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A Decision-Support Tool to Build Water Supply Capacity: Methodological Development

John Peckenham
University of Maine, jpeck@maine.edu

Trupi Ashtankar

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By John Peckenham* and Trupti Ashtankar**

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Abstract

Tools are needed to inform decision-makers as they seek to improve water supply capacity from source protection to operational efficiency. This paper presents a methodological approach to build a decision-support tool that can account for natural system characteristics, water utility operations, and social dynamics. The method starts with an analysis of metrics to index performance and assess natural conditions. As an example metrics for surface water supplies in Maine illustrate the availability and reliability of measures that can serve as indicators. relative performance and capacity. Based on public and accessible information, a total of 33 metrics have been identified that provide information on the biophysical, operational, and social domains that affect the production of safe drinking water.

Introduction

Public drinking water in the United States is regulated the 1974 Safe Drinking Water Act (SDWA) as amended in 1986 and 1996. Public health and safety are protected by the requirement for water utilities to manage quality from source to tap. Protecting the integrity and operation of water supply requires the combined efforts of many partners such as public water systems, local communities, resource managers and regulatory agencies. As such, the protection of drinking water is an example of a coupled human-natural system with interacting governance systems (Ostrom, 2009).

The philosophy behind these regulations includes the overarching goal that on a time scale of years, drinking water utilities will develop the capacity to protect source water, maintain infrastructure, operate with efficiency, and meet customer needs. This goal presupposes that utilities have the ability to meet all of these objectives. However, in reality few utilities have the total combination of adequately sized and protected sources, strong infrastructure, personnel, or financial capacity to attain these objectives. Small and mid-sized utilities often face difficulty complying with the SDWA due to insufficient personnel, aging infrastructure, or access to capital (USEPA, 2009). Functionally managing water quality becomes even more difficult once we recognize that the human and natural systems are coupled in complex ways.

Tools are needed to help visualize successes, limitations, or short-comings in order to set action priorities to sustain water systems. Tools can aid in decision-making through an evaluation of natural systems (hydrology), water utility operations, and social dynamics. This paper presents a methodological approach to analyze surface water supplies to be used to develop such a tool. This tool can be applied to provide a symbolic representation of utility performance and capacity.

*Associate Director, Senator George J. Mitchell Center for Sustainability Solutions, University of Maine, Orono, ME

**Water, Sanitation and Hygiene Consultant, New Delhi, India

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This analytical method can help evaluate strengths and weaknesses within and among water utilities. Another intended application is to develop a greater understanding of how physical and social conditions may affect the delivery of safe drinking water. Managers can use this tool for decision-support and regulators can use it to assess utilities for areas of excellence or under-performance to guide intervention.

Rationale

As a sample case, Maine has approximately 1,875 public water systems that provide drinking water to nearly one million people by drawing water from wells and surface water intakes (Maine DWP, 2010). The responsibility for protecting public health via drinking water falls largely to public water suppliers. However, water utilities do not control all of the potential variables that affect water quality. For example, most land-use decisions are made independently by state, regional, and municipal entities, not water suppliers. This means that assurances of water quality and safety requires knowledge and actions to be shared between water suppliers, state and federal regulators, local land owners, municipalities, and concerned citizens (Rizak and Hrudey, 2007).

Water system managers work to meet the quality and integrity goals but success may be hindered by financial, geographical, socio-economic, or capacity limitations. For example, it is not unusual for water utility rates to be strictly regulated which affects response time to new financial needs. Confounding factors such as limited staff flexibility, geographically restricted resources, lack of community engagement or support, or insufficient institutional authority all affect operational and strategic decisions. Increasing capacity to sustain water systems is difficult because the needed time and effort strains personnel and fiscal resources (Marlow et al., 2010). Therefore, the decisions that managers are forced to make about which water system objective to address have to be made with incomplete information and limited resources (Hrudey et al., 2011). As a result, outcomes may favor short term benefits that become partial or temporary fixes. A decision-support tool can provide perspective on the multiple dimensions of water systems to inform decision-makers through broader inputs.

