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DEPARTAMENTO DE ENGENHARIA CIVIL E AMBIENTAL

CURSO DE GRADUAÇÃO EM ENGENHARIA CIVIL

FELIPE FILGUEIRAS DE ALMEIDA

MONITORAMENTO DOS SISTEMAS DE ABASTECIMENTO DE ÁGUA E UTILIZAÇÃO DE FERRAMENTAS DE SIG: estudo de caso

Recife

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MONITORAMENTO DOS SISTEMAS DE ABASTECIMENTO DE ÁGUA E UTILIZAÇÃO DE FERRAMENTAS DE SIG: estudo de caso

Monografia apresentada à Universidade Federal de Pernambuco como parte dos requisitos para obtenção do título em bacharel em Engenharia Civil.

Orientadora: Profa. Dra. Sávia Gavazza dos Santos.

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CENTRO DE TECNOLOGIA E GEOCIÊNCIAS
DEPARTAMENTO DE ENGENHARIA CIVIL E AMBIENTAL
COORDENAÇÃO DO CURSO DE GRADUAÇÃO EM ENGENHARIA CIVIL

ATA DA DEFESA DO TRABALHO DE CONCLUSÃO DE CURSO PARA CONCESSÃO DO GRAU DE ENGENHEIRO CIVIL

CANDIDATO: FELIPE FILGUEIRAS DE ALMEIDA

BANCA EXAMINADORA:
Orientador: SÁVIA GAVAZZA DOS SANTOS
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Examinador 2: SYLVANA MELO DOS SANTOS

TÍTULO DO TRABALHO DE CONCLUSÃO DE CURSO: MONITORAMENTO DOS SISTEMAS DE ABASTECIMENTO DE ÁGUA E UTILIZAÇÃO DE FERRAMENTAS DE SIG: ESTUDO DE CASO

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Em sessão pública, após exposição de cerca de 30 minutos, o(s) candidato(s) foi (foram) arguido(s) oralmente pelos membros da banca com NOTA: ______(deixar 'Exame Final', quando for o caso).
1) ( ) aprovado(s) (nota > = 7,0), pois foi demonstrado suficiência de conhecimento e capacidade de sistematização no tema da monografia e o texto do trabalho aceito.
As revisões observadas pela banca examinadora deverão ser corrigidas e verificadas pelo orientador no prazo máximo de 30 dias (o verso da folha da ata poderá ser utilizado para pontuar revisões).
O trabalho com nota no seguinte intervalo, **3,0 = < nota < 7,0,** será reapresentado, gerando-se uma nota ata; sendo o trabalho aprovado na reapresentação, o aluno será considerado **aprovado com exame final**.
2) ( ) reprovado(s). (nota <3,0)

Na forma regulamentar foi lavrada a presente ata que é assinada pelos membros da banca e pelo(s) candidato(s).

Recife, 30 de janeiro de 2019

Orientador: ....

Avaliador 1: ....

Avaliador 2: ....

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RESUMO

Nos últimos anos o uso de tecnologias de Sistemas de Informações Geográficas (SIG) se tornou cada vez mais comum nas mais diversas áreas da ciência. Sistemas SIG se baseiam em funções de processamento, integração, manipulação e uso de bancos de dados geográficos. Em áreas relacionadas a recursos hídricos, os sistemas SIG tem contribuído de diversas formas, tais como para análise temporal de chuvas, mapeamento e monitoramento de vegetação em leitos de rios, processamento de dados pluviométrico, entre outros. No entanto, para sistemas de abastecimento de água o uso dessa tecnologia ainda tem uso limitado, principalmente devido ao custo dos equipamentos de aquisição de dados e ao requerimento de mão de obra qualificada para operação, manutenção e análise de dados, em alguns casos. O uso de SIG é particularmente importante em áreas remotas, com difícil acesso a mananciais, por exemplo, ou em áreas de risco ou conflitos em que se pode potencialmente acessar grande quantidade de dados referentes à qualidade da água, com muito mais rapidez e segurança em relação aos métodos tradicionais de amostragem e monitoramento. Neste contexto foi considerado pertinente a análise de algumas das tecnologias utilizadas para o monitoramento da qualidade da água. Nele foram analisadas três experiências em sistemas distintos: Sistema de distribuição de água de Ann Harbor (EUA), rede de sensores em Boston (EUA) e o monitoramento online e sistema de gerenciamento do Rio Liming (China). Tratam-se de experiências reportadas fora do Brasil, pois nesta pesquisa bibliográfica se observou que o uso de SIG para esta finalidade no Brasil ou é pouco utilizada ou é pouco reportada, ou ambos. A partir dos estudos de caso abordados neste trabalho notou-se que a incorporação do SIG à outras tecnologias é essencial para um monitoramento em tempo real e para a simulação dos indicadores de qualidade da água dos sistemas de abastecimentos.

Palavras-chave: SIG. Qualidade da água. Monitoramento. Sensores. Amostragem.

ABSTRACT

In recent years, the use of Geographic Information Systems (GIS) technologies has become increasingly common in many areas of science. GIS systems are based on functions of processing, integration, manipulation and use of geographic databases. In areas related to water resources, GIS systems have contributed in several ways, such as for rainfall analysis, mapping and monitoring of vegetation in riverbeds, rainfall data processing, among others. However, for water supply systems the use of this technology still has limited use, mainly due to the cost of data acquisition equipment and the requirement of skilled labor for operation, maintenance and data analysis in some cases. The use of GIS is particularly important in remote areas with difficult access to water sources, for example, or in areas of risk or conflict where a large amount of water quality data can potentially be accessed much more quickly and safely traditional methods of sampling and monitoring. In this context, it was considered relevant to analyze some of the technologies used for the monitoring of water quality. Three experiments were carried out on different systems: Ann Harbor water distribution system, Boston sensor network, and the online monitoring and management system of the Liming River in China. These are experiences reported outside Brazil, because in this bibliographic research it was observed that the use of GIS for this purpose in Brazil is either little used or it is little reported, or both. From the case studies addressed in this work it was noted that the incorporation of GIS to other technologies is essential for real-time monitoring and simulation of the water quality indicators of the supply systems.

Keywords: GIS. Water quality. Monitoring. Sensors. Sampling.

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ANN	*Artificial Neural Network*
AWWA	*American Water Works Associations*
CAE	Coeficiente de Absorção Espectral
COT	Carbono Orgânico Total
CONAMA	Conselho Nacional do Meio Ambiente
DBO	Demanda Bioquímica de Oxigênio
DQO	Demanda Química de Oxigênio
ETA	Estação de Tratamento de Águas
GPS	*Global Positioning System*
IBGE	Instituto Brasileiro de Geografia e Estatística
OD	Oxigênio Dissolvido
PNRH	Política Nacional de Recursos Hídricos
PPS	*Pulse-per-second*
RNA	Rede Neural Artificial
SCADA	*Supervisory Control and Data Acquisition*
SIG	Sistemas de Informações Geográficas
SMS	*Short-mesage servisse*
USEPA	*United States Environmental Protection Agency*
UVT	*UV Transmitance*

SUMÁRIO

INTRODUÇÃO

A Terra possui 9 mil quilômetros cúbicos de água disponível para o consumo. Isso é equivalente a 0,0006% do volume de água existente em todo o planeta. Como resultado das melhorias dos padrões de vida em todo o mundo e da constante necessidade da ampliação dos processos produtivos, o consumo de água vem aumentando rapidamente. Em 2014 o consumo de água era 50% maior que na década de 1950 (FUNASA, 2014).

