As a result, depending on their severity and length, such advisories can result in significant costs to individuals and communities (Laughland et al., 1993; Nadebaum et al., 2004). Occurrences of damage to water infrastructure during extreme weather could be prevented by adaptive management of not just the water infrastructure, but the natural systems around us. Using data from the Mohawk-Hudson watershed of New York during Tropical Storm Irene, the objective of this study is to identify factors that led to the issuance of boil water advisories and suggest preventive measures.

2. Boil water advisory

A boil water advisory (BWA) or a boil water notice is a public notification issued by water utilities informing the public of the need to boil water (New York State Department of Health, 2013b). The advisory is typically accompanied by directions on how to boil water, the expected duration of the advisory and contact information of the utility and the local health department. BWAs are issued in response to the presence of a health hazard such as when the water is or likely to be unfit for consumption. Typically, BWAs are issued in response to an exceedance of microbial (*E. coli*) standards; however, other events such as water main breaks, interruption in treatment or distribution, depressurization or low pressure in the line, power failures, etc. can also necessitate the issuance of a BWA. During extreme weather events such as heavy precipitation, BWAs are issued due to the potential for contamination of water storage reservoirs through surface runoff, and following disruption in the supply due to water main breaks and power failures.

BWAs come at a significant cost to the consumers. A study assessing the household cost of a BWA issued in 1989 in Milesburg, Pennsylvania, USA following a *Giardia lamblia* contamination found that time lost in boiling, hauling, or purchasing water to avert infections cost an average household $5.60 to $33.47 per month in 1989 dollars (Laughland et al., 1993). Factoring in inflation, the avoidance cost of a BWA amounts to $10.36 to $61.92 per household in 2012 dollars. Businesses such as restaurants and establishments such as schools and community centers incur additional losses, none of which are factored in the Laughland et al. (1993) study. In the absence of more recent studies assessing the cost of BWAs, we can take this amount to be the low-bound estimate of the cost incurred per household.

Several studies, mostly conducted in Canada (Hrudey et al., 2003; Wallis et al., 2001) and Northern Europe (Kargiannis et al., 2009; Rimhanen-Finne et al., 2010; Robertson, et al, 2009) have analyzed the situations leading to BWAs in a particular city or municipality. All the incidents leading to the issuance of BWA were caused by bacterial or protozoan contamination from animal or human sources. Others have investigated the behavioral response of the customers affected by the advisories, and reported high levels of non-compliance to the advisories (Kargiannis et al., 2009; O'Donnell et al., 2000; Ram et al., 2007; Rundblad et al., 2010). Since the system of issuing advisories is designed on an implicit public understanding of the process, we review key findings from the behavioral response studies. A survey of households affected by a boil water advisory in the UK in 1998 reported that eighty-one percent of the households had engaged in behavior that was likely to increase the risk of waterborne infection such as brushing, washing dishes, etc. (O'Donnell et al., 2000). Households that received the notice to boil water in the form of a red leaflet soon after the advisory were just as likely to engage in unsafe behavior as those who received the notice late, indicating limited effectiveness of the leaflet. A somewhat lower, but still significantly high, non-compliance was reported in a study conducted in Gloucestershire, UK after heavy floods in 2007 led to two separate notices while the water supply was being restored– a 'do not drink' notice followed by a 'boil water' notice (Rundblad et al., 2010). A majority of the respondents affected by Hurricane Rita in Louisiana, USA in 2005 reported being unaware of the advisory and of alternate disinfection methods (Ram et al., 2007).

Hrudey et al. (2006) analyzed data from 70 disease outbreaks from 15 countries over 30 years and found that bacterial contamination is caused by conditions that are event-driven, such as extreme weather or unusual operating conditions. In an investigation of waterborne disease outbreaks in the U.S. during 1997-98, the Centers for Disease Control (CDC) found that 15 of the 17 outbreaks were linked to groundwater sources (Barwick et al., 2000). A study on hazard identification and risk assessment of water supply from Australia collated the key characteristics and common sources of hazards to water quality (Nadebaum et al., 2004). The study identified 36 hazards and categorized them under five broad topics:(a) watershed characteristics such as land use, agriculture, urban development, and wastewater management; (b) reservoir properties such as algal blooms and contaminated inflows; (c) reliability and design capabilities of water treatment plants to remove pathogens, industrial effluents and other pollutants; (d) disinfection capability; and (e) resilience of the distribution system during repairs, main breaks, cleaning and other unanticipated events (Nadebaum et al., 2004).

Based on our literature review, it appears that isolated incidents causing BWAs are well investigated. However, there is a critical lack of studies that investigate the underlying factors that lead to boil water advisories. Although it is difficult to gather data on all the hazards described in Nadebaum et al. (2004), we focus on some of the key hazards, especially the ones relating to watershed characteristics, water treatment plant properties and disinfection capability. We model these hazards as independent variables to explain the probability that a particular water supply district will issue a BWA. The study's setting in an extreme weather event is circumstantial. Under ordinary circumstances, it is difficult to foresee the possibility of BWAs being simultaneously issued by multiple water districts. The heavy precipitation during Tropical Storm Irene that led to multiple BWAs across a large region provided a suitable setting for this study. The only BWA studies that involved extreme weather investigated the compliance with public health advisories (Ram et al., 2007; Rundblad et al., 2010). Regardless of the setting, this is the first study that investigates the factors that contribute to the issuance of boil water advisories over a large spatial scale.

3. Methods

During late August 2011, Hurricane Irene formed in the Atlantic Ocean and made multiple landfalls in the Central American islands and the coastal U.S. states of North Carolina and New Jersey. Throughout this process, the cyclone gained and lost strength, switching from a hurricane to tropical storm several times. The storm system made its last landfall in New York City, NY as a tropical storm and made its way through the eastern part of New York State moving north along the Hudson River, before veering east towards Vermont and New Hampshire. Parts of the Hudson watershed received over 10 in (254 mm) of precipitation over 3 days, nearly a fourth of the average annual precipitation.

3.1 Data

Boil water advisories issued during the period were tracked using information provided by the New York State Department of Health (NYSDOH) and are presented in Figure 1. This data set included the start and end dates of each BWA. The Mohawk-Hudson watershed in New York spans over 34,700 sq. km. and is home to over 2.7 million people. Not including the New York City (NYC) water supply system, the watershed contains 678 water supply districts, providing a large enough sample size to analyze spatially. Although a part of NYC falls within the Mohawk-Hudson watershed, the NYC system was not included because of its enormous size (it serves approximately 9 million residents) in relation to other systems in the watershed, the spatial separation between the water source and the city, and administrative and operational resources that are available to the system in relation to other districts in the watershed. Based on the classification used by the USEPA, water supply districts in the Mohawk- Hudson watershed are similar in size to those in New York State and the entire United States (Table 1). Therefore, results drawn from this study has national applications.

A Freedom of Information Law request made to the NYSDOH yielded a complete dataset of public water supply systems in the state with information on location, population served, area served, water source, type of disinfection, and design and average daily production of water (NYSDOH, 2012). Data on violations recorded by water treatment plants in prior years (2009 and 2010) were obtained from the NYSDOH through their collection of Annual Reports of Public Water Supply Violations (NYSDOH, 2013a).The Northeast Regional Climate Center provided the precipitation data during the period August 27-29, 2011 for the Northeast region (NRCC, 2012). Vector data from the weather stations in New York and neighboring states was converted to a raster format using the inverse distance weighted (IDW) interpolation in ArcGIS to obtain precipitation data for every point in the watershed (Dirks et al., 1998) (Figure 2).

Land cover data was obtained from the 2006 National Land Cover Database (NLCD, Fry et al., 2011). The NLCD provides spatial mapping of 17 different types of land cover for any given region in the continental U.S. The categories include variations of similar land covers. For e.g., deciduous, evergreen and mixed forests are marked separately. Similarly, urban lands with varying intensities of development are presented as four land cover categories. For the purposes of this study, it is appropriate to combine similar land cover categories to arrive at a few important ones. The resultant land cover categories include developed land; forests; shrubs, grassland and barren land; pasture and cropland (agriculture); and wetlands and open water. Several districts purchase water from nearby districts, and in such cases, the land cover characteristics of the district with the source water are used. The spatial unit of analysis for land cover categorization is the Hydrologic Unit Code 12 (HUC-12) watershed within which the water supply district is located. The HUC-12 watershed boundaries were obtained from the GeoSpatial Data Gateway at the Natural Resources Conservation Service (NRCS, 2013). Since several districts used multiple sources of water, and a large majority relied on groundwater, it was difficult to map the "supplyshed" of the water districts. The HUC-12 watersheds serve as a reasonable proxy, since they are a considerably small unit of area and are numerous – 412 across the Mohawk-Hudson watershed. For e.g., Figure 3 shows the proportion of developed land within each HUC-12 watershed, where darker color represents high level of development. An additional land use data, not represented in the NLCD, is the use of septic systems for wastewater management. Comprehensive data on septic systems by Census tract dates back to the 1990 Decennial Census (U.S. Census Bureau, 1990; Minnesota Population Center, 2011). In the absence of an updated dataset, the 1990 data is used as a proxy for the use of septic systems in the water district.

In addition, semi-structured interviews were conducted with the water treatment plant operators in the region, who had issued BWAs during TS Irene. At least two attempts were made to contact each of the operators, and a voice message containing the caller information was left at the second attempt. Based on a pre-determined script, the operators were asked questions about the relative frequency of BWAs, most common causes, steps taken to inform customers, the process of repealing the BWA, and the involvement of local and state health departments in the entire process. Apart from gathering information regarding the Irene BWAs, the interviews were structured to gather general information about BWAs issued at other times of the year as well. A summary of data sources is presented in Table 2. Spatial representation of the data was performed using ArcGIS 10.1 (ESRI, 2012) and statistical analysis was done in STATA (StataCorp, 2013).

3.2 Variables, hypothesis and model

Boil water advisory data was recorded both in binary form (1=issued; 0=not issued) and in numerical form, denoting the length of the advisory in days, allowing us to use two versions of the dependent variable. Next, we discuss the independent variables, which broadly fall under the categories of water supply system characteristics, land cover/land use characteristics and water treatment plant parameters. A summary of the independent variables is presented in Table 3.

