Journal of Environmental Management 129 (2013) 124–133

Contents lists available at SciVerse ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

A watershed-scale goals approach to assessing and funding wastewater infrastructure

Brian G. Rahm [a,*], Sridhar Vedachalam [a], Jerry Shen [a], Peter B. Woodbury [b], Susan J. Riha [a]

[a] New York State Water Resources Institute, Department of Earth & Atmospheric Sciences, Cornell University, 1123 Bradfield Hall, Ithaca, NY 14853, USA
[b] Department of Crop & Soil Sciences, Cornell University, 232 Emerson Hall, Ithaca, NY 14853, USA

ARTICLE INFO

Article history:
Received 21 December 2012
Received in revised form
2 May 2013
Accepted 26 June 2013
Available online

Keywords:
Infrastructure
Wastewater
POTW
Planning
Watershed
Smart growth
Clean water state revolving fund

ABSTRACT

Capital needs during the next twenty years for public wastewater treatment, piping, combined sewer overflow correction, and storm-water management are estimated to be approximately $300 billion for the USA. Financing these needs is a significant challenge, as Federal funding for the Clean Water Act has been reduced by 70% during the last twenty years. There is an urgent need for new approaches to assist states and other decision makers to prioritize wastewater maintenance and improvements. We present a methodology for performing an integrated quantitative watershed-scale goals assessment for sustaining wastewater infrastructure. We applied this methodology to ten watersheds of the Hudson-Mohawk basin in New York State, USA that together are home to more than 2.7 million people, cover 3.5 million hectares, and contain more than 36,000 km of streams. We assembled data on 183 POTWs treating approximately 1.5 million m^3 of wastewater per day. For each watershed, we analyzed eight metrics: Growth Capacity, Capacity Density, Soil Suitability, Violations, Tributary Length Impacted, Tributary Capital Cost, Volume Capital Cost, and Population Capital Cost. These metrics were integrated into three goals for watershed-scale management: Tributary Protection, Urban Development, and Urban-Rural Integration. Our results demonstrate that the methodology can be implemented using widely available data, although some verification of data is required. Furthermore, we demonstrate substantial differences in character, need, and the appropriateness of different management strategies among the ten watersheds. These results suggest that it is feasible to perform watershed-scale goals assessment to augment existing approaches to wastewater infrastructure analysis and planning.

1. Introduction

Wastewater infrastructure is critical to maintaining and improving environmental and public health. On a global level, it is increasingly being recognized that trillions of dollars will be needed to upgrade aging infrastructure and expand water resource infrastructure assets (Deloitte, 2012). This at a time when global financial markets and shifting population dynamics make investment in, and capitalization of, infrastructure projects particularly challenging. Allocating scarce financial resources to maintain, upgrade, and address aging water resource infrastructure is a challenge faced by many countries around the world, including Australia (Hajkowicz, 2007; Hardisty et al., 2013), Canada (Mirza and Haider, 2003), and Germany (Hummel and Lux, 2007), to name a few.

Wastewater infrastructure across the United States (US) is also aging and in need of repair and replacement. Capital needs during the next twenty years for public wastewater treatment, piping, combined sewer overflow correction, and storm-water management are estimated to be approximately $300 billion (USEPA, 2008). Financing public wastewater infrastructure is a significant challenge. Federal funding for the Clean Water Act (CWA) has been reduced by 70% during the last 20 years (NYSDEC, 2008). State governments are charged with administering the Clean Water State Revolving Fund (CWSRF), the primary mechanism for funding public wastewater projects and, along with local governments, are increasingly tasked with filling the large gap between needed and available funding.

In New York State (NY), projected capital needs for wastewater systems total nearly $30 billion over the next two decades alone (USEPA, 2008). As they are across the US, many NY wastewater systems were built in the 1970s in response to the CWA and are now due for replacement, repair, and upgrade as populations shift, and discharge regulations become increasingly stringent. State

* Corresponding author. Tel.: +1 607 254 7163; fax: +1 607 255 2106.
E-mail address: bgr4@cornell.edu (B.G. Rahm).

0301-4797/$ – see front matter
http://dx.doi.org/10.1016/j.jenvman.2013.06.053

agencies tasked with overseeing water quality and wastewater infrastructure describe these developments as a "gathering storm" of infrastructure need, funding deficits, and impending water quality impacts (see http://www.dec.ny.gov/chemical/48803.html). In NY, this storm has begun: wastewater infrastructure project funding requests submitted in 2012 equaled $7.7 billion but budgeted funds amounted to only $1.3 billion, of which only 5% was projected to come from federal grants (NYSDEC & EFC, 2012). Meanwhile, aging and inadequate wastewater treatment infrastructure is a prominent cause of water quality impairment (NYSDEC, 2004a).

What can be done to increase the effectiveness of public funding, when project needs are growing beyond available resources? One way that states have attempted to increase the efficiency of allocating CWSRF funds is through development of integrated planning and priority setting systems that use a set of criteria to score and rank potential infrastructure projects, called an "integrated ranking system." In general, an integrated ranking system attempts to address the value of impacted waterbodies, the level of current waterbody impairment, and the effect a project may have on waterbody impairment (USEPA, 2001). In NY, water quality impairment assessments are linked to state designated "best uses" which include drinking water, fishing, and recreation. Ranking also depends on a project's consistency with existing management or planning documents, the presence of enforcement actions, current construction activity, and financial need of the communities involved (NYSDEC & EFC, 2012). Use of an integrated ranking system results in a queue of projects, each scored on its individual merits. While the EPA does not require that states fund projects in strict priority order, higher scoring projects are most likely to be funded.

The current integrated ranking system used by NY offers a reasonable, transparent, and defensible way to allocate public funds to individual projects. However, there is an alternative planning and priority setting system specified within the CWSRF Funding Framework described as a "goals" approach (USEPA, 1996). With a goals approach, project evaluation is carried out within a broader framework of specific water resource goals articulated by the State. Such goals may include, for example, minimizing sediment and nutrient transport to coastal zones or eliminating specified contaminant releases. These goals are most relevant at a watershed scale. This goals approach has been advocated in a limited way in states such as Massachusetts (MassDEP, 2012), New Hampshire (NHDES, 2012) and Florida (SWFWMD, 2005).

Despite its currently limited use, goal-based, watershed-scale evaluation of infrastructure could help to achieve desired regional water quality outcomes. Because downstream water quality is affected by upstream conditions, wastewater treatment facilities cannot be considered in isolation of each other. Recent regulatory developments, especially establishment of total maximum daily loadings (TMDLs), illustrate the need to simultaneously account for water quality stressors at the watershed scale. Recent studies have demonstrated that watershed and/or regional-scale analysis and cooperation can lead to environmental and economic benefits with respect to nutrient management (Love and Donigan, 2002), the impact of dams (Graf, 1999), and the management of water resource utilities (Cromwell and Rubin, 2008). For the NY Hudson valley, the watershed approach to planning and decision-making has been described as essential to meeting regional water resource challenges (Cuppett and Urban-Mead, 2010; Negro and Porter, 2009). In general, analysis at the watershed scale provides an opportunity to delineate water quality issues in a physically meaningful way, and also provides an opportunity to link and motivate communities to work together toward common objectives.