O Brasil é um dos países com maior disponibilidade de água para consumo humano. Porém, grande parte desse recurso está concentrada na região Norte do país, onde há a menor densidade demográfica. A demanda por recursos hídricos nos grandes centros urbanos é um desafio, pois muitas vezes estes são atingidos pela poluição, havendo assim uma piora considerável na disponibilidade de água de qualidade (ANA, 2017).

Segundo dados da pesquisa nacional de saneamento básico, realizada em 2008 pelo IBGE, 99,4% dos municípios brasileiros são atendidos pelo serviço de abastecimento de água, porém apenas 45,3 milhões das economias residenciais, equivalente a 78,6%, são atendidas por este serviço. A maior parte dos municípios brasileiros (87,2%) recebe água totalmente tratada, em 6,2% dos mesmos a água é parcialmente tratada e em 6,2% a água não possui nenhum tratamento (IBGE, 2008).

Do Carmo e Cunha (2013) afirmam que o fornecimento de água de abastecimento contaminada, por exemplo, tem o potencial de rapidamente atingir grande número de pessoas. As vias de transmissão de doenças de origens hídricas podem ser suspensas pela retirada ou pela inativação do patógeno nas estações de tratamento de água.

Além dos patógenos, a presença de micropoluentes e microcontaminantes também podem apresentar risco à saúde humana. A presença de metais na água normalmente está relacionada a atividades industriais. Um exemplo de micropoluente é o mercúrio, que, normalmente é proveniente do descarte inadequado de baterias, equipamentos elétricos ou atividades de garimpo. Uma substância é considerada microcontaminante quando são encontradas no meio ambiente em concentração da ordem de grandeza de microgramas por litro ou inferiores. (AQUINO, BRANDT E CHERNICHARO, 2013).

O monitoramento da qualidade da água permite a caracterização e a análise de tendências em bacias hidrográficas. Dentre os indicadores utilizados para o monitoramento da qualidade da água, os parâmetros físico-químicos e biológicos de amostras de água são amplamente empregados como indicadores. No Brasil, os níveis e concentrações de vários indicadores na água são usados como referência para o enquadramento dos corpos hídricos segundo classes de qualidade de água (ANA, 2017).

Segundo a ANA (2017), apesar da grande disponibilidade de dados, ainda há grandes lacunas de informação no país. Alguns estados não realizam qualquer monitoramento da qualidade da água e quando há o monitoramento, existem deficiências quanto à representatividade temporal e espacial.

A atual gestão de recursos hídricos do Brasil está baseada na Política Nacional de Recursos Hídricos (PNRH), conhecida como "Lei das Águas", definida na Lei nº 9.433 de 1997. Essa ferramenta é de grande importância para assegurar a disponibilidade de água nos padrões adequados para a atual e futuras gerações.

1.1 Justificativa e motivação

A avaliação das atuais tecnologias disponíveis para monitoramento e controle da qualidade da água é essencial para a adequada escolha de técnicas, bem como de suas aplicações e limitações. Segundo Alva (1984, apud OLIVEIRA e MORAES, 2005)[1] *"a definição de tecnologias apropriadas tem sentido prático só enquanto relacionada a um conjunto de circunstâncias específicas de tempo, lugar e culturas"*.

Diversos fatores influenciam a escolha do tipo de monitoramento a ser adotado, dentre os quais destacam-se: sua finalidade (monitoramento de redes de abastecimento, de reservatórios ou de corpos hídricos); a disponibilidade do equipamento e infraestrutura para sua implantação; a relevância social e econômica do monitoramento e a disposição de mão-de-obra qualificada para operar e/ou coletar dados. A análise conjunta dos fatores supracitados pode determinar a viabilidade do projeto, sendo, portanto, um ponto crucial para a escolha da tecnologia a ser adotada, e deve ser avaliada a partir do tipo de dados finais que se deseja obter. De tal modo, ganha mais relevância o monitoramento da situação dos sistemas de abastecimento de água, no sentido de garantir a sua correta funcionalidade e a potencial universalização do atendimento. A importância dessas análises se torna ainda mais evidente diante dos recentes episódios de crise hídrica no Brasil e no mundo.

1.2 Objetivos gerais e específicos

[1] ALVA, E. N. Tecnologias apropriadas à produção de bens e serviços. **Revista Brasileira de Tecnologia, Brasília**, v.5, n.1, p. 14-19, jan./fev. 1984.

O objetivo geral deste trabalho foi fazer uma descrição dos métodos usuais para monitoramento remoto de qualidade de água, com foco nos aplicados a redes de abastecimento, reservatórios e corpos hídricos.

Como objetivo específico estão:

- O levantamento bibliográfico do monitoramento da qualidade da água;
- Levantamento de casos com uso de monitoramento remoto de parâmetros de qualidade de água;
- Identificação dos avanços observados nos estudos de caso que podem estimular o emprego da técnica no Brasil.

REFERENCIAL TEÓRICO

1.3 Qualidade da água

Qualidade da água é o termo usado para expressar a adequação da água para diferentes usos. A legislação brasileira estabelece os instrumentos de gestão dos recursos hídricos, enquanto a Resolução de N° 357 do CONAMA define os parâmetros físicos, químicos e biológicos da água para seus diferentes usos (0).

Quadro 1 - Resumo da classificação de águas naturais adotada pela Resolução Conama nº 357 de 2005

(continua)

Águas Doces
I - Classe Especial - Águas destinadas:
a) ao abastecimento para o consoumo humano, com desincefção;
b) à preservação do equilíbrio natural das comunidades aquáticas;
c) à preservação dos ambientes aquáticos em unidades de conservação de proteção Integral
II - Classe 1 - Águas que podem ser destinadas:
a) ao abastecimento para o consoumo humano, após tratamento simplificado;
b) à proteção de comunidades aquáticas;
c) à recreação de contato primário, conforme Resolução Conama 274/2000;
d) à irrigação de hortaliças que são consumidas cruas e de frutas que se desenvolvem rentes ao solo e que sejam ingeridas cruas sem remoção de película;
e) à proteção das comuniudades aquáticas em terras indígenas;
III - Classe 2 - Águas que podem ser destinadas:
a) ao abastecimento para o consoumo humano, após tratamento convencional;
b) à proteção de comunidades aquáticas;
c) à recreação de contato primário, conforme Resolução Conama 274/2000;
d) à irrigação de hortaliças, plantas frutíferas e de parques, jardins, campos de esporte e lazer com os quais o público possa vir a ter contato direto;
e) à aquicultura e à atividade de pesca

Quadro 1 - Resumo da classificação de águas naturais adotada pela Resolução Conama nº 357 de 2005 (continuação)

IV - Classe 3 - Águas destinadas:
a) ao abastecimento para o consoumo humano, após tratamento convencional ou avançado;
b) à irrigação de culturas arbóreas, cerealíferos e forrageiros;
c) à pesca amadora;
d) à recreação de contato secundário;
e) à dessedentação de animais.
V - Classe 4 - Águas destinadas:
a) à navegação;
b) à harmonia paisagística

Fonte: CONAMA, 2005

Segundo o Manual Prático de análise de água da Fundação Nacional de Saúde (FUNASA, 2004), o exame de qualidade para potabilidade, visa analisar amostras de água destinadas ao consumo humano, as quais não podem conter substâncias micro-organismos patogênicos. Estes testes são chamados de exames microbiológicos. A 0 mostra algumas doenças que podem ser transmitidas pela ingestão de água contaminada.