Source of water: Water supply districts obtain water from one or more of three sources – groundwater (GW), surface water (SW) and groundwater under direct influence of surface water (UDI). Water supply districts that relied on more than one source of water were associated with the one which provided the largest proportion of water.

Population: Population (POP) and population density (POPDENS, persons per sq. km) of the water supply district are used to capture the size of the district. The relationship between BWAs and the size of the water supply district could be hypothesized both ways. Districts serving a larger population are more likely to be concerned about a large-scale contamination event, and could issue an advisory pre-emptively. On the other hand, larger districts have better treatment and monitoring systems, and therefore, are likely to fare much better than their smaller counterparts in similar circumstances. We hypothesize that smaller districts are more likely to issue a BWA as compared to larger districts.

Irene precipitation: Precipitation during Tropical Storm Irene (IRPREC, mm) recorded at the geographical center of the water supply district polygon. Higher precipitation results in surface runoff increasing the probability of issuing a BWA. Therefore, we expect IRPREC to have a positive effect on the issuance of BWA. We also expect flooding from the precipitation to cause physical damage to water treatment plants. Although the model is not designed to isolate this effect, we expect to verify this hypothesis during interviews with water treatment operators.

Land cover: Of the aggregated land cover categories, the most useful predictors in the model are likely to be the proportion of land that is devoted to developed land, forests and agriculture. They are expected to have a positive, negative, and positive correlation with BWAs, respectively. Since, all three variables are somewhat correlated to each other[1], two of the land cover variables – the proportion of developed land (DEV) and proportion of agricultural land (AGRI)– will be used in the model.

Septic systems: The density of onsite septic systems (SEPDENS) in the HUC-12 watershed that contains the water supply district. Poorly designed and installed septic systems pose nutrient problems in surface and groundwater. Although there are no data to accurately identify the proportion of failed septic systems in each watershed of our study area, we can hypothesize that, in general, the presence of a larger proportion of these treatment systems would result in a higher probability of issuing a BWA.

Disinfection: Water treatment plants use one of several disinfection techniques such as gaseous chlorination, hypochlorination, ultraviolet radiation, etc. A few treatment plants use multiple forms of disinfection. Only six of the 678 plants used ultraviolet radiation or chlorination to remove free radicals as their only method of disinfection, so those categories were not included in the study. GASCHLOR, HYPO and MULTIDIS are dummy variables for gaseous chlorination, hypo-chlorination and multiple forms of disinfection, respectively. We hypothesize

[1] The coefficient of correlations (r) are forest-developed land = -0.45, forest-agriculture = -0.46 and agriculture-developed land = -0.39

that treatment plants using multiple types of disinfection are less likely to issue a BWA, due to the multiple barriers to entry for disease-causing microorganisms.

Violations: The NYSDOH records water treatment violations through their collection of Annual Reports of Public Water Supply Violations. Although the data go back to 1998, violations recorded in two preceding years, 2009 and 2010 were used in the study. Further, only those violations classified as contaminants were considered; administrative violations were not considered relevant to the scope of the study. Due to the heterogeneity of water treatment plants with respect to size, the average violations recorded in the two years were normalized to their average daily treatment capacity (VIOL). The violation record of water treatment plants for two years preceding the storm should give enough information on how a plant is functioning. Treatment plants recording a higher rate of violation in prior years signify weak monitoring and operational support, and thus more likely to issue a BWA.

We use two estimation strategies to model the relationship between BWA and the independent variables. We use the ordinary least squares (OLS) regression model to model the length of the BWAs. Next, we use a logistic regression model to estimate the probability of a BWA being issued by a water district, since the OLS model assumes a strictly linear relationship between the severity of BWA and the explanatory variables. Both models can be represented as follows:

$$BWA_i = \alpha + \beta_1 \, UDI_i + \beta_2 \, SW_i + \beta_3 \, POP_i + \beta_4 \, POPDENS_i + \beta_5 \, IRPREC_i + \beta_6 \, DEV_i + \beta_7 \, SEPDENS_i + \beta_8 \, HYPO_i + \beta_9 \, MULTIDIS_i + \beta_{10} \, VIOL_i + \varepsilon_i \quad (1)$$

Model specification was tested (using *linktest* function in STATA) to assess the validity of the variables in the model, and to test omitted variable bias. Multicollinearity was tested using the variable inflation factor. Spatial autocorrelation was tested using Moran's *I*.

4. Results

A large majority of water supply districts in the Mohawk-Hudson region rely on groundwater as their primary source of water (Figure 4). Most of these districts are small; over two-thirds of the districts serve less than 1000 residents each. However, much of the population in the region is served primarily by surface water (Figure 4). Of the 678 water supply districts considered in this study, 31 (about 5%) issued BWAs during Tropical Storm Irene[2]. When BWAs were issued, the duration ranged from 2 days to 93 days. More than three-quarters of the districts that issued a BWA were either small or very small districts[3]. None of the four very large districts issued a BWA[4] (Table 4).

A logistic regression model was constructed using explanatory variables to identify the factors associated with the probability of a BWA issuance (Table 5). No significant autocorrelation was detected among the boil water advisories at $\alpha_{.05}$. Multicollinearity was not observed as the variable inflation factor for all the explanatory variables was under 10. Heterogeneity among water districts suggests that all districts do not act and respond in the same ways when faced with logistical and operational challenges during extreme weather events. To test if small districts

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[2] An additional four districts issued BWAs during Tropical Storm Lee that followed two weeks after Irene. One district issued BWAs during both TS Irene and Lee.
[3] Refer Table 1 for an explanation of the terms
[4] United Water New York which serves Rockland County's nearly 280,000 residents, issued a BWA during TS Irene. A small part of the district falls within the Mohawk-Hudson watershed, but the geographical apportioning method chosen in the study excluded that district from our watershed boundary.

behave significantly differently than the large districts, we present two models: Model I includes only districts classified as small and very small, while Model II includes all districts. Both models employ the same independent variables. The OLS model that used number of BWA days as the dependent variable yielded specification errors, and is not shown here. This might have been due to the long periods of BWAs issued in certain districts that were a result of regulatory protocols and not due to actual damage suffered during the storm[5].

Model I, containing only the small and very small districts, has a higher R^2 and chi-square value than Model II. This is likely due to the lower levels of heterogeneity among the small districts, making the model perform better than the expanded Model II. In Model I, precipitation during Irene (IRPREC; OR = 1.01, $p = .05$) is positively significant, while developed land (DEV; OR = 0.95, $p = .07$), disinfection with hypochlorination (HYPO; OR = 0.11, $p = .03$) and violations (VIOL; OR = 0.86, $p = .01$) are negatively significant. In Model II, IRPREC (OR = 1.01, $p = .02$) and septic systems density (SEPDENS; OR = 1.01, $p = .08$) are positively significant, while, population density (POPDENS; OR = 0.99, $p = 0.09$) and VIOL (OR = 0.84, $p = .03$) are negatively significant.

5. Discussion

IRPREC and VIOL are the only variables that are consistently significant across both models, indicating their strong predictive power in the models. Tropical Storm Irene was accompanied by heavy precipitation and broke several flood gage records in the region (Meyer et al., 2012b). The severity of the excessive precipitation was compounded by the high soil moisture content in the

[5] In the case of the district that was under BWA for 93 days, a broken water main was replaced by a flexible pipe (hose) initially. According to the NYSDOH rules, water supplied through non-standard pipes must be accompanied by a BWA. The BWA was lifted after the replacement of the hose with a concrete pipe.

region preceding TS Irene (National Weather Service, 2011). Therefore, the positive significance of precipitation in the model was not unexpected, but the negative significance of violations issued in prior years was not expected *a priori*. The likely explanation is that water treatment plants that were issued these violations could have upgraded their facilities to bring them into compliance, and thereby, making the systems more resilient during extreme weather. This hypothesis is supported by the fact the negative significance holds if just the violations recorded in 2009 were used in the models instead of the average violations. Further, violations issued in 2010 have no effect in the models.

The source of water did not play a role in the issuance of BWAs, even though water supply districts using GW issued a larger proportion of BWAs (23 out of the 31). In Model I, the choice of disinfection displays some predictive power. Although our hypothesis that MULTIDIS would lead to a lower probability of BWA did not hold up, water treatment plants using HYPO were less likely to issue BWAs. The negative significance of DEV is counterintuitive. One would expect that more developed land would lead to surface runoff, creating water quality problems. However, the results seem to suggest the land cover may not be as critical a factor as initially thought, and DEV may be capturing some of the urban and water infrastructure planning effects. Both HYPO and DEV are not significant in the expanded model, suggesting that their effects are restricted only to small water districts.

Despite the lack of significance of DEV in Model II, the positive association of SEPDENS with BWAs suggests that land use factors are important in the determination of BWAs. Poorly maintained septic systems, especially their increased density, are associated with water quality problems (Hatt et al., 2004). However, since septic systems are associated with rural areas, SEPDENS could be capturing the effects of runoff from agricultural lands and feedlots. With regard to the size of the district, we had hypothesized that larger districts would fare well against smaller ones in extreme weather situations. Although the population of the water district was not a determinant of BWA, POPDENS was significant at the 10% level. The negative significance suggests that BWAs are more likely to be related to the design and layout of the infrastructure, a hypothesis that was strengthened during conversations with the water treatment operators.

5.1 Water treatment plant operators: Opinions and perspectives

In an attempt to understand some of the non-quantitative factors that may have led to a BWA, we interviewed water treatment operators of those districts that issued BWAs during TS Irene. An attempt was made to contact all the water districts affected during the storm. Despite repeated attempts, several calls to the operators were not returned, especially the ones from very small districts. Ultimately, we were able to contact ten water treatment operators, most of whom were associated with a medium or large water supply district (Table 4). Even though this number is not representative of all the water districts affected by Irene, these conversations yielded valuable insights on the regulatory process at the level of the water districts that would be otherwise impossible to ascertain from secondary datasets.