Despite the many good reasons for engaging in watershed-scale analysis and decision making, there is still a challenge in determining just what metrics go into such an analysis. Metrics are generally thought of as measurable parameters that reflect the state of variables important to a desired outcome. That being said, watersheds contain a variety of stakeholders, and desired outcomes vary with perspective. Guidance is needed with respect to identifying a set of metrics that address these various, and sometimes competing, perspectives. The concept of sustainability provides a framework that might be useful in this way. For example, recent thinking on sustainability presents a new paradigm that is structured in such a way as to view the "Economy" within "Society," both of which sit within "Earth's life-support system" (e.g. Griggs, 2013). The New York State DEC's mission statement also describes a pursuit of "environmental quality, public health, economic prosperity and social well-being" (http://www.dec.ny.gov/24.html). Given these broader frameworks, it seems that metrics must address not just environmental factors, but also economic and social factors as well.

Herein, we assemble a watershed-scale inventory of wastewater treatment infrastructure. As a case study, we focus on the Hudson and Mohawk River basins of New York because of their large size, diversity in land use, population dynamics, and importance to both inland and coastal aquatic environments. We develop watershed-scale metrics that quantify wastewater infrastructure performance and efficiency, as well as key watershed characteristics within the framework of sustainability discussed above. Finally, we articulate infrastructure management goals and assess their application at the watershed scale within an integrated planning and priority setting system. We suggest that this "goals" approach, applied by states at a watershed scale, can be a framework for more effectively achieving water quality objectives with limited funding resources.

2. Methods

2.1. Regional wastewater infrastructure inventory

An inventory of publicly owned wastewater treatment works (POTWs) was created for the Mohawk and Hudson River basins, not including New York City, parts of which are in the Hudson River basin. POTWs in New York City were excluded due to their large size compared to other POTWs in the dataset. Inventory data included POTW physical and process characteristics, information on receiving waters, and data on the communities served. Sources used to compile this inventory are listed in Table 1. We contacted POTW operators to verify questionable data or obtain missing data. Geospatial analyses were structured within HUC-8 watershed boundary delineations except that the Mohawk was divided into Upper and Lower to be consistent with the New York State Department of Environmental Conservation (NYSDEC) divisions within the Waterbody Inventory and Priority Waterbodies List (WI/PWL). Geospatial analyses of the resulting ten watersheds were carried out in ArcGIS 10.0 and statistical analyses were conducted in Microsoft Excel and SPSS.

2.2. Metric development

To characterize planning constraints, we developed eight metrics that quantify wastewater infrastructure, physical, and socioeconomic characteristics of each watershed (Table 1). We chose these metrics because they reflect the environmental, social and economic values intrinsic to the sustainability paradigm and the mission statement of NY's environmental regulatory agency, and also because they were based on readily available data sets. While we have chosen these metrics, others may modify them or choose

Table 1
Data used during compilation of infrastructure inventory.

Database name	Data type	Source
Descriptive data of municipal wastewater treatment plants in New York State	POTW physical and process characteristics	NYSDEC, 2004b
Clean watersheds needs survey 2008 (CWNS)	POTW physical and process characteristics; Community characteristics	USEPA, 2008
State pollutant discharge elimination system (SPDES)	POTW geospatial characteristics	NYSGIS, 2012
Enforcement and compliance history online (ECHO)	POTW effluent characteristics and violation history	USEPA, 2012
HUC-8 watershed boundaries	Watershed boundary geospatial data	USGS, 2012
Waterbody inventory and priority waterbodies list (WI/PWL)	Surface water hydrography geospatial data; Water quality assessment characteristics	NYSDEC, 2010

different metrics based on value systems and/or data constraints related to their region of analysis:

2.3. Growth capacity

This metric is a measure of the ability of a watershed's wastewater infrastructure to accommodate additional population, given the rate at which it is currently growing (Equation (1)). Census tracts were assigned to watersheds based on their location, and population trends were estimated using data from the 2000 and 2010 censuses (USCB, 2000; USCB, 2010). We assumed that per capita wastewater generation remains constant over time in a particular watershed. We also assumed the rate of population change in areas serviced by infrastructure to be equal to the rate of growth in the watershed in general. This metric describes the number of years before wastewater facilities reach their maximum design volume given trends in population growth.

$$\mathrm{GC} = \frac{\frac{\sum_{i=1}^{n}\left(Q_{d_i} - Q_{a_i}\right)}{Q_{a_i}/P_{\mathrm{served}_i}}}{P_{2010} - P_{2000}/10^{*}\mathrm{yr}} \tag{1}$$

where

GC = time until excess capacity is used [yrs],
Q_d = POTW maximum design flow [m^3/d],
Q_a = POTW actual flow [m^3/d],
P_{served} = Population served by POTW [persons],
P_{2010} = 2010 watershed population [persons],
P_{2000} = 2000 watershed population [persons],
n = Number of POTWs in watershed

2.4. Capacity density

This metric is a measure of the variability in existing wastewater treatment infrastructure capacity within a watershed (Equation (2)). A normalized variance was calculated to determine the distribution of excess capacity for POTWs within individual watersheds. High normalized variance indicates that most available excess capacity is accounted for by only a few POTWs, while low variance indicates that capacity is spread relatively evenly across all POTWs.

$$\mathrm{CD} = \frac{\sum (x - \overline{x})^2}{n} \tag{2}$$

$$\text{where } X = \frac{\left(Q_{d_i} - Q_{a_i}\right)}{\sum_{i=1}^{n}\left(Q_{d_i} - Q_{a_i}\right)} \tag{3}$$

2.5. Soil suitability

The Natural Resource Conservation Service of the U.S. Department of Agriculture has established criteria for determining the suitability of various soil series for siting sub-surface wastewater treatment systems (NRCS, 1993). Each soil series is measured against various physical parameters such as depth to a restrictive layer, slope, etc. and placed into one of three categories: not limiting, somewhat limiting, or very limiting. Soils rated "not limiting" are most suitable for basic absorption field systems, while those rated "somewhat limiting" may be appropriate for more advanced engineered and above-grade systems. "Very limiting" soils are not recommended for soil-based systems. For this analysis, areas with soils rated "not limiting" and "somewhat limiting" were deemed "suitable" for decentralized systems. Watershed soil characteristics were assessed using the SSURGO soils database (NRCS, 1993). This metric measures the potential, as a percentage of total soil area, for implementing decentralized wastewater treatment without natural restrictions within a watershed, an approach similar to that of Engebretson and Tyler (2001).