Tabela 1 - Doenças causadas por micro-organismos

Doenças	**Agentes Patogênicos**
Origem Bacteriana	Salmonella typhi
Febre tifóide e paratifóide	Salmonella parathyphi A e B
Cólera	Vibrio cholerae
Gastroenterites aguda e Diarreia	Shigella sp
Disenteria bacilar	Escherichia
Origem viral	
Hepatite A e E	Vírus da hepatite A e E
Poliomielite	Vírus da poliomielite
	Vírus Norwalk
	Rotavirus
	Enterovirus
Gastroenterites agudas e Crônicas	Adenovirus

Fonte: OPAS, 2001

O monitoramento é o conjunto de práticas que tem como função o acompanhamento de características de um sistema, sempre associado a um objetivo. As práticas relacionadas ao monitoramento de qualidade de água incluem a coleta de dados e de amostras de água em locais específicos, feita em intervalos regulares de tempo, de modo a gerar informações que possam ser utilizadas para a definição das condições presentes de qualidade da água.

Para o desenvolvimento de um programa de monitoramento de água, os principais elementos do plano de estudo, segundo Bartram et al (1996) são:

- Definição clara dos objetivos e metas;
- Expectativas de informação e usos pretendidos;
- Descrição da área de estudo de caso;
- Descrição dos locais de amostragem;
- Listagem das variáveis de qualidade da água que serão medidas;
- Frequência proposta e tempo de amostragem;
- Estimativa dos recursos necessários para implementar o programa;
- Plano de controle de qualidade e garantia de qualidade.

Dentre os objetos de estudo deste trabalho estão os cursos d'água e as redes de abastecimento. Este tipo de conformação está sujeito a várias influências que fazem com que a qualidade da água varie de local a local e de tempo em tempo, devido à sua vasta área de influência. Logo, é recomendado a execução de análises preliminares para a escolha dos locais de amostragem, fazendo com que haja a representatividade desejada.

1.4 Considerações sobre o monitoramento da qualidade da água

1.4.1 Amostragem

Mananciais, que incluem nascentes, rios, lagos ou represas, são todas as fontes de água superficiais, subterrâneas e de chuva, que podem ser usadas para o abastecimento humano. (FUNASA, 2014).

O conjunto de obras, instalações e serviços destinados à produzir e distribuir água para a população é chamado de Sistema de Abastecimento de Água. Tal empreendimento normalmente é executado pelo poder público, mesmo que administrada em regime de concessão ou permissão (MINISTÉRIO DA SAÚDE, 2011).

O monitoramento de qualidade das águas destinadas ao abastecimento da população se faz normalmente em cada etapa das estações de tratamento de água (ETAs), enquanto o monitoramento dos mananciais é executado em uma rede de pontos devidamente estudada.

Brandão *et al* (2011) sugerem que a análise da água contida na rede de distribuição seja feita com a água proveniente de uma torneira localizada próximo ao hidrômetro de uma residência que receba água diretamente da rede de abastecimento público. Tal medida ajuda a caracterizar possíveis contaminações no sistema de abastecimento, que não seriam detectadas se a amostragem fosse feita apenas na saída das ETAs. Entretanto, alguns cuidados devem ser tomados nessa amostragem, como a desinfecção da torneira com aplicação de hipoclorito de sódio.

A definição dos usos previstos para o corpo d'água, o conhecimento dos riscos à saúde para a população, os danos aos ecossistemas, a toxicidade dos efluentes, os efluentes industriais e domésticos, e as medidas de vazão, constituem algumas das informações básicas necessárias para se definirem as técnicas e as metodologias de coleta que devem ser utilizadas bem como para definir os locais de amostragem e a seleção de parâmetros que serão analisados. Sem isso, qualquer programa para avaliar a qualidade ambiental pode gerar dados não representativos sobre a área de estudo (BRANDÃO *et al*, 2011).

Segundo Brandão *et al* (2011), a primeira etapa da coleta e análise de dados acontece antes mesmo de se ir a campo, sendo ela a definição do programa de amostragem. Nessa etapa determinam-se características preliminares sobre o objeto da coleta, tais como:

- Utilização principal do corpo hídrico: consumo humano, dessedentação de animais, irrigação, abastecimento industrial, entre outros;
- Natureza da amostra: água bruta, tratada ou residuária; superficial ou subterrânea; doce, salobra ou salina;
- Informações preliminares sobre a área de influência: estudos pré-existentes sobre a área de projeto, bem como definição preliminar dos pontos de coleta, verificação dos acessos e levantamento fotográfico.
- Apoio operacional e laboratorial: definição da disponibilidade de veículos, pessoas e materiais para amostragem, bem como os recursos financeiros que estão disponíveis para o programa de amostragem. Também nessa etapa é levado em conta a capacidade do laboratório onde será feita a análise das amostras, e o levantamento das incertezas relacionadas aos equipamentos disponíveis;
- Parâmetros da área de estudo: diversas são as variáveis que devem ser levadas em conta neste ponto. Devem ser levantados os dados mais relevantes da área, podendo variar espacialmente e temporalmente, tais como temperatura, pontos de lançamento de efluentes, existência de captação, etc.
- Definição do número de amostras: É necessário a definição correta do número mínimo de amostras, para que não haja apenas uma caracterização instantânea da água. Para o tamanho da amostra em coletas de águas de rios, Brandão *et al* (2011) sugerem que seja adotada uma distribuição normal da variável de qualidade e amostras aleatórias e independentes (Equação 01Destino não encontrado!).

$$n = \left(\frac{t \times s}{I}\right)^2 \qquad (1)$$

Onde:

n = número de amostras a serem coletadas;

t = fator da distribuição t de *Student* para (n – 1) graus de liberdade e determinado limite de confiança, geralmente entre 90 e 99%. Para a primeira estimativa, usar o valor de t para $n = \infty$

s = estimativa do desvio padrão da característica medida;

I = incerteza desejada.

α = nível de significância.

De acordo com Chapman *et al* (1996a), existem três principais fatores que podem ser usados para o monitoramento de água: o meio líquido, o material sólido e os micro-organismos. Cada um desses meios possui um modo diferente de ser estudado. Os dois primeiros, a água e o material sólido podem ser estudados através de análises químicas e físicas. Já para o monitoramento de micro-organismos diversas formas podem ser utilizadas, como levantamentos e observações ecológicas, estudos histológicos e enzimáticos e a análises microscópicas dos organismos selecionados, tais como a colimetria.