Based on the conversations, it appears that BWAs are not a common occurrence. On average, water districts issue BWAs less than once a year. Typically, BWAs are issued by the water treatment operator, while the local health department is kept informed during the issuance of the BWA. It requires two negative coliform samples and the approval of the local health department before the BWA can be lifted. Customers are notified in a variety of ways – telephone messages (reverse 911) and hand-delivered notices being the most common. Water treatment plant operators were unaware of the involvement of the state-level Department of Health in the BWA process.

Districts that issued a BWA as a precautionary measure (Rotterdam WD #3 and #5) had direction from the local health department to do so. The area surrounding the water treatment plants in both districts was evacuated due to flooding concerns. Water districts whose primary water source was a reservoir (Coxsackie, Newburgh) cited high turbidity as the cause of BWA. To meet New York standards, effluent turbidity must be below 0.3 Nephelometric Turbidity Units (NTU), and these plants were unable to meet the requirement because of the large amounts of debris and sediment in the reservoirs following heavy precipitation. In the case of Newburgh Consolidated Water District, a beaver dam upstream of the district's reservoir broke during the storm, sending the stored sediment into the water supply. Districts relying on surface water sources often have to deal with sediments from storm runoff. Following TS Irene, New York City had to use aluminum sulfate to coagulate and settle out the sediments[6].

Overall, the water districts cited water main breaks and positive coliform bacteria tests during routine sampling as the most common causes of BWAs year-round. According to New York rules, any service interruption for more than 4 hours should be followed up with a BWA. Water main breaks were the most common cause of BWAs during TS Irene (Table 6). This evidence

[6] NYC is currently investing in an integrated reservoir-management system costing $8 million that incorporates short-term weather forecasts and seasonal climate forecasts to plan ahead for major extreme events and prevent the sediment from washing into the reservoirs (Tollefson, 2013).

supports the negative significance of population density in Model II. Sparsely populated districts are likely to include long stretches of pipes to provide “last mile” coverage. In addition, these pipes likely traverse highways, bridges and uninhabited areas that may experience a lot of wear-out. As a result, these pipes may not be maintained on a regular basis. Indeed, in one case, the collapse of a bridge running over a water main caused a break in the water line, leading to the issuance of a BWA.

5.2 Additional thoughts

The aging of the water infrastructure and the increased probability of high-intensity storms occurring in the future require water utilities to prioritize their "asset management plans". As part of the plan, water supply districts should inventory their distribution lines across the district, preferably using a visual mapping tool. This will allow identification of weaknesses in the distribution system, such as exposed and vulnerable pipes and junctions, and locations where the distribution lines interact with other forms of infrastructure such as roads, bridges and railway lines. Districts with aging water mains will find this exercise especially useful, since preventive maintenance can be significantly cheaper than repairing leaks as and when they occur, especially if they occur during extreme weather situations. This could prevent or reduce the incidences of BWA issuance under normal conditions as well as during extreme weather events. These suggestions add to the recommendations of the NYS 2100 Commission (2013) that was set up to examine key vulnerabilities in New York’s critical infrastructure systems in light of recent extreme weather events like Hurricane Sandy and Tropical Storms Irene and Lee. The Commission has recommended bringing aging water infrastructure to a state of good repair, replacing damaged infrastructure with more resilient alternatives and water-proofing low-lying water treatment plants, among several others.

This study makes a significant contribution to the existing literature on the effect of extreme weather events on water infrastructure. Previous studies have investigated individual BWAs in medium and large cities, but none of them have investigated the factors leading to BWAs at this large spatial scale. We bring together information from various datasets to present a simple, yet powerful model that results in a proximate analysis of BWAs. This study encountered a few data challenges, and is therefore, not without its limitations. The NYSDOH typically does not gather data on BWAs, except during special circumstances such as this one following TS Irene. Even then, the Irene BWA was not publicly available, and had to be requested[7]. Since only 5 percent of the 678 water districts issued a BWA, the results are highly influenced by the features of a small proportion of districts. While we do not wish to have more districts issue BWAs, availability of BWA data across several storms over the years will result in a more robust analysis that is unaffected by small variations in the district-level data. The 2006 land cover data is the most recent available. Although no major changes in land cover since then are expected, we had to aggregate the various categories into a few to keep the results simpler and easier to interpret. Septic systems data, on the other hand, are extremely outdated. Ever since the U.S. Census Bureau stopped collecting tract-level data on septic systems in 1991, states have responded in variety of ways. Some states like Florida and North Carolina maintain county-level annual data on existing and newly constructed septic systems; New York does not.

The largest source of data limitations was the unavailability of information regarding the "supplyshed" of water districts. Attempts to trace the supplysheds were complicated by the fact

[7] BWA data was again collected during Tropical Storm Sandy in 2012, and was made publicly available on the NYSDOH website (http://www.health.ny.gov/environmental/water/drinking/boilwater/sandy/).

that several districts use multiple sources of water, and a large majority rely on groundwater. As a result, approximations resulting from the use of HUC-12 watersheds instead of the supplysheds could have introduced errors in the models. The low R^2 in the regression models suggests that factors other than those presented in the models could explain the probability of issuing a BWA. The lack of comparable studies precludes an accurate assessment of the role of omitted variable bias. The robustness of our results can be strengthened by analyzing BWAs across space and time.

6. Conclusions

Boil water advisories issued by water districts result in costs to residents, businesses and communities. Moreover, evidence suggests that the non-compliance of instructions provided during a BWA is extremely high, and therefore, minimizing BWAs should be a high priority for water supply systems. Thirty one of the 678 water districts in the Mohawk-Hudson watershed of New York issued BWAs in the aftermath of TS Irene in August 2011. A spatial analysis of those BWAs suggests that BWAs are positively correlated with high precipitation and density of septic systems, and negatively correlated with violations incurred in previous years and population density. Interviews with water treatment operators revealed that BWAs are primarily caused by water main breaks. Our ex-ante assumption that BWAs may have been caused by physical damage suffered by water treatment plants was not confirmed during these conversations. Proper planning and placement of water mains in relation to other infrastructure such as roads and bridges, and regular maintenance of pipes can prevent a significant proportion of the future incidences of BWAs. The inverse relationship with prior violations suggests maintenance of water treatment facilities as an additional preventive factor. Proper design and maintenance of septic systems, coupled with a strong management program, can minimize fecal contamination in sensitive waterbodies. Even though the number of BWAs issued after TS Irene is a small proportion of the total number of water districts in the watershed, minimizing or preventing future BWAs should be an action item high on the list of water districts, municipalities, and local and state health departments. Since a large proportion of those BWAs were issued by very small water districts (population < 500), steps must be taken to either consolidate neighboring water districts administratively into larger entities, or provide a funding mechanism to strengthen their infrastructure. Districts that have a history of issuing BWAs and those likely to issue one, must educate their consumers on the protocol to be followed in the event of such an emergency.

Acknowledgments

This work was supported in part by the New York State Environmental Protection Fund via the Hudson River Estuary Program of the New York State Department of Environmental Conservation. Andrew Meyer and Collin Hodges collected the initial data on BWAs from the NYSDOH. Jessica Spaccio of the Northeast Regional Climate Center provided the Irene precipitation data. Early discussions with Andrew Meyer and Peter Woodbury, and comments from anonymous reviewers were helpful. Keith Jenkins and Stephen Smith clarified several queries related to GIS mapping.

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Tables

Table 1. Characteristics of water supply districts in the Mohawk-Hudson watershed

Water supply districts		**Very Small (500 or less)**	**Small (501-3,300)**	**Medium (3,301-10,000)**	**Large (10,001-100,000)**	**Very Large (>100,000)**	**Totals**
USA[1]	# Systems (%)	283,462 (55%)	13,737 (27%)	4,936 (10%)	3,802 (7%)	419 (1%)	51,356
	Population (%)	2%	7%	10%	36%	46%	100%
New York[2]	# Systems (%)	946 (50%)	582 (31%)	183 (10%)	158 (8%)	24 (1%)	1893
	Population (%)	1%	3%	5%	21%	70%	100%
Mohawk-Hudson watershed[2]	# Systems (%)	348 (58%)	158 (26%)	56 (9%)	38 (6%)	4 (1%)	604
	Population (%)	3%	9%	14%	51%	23%	100%

The water supply districts are categorized by USEPA according to the number of people served.
Source: [1]2006 Community Water System Survey (USEPA, 2009), [2]NYSDOH (2012)

Table 2. Data sources

Database Name	Data Type	Source
Tropical Storm Irene precipitation data	Total rainfall during Tropical Storm Irene (Aug 27-29, 2011)	NRCC, 2012
Annual reports of public water supply violations	NYS water supply district violation descriptions and history	NYSDOH, 2013a
National land cover database	Land cover characteristics	NLCD (Fry et al., 2011)
HUC-12 watershed boundaries	Watershed boundary geospatial data	NRCS, 2013
1990 decennial census	Number of septic systems per census block group	NHGIS (Minnesota Population Center, 2011)
Data on public water supply systems	Water supply system characteristics and treatment plant parameters	NYSDOH, 2012
Descriptive information on the BWA process	Frequency, causes and resolutions of BWAs	Phone interviews with water treatment plant operators

Table 3. Variable definitions and statistics

Variables	Description	Min	Max	Median	Mean	St. dev.
GW	Dummy for systems using groundwater as their water source	0	1	1	0.71	0.45
UDI	Dummy for systems using Ground water under the direct influence (UDI) of surface water as their water source	0	1	0	0.06	0.23
SW	Dummy for systems using surface water as their water source	0	1	0	0.23	0.42
POP	Number of people[1]	10	223082	408	4140.44	15190.38
POPDENS	Population density[1] (persons per sq. km)	5.39	34022.0	1259.92	1957.94	2604.07
IRPREC	Average rainfall during TS Irene[1] (mm)	35.14	291.57	173.99	162.55	41.66
DEV	Developed land[2] (%)	0.31	75.05	13.42	18.91	14.20
AGRI	Agricultural land[2] (%)	0	62.30	14.15	17.21	13.94
SEPDENS	Density of septic systems[2] (per sq. km)	0	84653.6	513.24	3914.89	8347.24
GASCHLOR	Dummy for systems that use gaseous chlorination as	0	1	0	0.07	0.26

	their only form of disinfection					
HYPO	Dummy for systems that use hypochlorination as their only form of disinfection	0	1	1	0.85	0.36
MULTIDIS	Dummy for systems that use multiple forms of disinfection	0	1	0	0.07	0.26
VIOL	Average violations per daily production[1] (per million gal)	0	3000	0	31.85	149.80

Notes: The areas of measurement are [1]water districts and [2]HUC-12 watersheds that contain the water district.