2.6. Violations

This metric quantifies the degree to which effluent water quality violations issued to POTWs within a watershed match water quality impairments identified in receiving waterbodies. Violation data were obtained from USEPA's Enforcement & Compliance History Online database during the three year time period July 2009 to July 2012 (USEPA, 2012). Data were categorized into 4 groups. (1) Violations associated with ammonia, total kjeldahl nitrogen, nitrite or nitrate were grouped as "nitrogen" violations. (2) Fecal coliform violations were grouped as "pathogen" violations. (3) Dissolved oxygen, biochemical oxygen demand (BOD), chemical oxygen demand, and ultimate oxygen demand were grouped as "oxygen" violations. (4) Total suspended solids, solids removal and settleable solids were grouped as "sediment" violations. These violations were compared to impairment causes listed for receiving waterbody segments within the NYSDEC WI/PWL. The WI/PWL assessment cited waterbody impairments such as nitrogen, phosphorus, nutrients, oxygen depletion, sediments, pathogens, and flow related impairment. Across all POTWs in each watershed, the violations metric is calculated by summing violations matching documented impairments and dividing by the number of POTWs.

2.7. Tributary length impacted

This metric quantifies the distance, or stream length, downstream of a POTW, and represents the stream length over which POTWs might exert a water quality impact. The main stem of the Hudson and the main branch of the Mohawk were not included in this calculation because main branches receive effluent from all upstream facilities and streams. This metric is an attempt to characterize how tributaries may be sensitive to specific treatment facilities that discharge to them.

2.8. Tributary capital cost

This metric expresses the degree to which POTW funding may result in increased protection of waterways and ecological services. Within each watershed, it is calculated by first identifying POTWs with project needs documented in the state multi-year Intended

Use Plan (IUP), the document issued by New York compiling project funding requests to the CWSRF. Capital funding requests associated with these facilities are then divided by the length of tributaries over which these POTWs might exert an impact. Capital funding requests are compiled at the watershed scale by summing multi-year requests entered into the NY CWSRF 2012 IUP – Clean Water State Revolving Fund for Water Pollution Control (NYSDEC & EFC, 2012). We would have also liked to incorporate operational costs, but these data were unavailable. We note that projects identified in the IUP may not fully reflect POTW infrastructure upgrade and repair needs of a given watershed.

2.9. Volume capital cost

This metric expresses the efficiency of POTWs in treating wastewater given requested funding. Within each watershed it is calculated by dividing total CWSRF capital funding requests for POTWs with projects in the multi-year IUP by their aggregated actual daily volume of wastewater treated.

2.10. Population capital cost

This metric attempts to quantify the ability of a watershed to pay for local infrastructure improvements. We divide total capital funding requests made by POTWs within a watershed by the population served by those facilities.

3. Results & discussion

3.1. Wastewater infrastructure inventory

The ten studied watersheds are home to more than 2.7 million people, cover an area of 3.5 million hectares, and contain more than 36,000 km of streams (Fig. 1, Table 2). Within these ten watersheds we collected data on 183 POTWs serving nearly 2.2 million people, and treating approximately 1.5 million m^3 of wastewater per day – roughly one third of total wastewater treated centrally in NY, not including New York City (Table 3).

Among watersheds, the number of POTWs varies from 4 to 42, reflecting differences in population density, watershed area, and development history (Table 3). Similarly, wastewater flow processed within these watersheds ranges from 1000 to over 100,000 m^3 per day. In terms of volumetric treatment capacity, the Hoosic and Schoharie watersheds currently utilize less than 40% of that available, while others such as Lower Mohawk and Rondout utilize more than 70%. Available treatment infrastructure capacity could be used as a criterion for prioritizing new construction and for incentivizing infill development – the use or reuse of land or building sites within existing urban areas for construction, development, and growth.

POTWs in some watersheds are more prone to effluent violations (Table 3), suggesting a need to focus on facility upgrades or other water quality-associated investments. Sacandaga and Lower Mohawk have relatively few violations per POTW, while Wappinger, Upper Hudson, and Rondout have relatively large numbers of violations per POTW. To determine if these watershed-scale differences were a function of POTW size, we categorized all 183 facilities on the basis of flow class (Table 4). We were unable to detect any significant relationship between flow class and number of violations per POTW ($R^2 = 0.003$, $p > 0.05$). Other studies have suggested that flow class may help explain certain kinds of violations (Weirich et al., 2011), such as those related to BOD, a hypothesis that we would like to test in further research using a larger sample size.

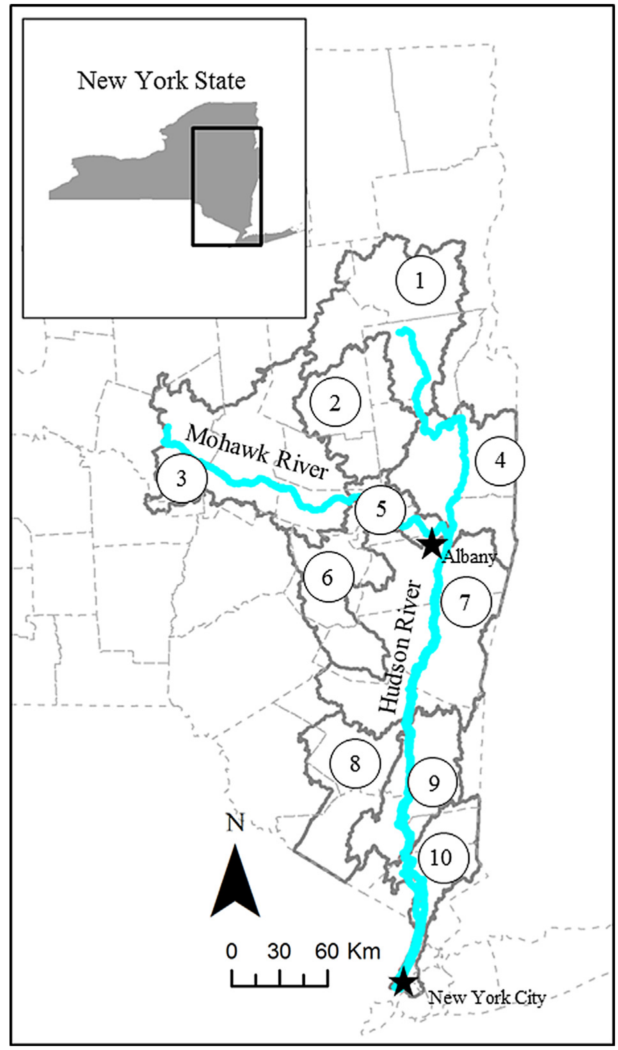

Fig. 1. New York State (inset) and the ten studied watersheds within the Hudson and Mohawk basins: 1) Upper Hudson; 2) Sacandaga; 3) Upper Mohawk; 4) Hoosic; 5) Lower Mohawk; 6) Schoharie; 7) Middle Hudson; 8) Rondout; 9) Wappinger; 10) Lower Hudson.