A escolha da coleta de amostras manual depende de inúmeros fatores, incluindo a característica geográfica da região e o sistema de transporte. Chapman *et al* (1996a) citam o exemplo da cidade do Panamá, em que a amostragem é feita por pessoas do laboratório que vão a campo por uma semana para coletar e fazer análises de campo, e depois voltam ao laboratório usando transporte público. A situação é ainda pior em cidades maiores que possuem infraestrutura inadequada, pois mais pessoas são necessárias para as amostragens, e a precariedade na manutenção dos sistemas de transportes tende a ser pior. Tal situação poderia ser contornada caso houvessem pessoas treinadas para operar unidades hidrometeorológicas e hidrológicas que também tivessem conhecimento para amostragem.

Segundo a Funasa (2014), além do tipo de manancial, as técnicas de amostragem também variam de acordo com a finalidade das análises: coletas para análises físico-químicas devem ser feitas em frascos de polietileno, limpos, secos e devidamente esterelizados, com capacidade mínima de um litro, devidamente vedados e identificados, tendo-se o cuidado de enxaguá-lo duas a três vezes com a água a ser coletada e completar o volume da amostra. Já as coletas para análises bacteriológicas, a amostragem deve ser feita utilizando-se frascos de vidro neutro ou plástico autolavável, não tóxico, boca larga e tampa a prova de vazamento. O período entre a coleta da amostra e o início das análises bacteriológicas não deve ser superior a 24 horas e seu armazenamento é feito sob refrigeração a uma temperatura de 4 a 10º C. Antes da esterilização do frasco de coleta para amostras, recomenda-se adicionar ao mesmo

0,1 mL de uma solução de tiossulfato de sódio a 1,8% (agente neutralizador de cloro residual).

1.4.2 Análises físico-químicas – Metodologia Convencional

No Brasil tem-se usado para a escolha metodologia de análise da qualidade da água o "*Standard Methods for the Examination of Water and Wastewater*", publicado inicialmente em 1905. Em cada nova edição foram adicionados novos métodos de análise, bem como aprimorados os já existentes, criando assim um manual sólido e com credibilidade mundial (AMERICAN PUBLIC HEALTH ASSOCIATION, 2005).

Determinação do pH

A Portaria nº 518/2004 do Ministério da Saúde recomenda que o pH da água seja mantido na faixa de 6,0 a 9,0 no sistema de distribuição.

Utiliza-se tradicionalmente o medidor de pH (potenciômetro) calibrado em soluções-tampão de pH 4, 7 e 10. A sequência do ensaio e consiste em:

1) Ligar o aparelho e aguardar a sua estabilização;
2) Lavar os eletrodos com água destilada e enxuga-los;
3) Calibrar o aparelho com as soluções-tampão, que são soluções cujos constituintes são capazes de evitar grandes variações de pH quando a elas são adicionados ácidos ou bases;
4) Lavar novamente os eletrodos com água destilada e enxuga-los;
5) Introduzir novamente os eletrodos na amostra a ser examinada e realizar a leitura;
6) Lavar novamente e colocar em água destilada;
7) Desligar o aparelho.

O valor permitido para o pH segundo o MS (2011) encontra-se no ANEXO 03.

Determinação do cloro residual

A Portaria nº 518/2004 do Ministério da Saúde determina a obrigatoriedade de se manter em qualquer ponto na rede de distribuição de água a concentração mínima de cloro residual livre em 0,2 mg/L. Recomenda, ainda, que o teor máximo seja de 2,0 mg/L de cloro residual livre em qualquer ponto do sistema de abastecimento.

A determinação da concentração (mg/L) de cloro residual livre normalmente é efetuada por meio de visualização colorimétrica (disco comparador). Para tal análise faz-se necessário um comparador colorimétrico, cubetas de vidro ou acrílico e reagente DPD para cloro livre em cápsula. DPD é a sigla para o composto N,N-dietil-p-fenileno-diamina, que é um composto que reage com o cloro livre (Cl_2), com o ácido hipocloroso (HClO) e com íons hipoclorito (ClO-), formando um complexo de cor rósea.

A técnica resume-se a encher duas cubetas até a marca de 5,0 mL, adicionando em uma delas o reagente DPD e homogeneizando. Deve ser inserida a cubeta com DPD do lado direito do aparelho, e a outra do lado esquerdo, realizando assim a leitura entre 3 e 6 minutos após a adição do reagente. A FUNASA (2014) sugere que quando for feita a leitura deve-se posicionar o comparador (equipamento) contra uma fonte de luz como, por exemplo, uma janela, o céu ou uma lâmpada, rotacionando o disco até que se obtenha a mesma tonalidade nos dois tubos. O valor permitido para o cloro residual segundo o MS (2011) encontram-se no ANEXO 03.

Determinação da Cor

Cor na água é geralmente proveniente de substâncias dissolvidas de origem mineral e orgânica nas águas que acarretam maior ou menor intensidade da cor, dependendo da concentração dessas substâncias. A Portaria nº 518/2004 do Ministério da Saúde estabelece para cor aparente o Valor Máximo Permitido de 15 uH como padrão de aceitação para consumo humano.

A determinação da cor em laboratório pode ser feita por espectrofotômetro ou mais rudimentarmente de maneira visual, utilizando como base a solução-padrão de Cloroplatinato de Potássio (500 uH). Devem ser preparados padrões de cor na faixa de 5 a 50 Uh, utilizando-se de tubos Nessler de 50 ml, cada um contendo 0,5; 1,0; 1,5; 2,0; 2,5; 3,0; 3,5; 4,0;4,5; 5,0; 6,0 e 7,0 ml da solução padrão, e diluídos com água destilada até a marca de 50 ml. A comparação da amostra deve ser feita visualmente com as amostras diluídas nos tubos anteriormente. O valor permitido para a cor aparente segundo o MS (2011) encontra-se no ANEXO 03.

Determinação da Turbidez

Um dos métodos mais comuns para a determinação da turbidez é feito a partir do aparelho nefelométrico. Este instrumento determina a concentração de partículas insolúveis em um líquido a partir da medição da intensidade de luz que elas dispersam. (AMERICAN PUBLIC HEALTH ASSOCIATION, 2005).

O aparelho segue os seguintes critérios:

1) Fonte de luz – Lâmpada de filamento de tungstênio, com temperatura de cor entre 2200 e 3000ºK
2) Distância percorrida pela luz incidente e luz difusa dentro do tubo de amostra – Total não pode exceder 10cm
3) Ângulo de aceitação da luz pelo detector – Centrado 90º do caminho de incidência, e não exceder ± 30 ° a partir de 90º. Além disso, o sistema detector e o filtro (caso usado), deve ter um pico espectral de resposta de 400 a 600 nm

A medição é feita com a amostra levemente agitada, para que não haja precipitação do material não solúvel. Para a eliminação das bolhas é feita a imersão em banho ultrasônico ou por meio de vácuo. Após esses procedimentos, realiza-se a medição no aparelho nefelométrico (AMERICAN PUBLIC HEALTH ASSOCIATION, 2005).

De acordo com a FUNASA (2004), a turbidez indica a presença de sólidos em suspenção, e é definida como o grau de interferência à passagem de luz através do líquido. Para a água bruta esse índice está intimamente relacionado com o tipo de solo em que o corpo d'água se encontra. O valor permitido para a turbidez segundo o MS 2914 (2011) encontram-se no ANEXO 03.