Table 4. Classification of water districts that issued BWA during TS Irene

	Very Small (500 or less)	**Small (501-3,300)**	**Medium (3,301-10,000)**	**Large (10,001-100,000)**	**Very Large (>100,000)**	**Total**
Districts issuing BWA	20	4	5	2	0	31
Interviewed water treatment operators	2	2	4	2	-	10

Table 5. Logistic regression estimates for factors resulting in BWA

Variable	Model I[1]	Model II[2]
Water supply source GW[3]	-	-
UDI	1.08 (1.31)	0.81 (.889)
SW	0.73 (.666)	1.22 (.861)
POP	0.99 (.001)	1.01 (.001)
POPDENS	0.99 (.001)	0.99* (.001)
IRPREC	1.01** (.007)	1.01** (.006)
DEV	0.94* (.029)	0.97 (.023)
AGRI	1.01 (.019)	1.01 (.015)
SEPDENS	1.01 (.001)	1.01* (.001)
Disinfection GASCHLOR[3]	-	-
HYPO	0.11** (.110)	1.79 (2.23)
MULTIDIS	Omitted[4]	4.93 (6.07)
VIOL	.86*** (.049)	0.84** (.066)
Constant	0.17 (.218)	0.01*** (.010)
N	471	576
Chi-sq (prob.)	70.83 (.000)	29.84 (.002)
Pseudo-R^2	0.19	0.14

[1]Only systems classified as small and very small (POP < 3300), [2]all systems, [3]reference variable, [4]omitted by the model due to lack of sufficient data points.

Parameter estimates are odds ratios (robust standard errors in parenthesis), *p < 0.1, **p < 0.05, ***p < 0.01

Table 6. Summary description of water supply districts that were interviewed.

Water supply district	County	Population	Water source	Reported failure	BWA duration (days)
Newburgh Consolidated WD	Orange	56113	SW	High turbidity	30
Rotterdam WD #5	Schenectady	28000	GW	Precautionary issuance	2
Washingtonville Village	Orange	8000	GW	Water main break	7
Warwick Village	Orange	6083	SW	Water main break	5
Coxsackie Village	Greene	4474	SW	High turbidity	4
Rhinebeck Village Water	Dutchess	4300	SW	Water main break	6
Rotterdam WD #3	Schenectady	1955	GW	Precautionary issuance	5
Schoharie Village	Schoharie	922	UDI	Water main break, drained water supply	12
Windham WD	Greene	230	GW	Water main break	16
Hill N Dale Trailer Park	Orange	50	GW	Pump failure	6

Figures

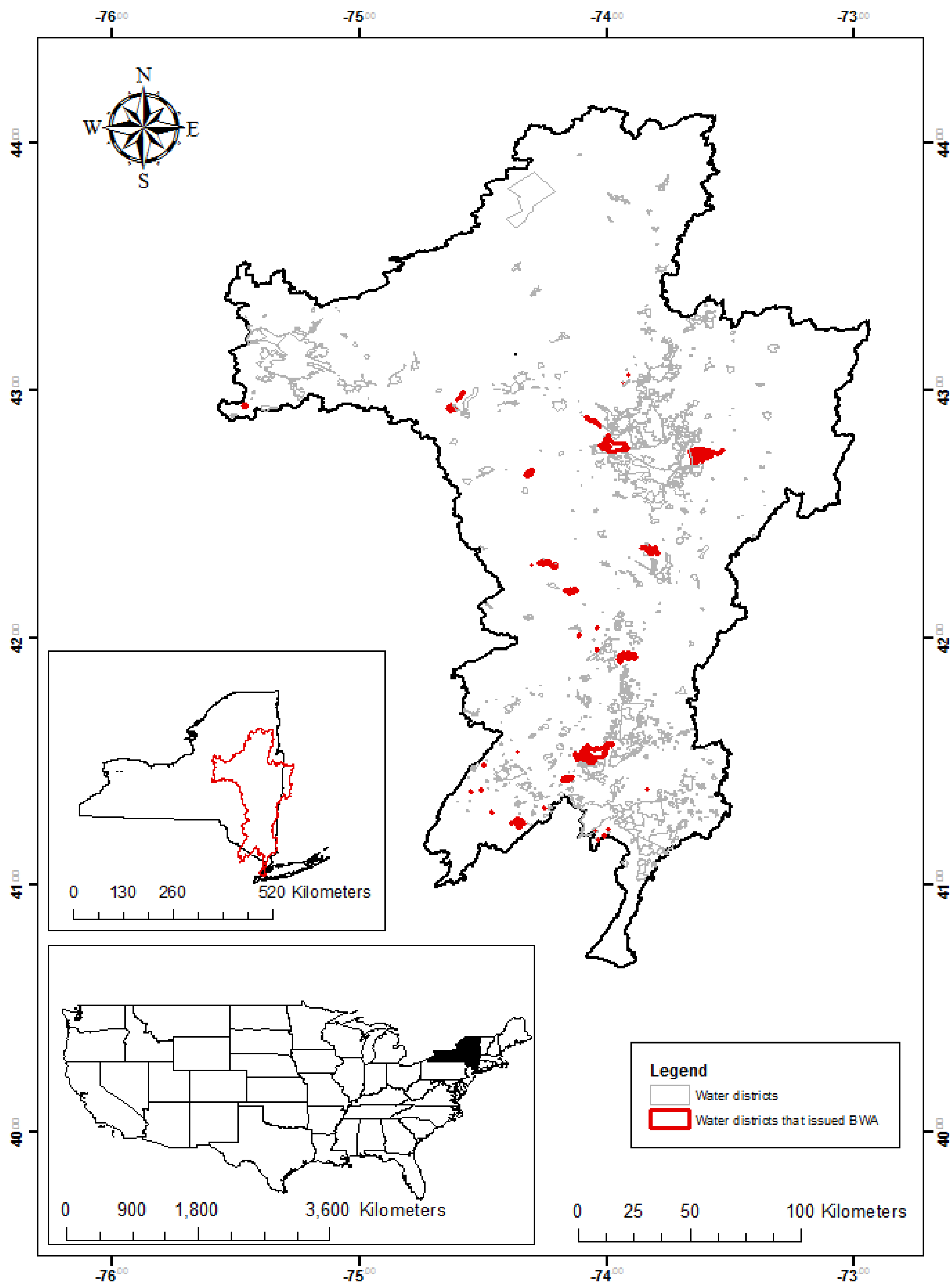

Figure 1. Water supply districts in the Mohawk-Hudson watershed. Districts that issued a boil water advisory during Tropical Storm Irene are highlighted in red.

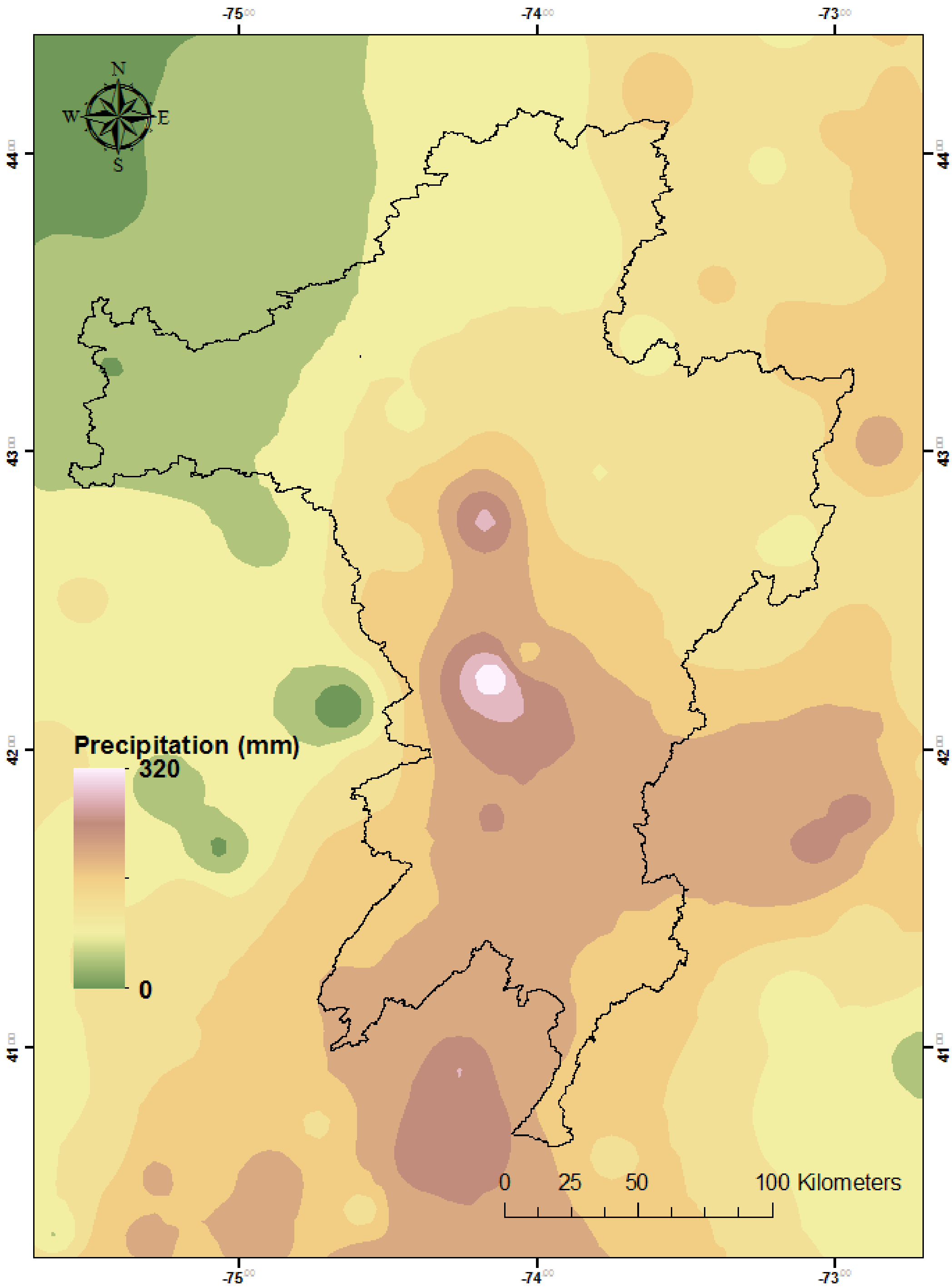

Figure 2. Precipitation in the Mohawk-Hudson watershed during Tropical Storm Irene (August 27-29, 2011).