These inventory results establish that there is a high degree of variability in POTW number, size, excess treatment capacity, and violation history among watersheds. To be more useful in prioritizing wastewater infrastructure investment, and to begin to address the full meaning of sustainability, this inventory data needs to be understood in the context of the physical and socio-economic

Table 2
General characteristics of Hudson-Mohawk basin watersheds.

Watershed	Approx. 2010 population ('000)	% population change (2000–2010)	Area ('000 ha)	Total stream length (km)
Upper Hudson	20.5	−4%	431	4413
Sacandaga	20.9	−1%	273	2767
Upper Mohawk	276	2%	564	6920
Hoosic	279	4%	493	4278
Lower Mohawk	259	9%	96.6	1076
Schoharie	44.7	10%	240	2639
Middle Hudson	553	2%	629	7412
Rondout	242	8%	307	2608
Wappinger	466	6%	245	2645
Lower Hudson	597	3%	194	1468

Table 3
Summary of key data on publically owned water treatment infrastructure.

Watershed	POTW number	Design flow ('000 m^3/d)	Actual flow ('000 m^3/d)	Actual/design flow ratio	Excess capacity (person equivalent)	Effluent violations (3 years)	Yearly effluent violations per POTW
Upper Hudson	5	3.38	1.94	0.57	3932	69	4.6
Sacandaga	4	2.46	1.17	0.48	2926	8	0.7
Upper Mohawk	19	414	277	0.67	141,728	153	2.7
Hoosic	9	218	82.7	0.38	254,172	79	2.9
Lower Mohawk	9	139	101	0.73	66,030	26	1.0
Schoharie	11	16.3	6.33	0.39	19,233	77	2.3
Middle Hudson	42	455	320	0.70	175,303	376	3.0
Rondout	26	80.1	57.6	0.72	40,302	284	3.6
Wappinger	38	172	119.0	0.69	102,365	555	4.9
Lower Hudson	20	821	518	0.63	504,732	133	2.2
Total	183	2321	1485		1,310,724	1760	

characteristics of the watersheds. The eight wastewater infrastructure metrics described earlier, based on a mix of infrastructure, economic, and social data, help accomplish this.

3.2. Watershed-scale wastewater infrastructure metrics

For each watershed, the numerical results of metric calculation are provided in Table 5, and are shown graphically in Fig. 2. Significant differences between watersheds are apparent. For example, some watersheds (Upper Mohawk, Hoosic, Lower Hudson) have enough existing wastewater treatment capacity to accommodate over 200 years of population growth at current rates (Growth Capacity metric). The Upper Hudson and Sacandaga have either no growth or such slow population growth (Table 2) that, on a watershed scale, existing capacity can accommodate needs for the foreseeable future (Fig. 2a). In the Lower Mohawk, Schoharie, Rondout, and Wappinger, however, wastewater treatment capacity is relatively limited and is only adequate for a few decades at most given current growth rates.

Assessment of the Capacity Density metric indicates that some watersheds, such as the Hoosic and Sacandaga, have available wastewater treatment capacity concentrated in only one or a few facilities (Fig. 2b). This may reflect a dense urban center in one portion of the watershed, but relatively rural development elsewhere. Alternatively, there may be POTWs overdesigned for current populations in areas where populations have shifted over previous decades. Lastly, some POTWs may be accepting large volumes of industrial and/or commercial waste, leading to a relatively large ratio of wastewater flow to population. Overall, a high value for Capacity Density suggests that future development should be located in areas with extant capacity. On the other hand, low Capacity Density (e.g. Rondout, Wappinger) indicates distributed wastewater treatment capacity across multiple POTWs, suggesting that modest development could be supported throughout the watershed. Distributed capacity may also provide resiliency during unexpected events that disrupt or disable one or more facilities. Watersheds that are/might become vulnerable to extreme weather as a result of climate change may consider this when planning regional infrastructure during coming decades.

Another metric with implications for development is Soil Suitability; over 35% of soils are suitable for decentralized wastewater systems in some watersheds (Lower Hudson), while less than 20% of soils are suitable in others (Upper Hudson, Schoharie)(Fig. 2c). In high-growth watersheds such as the Rondout and Wappinger, where excess POTW treatment capacity is limited, moderate soil suitability suggests that decentralized or soil-based treatment systems may provide support for modest development throughout the watershed. In contrast, the Sacandaga has low growth, considerable excess treatment capacity concentrated in a single facility, and soils that are generally not suitable for septic systems (Table 2, Fig. 2a–c). From a wastewater infrastructure perspective, development planning in this watershed should focus on containing most growth within the areas served by existing facilities.

The Violations metric, a measure of violations per POTW related to stream water quality impairments over three years, varied from 0 to more than 3. Low scores in some watersheds such as the Upper Hudson and Sacandaga (Fig. 2d) indicate that while effluent violations did occur they were not linked to documented water quality impairments. This may be due to the relatively small ratio of POTW discharge to receiving stream flow, the relatively pristine nature of the streams themselves, or a combination thereof. High violation scores were generally found in the Mohawk basin, particularly the Upper Mohawk and Schoharie watersheds where sediment and nutrient impairment is common. Overall, the Mohawk contributed 68% of the sediment load to the Hudson estuary from 2002 to 2005 (Wall et al., 2008), and POTW effluent violations associated with sediment were relatively frequent. Although there are more dominant non-point sources of sediment and nutrients to streams in the basin, notably agriculture (Swaney et al., 1996), funding projects that minimize these constituents from POTW point sources may still result in significant improvements to local and regional water quality.

With respect to downstream water quality, it is also interesting to note that wastewater infrastructure in some watersheds, such as the Hoosic and Lower Mohawk, is almost completely located on main stem rivers. These watersheds therefore have a low Tributary Length Impacted metric (Fig. 2e). Large rivers have a greater contaminant assimilation capacity due to the large ratio of stream to effluent flow, and some violations may not have measurable impact on downstream water quality. In contrast, the Middle Hudson and Rondout score highly for Tributary Length Impacted. In these watersheds, POTWs discharging to tributaries have the

Table 4
Summary of key data on publically owned water treatment infrastructure based on flow class.

Flow class[a]	POTW number	Design flow ('000 m^3/d)	Actual flow ('000 m^3/d)	Actual/design flow ratio	Yearly effluent violations per POTW
1 (<379 m^3/d)	61	12.9	7.70	0.60	4.2
2 (379–3790 m^3/d)	64	95.5	60.0	0.63	2.2
3 (3790 to 37,900 m^3/d)	48	713	472	0.66	3.4
4 (>37,900 m^3/d)	10	1500	945	0.63	3.1
Total	183	2321	1485		

[a] Volumes correspond to 0.1, 1, and 10 million gallons per day.

Table 5
Results of each assessment metric for each of the ten watersheds; see text for details.