Oxigênio Dissolvido

Existem três métodos eletrométricos para a determinação de oxigênio dissolvido em corpos d'água (BRANDÃO *et al*, 2011):

- Polarográfico - ideal para águas que não apresentam concentrações de oxigênio dissolvido próximo ao zero e presença de sulfeto elevada. O sistema trabalha por pulso elétrico e não necessita de agitação.
- Galvânico – o sistema é constituído de uma célula galvânica que, pela difusão do oxigênio dissolvido através da membrana, realiza a determinação. Necessita de agitação e é ideal para determinação de oxigênio dissolvido em todos os tipos de água.
- Óptico – o sistema realiza a determinação por luminescência, não necessita de agitação, e é ideal para a determinação de oxigênio dissolvido em todos os tipos de água.

Os valores permitidos para o OD segundo o CONAMA (2005), encontram-se no ANEXO 01

1.4.3 Análises biológicas

.

E. Coli e Coliformes Totais

A determinação do *E. Coli* para sistemas de abastecimento consiste apenas na verificação de sua presença ou ausência em determinada quantidade de amostra. Segundo normativas do ministério de saúde, deve ser constatada sua ausência em 100 mL.

Um dos processos de análise bacteriológica mais usado é o do Substrato Cromogênico, aprovado pelo *Standard Methods of Examination of Water and Wastewater*.

O método consiste na coleta de 100 mL da amostra em bolsa estéril ou frasco, com ou sem tiossulfato de sódio, adicionando então o conteúdo do frasconete de Colilert (substrato Cromogênico Definido ONPG-MUG). O frasco deve ser fechado e agitado para dissolver o reagente, e, em seguida, encubado por 24 h a 35ºC. O resultado é proporcionado pela mudança de cor do conteúdo do frasco. Caso a amostra se apresente incolor, o resultado é negativo. Caso apresente-se em coloração amarelada à iluminação ambiente, o resultado é positivo para Coliformes Totais. Se apresentar coloração amarelada e fluorescente sob luz UV-365mm, o resultado é positivo para *E. Coli*.

Além do método do substrato cromogênico, também é bastante usado o Método das Membranas Filtrantes (MF). Neste, há a filtração, sob vácuo, de um volume de água em uma membrana com porosidade controlada, onde nela ficarão retidas as células das bactérias contaminantes. Após a filtragem, a membrana é colocada sobre uma placa de Petri e incubada invertida a 35ºC durante 24 ± 2 horas. Após a incubação, ocorre a contagem das colônias, de preferência sob fonte de luz difusa (FUNASA, 2004).

O valor permitido para *E. Coli* e Coliformes Totais segundo o MS (2011) encontram-se no ANEXO 03.

1.4.4 Problemas atrelados aos métodos de monitoramento convencionais

O uso da metodologia convencional de coleta e análise de amostras de águas está vinculado a várias fontes de erro, tais como a representabilidade,da amotra, o transporte dela e a transcrição dos dados de amostragem

. Ao fazer a amostragem é necessário seguir as recomendações normativas a fim de evitar a coleta de amostras não representativas, seja temporal, espacial ou qualitativamente. Durante a etapa de transporte e armazenagem, é necessária a atenção a substâncias ou até mesmo movimentos que possam descaracterizar a amostragem. Além disso, na etapa de armazenagem de dados após a análise laboratorial é necessário atentar-se aos possíveis erros de transcrição (CHAPMAN *et al*, 1996b).

1.5 Sistema de Informações Geográficas (SIG)

De acordo com Burrough (1986), um SIG é constituído por um conjunto de instrumentos especializados em adquirir, armazenar, recuperar, transformar e emitir informações espaciais. Esses dados geográficos descrevem objetos do mundo real em termos de posicionamento, com relação a um sistema de coordenadas, seus atributos não aparentes (como a cor, pH, custo, incidência de pragas, etc) e das relações topológicas existentes. Portanto, um SIG pode ser utilizado em estudos relativos ao meio ambiente e recursos naturais, na pesquisa da previsão de determinados fenômenos ou na tomada de decisões, considerando a concepção de que os dados armazenados representam um modelo do mundo real.

Do Carmo e Cunha (2013) caracterizam os Sistema de Informações Geográficas – SIG pela utilização dos meios digitais, a necessidade de uma base de dados integrada, georreferenciada e com controle de erro. Essa tecnologia também contém funções de análise dos dados e realizam operações algébricas simples, complexas e lógicas, e está comumente relacionada a outras técnicas e tecnologias digitais e computacionais.

Os dados no SIG podem ser classificados como primários ou secundários. O primeiro caso refere-se às medidas executadas diretamente em levantamentos de campo, utilizando técnicas de sensoriamento remoto, ensaios de campo e laboratório, entre outros. A caracterização como dado secundário ocorre quando são derivados de mapas, planos de informações ou bancos de dados pré-existentes (DO CARMO e CUNHA, 2013).

Os *softwares* de SIG não suprem todas as demandas de um sistema de abastecimento de água, sendo necessário, então o desenvolvimento de novas metodologias, agregando *softwares* básicos de geoprocessamento a objetivos específicos, como a de modelagem hidráulica, que visando à reabilitação e conhecimento destes sistemas, objetivam o funcionamento adequado dos mesmos, dentro de padrões técnicos satisfatórios e de condições que gerem menor impacto social e ambiental.

A possibilidade da execução de análises espaciais disponível nos programas de SIG e a possibilidade da criação de modelos de estudo, combinando funções em estruturas lógicas e automatizadas permitem ao usuário a realização de casos com diferentes cenários, o que seria inexequível manualmente. Esta característica é, sobretudo, essencial para estudos ambientais, nos quais estão envolvidos, frequentemente, muitos dados e variáveis de diferentes naturezas. (DO CARMO e CUNHA, 2013).

Todo o sistema de monitoramento de qualidade de água tem como objetivo a geração de dados confiáveis. Além da geração de dados, é necessário seu processamento e apresentação adequada, de modo que seja viável a análise espacial e temporal (BARTRAM *et al*, 1996).

Vinculado à gestão e modelagem de redes de abastecimento, um *software* comumente usado é o EPANET, quepermite a execução de simulações dinâmicas e estatísticas do comportamento hidráulico e da qualidade da água de redes de abastecimento, sendo um dos *softwares* mais utilizados no Brasil para este fim.

A vinculação de sensores que, em geral não se utilizam de reagentes comunicando-se com microcontroladores parece uma solução óbvia quando pretende-se identificar exatamente onde ocorreram as falhas em um sistema, seja ele uma rede de abastecimento ou leitos de rios.

O monitoramento ininterrupto proporcionado pelo sistema de monitoramento online permite o detalhamento mais preciso da qualidade da água ao longo do tempo, identificando quais são os eventos cíclicos e pontuais de cada região (BRANDÃO *et al*, 2011). De tal maneira pode-se dizer que o uso do sensoriamento online aumenta a resolução temporal dos dados.

A tecnologia de sensoriamento avançou a tal ponto que a implantação de redes densas de dispositivos para monitoramento de infraestrutura em tempo real agora está mais acessível às empresas de saneamento, órgãos de controle ambiental ou academia. Quando combinado com técnicas de processamento de dados apropriadas, o aumento da densidade e disponibilidade dessas medições permite melhor resposta, gerenciamento e previsão de falhas de infra-estrutura (WHITTLE, *et al*, 2013).