Dimensions of Drinking Water Systems

This conceptual model of source water protection combines metrics of the physical world with those of human organization and water utility operations. The goal is to map these variables and their associated metrics onto dimensions of geographic, human, institutional, and hydrologic space. This mapping tool concept can be used to visualize physical, financial, and social dynamics simultaneously. The visualizations aid the analysis of coupled human-natural systems to support management decisions. This analytical technique can also provide a template against which to measure changes over time that have occurred within these coupled systems.

A common theme that emerges from research is that the approach to maintaining safe drinking water in a particular locale is influenced by the hydrological, socio-economic, cultural and institutional context (Yangeen and Born, 1990; Huebner et. al., 1992; de Loe and Kreutzwiser, 2005; Ferreyra and Beard, 2005a). While managers of drinking water utilities understand the importance of capacity and capacity building, the constraints from institutional, organizational, and human resources affect management capacity (Hartvelt and Okun, 1991; Biswas, 1996; Hamdy et al., 1998; Franks, 1999). For example, de Loe and Kreutzwiser (2005), showed how a community's capacity to achieve its groundwater protection objectives was shaped by technical, financial, institutional, political, and social factors. These analyses of capacity have been very helpful in developing a understanding of the bounding conditions that influence how a water utility manages water quality. Widespread progress to act on this knowledge may be difficult both to measure and to track since disparate types of metrics are used and there is no consistent method to measure progress across many the variables.

A decision support tool needs to accommodate these differences in attributes and metrics. The approach presented here builds on these concepts and models to derive a broad decision-support tool to aid in interpretation and evaluation of metrics. Sources of supply have hydrological properties, geographical settings, institutional strengths and economic conditions within the service community that differ markedly between water systems in terms of relative magnitudes and spatial scales (Smith and Porter, 2010). Once we identify metrics then we can build the tool to analyze systems for strengths, vulnerabilities, and commonalities. Since the coupling of the natural and human context of an individual water utility is unique, each water system is expected to have a characteristic relationships among metrics.

Defining Metrics

The process of identifying metrics to populate a decision-support model required an inventory of data from diverse sources. As a test case to identify and test the viability of metrics, public water supply systems in Maine that use surface water served as the test population. In Maine there are 79 public water systems using surface water that serve in total more than 200,000 connections. This service community represents approximately one-sixth of the state's total population. These surface-water systems include 57 community water systems, 20 non-community (NC) water systems, and two non-transient non-community (NTNC) water systems. Not all systems were suitable for analysis, for example, scant information exists for some of the smallest systems, such as summer camps. Also, water supplies using ocean water or large rivers were excluded; this left 43 water utilities using surface water for our analysis. Some water suppliers had several hydrologically distinct sources and these were assessed independently so the total number of sources used was 46.

The attributes of drinking water supply systems were assessed using three organizational domains: biophysical; social; and operational. The biophysical domain includes the traditional hydrological aspects of the source, water quality, biological conditions (trophic status), and source watershed attributes. The social domain includes the size and wealth of the service community, community demographics, and community economic health. The operational domain includes the physical infrastructure, human resources, financial strength, and overall production efficiency. The goal was to have metrics within all of these domains across all of the supplies.

Ideal metrics will provide reliable information that is consistent across utilities with repetition over multiple years. In the biophysical domain metrics should indicate adequacy of the source in terms of quantity and quality, reliability of the source from year to year, and vulnerability of the source to harm. In the social domain metrics should indicate the size and stability of the customer base, the economic health of the community, willingness and ability of customers to pay for services, and the degree of social capital available to the utility. Finally, in the operational domain metrics should indicate the status of the physical infrastructure, the financial health of the utility, capacity to produce safe water, and strategic plan to position the utility for future conditions. The following descriptions explain the metrics found and how they relate to the general domains.

Biophysical Domain Metrics. The biophysical attributes of the source of supply set absolute limits on the volumetric capacity to produce quality water and the 14 metrics found are listed in Table 1. Key attributes affecting quantity include watershed size, volume of water in storage that is accessible to extraction, and natural watershed yield (the average amount of accessible water flowing through the watershed each day). Key attributes affecting quality include source flushing rate, trophic state, and amount of phosphorus available to produce algal blooms. Most of these data have been tallied by the State of Maine Departments of Conservation and Environmental Protection. These data are accessible through online sources such as Knowledge Base (http://

Table 1. Metrics used to assess the biophysical domain of surface water supplies. Metric ranges and median values are presented along with a count of missing values for the 46 sources.