Watershed	Growth capacity (yrs)	Capacity density[a]	Soil suitability (%)	Violations (matches/POTW)	Tributary length impacted (km)	Tributary capital cost ($000,000/km)	Volume capital cost ($000,000/['000 m^3])	Population capital cost ($/person)
Upper Hudson	–	1.5	19	0.0	206	0.11	77.4	407
Sacandaga	–	5.7	26	0.0	122	0.23	184	477
Upper Mohawk	231	0.7	31	3.3	117	11.2	18.1	845
Hoosic	250	7.5	21	0.2	56	–	25.3	492
Lower Mohawk	32	1.6	26	1.2	29	19.6	7.05	137
Schoharie	49	1.4	18	2.8	151	0.26	31.7	184
Middle Hudson	172	0.4	20	0.9	428	1.06	4.38	159
Rondout	22	0.3	23	0.6	386	1.34	28.8	449
Wappinger	37	0.3	23	1.3	270	12.3	43.0	442
Lower Hudson	270	2.2	38	0.8	142	18.4	8.95	537

[a] Capacity Density is a dimensionless value representing normalized variance of excess capacity distribution within a watershed.

potential to impact receiving waters to a greater degree, especially when effluent flows make up larger portions of downstream flow during the summer and early fall. This suggests that addressing infrastructure needs associated with POTWs located on tributaries could have a larger beneficial impact on downstream water quality relative to POTWs on main stems.

Cost metrics relate capital funding requests to tributary length that will be impacted (Tributary Capital Cost), to the volume of

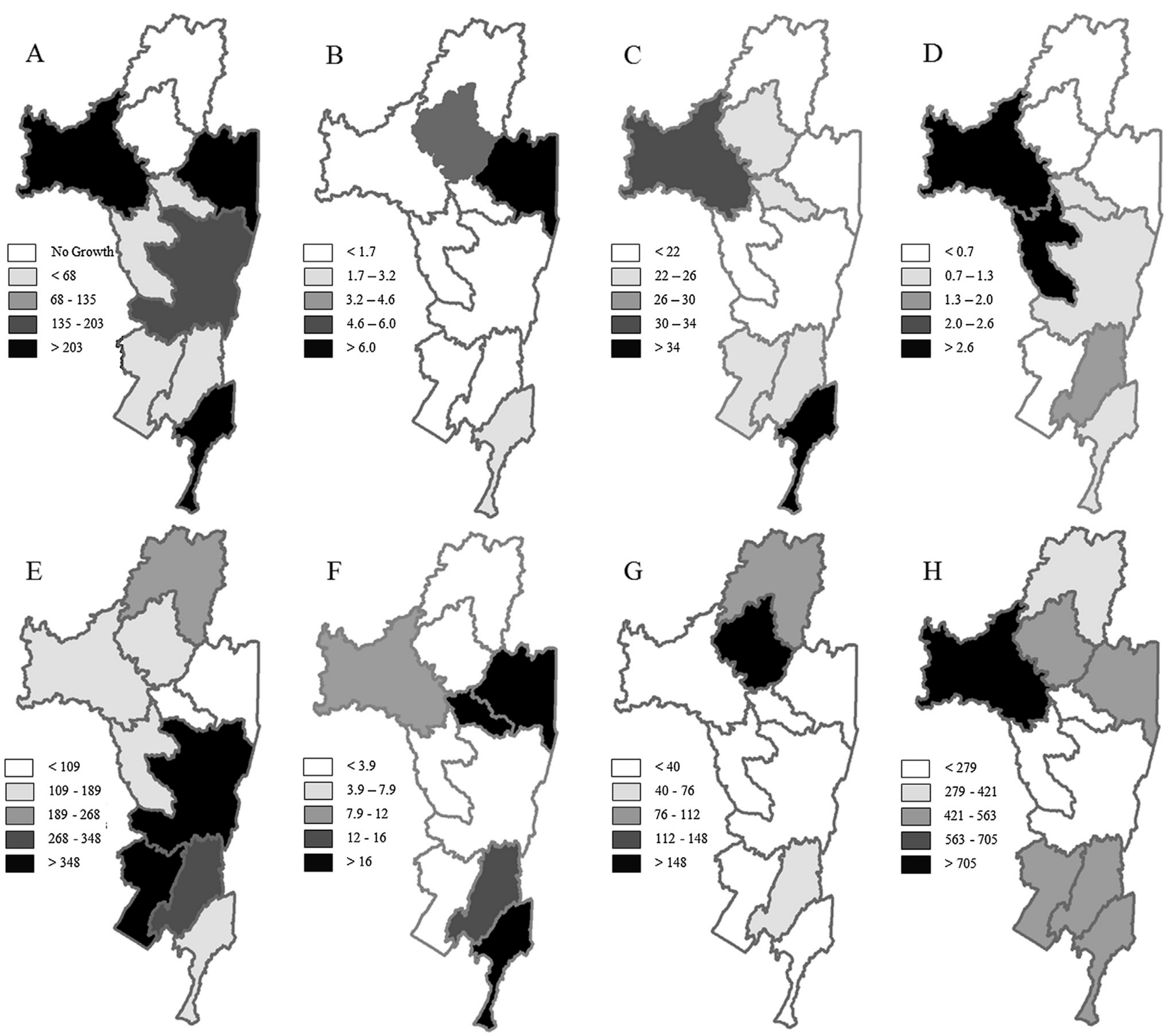

Fig. 2. Results of watershed-scale metric calculation for A) Growth Capacity [yrs]; B) Capacity Density; C) Soil Suitability [%]; D) Violations [# per POTW matching impairments]; E) Tributary Length Impacted [km]; F) Tributary Capital Cost [$000,000/km]; G) Volume Capital Cost [$000,000/000 m^3]; H) Population Capital Cost [$/person].

wastewater that will be treated (Volume Capital Cost) and to the population that will be served (Population Capital Cost). These metrics vary considerably among the watersheds (Fig. 2f–h). The adjacent Middle Hudson, Schoharie and Rondout watersheds all have low capital funding requests relative to tributary length impacted, volume of wastewater treated and population served. This may reflect fewer projects in the current IUP for POTWs located on tributaries, or perhaps reflects fewer projects in the IUP overall for these watersheds. The remaining watersheds tend to have a range of scores on cost-related metrics. Sacandaga, for example, has low capital funding requests per tributary length impacted, reflecting the fact that POTWs here tend to be located on tributaries far from main stem rivers. However, on a volume treated basis, capital funding requests are high. This may be because POTWs in Sacandaga are small and unable to capture economies of scale. Overall, the rural/urban character of a watershed to some extent dictates how regions will score on cost-related metrics.

While metric analysis provides some basis for evaluating and prioritizing water infrastructure investment and management, our final objective was to develop a goal-based, watershed-scale evaluation of infrastructure to support the attainment of desired regional water quality outcomes.

3.3. Goal formulation and goal-based watershed assessment

We propose three possible watershed management goals that emphasize different approaches to infrastructure planning, economic development, and environmental values. These goals do not necessarily represent the best set of goals for the watersheds studied or other locations in general, and they are not necessarily mutually exclusive. Instead, they are intended to demonstrate how multiple individual metrics can be integrated to meet a range of potential management goals at the watershed scale and to provide a broader framework for evaluating specific wastewater infrastructure decisions.