Devido ao seu grande potencial, no Brasil, os Sistemas de Informações Geográficas tem sido aplicados em diversas áreas da ciência, dentre alguns dos casos, estão:

- Planejamento de sistemas de transporte no Brasil com o auxílio de tecnologias de SIG. (DA SILVA, 1998)
- Estimação do potencial aurífero no Vale do Ribeira por meio de um sistema de informações geográficas, em 1999 por Mônica Mazzini e Mário da Costa Campos (PERROTA e NETO, 1999);
- Estudo de uso e ocupação de solo na bacia do Ribeirão Água Fria – Bofete (SP) por meio de SIG (WILSSON *et al*, 2001);
- Investigação de uma sub-bacia hidrográfica urbana em Fortaleza-CE com utilização de SIG. (PEIXOTO *et al*, 2017)

- Análise de casos de dengue nas grandes regiões e unidades federativas do brasil com auxílio de sistema de informação geográfica (COTRIM *et al*, 2017)

1.6 Sensores e instrumentação disponíveis no mercado

Nos primeiros projetos de monitoramento automático de cursos d'água, as medições eram realizadas por instrumentos mais rústicos e os registros efetuados em papel. Os registros, em forma de gráfico, representavam as variações do parâmetro medido, em função do tempo. (BRANDÃO *et al*, 2011).

Segundo Brandão *et al* (2011) o desenvolvimento tecnológico do monitoramento automático foi definido pela evolução dos processos eletroeletrônicos, que possibilitaram a substituição dos movimentos mecânicos dos sensores por impulsos elétricos. Os mecanismos de relojoaria deram lugar a motores elétricos sincronizados, alimentados por baterias. Mais recentemente, os progressos na área da informática propiciaram a transformação dos impulsos elétricos em códigos digitais que podiam ser gravados em dispositivos magnéticos com capacidade de armazenamento gigantesca. Registradores virtuais de tempo sincronizados às leituras dos dados dispensaram os sensores mecânicos, permitindo informar, para cada dado coletado, a hora correspondente.

A diversidade dos sensores e equipamentos para monitoramento da qualidade da água é bastante extensa. Para cada aplicação faz-se necessário o uso de sensores diferentes, com características adequadas ao local, tais como resolução espacial e temporal, sensibilidade, acurácia, entre outros. Alguns dos sensores citados na bibliografia utilizada encontra-se no Anexo 02.

Diversos são os métodos alternativos à metodologia tradicional de monitoramento de qualidade de água. Medidores portáteis, medidores de bancadas, medidores multifuncionais e sistemas de sensores sem fios são exemplos dessas alternativas. O uso dessas tecnologias visa reduzir erros que podem ser cometidos nos ensaios laboratoriais, porém, algumas dessas soluções ainda envolvem o uso de reagentes químicos, o que encarece o seu uso. Dentre alguns disponíveis no mercado podemos citar:

1.6.1 Medidor Portátil PHH-60BMS

É um medidor portátil com eletrodos removíveis que tem como característica a medição de pH e condutividade elétrica. Este tipo de medidor possui custo elevado, cerca de US$850,00, e não necessita de reagentes. Esse dispositivo requer a leitura manual dos dados, e não possui suporte de nenhum banco de dados (0).

Figura 1 - Medidor portátil de pH e condutividade elétrica

Fonte: OMEGA Engineering inc.

1.6.2 Medidor multifuncional portátil CDS107

O CDS107 é um medidor multifuncional que funciona com um microprocessador. Pode ser usado como medidor portátil ou de bancada para medir pH, potencial de oxidação/redução, condutividade elétrica, sólidos totais dissolvidos, salinidade e temperatura. Este equipamento encontra-se disponível pelo preço de US$800,00. Este medidor possui a capacidade de armazenagem de até 150 pontos de dados, porém não possui suporte de transferência de dados (0).

Figura 2 - Medidor multifuncional CDS107

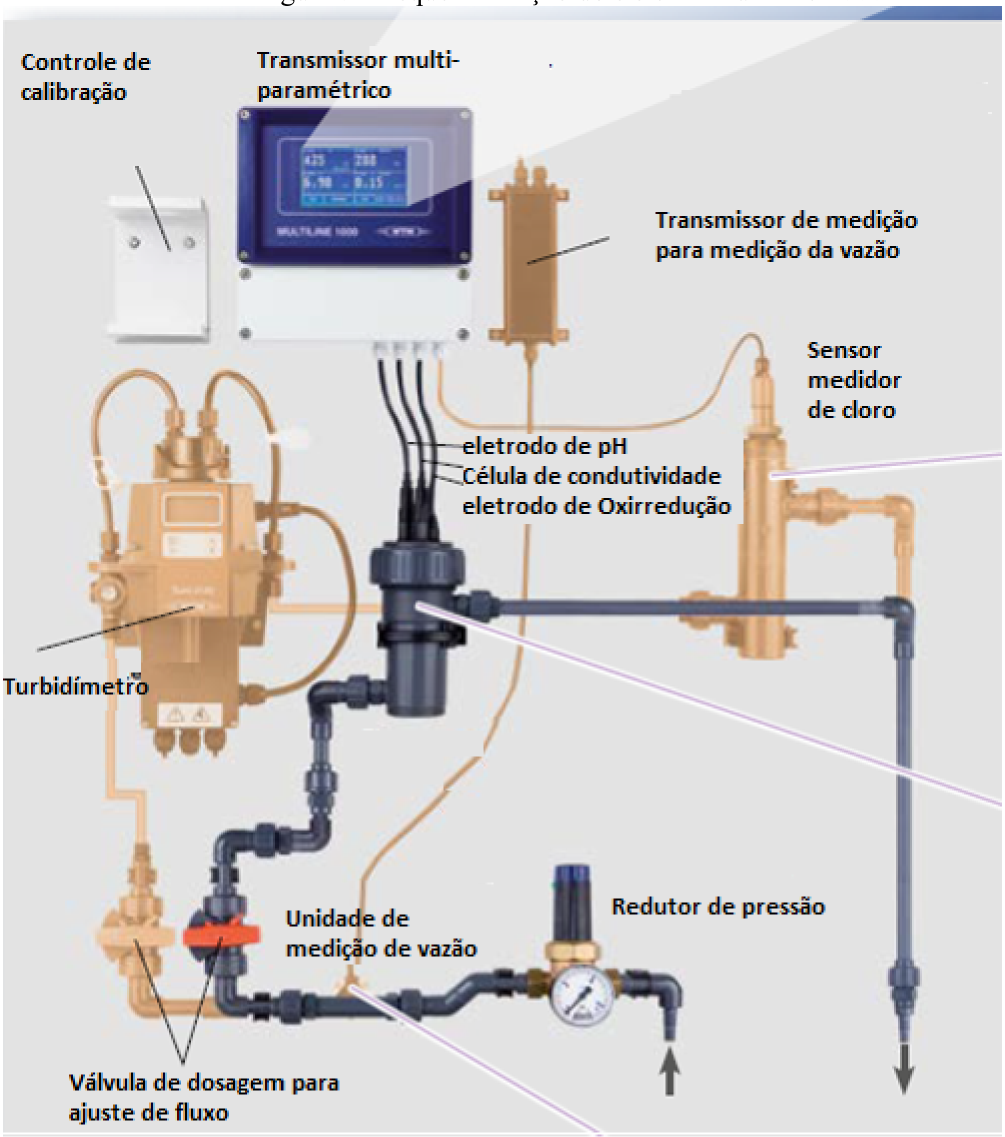
Fonte: OMEGA Engineering inc.