Metric	Description	Minimum	Maximum	Median	Count Missing
Average Daily Yield (gallons x1,000)	Natural Water Flux	1,910,000	1.7×10^{10}	2,750,000,000	20
Direct Drainage Area (square miles)	Contributing Shoreland Area	0.089	2,125	3.64	11
Size of Watershed (square miles)	Total Watershed Size	31.0	109,440	2,145	0
Total Drainage Area (square miles)	Maximum Potential Contribution Area	0.09	3,439	3.94	8
Source Perimeter (miles)	Linear Extent of Shore	0.50	98.2	4.6	8
Source Area (acres)	Source Size	3.72	29,992	174	0
Flush Rate (per year)	Volume Replacement Rate	0.15	4.6	0.88	12
Volume (acre-feet)	Source Volume	118	3,224,233	5,796	13
Storage Volume (gallons)	Gallons Available	2,000	4×10^9	553,000	15
Maximum Depth (feet)	Depth	3.0	316	54	13
Mean Depth (feet)	Average Morphometry	3.0	107	27.5	18
Surface Elevation (feet a.m.s.l.)	Landscape Position	8.0	1,244	263	8
Secchi Depth (feet)	Water Clarity	3.0	12.71	6.21	14
Phosphorus (ppb)	Algae Bloom Potential	0.003	0.140	0.009	18
Storage-Total Volume Ratio	Portion of Water Used	0.000	1.063	0.001	23
Volume-Watershed Ratio	Storage Within Watershed	0.588	39.668	3.481	20

www.lakesofmaine.org/). Factors affecting source quality were evaluated as part of the Source Water Assessment Program by the Maine Drinking Water Program. In Maine, most surface water supplies were found to have few short-term risks to quality but many have long-term risks posed by human activities. Also, derivative metrics were calculated to show the fraction of static total source volume that was accessible to consumption and the volume of the source relative to the size of the watershed to indicate potential replenishment or hydrological resilience.

Social Domain. The socio-economic setting affects many aspects of water supply including the physical relationship with the source watershed, land use management, willingness-to-pay, financial capacity, and support for water resource policies (ADB, 1999). The social context can strongly influence water utility managers and trustees through relationships with service customers, local communities served, communities within the source area, state and federal regulatory agencies, and other stakeholders. As a measure of this social context, social capital can be thought of as the overall willingness of a community to support a water utility's goal to produce safe drinking water. As an example, social capital with the community is enhanced in a productive manner when citizens are involved in municipal decision making and implementation of management plans (Koudstaal et al., 1992; NRC, 2000). However, no metrics were found to measure community engagement by community water supplies using surface water that were similar to those described by Thornton and Leahy (2012) for private wells.

Secondary measures are needed, such as metrics related to demographics and community wealth that can serve as surrogates for factors that influence attitudes and opinions. To address this need nine metrics were identified (Table 2). For demographics, local populations were segmented into number of customers for a utility and total housing units in the local civic division. The local population was characterized by median age and further disaggregated into three groups representing dependent youth (<20 years), working age (20-65 years), and retiree (>65 years). Economic capacity (health) was measured through median income, unemployment rate, and percent of population below the poverty limit. Derivative metrics were devised that related utility operations to its customers through consumption per customer and revenue per customer.

The socio-economic setting of a water utility is dynamic and changes with the wealth, values and demands of the customers. This dynamism may be displayed in social values related to willingness to pay for source protection or other types of utility investment (Polyzou et al., 2011). Clearly, social values and attitudes towards land use affect development pressure in the source watershed. Attitudes and values probably also are linked to local financial stability and population density (Imgrund et al., 2011). Unfortunately, these metrics were not commonly available for the region, so the metrics listed in Table 2 serve as direct and indirect measures.

Operational Domain. Water utilities operate under a mandate to provide safe reliable water to their customers. In order to meet this mandate a utility must have adequate resources (capital and infrastructure) and the ability to respond to changes in both the supply and demand sides of the system. Day and Litke (1998) found that a lack of financial resources can reduce the capacity of agencies, organizations and citizens to complete effective watershed planning. The 11 metrics used came from annual reports and reports to the Maine Public Utilities Commission and are provided in Table 3. The total assets, gross revenue, expenses, and income for each utility were used to measure fiscal position. Gallons sold, non-revenue water, daily demand, and daily draft were used to measure operational capacity. Several fiscal and operational metrics were then indexed to the number of customers as revenue per customer and income per customer.