3.3.1. Goal 1: tributary protection

This goal focuses on maintaining and enhancing high-quality, pristine waterways, and the ecosystem, social, and economic services that they provide. Watersheds pursuing this goal may try to minimize the amount and impact of engineered infrastructure and place a higher emphasis on values associated with wildlife and environmental tourism relative to more urbanized watersheds. With respect to metrics, these watersheds are generally not areas of rapid population growth. Ideally, soils are relatively well suited for decentralized wastewater treatment systems, which might be appropriate in rural regions that are commonly sparsely populated. These watersheds contain POTWs that are able to minimize the number of violations matching stream impairments, and have high tributary lengths reflecting the relatively close association between infrastructure and water quality. Capital investment similarly has the potential to improve or protect water quality in tributaries to the extent that projects address water quality issues that specifically threaten receiving waters in that location. Therefore, we selected Soil Suitability, Violations, Tributary Length Impacted and Tributary Capital Cost as the key metrics for watersheds pursuing this goal (Table 6).

3.3.2. Goal 2: urban development

This goal emphasizes dense urban development and employment of centralized wastewater infrastructure. Watersheds pursuing this goal may incentivize infill development as opposed to suburban or rural development, and ecosystem services are often replaced with engineered systems. Assessment metrics proposed here (Growth Capacity, Capacity Density, Tributary Length Impacted and Volume Capital Cost, Table 6) identify watersheds that have the ability to accommodate significant population increases using existing POTW infrastructure, as well as regions in which growth capacity is concentrated in relatively few, dense areas. Tributary length impacted by POTWs is minimized, since facilities will likely be too large for placement on smaller, more pristine streams. Watersheds for which this goal is appropriate may concentrate their wastewater treatment infrastructure on main stem rivers large enough to assimilate heavier loadings of nutrients and sediment. Lastly, POTWs in these watersheds serve many people at relatively low cost; economies of scale are desired, and public health is highly valued.

3.3.3. Goal 3: urban-rural integration

This goal emphasizes a compromise between the two goals discussed above and seeks to preserve environmental quality and benefits while also providing robust engineered services. Watersheds pursuing this goal might be defined by nodal or clustered growth and development. Regional planning and coordinated

Table 6
Metrics used for watershed characterization and their use toward goal-based assessments.

Metric	Tributary protection	Urban development	Urban-rural integration
Growth capacity		Large capacity at current population growth rate	Medium capacity at current population growth rate
Capacity density		Concentrated capacity in few POTWs	Distributed capacity across all POTWs
Soil suitability	High proportion suited for decentralized treatment		Medium proportion suited for decentralized treatment
Violations	Minimize violations per POTW matching stream impairments		
Tributary length impacted	Large tributary network downstream of POTW	Small tributary network downstream of POTW	
Tributary capital cost	Maximize tributary network impacted per capital expenditure		
Volume capital cost		Maximize wastewater volume treated per capital expenditure	
Population capital cost			Maximize population served per capital expenditure

management are valued. With respect to POTWs, a moderate amount of growth capacity is valued, but too much or too little capacity may indicate inefficiency, poor planning, or both. POTW infrastructure is locally centralized but regionally distributed and is not dominated by any one or two facilities. POTWs in these watersheds, due to more coordinated management and use of ecosystem services, are able to minimize capital expenditure needs per capita. We selected Growth Capacity, Capacity Density, Soil Suitability and Population Capital Cost as the metrics of greatest importance for watersheds pursuing this goal (Table 6).

For watershed assessments, we converted each of our eight raw metric values for the ten watersheds into relative integer scores based on an ordinal scale from 1 (lowest) to 5 (highest) for each metric. For each goal, four out of the eight possible metrics were used (Table 6), and a composite average score between 1 and 5 was calculated. The purpose of the exercise was to associate each watershed with a goal for which it scored highest relative to other possible goals.

3.3.4. Watershed assessment

Ordinal scale scoring results are provided in Table S1. A summary of composite scores for each watershed is given in Table 7. We used the following questions as a guide for evaluating assessment results, and for generating further discussion on funding watershed infrastructure projects:

1. What kind of growth should infrastructure funding be encouraging or responding to?
2. Should wastewater infrastructure be centralized or decentralized?
3. What is the economic basis on which project value should be judged?
4. Given watershed characteristics, how should water quality goals be prioritized within the broad framework of sustainability?

Upper Hudson and Sacandaga both scored high on the Tributary Protection goal. This was expected, as these regions have the lowest population, lowest density, and the fewest number of POTWs among the ten watersheds. They are also relatively forested watersheds, and contain large areas of state park land. It is important to note that these watersheds are losing population. It would not make sense to fund POTW construction outside of current population centers; rather, funding should support maintenance of existing infrastructure, sometimes called a “fix-it first” approach. Green wastewater infrastructure, or decentralized forms of wastewater management, could be encouraged or incentivized as a way to augment current centralized systems in town centers, and as an alternative to centralized infrastructure in new developments. Assessing infrastructure projects in these watersheds too narrowly, with too much emphasis on capital cost per capita or per wastewater volume treated, is not reasonable, as projects in such sparsely populated areas cannot achieve economies of scale possible in other regions. That being said, investing in POTWs in the Upper Hudson and Sacandaga helps ensure high tributary water quality, and could benefit the regional economy through tourism and environment-based activities.

Assessment of the Hoosic, Lower Hudson, and Upper Mohawk suggests Urban Development as the best possible goal. These regions tend to have population centers that contain a large majority of the watershed’s inhabitants. With respect to wastewater infrastructure, the hallmark of these regions is large centralized facilities built for a growing, urban population. In some cases, urban centers that once prospered have now lost population as manufacturing and industrial activity declined, leaving large POTWs underutilized. Cities in these watersheds tend to have space and facilities, brownfields, and urban land that can be targeted for infill development. Maintaining centralized facilities should be encouraged, rather than building satellite infrastructure in suburbs, which adds cost, creates sprawl, and duplicates nearby treatment capacity. Large facilities in dense urban areas should be able to capture economies of scale, allowing the treatment of large volumes of waste at relatively low cost. While water quality of streams and rivers is always important, the focus in these regions is on public health. These urban centers also tend to be located on main river segments where water quality issues are a complex mixture of upstream contamination, urban runoff, industry, etc. Fixing these problems through changes in POTW infrastructure alone is unlikely.

Assessment of the Schoharie and Wappinger watersheds suggests Urban-Rural Integration as the most appropriate goal. These regions are not particularly rural or urban, forested or developed;

Table 7
Overall composite scores for goal-based watershed assessments. Grey boxes indicate goals for which each watershed scored most highly. Comments reflect key features to consider for watershed planning and management.