1.6.3 Sistema multi-paramétrico MULTILINE 1000

O Multiline 1000 é um sistema multi-paramétrico para uso em sistemas de abastecimento de água potável. Esse sistema pode medir pH, potencial de oxidação/redução, oxigênio dissolvido, condutividade elétrica, turbidez e cloro livre e total. Tal sistema conta com transmissor, permitindo que os dados sejam enviados para um terminal receptor (0).

Não foi possível obter estimativas de preço para este sistema

Figura 3 - Esquematização do sistema Multiline 1000



Fonte: Modificado de WTW inc

1.6.4 Medidor multifuncional CarboVis

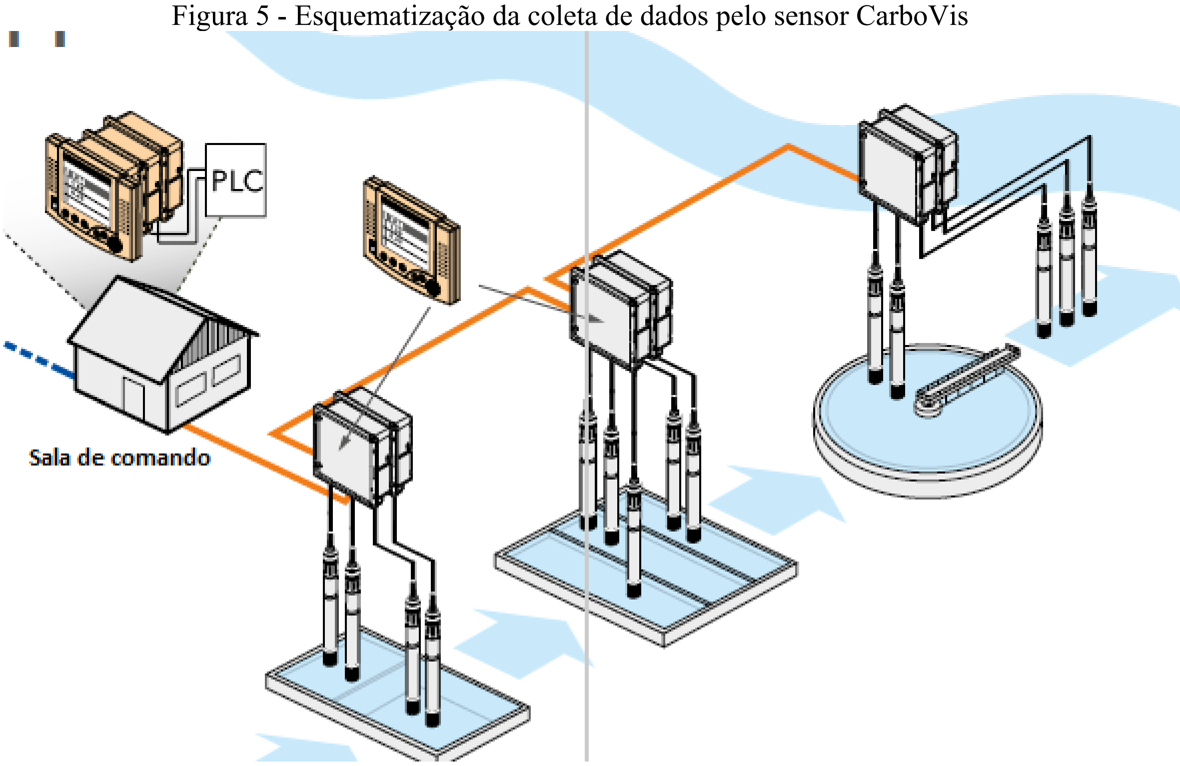
CarboVis é um sensor ótico que permite, enquanto submerso no meio, o monitoramento de parâmetros como DQO (Demanda química de oxigênio), DBO (Demanda bioquímica de oxigênio), CAE (Coeficiente de absorção espectral), COT (carbono orgânico total) e UVT (Transmissividade da luz UV). Por se tratar de um sensor óptico, dispensa a necessidade de reagentes (0).

Figura 4 - Instalação do sensor CarboVis.

Em (A), a instalação vertical. Em (B), o dispositivo é instalado horizontalmente
Fonte: WTW inc

Tal sensor é recomendado pela fabricante para uso em Estações de Tratamento de Água, em qualquer uma de suas etapas. O sensor conta com acessórios que permitem o envio de sinais e dados via cabo ou mensagem, além de ser possível o monitoramento via SMS e online, como representado na 0.

Figura 5 - Esquematização da coleta de dados pelo sensor CarboVis



Fonte: Modificado de WTW inc

MATERIAL E MÉTODOS

No presente trabalho foram analisadas diferentes aplicações da tecnologia de geoprocessamento para o monitoramento da qualidade da água, dando enfoque no monitoramento online, e comparando suas vantagens e desvantagens em relação à metodologia tradicional de coleta de dados *in situ*. Parâmetros como a quantidade de amostras e locais de coleta não destoam entre as diferentes metodologias, visto que são parâmetros mínimos estatísticos para a caracterização do corpo hídrico ou da rede de abastecimento.

Devido ao enquadramento da maior parte dos mananciais superficiais ser de Classe 2, para o presente trabalho este será o padrão adotado para águas doces, definida na resolução Nº 357 do CONAMA, e seus principais parâmetros estão dispostos no Anexo 1. Já para as redes de distribuição, os parâmetros a serem observados são definidos pela Portaria de Nº 2914 do Ministério da Saúde, e o resumo de seus parâmetros mais usuais estão dispostos no ANEXO 3.

Os estudos de caso utilizados neste trabalho são provenientes de pesquisa bibliográfica realizada no portal *Science Direct*, plataforma *online* de acesso a revistas e artigos científicos. As áreas escolhidas e os objetos de análise para o estudo foram:

- Caso 01 - Rede de distribuição de água de Ann Harbor: localizada no estado norte-americano de Michigan. O trabalho tem como autores Janice Skadsen, Robert Janke, Walter Grayman, William Samuels, Mark Tenbroek, Brian Steglitz e Sumedh Bah, e foi publicado em 2008, na revista *American Water Works Associations* (AWWA). O artigo encontra-se disponível no Anexo 11.
- Caso 02 - Rede de distribuição de água de Boston: localizado no estado norte-americano de Massachusetts. O trabalho tem como autores Ivan Stoianov, Lama Nachman, Andrew Whittle, Sam Madden e Ralph Kling, e foi publicado em 2006, no *Water Distribution Systems Analysis Symposium 2006.* O artigo encontra-se disponível no Anexo 12.
- Caso 03 - Rio Liming: Localizado na cidade de Daqing, China. O trabalho tem como autores Wei Yang, Jun Nan, Dezhi Su, foi publicado em 2008, na revista *Journal of Environmental Management – ed.88.* O artigo encontra-se disponível no Anexo 13.