Table 2. Metrics used to assess the social domain of surface water supplies. Metric ranges and median values are presented along with a count of missing values for the 46 sources.

Metric	Description	Minimum	Maximum	Median	Count Missing
Number of Customers	**System Size**	93	136,945	2,600	0
Total Housing Units	**Service Community Size**	287	31,864	2,600	2
Median Age	**Age Structure**	23.8	48.0	40.3	2
Percent Aged 20 to 65 Years	**Working Age**	48.4	65.1	57.9	2
Percent over Age 65	**Retired/Fixed Income**	7.0	30.5	17.1	2
Percent Under Age 20	**Dependent Population**	19.7	29.2	25.2	2
Median Income	**Community Wealth**	23,488	56,171	36,062	2
Percent Below Poverty Limit	**Economic Health**	3.8	19.4	10.4	2
Percent Unemployed	**Business Health**	0.8	8.6	2.9	2
Consumption per Customer (x1,000 gallons)	**Water Use**	5.04	243	39	0

Operational and fiscal efficiencies were measured by cost per gallon, percent non-revenue water, return on assets, current ratio (assets/liabilities), debt to equity ratio, operating funds ratio, and cash flow coverage (Jordan et al., 1997; Rogers and Louis, 2005). Together these metrics provide a measure of the operational efficiency of a utility.

Discussion

The objective of this paper was to identify metrics to characterize the source of supply (biophysical domain), the socio-economic setting (social domain), and water utility functionality (operational domain). A total of 33 metrics were identified within these domains: biophysical n=14; social n=9; and operational n=11. Some of the raw metrics were further processed to produce a set of 12 rationalized metrics; rationalized metrics are used as indices of financial performance, operational efficiency, and watershed hydrology. These rationalized metrics are described in Table 4.

The diversity of surface water supplies is substantial in terms of the types and existence of metrics in each of the three domains. As shown in the tables, the ranges found sometimes span several orders of magnitude. The challenge of utilizing these diverse metrics is to harmonize the variations to be meaningful across the spectrum of utility sizes. A future paper will present the analytical approach applied to these metrics to produce a decision-support tool.

A significant problem in this assessment is the quality for data reported. Data reported to the Maine Public Utilities Commission are not always verifiable. For example, a utility may report the same volume of water as total gallons sold and non-revenue water; clearly it can't be both. Sometimes,

Table 3. Metrics used to assess the operational domain of surface water supplies. Metric ranges and median values are presented along with a count of missing values for the 46 sources.