Watershed	Goals			Assessment comment
	Tributary protection	Urban development	Urban-rural integration	
Upper Hudson	3.5	2.0	2.8	Tributary protection – minimal violation/impairment relationship
Sacandaga	3.5	2.5	2.3	Tributary protection – minimal violation/impairment relationship
Upper Mohawk	2.5	3.8	2.5	Urban development – high growth capacity; limited impact on tributaries; large volume treated per capital expenditure
Hoosic	2.0	5.0	1.5	Urban development – high growth capacity & density; focus on engineered systems; minimal impact on tributaries; large volume treated per capital expenditure
Lower Mohawk	2.0	3.3	4.0	Urban-rural integration – moderate growth capacity; dispersed infrastructure; mix of engineered & ecosystem services; capital expenditure low per capita
Schoharie	2.3	3.0	3.5	Urban-rural integration – moderate growth capacity; dispersed infrastructure; capital expenditure low per capita
Middle Hudson	3.8	2.8	3.5	Tributary protection[a] – large impact on tributaries; limited violation/impairment relationship
Rondout	4.3	2.3	3.5	Tributary protection[b] – limited growth capacity; large impact on tributaries; minimal violation/impairment relationship
Wappinger	2.8	2.3	3.5	Urban-rural integration – moderate growth capacity; dispersed infrastructure; moderate soil suitability
Lower Hudson	3.0	4.0	2.3	Urban development – high growth capacity; focus on engineered systems; limited impact on tributaries; large volume treated per capital expenditure

[a] Middle Hudson also scores highly for Urban-Rural Integration, indicating potential for mixed goals or need for further analysis at finer HUC scale.
[b] Rondout also scores highly for Urban-Rural Integration, indicating potential for mixed goals or need for further analysis at finer HUC scale.

rather, they have a mixture of land uses and communities. The wastewater treatment capacity in these regions is spread out among multiple POTWs, implying many municipalities could support moderate growth at least in the near future. Local soils allow decentralized systems, but are not utilized or needed in areas of denser development. These watersheds may represent regions outside of major urban centers, or could encompass an important transportation corridor.

The Middle Hudson and Rondout score well for two of three goals: Tributary Protection and Urban-Rural Integration. Both watersheds contain relatively large cities, but otherwise encompass large tracts of rural and forested land. Examples of cases in which a single goal cannot be decisively determined suggest that an alternative goal not articulated in this discussion might be appropriate. Alternatively, it may be that the watershed scale we have chosen is not fine enough to distinguish important features of the region. Examination of smaller watersheds may be better for highlighting local infrastructure needs and management goals in certain regions where, for example, major population centers are located on the main stem Hudson but peripheral areas contain few people and little development.

3.4. Putting assessments into practice: implications for smart growth

With limited funds, state and municipal agencies in New York and other states cannot hope to make all the needed repair and upgrades to wastewater infrastructure. Some facilities will be selected for immediate funding while others will likely wait for years or decades. To make difficult funding decisions state agencies are increasingly recognizing the need to consider a broad variety of development factors, including water infrastructure, financing, environmental water quality, and community characteristics. However, making investment decisions on a project-by-project basis does not provide an adequate framework for optimally addressing these inter-related factors at the regional scale. Watershed-scale analyses and goals provide a way for the state to acknowledge spatial differences in wastewater management needs, and to more broadly consider factors such as the rate and location of regional population growth, the density of municipal centers, the potential for decentralized forms of treatment, the ability to finance capital expenditures, and the relationship between infrastructure and environmental water quality. This watershed perspective has the potential to reveal quantifiable benefits beyond project-level assessment as multiple projects considered together achieve economies of scale, work toward watershed-scale goals of water quality, foster municipal cooperation in appropriate areas and make the most effective use of limited funding.

Making more effective funding decisions was also the driving force behind the NY Smart Growth Public Infrastructure Policy Act of 2010, which prioritizes the funding of public infrastructure projects that are consistent with *smart growth* criteria (NYSECL, 2010). Like the goals approach outlined above for wastewater infrastructure, the Smart Growth Act is an attempt to evaluate project funding within a broader context of community and regional development; where appropriate, it can be used to encourage municipal coordination and economies of scale. According to criteria outlined by the Act, preferred infrastructure projects can include those that:

- maintain existing infrastructure rather than build new infrastructure (“fix-it first”),
- are located in municipal centers,
- are located in areas designated for infill or brownfield development,
- protect and preserve water resources, agricultural land, forests, and open space,
- demonstrate planning on an inter-municipal and regional scale,

For state agencies, such as those charged with administering the CWSRF, interpretation of this new mandate is a challenge and opportunity. What does smart growth mean within the context of wastewater infrastructure funding and development? Results presented here indicate that wastewater infrastructure as well as goal-based watershed assessment could be important components of smart growth. We have articulated three goals for the purposes of illustration, but states are free to create goals that suit local conditions. The principles of smart growth as defined above could help provide the foundation for articulating watershed-scale goals that can inform decisions about allocating public funds.

The results of our analysis could generate discussion at various management and governance levels about the need to consider watershed-scale issues when prioritizing funding of wastewater treatment infrastructure. Additionally, a watershed-scale approach to goal formulation, and a funding framework that incentivizes regional awareness and cooperation, could encourage municipalities to work together to explore benefits of consolidated services. Using a watershed goal assessment does not mean that states such as NY should abandon their integrated ranking systems. Instead, goal-based assessments could be used in conjunction with project level evaluation. For example, a percentage of available funding could be set aside for “goal-based” projects. Each watershed may be guaranteed some funding to ensure statewide equity. It may also be possible to revise current ranking systems to include additional points for applicants if groups of municipalities, counties, or some other regional or watershed-scale entity can demonstrate the benefits of funding multiple projects concurrently instead of one at a time. Such applicants would have to show cumulative positive impact on water quality, or explain how inclusion of multiple stakeholders allows them to manage their resources and funds in a more effective way. Applicants for new small-sized POTWs (<379 m^3/d [0.1 MGD]) could be asked to explore alternative options such as connection to an existing treatment facility in a neighboring municipality, or the use of decentralized treatment (e.g., a combination of cluster and individual systems).

4. Conclusions

In summary, we present a methodology for performing a quantitative, integrated watershed-scale goals assessment for sustaining wastewater infrastructure. Application of this methodology to ten watersheds within the Hudson-Mohawk basin in New York State demonstrates that it can be implemented using widely available data, although some verification of data is required. The use of eight metrics covering wastewater infrastructure, receiving water quality, hydrology, community information, and compliance history integrated into three different goals reveal substantial differences in character, need, and likely management strategies among watersheds. These results suggest that it is feasible to perform watershed-scale goals assessment to augment existing approaches to wastewater infrastructure analysis and planning. Goal-based watershed assessments could be used to encourage more coordination among management agencies to address regional water quality challenges. Watershed-scale goal-based assessment can also contribute to states' attempts to incorporate smart growth principles into planning and funding decisions, and can be used to generate discussion about what smart growth means for diverse communities facing different development paths. New tools such as the methodology presented herein are critically important given the huge need for capital improvements to wastewater infrastructure and the limited funding currently available.