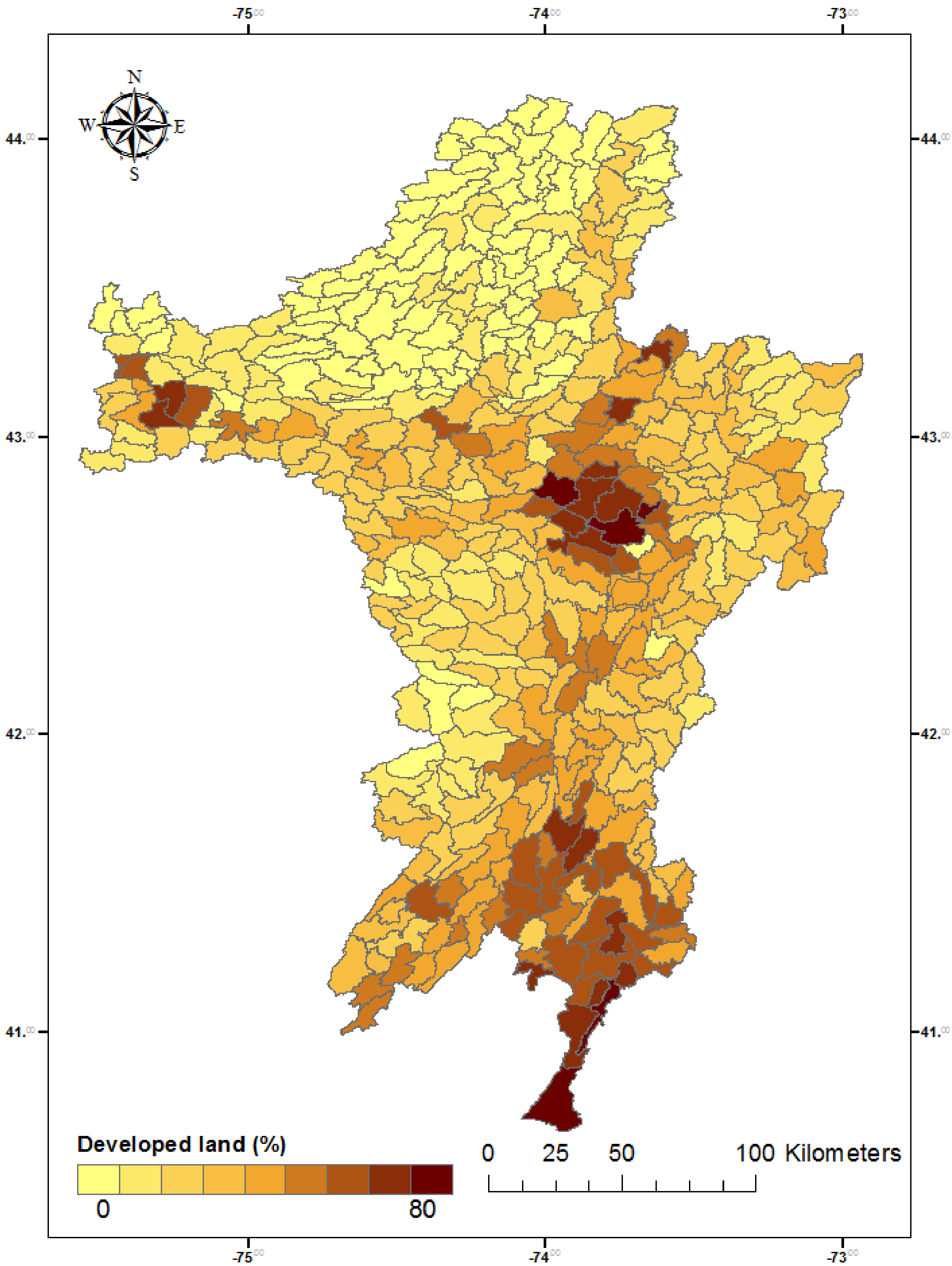

Figure 3. Proportion of developed land within each HUC-12 watershed. Darker color indicates high level of development.

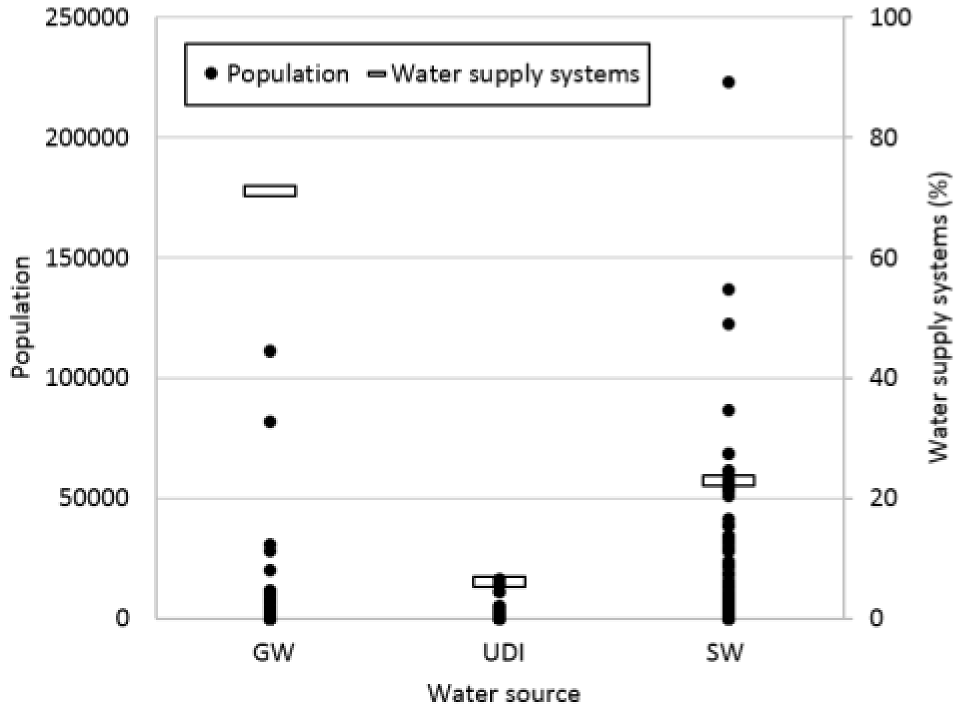

Figure 4. Water supply systems and their population served, categorized by water source. GW: groundwater, UDI: groundwater under direct influence of surface water, SW: surface water. Even though SW is the primary water source for only a quarter of the systems, it serves three-quarters of the residents in the region.

Information Transfer Program Introduction

The Director and staff of the NYS Water Resources Institute undertake public service, outreach, education and communication activities. Most are conducted through multidisciplinary projects funded outside the Water Resources Research Act (WRRA) context. In order to couple WRRA activities to other NYS WRI activities, a portion of WRRA resources are devoted to information transfer through a partnership program with the Hudson River Estuary Program, dissemination of information related to emerging issues, and student training.

Coordination of a Flood Resilience Research, Outreach, and Implementation Project for the Hudson River Estuary Program

Basic Information

Title:	Coordination of a Flood Resilience Research, Outreach, and Implementation Project for the Hudson River Estuary Program
Project Number:	2013NY204B
Start Date:	3/1/2013
End Date:	12/31/2013
Funding Source:	104B
Congressional District:	NY-23
Research Category:	Climate and Hydrologic Processes
Focus Category:	Management and Planning, Climatological Processes, Floods
Descriptors:	None
Principal Investigators:	Susan Riha

Publications

1. Gary, Gretchen; Shorna Allred; Elizabeth LoGiudice; Allison Chatrchyan; Rosemarie Baglia; Theresa Mayhew; Dianne Olsen; and Marilyn Wyman; Community Adaptation to Flooding in a Changing Climate: Municipal Officials' Actions, Decision-Making, and Barriers, Cornell University's Community & Regional Development Institute, Research & Policy Brief Series, No 57
2. Website created at: http://wri.eas.cornell.edu/estuary-resilience.html

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Estuary Resilience Project:

Building Long-term Resilience to Extreme Weather and Climate Change in the Hudson River Estuary Watershed

Summary prepared September 17, 2013

Overview

The Estuary Resilience Project is a combination of research, demonstration, and educational outreach projects to address the challenges of flooding, stream and watershed management, and climate change. It is a partnership being led by the New York State Water Resources Institute (NYS WRI) at Cornell University and Cornell Cooperative Extension (CCE), with support from the New York State Department of Environmental Conservation's Hudson River Estuary Program (HREP). Project website: http://hudsonestuaryresilience.net

Timeframe

The overall project started July 2012, with specific components starting fall 2012 or spring 2013 and continuing through December 2013..

DEPARTMENT OF ENVIRONMENTAL CONSERVATION · NEW YORK STATE

Hudson River Estuary

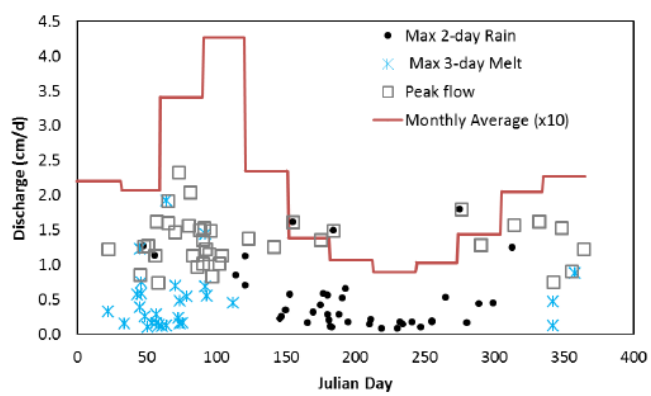
Project Components

Research to understand causes and spatial patterns of flooding, identify watershed planning and infrastructure management options, and inform outreach and education.