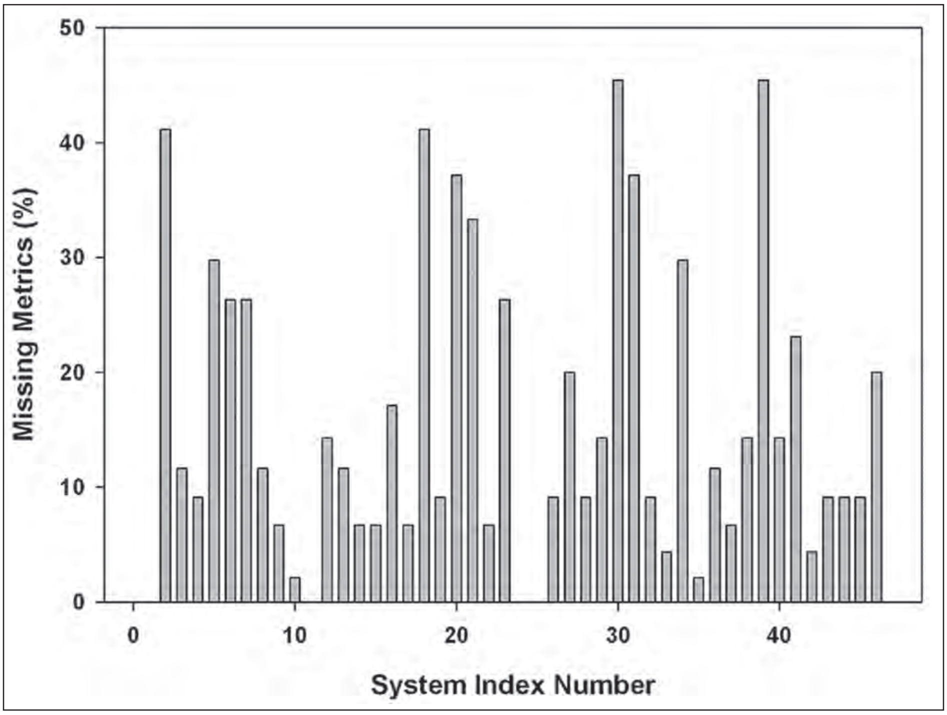
Metric	Description	Minimum	Maximum	Median	Count Missing
Assets	Value of System	$933,711	$186,400,000	$6,849,100	2
Revenue	Cash Inflow	$97,737	$20,173,814	$794,226	0
Expenses	Cash Outflow	$76,925	$13,466,866	$503,742	0
Income	Cash Balance	-$199,242	$3,703,369	$104,615	0
Total Water Produced (gallons x1,000)	Production Quantity	9,964	8,022,997	146,515	0
Gallons Sold (x1,000)	Quantity Sold	9,294	6,777,343	112,150	0
Non-Revenue Water (x 1,000)	Lost or Wasted Water	1,987	1,245,654	58,181	8
Average Daily Demand	System Demand	1,000	21,986,000	528,000	6
Maximum Daily Demand	Maximum Short-Term Demand	5,000	146,000,000	1,596,000	15
Average Daily Draft	Daily Inflow	1,523	486,000,000	2,360,000	18
SDWA Health Violations	Safe Water Maintenance	0	24	1	0
Income per Revenue Dollar	Profitability	-0.871	1.040	0.145	0
Revenue per Customer	Economic Burden	$99.11	$1,362.65	$248,95	0
Percent Non-Revenue Water	Water Loss Management	0%	100%	21.2%	5
Cost per Million Gallons	Operational Efficiency	0.001	0.030	0.005	1
Return on Assets	Income from Infrastructure	-$0.022	$0.044	$0.020	12
Current Ratio	Asset/Liability	0.250	175.1	2.853	10
Debt-Equity Ratio	Debt Leverage	-14.552	17.783	0.802	10
Cash Flow	Ability to Cover Expenses	-0.315	6.294	1.372	6

useful metrics are missing from the reports such as average daily draw or number of connections. The quantity of missing metrics ranged from none to 45 per cent (Figure 1) and institutional changes in record keeping will be needed to improve this situation.

Table 4. Rationalized metrics showing derivation and application.

Rationalized Metric	Units	Measures
Income per Revenue Dollar	Dollar/Dollar	Standardized Income
Revenue per Customer	Dollar/Connection	Average Revenue per Connection
Percent Non-Revenue Water	Percent of Total Gallons Produced	System Losses
Cost per Million Gallons Sold	Dollar/Gallon	Production Efficiency
Return on Assets	Income Dollar/Asset Dollar	Financial Health
Current Ratio	Current Assets/Current Liabilities	Ability to Service Current Obligations (short term)
Debt-Equity Ratio	Total Debt/Total Equity	Credit Worthiness
Cash Flow	Net Income/Principal & Interest Expense	Ability to Cover Debts
Source Storage/Total Volume	Gallon/Gallon	Resilience of Source
Source Volume/Watershed Area	Gallons/Unit Area	Potential Reserve Capacity
Gallons per Customer	Gallons/Connection	Water Use Efficiency
Percent Unemployment	Percent of Community Population	Economic Strength of Community
Percent Below Poverty Limit	Percent of Community Population	Financial Capacity of Community

Figure 1. Summary of metric completeness for water supplies using surface water.



Conclusions

This paper describes the identification of 33 metrics of the biophysical, operational, and social domains of public water supply. The records reported to the Public Utilities Commission and other public sources are inconsistent in quality. In order to develop an effective decision-support tool, data needs to be collected and reported in a consistent and accurate manner. The irregularity of the data, reliability of the sources, and costs to produce such data reinforce the motivation for making a decision-support tool to improve water supply. Accurately tracking the metrics presented over time will provide valuable information for both water system managers and regulatory agencies.

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