Acknowledgments

We wish to thank Ramsay McConnell, Chris Perry, and Roxana Orellana for assistance in organizing and verifying data, as well as members of the New York State Department of Environmental Conservation, Hudson River Estuary Program, and other state agencies for helpful data and discussions. This manuscript was prepared for NYS WRI and the NYSDEC HREP, with support from the NYS Environmental Protection Fund.

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jenvman.2013.06.053.

References

Cromwell, J., Rubin, S., 2008. Estimating Benefits of Regional Solutions for Water and Wastewater Service. American Water Works Association.
Cuppett, S., Urban-Mead, R., 2010. Hudson Valley Water: Opportunities and Challenges. Discussion Brief #4. Center for Research, Regional Education and Outreach, State University of New York, New Paltz http://www.newpaltz.edu/crreo/brief4_water_online_version.pdf.
Deloitte, 2012. Water Tight 2012: the Top Issues in the Global Water Sector. http://www.deloitte.com/assets/Dcom-SouthAfrica/Local%20Assets/Documents/water_tight.pdf (accessed February, 2013).
Engebretson, A.C., Tyler, E.J., 2001. On-site wastewater treatment. In: Mancl, K. (Ed.), Proceedings of the Ninth International Symposium on Individual and Small Community Sewage Systems. ASAE, St. Joseph, MI, pp. 116–124.
Graf, W.L., 1999. Dam nation: a geographic census of American dams and their large-scale hydrologic impacts. Water Resources Research 35 (4), 1305–1311. http://www.wou.edu/las/physci/taylor/g407/graf_1999.pdf.
Hajkowicz, S., 2007. Allocating scarce financial resources across regions for environmental management in Queensland, Australia. Ecological Economics 61, 208–216.
Hardisty, P.E., Sivapalan, M., Humphries, R., 2013. Determining a sustainable and economically optimal wastewater treatment and discharge strategy. Journal of Environmental Management 114, 285–292.
Hummel, D., Lux, A., 2007. Population decline and infrastructure: the case of the German water supply system. Vienna Yearbook of Population Research 5, 167–191.
Love, J.T., Donigan Jr., A.S., 2002. The Connecticut Watershed Model – Model Development, Calibration, and Validation. WEF-watershed 2002 http://www.hspf.com/pdf/WTO206b.pdf.
Massachusetts Department of Environmental Protection (MassDEP), 2012. The Watershed Management Approach. http://www.mass.gov/dep/water/priorities/wshappr.htm (accessed August, 2012).
Mirza, M.S., Haider, M., 2003. The State of Infrastructure in Canada: Implication for Infrastructure Planning and Policy. Technical report dated March 27 http://www.regionomics.com/infra/Draft-July03.pdf.
Negro, S., Porter, K.S., 2009. Water stress in New York state: the regional imperative? The Journal of Water Law 20, 5–17.
New Hampshire Department of Environmental Services (NHDES), 2012. Watershed Assistance Grants for High Quality Waters. http://des.nh.gov/organization/divisions/water/wmb/was/categories/grants.htm (accessed August, 2012).
New York State Department of Environmental Conservation (NYSDEC), 2004a. 30 Year Trends in Water Quality of Rivers and Streams in New York State Based on Macroinvertebrate Data 1972–2002. NYSDEC, Albany, NY. http://www.dec.ny.gov/docs/water_pdf/sbu30yrintro.pdf.
NYSDEC, 2004b. Descriptive Data of Municipal Wastewater Treatment Plants in New York State. NYSDEC, Albany, NY. http://www.dec.ny.gov/chemical/8721.html.
NYSDEC, 2008. Wastewater Infrastructure Needs of New York State. NYSDEC, Albany, NY. http://www.dec.ny.gov/chemical/42383.html.
NYSDEC, 2010. The Waterbody Inventory and Priority Waterbodies List. NYSDEC, Albany, NY. http://www.dec.ny.gov/chemical/36730.html.
New York State Department of Environmental Conservation & Environmental Facilities Corporation (NYSDEC & EFC), 2012. Intended Use Plan – Clean Water State Revolving Fund for Water Pollution Control. NYSDEC, Albany, NY.
New York State Environmental Conservation Law (NYSECL), 2010. Article 6; State Smart Growth Public Infrastructure Policy Act; Enacted August 31, 2010.
New York State GIS Clearinghouse (NYSGIS), 2012. State Pollutant Discharge Elimination System Dataset. http://gis.ny.gov/ (accessed July, 2012).
Natural Resource Conservation Service (NRCS) Soil Survey Staff, 1993. Soil Survey Manual, Handbook 18, Chapter 6. NRCS, United States Department of Agriculture. http://soils.usda.gov/technical/manual/contents/chapter6.html.
Southwest Florida Water Management District (SWFWMD), 2005. Comprehensive Watershed Management. http://www.swfwmd.state.fl.us/about/isspapers/cwm.html (accessed August, 2012).
Swaney, D.P., Sherman, D., Howarth, R.W., 1996. Modeling water, sediment and organic carbon discharges in the Hudson-Mohawk basin: coupling to terrestrial sources. Estuaries 19 (4), 833–847.
United States Census Bureau (USCB), 2000. Cartographic Boundary Files. Census Tracts, New York. http://www.census.gov/geo/www/cob/cbf_tracts.html (accessed June, 2012).
USCB, 2010. Cartographic Boundary Files. Census Tracts, New York. http://www.census.gov/geo/www/cob/cbf_tracts.html (accessed June, 2012).
United States Environmental Protection Agency (USEPA), 1996. The Clean Water State Revolving Fund Funding Framework. USEPA Office of Water, Municipal Support Division. http://water.epa.gov/grants_funding/cwsrf/upload/2006_12_28_cwfinance_cwsrf_enhanceFiles_framewrk.pdf.
USEPA, 2001. Integrated Planning and Priority Setting in the Clean Water State Revolving Fund Program. USEPA Office of Water. http://water.epa.gov/grants_funding/cwsrf/upload/2002_06_28_cwfinance_cwsrf_ipps_web.pdf.
USEPA, 2008. Clean Watersheds Needs Survey (CWNS) 2008 Report to Congress. http://water.epa.gov/scitech/datait/databases/cwns/2008reportdata.cfm (accessed June, 2012).
USEPA, 2012. Enforcement & Compliance History Online (ECHO). http://www.epa-echo.gov/echo/index.html (accessed July, 2012).
United States Geological Survey (USGS), 2012. Watershed Boundary Dataset. http://water.usgs.gov/maps.html (accessed July, 2012).
Wall, G.R., Nystrom, E.A., Litten, S., 2008. Suspended sediment transport in the freshwater reach of the Hudson River estuary in eastern New York. Estuaries and Coasts 31 (3), 542–553.
Weirich, S.R., Silverstein, J., Rajagopalan, B., 2011. Effect of average flow and capacity utilization on effluent water quality from US municipal wastewater treatment facilities. Water Research 45, 4279–4286.