New York State has been impacted by many major floods in the last decade and will continue to experience high precipitation events and sea level rise in the coming decades. Research projects are underway at NYS WRI and our project partners to analyze the causes and spatial patterns of past floods; to identify watershed planning and infrastructure management options; develop information and tools for decision-makers to use to increase future flood resilience.

Assessing Flood Risk in a Changing Climate in the Mohawk and Hudson River Basins
Steven Shaw, Assistant Professor, and Ashley Ryan, graduate student, Dept. of Environmental Resources Engineering, SUNY Environmental Science and Forestry.

- This project is assessing historical causes of flooding in the Mohawk and Hudson River valleys, including high precipitation, ice dams, and snow melt.
- Most annual maximum discharges are not directly linked to the largest annual precipitation event or snowmelt event. Instead, they most often occur when there is a moderate amount of precipitation falling on already wet soils. Moderate stage heights in the Mid-Hudson are determined by a complex interaction of downriver ocean elevation, upland inflows from precipitation, and wind-induced river run-up. The very highest stage heights are associated with combinations of these factors with at least one exceptionally high.
- With respect to future climate change, we need to look not just at precipitation trends but whether there is evidence for greater clustering of high intensity precipitation or wetter soils.
- They are assessing patterns in the historical temperature records and reports of ice jams. If a temperature-based metric proves predictive, it can possibly be used to approximate frequency of ice jams in the future using climate change projections.
- The project will create a statistical framework for assessments of how future flood risk may change, summarized in a public outreach document.



Culvert Assessment: Determining Peak Flow Under Different Scenarios and Identifying Undersized Culverts

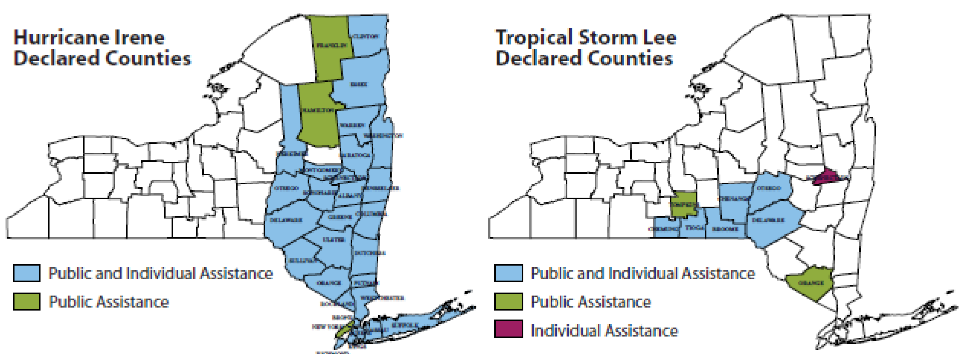
Todd Walter, Associate Professor, Dept. of Biological and Environmental Engineering, Cornell University; Art DeGaetano, Professor, Dept. of Earth and Atmospheric Sciences and Northeast Regional Climate Center, Cornell University; Emily Svenson, Coordinator, Lower Hudson Coalition of Conservation Districts; and Andrew Meyer, Shoreline Conservation Specialist, HREP.

- This project will identify culverts that are undersized for both current and future precipitation conditions. A geographic database of culvert capacities throughout several sub-watersheds in the Hudson River Basin is being developed. Peak storm discharges at each culvert for current and future weather conditions are being modeled.
- An online culvert-capacity calculator will be developed for use in additional watersheds.
- Information will be presented to local agencies including the economics of replacing culverts to allow for integration into municipal planning and maintenance programs.

Assessment of Extreme Weather Impacts on Water Infrastructure

Sri Vedachalam, Post-Doctoral Associate, NYS WRI, Cornell University.

- This project will document economic impacts of recent major storms such as Irene, Lee, and Sandy on the water and wastewater infrastructure in the Hudson River watershed.
- It will also document other economic and environmental impacts due to these storms in the Hudson River estuary and identify factors leading to the differences in the impacts in the various sub-watersheds in the region.



Literature review of stream restoration techniques

Amy Galford, Extension Associate, NYS WRI, Cornell University.

- A review of the scientific literature on stream restoration techniques will be used to inform educational components of the project and identify research gaps.
- The goals of stream restoration projects vary widely, from flood prevention to protecting specific infrastructure to habitat development. Monitoring and evaluation are infrequent and often qualitative, but should be built into projects as much as possible.

Outreach to local government to assess local government needs and provide training on stream function and watershed management to local officials and contractors.

Some stream restoration techniques used after flood events are counterproductive, possibly increasing the potential cost of future storm impacts; they do not stop major flooding, create erosive forces upstream and downstream, and may degrade habitat. Local government employees and contractors involved in post-flood response need be trained in stream and floodplain processes and provided with tools to make educated decisions about flood mitigation. Municipal officials also need to understand the functions of streams and floodplains and how land use decisions can reduce the impacts associated with flooding.

Local Needs Assessment and Educational Program Evaluation

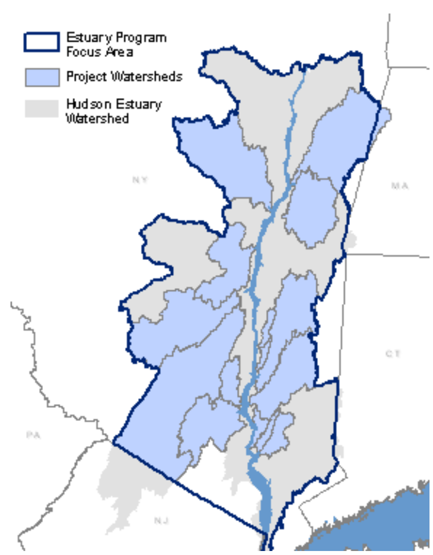
Shorna Allred, Associate Professor, and Gretchen Gary, Extension Associate, Dept. of Natural Resources, Cornell University.

- In close cooperation with the CCE & SWCD outreach described below, they are conducting needs assessments and behavioral surveys in multiple watersheds. Interviews with local municipal officials on recent flood experience have been completed and analysis is underway.
- They have assisted with program evaluation of specific training events and workshops.
- Ultimately the project will evaluate the capacity of communities to respond to floods in a manner that reduces future flooding impacts and ensures the long-term viability of stream systems. Literature reviews relevant to this have been completed.

Local Outreach and Education for Municipal Officials

Cornell Cooperative Extension educators (Liz LoGiudice, Ron Frisbee, Marilyn Wyman, and Terri Mayhew, CCE Columbia-Greene; Carolyn Klocker and Neil Curri, CCE Dutchess; Rosemarie Baglia, CCE Orange; Dianne Olsen, CCE Putnam; and others), and Lower Hudson Coalition of Conservation Districts (Emily Svenson and others).

- Extension educators are providing audiences such as town and planning board members with information about their local watershed, stream and floodplain functions, causes of flooding, the role of land use in flooding, and techniques to restore stream integrity after floods.
- The project has been introduced to town and planning board members in several counties and a variety of educational workshops have been held or are planned for this fall.



Local Outreach and Education for Highway Personnel and Contractors
Cornell Cooperative Extension educators (Ron Frisbee, Liz LoGiudice, CCE Columbia-Greene and others) and Lower Hudson Coalition of Conservation Districts (Emily Svenson and others).

- The DEC-endorsed training program on emergency post-flood stream intervention has been adapted for the Hudson Valley.
- Topics include stream and floodplain dynamics, impacts of land use and climate change on flood risk, post-flood stream damage assessment, how to decide whether in-stream work is needed, channel design and sizing, options for controlling erosion near infrastructure, and case studies from other New York watersheds.
- This effort is increasing local capacity by training SWCD personnel, local highway department personnel, and local contractors. Trainings have been held in Greene and Dutchess counties, with additional training events scheduled and curriculum development underway.

Public education including demonstration projects to educate the public of all ages about stream and watershed functions, why this matters for watershed management, and how climate change will affect the Hudson River Estuary.

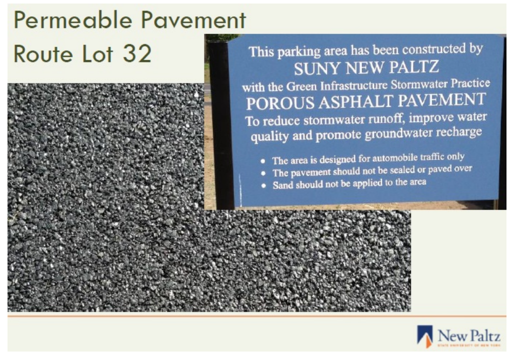
The consequences of flooding and climate change impact everyone in the estuary watershed. Our project partners will be educating multiple student groups, landowners, and the general public, and developing curriculum for a variety of future uses.

Local Outreach and Education for Streamside Landowners
Cornell Cooperative Extension educators (Liz LoGiudice, Ron Frisbee, Marilyn Wyman, and Terri Mayhew, CCE Columbia-Greene; Carolyn Klocker and Neil Curri, CCE Dutchess; Rosemarie Baglia, CCE Orange; Dianne Olsen, CCE Putnam; and others) and Shorna Allred, Associate Professor, and Gretchen Gary, Extension Associate, Dept. of Natural Resources, Cornell University.

- A variety of educational events will provide education to streamside landowners about local watersheds, stream and floodplain functions, land use, and actions they can take related to flood mitigation and stormwater management.
- A survey of homeowner attitudes and behaviors has been distributed to owners identified from real estate records and GIS analysis.

Green Infrastructure to Improve Watershed Resilience in the Saw Mill Brook Watershed and Village of New Paltz
K.T. Tobin, Assistant Director, Center for Research, Regional Education, and Outreach; Dave Richardson, Biology; Ro Millham, Elementary Education; additional faculty, SUNY New Paltz

- Green infrastructure is being implemented to manage stormwater in an area of the SUNY New Paltz campus and the village with a history of flooding. An accompanying walking tour with interpretive maps and signage and a curriculum for youth field trips will be developed. Assistance is being provided to the Village of New Paltz stream daylighting project.
- Water quality is being monitored in Saw Mill Brook relative to storm events and green infrastructure. Undergraduates are participating in this research and it will be integrated into interdisciplinary courses.
- They are organizing and participating in regional conferences and networking about green infrastructure on college campuses in the Hudson Valley and throughout SUNY.



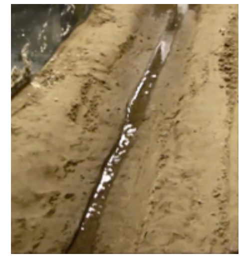
Integrating Climate Change Messages into K-12 Estuary Lesson Plans
Nordica Holochuck, Cornell University/New York Sea Grant

- Curriculum on climate change will be adapted and customized for students in the Hudson Estuary with a focus on inquiry and future job opportunities.
- Topics will include climate literacy, the carbon cycle, adaptation and mitigation, and structural and personal solutions.
- Curriculum will be included in Hudson Estuary web-based lesson plans available on the NYS DEC HREP website and advertised via regional educational conferences.

Physical Demonstrations of Stream Dynamics Appropriate for Tributaries of the Hudson River Estuary
Deb Grantham, Senior Extension Associate, Dept. of Crop and Soil Sciences; Amy Galford, Extension Associate, NYS WRI; Edwin (Todd) Cowen, Associate Professor, and Diego Muriel Delgado, graduate student, School of Civil and Environmental Engineering, Cornell University

- Videos of water flowing in a sediment flume will be used to convey concepts about stream dynamics, floodplains, upstream-downstream connections, and impacts of reinforcing stream edges.
- Videos will be posted

online with supplemental materials such as figures, photographs, and text.



Director's Office, Information Transfer

Basic Information

Title:	Director's Office, Information Transfer
Project Number:	2013NY217B
Start Date:	3/31/2013
End Date:	2/28/2014
Funding Source:	104B
Congressional District:	NY-23
Research Category:	Not Applicable
Focus Category:	None, None, None
Descriptors:	
Principal Investigators:	Susan Riha, Brian Gramlich Rahm

Publications

1. Vedachalam, S.; Riha, S.J. 2013. Comment on 'Energy and air emission implications of a decentralized wastewater system.' Environmental Research Letters, 8(1):019001
2. Rahm, B.G., Bates, J., Bertoia, L.R., Galford, A.E., Yoxtheimer, D.A.; Riha, S.J. 2012. Wastewater management and Marcellus Shale gas development: Trends, drivers, and planning implications. Journal of Environmental Management, 120:105-113
3. Armstrong, A.; Stedman, R.C.; Roessler, B.; Cuppett, C. 2013. Beyond the trees: Community as a riparian resotration outcome and resource. Water Resources Impact, 15(2):6-8.
4. Rahm, B.G.; Vedachalam, S.; Shen, J.; Woodbury, P.B.; Riha, S.J. 2013. A watershed-scale goals approach to assessing and funding wastewater infrastructure. Journal of Environmental Management, 129:124-133
5. Vedachalam, S.; Riha, S.J. 2013. Small is beautiful? State of the dams and management implications for the future. River Research and Applications, DOI: 10.1002/rra.2698
6. Vedachalam, S.; Kay, D.L.; Riha, S.J. 2013. Public opinion on water and wastewater infrastructure issues. Cornell University Community and Regional Development Institute Research & Policy Brief Series, Issue 56: October

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New York State Water Resources Institute FY2013

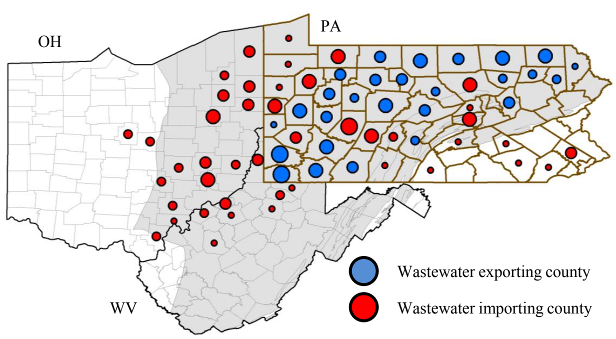
The mission of the New York State Water Resources Institute (WRI) is to increase awareness of emerging water resources issues and to identify creative ways to improve the management of water resources in New York State and beyond. Additionally, WRI acts as bridge to foster communication and knowledge exchange between the various stakeholder groups, government agencies, and research institutions that are engaged with water resources management in New York State.

During FY2013, staff research and information transfer focused on the following major areas:

1. **Responding to potential shale gas development and associated hydraulic fracturing**
2. **Assessment and funding of public water resource infrastructure**
3. **Long-term resilience to extreme weather events and climate change**

Additional research and information activities on various topics were conducted as appropriate and needed.

Shale Gas & Hydraulic Fracturing



Above: A figure from WRI publication "Wastewater management and Marcellus shale gas development: Trends, drivers, and planning implications," released in the Journal of Environmental Management

What we do

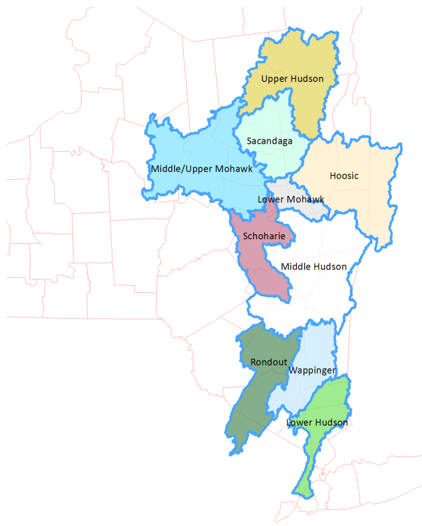
Activities associated with the recovery of natural gas from shale, such as the Marcellus Shale in NY, can have significant impacts on water resources. There remains a robust and at times contentious public discussion of the type and severity of these risks. WRI has supported and added to this discussion by providing objective and timely analyses. In the past year WRI has:

- Published a peer-reviewed study "Wastewater management and Marcellus shale gas development: Trends, drivers, and planning implications," in the *Journal of Environmental Management*, 2013
- Submitted commentary on NYSDEC's "Proposed High Volume Hydraulic Fracturing Regulations," 2013
- Written and oral testimony before the US House of Representatives Joint Subcommittees on Environment and Energy of the Committee on Science, Space, and Technology, "Lessons Learned: EPA's Investigations of Hydraulic Fracturing," July 24th, 2013

Public Water Infrastructure

What we do

Replacing and upgrading aging water infrastructure throughout the State will require investment of billions of dollars from both public and private entities over the coming decades. This infrastructure is critical to maintaining and improving environmental and public health. The Smart Growth Public Infrastructure Policy Act of 2010 prioritizes the funding of public infrastructure projects that promote *smart growth*.

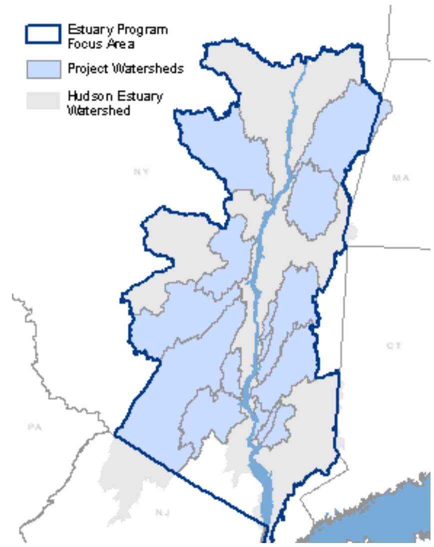


Above: New York watersheds in the Hudson and Mohawk basins, the location of WRI analyses of infrastructure function, efficiency, and funding

Using data from state and federal agencies, as well as local municipalities and utilities, WRI is investigating the state of public infrastructure and exploring strategies for investing in capital projects. The goal of these analyses is to aid planners and public decision makers at various levels of government, and to generate insight with respect to strategic management of state funds and the maintenance and improvement of public health and New York's environmental assets. In the past year WRI has:

- Published a peer-reviewed study "A watershed-scale goals approach to assessing and funding wastewater infrastructure," in the *Journal of Environmental Management*
- Continued and initiated multidisciplinary research with experts in city and regional planning, business management, natural resources, environmental engineering, and policy analysis
- Published a document synthesizing a range of WRI conducted and funded work throughout NY on water infrastructure: http://wri.eas.cornell.edu/WRI_Infrastructure_Research_Summary_2013.pdf

Extreme Weather & Climate Change



Above: Focus areas of research and outreach efforts in the Hudson River estuary of NY

What we do

New York State has been impacted by many major floods in the last decade and will continue to experience high precipitation events and sea level rise in the coming decades. Research projects are underway at WRI and our project partners to analyze the causes and spatial patterns of past floods, to identify watershed planning and infrastructure management options, and to develop information and tools for decision-makers to use to increase future flood resilience. Completed projects include:

- Assessing flood risk in a changing climate in the Mohawk and Hudson River Basins (SUNY ESF)
- Determining peak flow under different scenarios and identifying undersized culverts (Cornell University and county Soil and Water Conservation Districts)
- Documenting impacts of storms Irene, Lee, and Sandy on water and wastewater infrastructure and shoreline communities in the Hudson Valley (NYS WRI)
- Watershed resilience education in the Hudson River Estuary: Needs assessment and program evaluation (Cornell University)
- Integrating Climate Change Messages into K-12 Estuary Lesson Plan Offerings (NY Sea Grant)

A more complete list of NYSWRI activities follows. For more information please email Director Susan J Riha at nyswri@cornell.edu, or call (607) 255-3034, Website: wri.eas.cornell.edu

New York State Water Resources Institute FY2013 Activity

Peer Reviewed Publications

1. Vedachalam, S.; Kay, D.L.; Riha, S.J. 2013. Public opinion on water and wastewater infrastructure issues. *CaRDI Research & Policy Brief Series*, Issue 56: October [link]. Reprinted in 2013, *Clear Waters*, 43 (Winter): 53-55.

2. Vedachalam, S.; Riha, S.J. 2013. Small is beautiful? State of the dams and management implications for the future. *River Research and Applications* [link].

3. Rahm, B.G.; Vedachalam, S.; Shen, J.; Woodbury, P.B.; Riha, S.J. 2013. A watershed-scale goals approach to assessing and funding wastewater infrastructure. *Journal of Environmental Management*, 129:124-133 [link].

4. Rahm, B.G., Bates, J., Bertoia, L.R., Galford, A.E., Yoxtheimer, D.A.; Riha, S.J. 2012. Wastewater management and Marcellus Shale gas development: Trends, drivers, and planning implications. *Journal of Environmental Management*, 120:105-113 [link, preprint].

5. Vedachalam, S.; Riha, S.J. 2013. Comment on 'Energy and air emission implications of a decentralized wastewater system.' *Environmental Research Letters*, 8(1):019001 [link].

Outreach and non-Refereed Publications

1. NYSDEC/NYSWRI. 2013. Climate Summary: Town of Germantown. Report submitted to the Town of Germantown, NY [link].

2. NYSDEC/NYSWRI. 2013. Water Resource Summary: Town of Germantown. Report submitted to the Town of Germantown, NY [link].

3. Provided manuscript and information in support of S. 601 Water Resources Development Act of 2013 on request to the office of U.S. Sen. Charles Schumer (NY). April/May [link].

Conference Presentations & Invited Talks

1. Haeckel, I.; Meyer, A.; Murphy, E. 2013. Natural Resources and Climate Resiliency in Germantown: Presentation to the Town of Germantown. Germantown, NY. December 7 [link].

2. Rahm, B.G.; Vedachalam, S.; Woodbury, P.B.; Riha, S.J. 2013.Assessing Wastewater Infrastructure Using a Watershed-Scale Goals Approach. AWRA Annual Water Resources Conference. Portland, OR. November 4-7.

3. Vedachalam, S.; Rahm, B.G.; Choi, J.; Riha, S.J. 2013.The Effect of Size on Operational Efficiency of Wastewater Treatment Systems. AWRA Annual Water Resources Conference. Portland, OR. November 4-7.

4. Rahm, B.G.; Shaw, S.B.; Hill, N.; Perry, C.; Riha, S.J. 2013. In-Stream Nitrogen Dynamics and Engineered Systems: Opportunities at the End of the Pipe. AWRA Annual Water Resources Conference. Portland, OR. November 4-7.

5. Meyer, A. 2013. Culvert Sizing Project: Identifying Undersized Culverts in Three Focal Watersheds of the Hudson River Estuary Watershed. Moodna Watershed Intermunicipal Council. October 28. Also presented at the Rural Roads Workshop organized by Hudson River Estuary Program and Columbia Land Conservancy. October 29 [link].

6. Meyer, A. 2013. Dam and Culvert Barriers: Aquatic Barriers in the Hudson River Estuary Watershed. Trout Unlimited, Mid Hudson Chapter. October 16 [link].

7. Cuppett, S. 2013. Hudson River Watershed Management and Issues: A Watershed Dinner Story. Westchester Water Works Conference. Chappaqua, NY. October 7 [link].

8. Meyer, A; Vail, E.E.; Lamb-Lafay, C.; Gasper, D. 2013. Stormwater and Watershed Resiliency. NY Upstate Chapter of the American Planning Association and the American Society for Landscape Architects. Schenectady, NY. September 25-27 [link].

9. Vedachalam, S.; DeStefano, K.; Polan, S.; Lewenstein, B.; Riha, S.J. 2013. Media Discourse on Aging Water Infrastructure in the U.S. Association for Environmental Studies and Sciences 2013 Annual Conference. Pittsburgh, PA. June 19-22.

10. Meyer, A. Barriers to Aquatic Connectivity in the Hudson River Estuary Watershed. Black Rock Forest Consortium 8th

Research Symposium. Cornwall, NY. June 17 [link].

11. Rahm, B.G. 2013. Wastewater Management & Shale Gas Development: What NY Should Know About Trends in the Marcellus Shale and Elsewhere. NYWEA Spring Technical Conference. Syracuse, NY. June 4.

12. Cuppett, S. 2013. Watershed Protection, Management, and Action in the Hudson Estuary Watershed. Leadership Workshops for Local Water Systems. New Paltz, NY. June 13-14 [link].

13. Galford, A.; Vedachalam, S.; Riha, S.J. 2013. Homeowner Education Workshops on Wastewater Management in Two Lakeshore Communities. New York State Federation of Lake Associations. Hamilton, NY. May 4 [link].

14. Czajkowski, K. 2013. Phase II Stormwater and the MS4 Program. Presented to the Cities of Troy and Rensselaer, Village of Voorheesville, and Towns of Catskill and Rotterdam [link].

15. Czajkowski, K. 2013. Mohawk River Basin Program. University at Albany, Abany, NY. April 18 [link].

16. Czajkowski, K. 2013. Water Quality, Watersheds, and Opportunities for Action. Retirees in Service to the Environment (RISE), in association with the Cornell Cooperative Extension Schenectady. April 10 [link].

17. Rahm, B.G. 2013. Invited panelist at the Farm Foundation Forum: Natural Gas Extraction - Impacts on Rural America, held at the National Press Club, Washington, DC. April 3 [link].

18. Vail, E. 2013. Climate Smart Communities -- Green Infrastructure Case Studies. Presented as part of the NYS Climate Smart Communities webinar series. March 28 [link].

Press

1. Germantown plans Conservation Advisory Council in 2014. *Register-Star* (Hudson, NY), December 30 [link].

2. Students soak up science. *The New Paltz Oracle*, December 12 [link].

3. Green 'gem' will filter stormwater. *Poughkeepsie Journal*, Nov 17 [link].

4. Vassar students plant 1,000 trees, *Poughkeepsie Journal*, September 11 [link].

5. NYSWRI researcher testifies in front of a joint US House Subcomittee hearing [Press release]. Media coverage: Pittsburgh Post-Gazette, Poughkeepsie Journal,

6. CLMC hosts lake health workshop, *The Post-Journal*, May 12 [link].

7. "The Mystery of Eels", *Nature on PBS*, screening and live chat with experts, April 18 [link].

8. DEC issues final permit for Cornell University's lake source cooling facility, *NYSDEC Press Release*, March 27 [link].

9. Study: Shale gas fracking taints rivers in Pennsylvania, *Circle of Blue*, March 21 [link].

10. Septic maintenance key component to protecting watershed, *The Post-Journal* (Jamestown, NY), March 7 [link].

11. Workshop on wastewater management to be held at BOCES Center Wednesday, *The Post-Journal* (Jamestown, NY), March 3 [link].

12. Private frack water treatment expanding in Marcellus region, *Innovation Trail/WSKG*, March 1 [link].

13. NYSP2I announces recepients of 2012-2013 Community Grants Program, *NYSP2I Press Release*, February 22 [link].

USGS Summer Intern Program

None.

Student Support					
Category	**Section 104 Base Grant**	**Section 104 NCGP Award**	**NIWR-USGS Internship**	**Supplemental Awards**	**Total**
Undergraduate	4	0	0	0	4
Masters	0	0	0	0	0
Ph.D.	0	0	0	0	0
Post-Doc.	1	0	0	1	2
Total	5	0	0	1	6

Notable Awards and Achievements

July 24, 2013 – Brian G Rahm testified on "Lessons Learned: EPA's Investigations of Hydraulic Fracturing." US House of Representatives Subcommittee on Environment and Subcommitte on Energy Joint Hearing. Washington, D.C.

Publications from Prior Years

1. 2011NY162B ("Reach-Scale Patterns in Hyporheic Exchange at Pristine, Degraded and Restored Rivers") - Articles in Refereed Scientific Journals - Becker, Joseph F.; Theodore A. Endreny, Jesse D. Robinson, 2013, Natural channel design impacts on reach-scale transient storage, Ecological Engineering, 57, 380-392.
2. 2011NY161B ("NITROGEN (N) AVAILABILITY AS DRIVER OF METHYLMERCURY PRODUCTION IN FORESTED SOILS AND STREAM SEDIMENTS ") - Articles in Refereed Scientific Journals - Vidon, P., Carleton W., Mitchell M., 2014. Spatial and temporal variability in stream dissolved organic carbon quantity and quality in an Adirondack forested catchment. Applied Geochemistry, 46, 10-18.
3. 2011NY161B ("NITROGEN (N) AVAILABILITY AS DRIVER OF METHYLMERCURY PRODUCTION IN FORESTED SOILS AND STREAM SEDIMENTS ") - Conference Proceedings - Carleton, W., P. Vidon, M. Mitchell, 2012. Total mercury and methylmercury dynamics: Stream export in an upland forested watershed in the Adirondack region of New York State. Abstract # B31C-0432. American Geophysical Union Annual Meeting. San Francisco, California, December 2012.
4. 2011NY165B ("Two-Dimensional River Model for Predicting Bacterial Contamination of Bathing Beaches in the St. Lawrence River") - Conference Proceedings - Twiss, M. R., Smith, D. E., Ulrich, C., Kramer, S. J., Skufca, J. D., Bollt, E., 2011, Do Nearshore Water Quality Transitions Reflect Functional Process Zones Along the International Section of the St. Lawrence River? How 2-D Hydraulic Models Can Be Used to Describe Plankton Dynamics in this Major River Reach, 18th Annual Conference on the Great Lakes/St. Lawrence River Ecosystem, St. Lawrence River Institute of Environmental Sciences, Cornwall, ON.
5. 2011NY165B ("Two-Dimensional River Model for Predicting Bacterial Contamination of Bathing Beaches in the St. Lawrence River") - Conference Proceedings - Harvey, A. M., Marshall, N. F., Skufca, J. D., Twiss, M. R., 2012, Monitoring fecal coliforms to protect public health: Using 2D river modeling to help predict fecal coliform presence at Coles Creek State Park Beach", Great Lakes Research Consortium Annual Student/Faculty Conference, Great Lakes Research Consortium, Oswego, NY.