O primeiro estudo de caso se trata de uma rede de abastecimento que atende aproximadamente 130 mil usuários, numa área de aproximadamente 126 km², tendo demanda média de água de 657 L/s. O sistema de distribuição tem um tempo médio de retenção de dois dias e meio, porém existem áreas onde a água pode ficar retida por até 10 dias. Essa característica pode resultar na degradação da qualidade da água, sendo de extrema importância o monitoramento, principalmente nos pontos com maior tempo de detenção.

O segundo estudo de caso apresenta o monitoramento hidráulico e da qualidade da água do sistema de distribuição de água, incluindo a detecção de variação rápida de transientes hidráulicos. Em colaboração com *a Boston Water and Sewer Comission* foram instalados em 2004 três grupos de monitoramento para validar o conceito estudado.

No último caso estudado foi desenvolvido um sistema online de monitoramento de qualidade da água, combinando sensores de pH e de sensores de luz ultravioleta e visível com redes neurais artificiais e o uso de instrumentação virtual. Tal combinação teve como objetivo permitir que o conjunto tivesse a capacidade de desenvolver reconhecimento de padrões (redes neurais artificiais) e diminuir a quantidade de *hardwares* instalados para o monitoramento (instrumentação virtual).

RESULTADOS E DISCUSSÃO

1.7 Caso 01 – Monitoramento *online* do sistema de distribuição de Ann Harbor para detecção de contaminação e mudança na qualidade da água (SKADSEN *et al*., 2008)

A escolha dos locais de monitoramento da qualidade de água do sistema de abastecimento da cidade foi feita através do *software* TEVA-SPOT. Esse *software* faz análises probabilísticas de vulnerabilidade do sistema, trabalhando de modo em que é definida uma função para cada ponto, onde são levados em conta parâmetros como área de influência, tempo de detenção e possibilidade de contaminação, e as soluções com melhores valores são escolhidas.

Além do TEVA-SPOT, também se utilizou do *software* PineNet, que tem sua base no EPANET para simulação e modelagem, e teve como objetivo a escolha dos locais onde os valores de velocidade, idade e vazão da água eram críticos. Após a simulação em ambos os *softwares* supracitados, foram escolhidos os parâmetros que deveriam ser analisados (0), conforme similaridade na importância dos critérios descritos.

Tabela 2 - Parâmetros de monitoramento *online* e suas utilidades

Parâmetro	**Utilidade**
Cloro Total	Parâmetro principal identificado pelo estudo da U.S.EPA
UV254	Indicador geral de compostos orgânicos, substituto do COT
Amonia (Total e Livre)	Parâmetro de controle operacional, indicador de decomposição da cloramina e de ocorrência do processo de nitrificação
Cloreto	Indicador geral da presença de íons
Oxigênio Dissolvido	Indicador de demanda oxidante e índice para controle de corrosão
Condutividade	Indicador de presença de sais

Fonte: adaptado de Skadsen *et al*. (2008)

Para a escolha final dos locais de monitoramento após a simulação dos dois *softwares*, foram analisados fatores como infraestrutura e acessibilidade para a implantação do monitoramento (0).

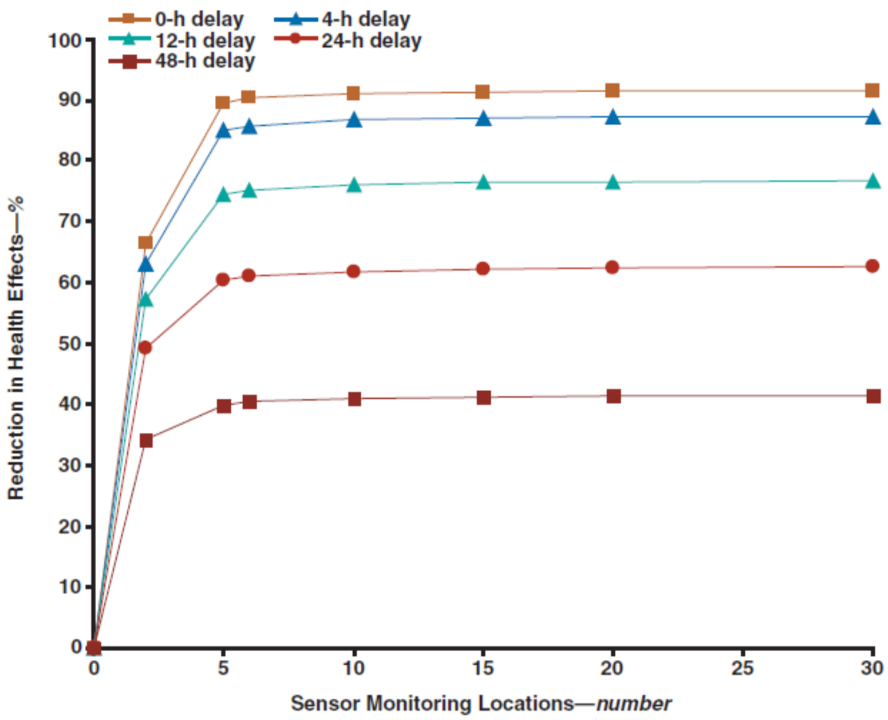
Tabela 3 - Critério de priorização utilizado para seleção final

Critério	Priorização	
	Baixa	**Alta**
Posse do Local	Privada	Pública
Conexão de Distribuição	não existente	Existente com fácil acesso
Eletricidade	não existente e de difícil conexão	Facilmente disponível
Drenagem e esgoto	não existente e de difícil conexão	Facilmente disponível
Comunicação	não existente	Suficiente capacidade e disponibilidade
Acesso	Espaço confinado ou inexistência de acesso	Facilmente disponível

Fonte: adaptado de Skadsen *et al*. (2008)

Os autores também analisaram a influência do tempo de resposta do monitoramento na efetividade da proteção da saúde pública. O parâmetro disposto como "*Reduction in health effects - %*" foi definido através de simulação hidráulica da liberação de diversos contaminantes e da exposição da população (SKADSEN *et al*, 2008). Para a análise foram verificados com 0, 4, 12, 24 e 48 horas. A influência desse fator pode ser observada na Figura 7.

Figura 6 - Efeitos dos intervalos de tempo de resposta



Fonte: Skadsen,*et al* (2008).

As simulações indicaram que o uso do monitoramento em tempo real (tempo de resposta igual a 0h) demonstra eficiência visivelmente superior aos demais e indica maior probabilidade de atenuação dos riscos à saúde. Além disso, os resultados de simulação também indicaram que o aumento do número de pontos de amostragem, a partir de 4 locais, mostrou pequenos benefícios.

Para validar a modelagem, foram selecionados quatro locais para análises de vulnerabilidade do sistema, e quatro para o monitoramento da qualidade da água, sendo um desses pontos em comum. Para tal foram criados critérios de correlação entre o monitoramento online e o convencional realizado em laboratorial (0).

Tabela 4 - Critérios de avaliação do instrumento para o projeto piloto

Medida	**Critério de Aceitação**	**Critério de Rejeição**
Acurácia	Resultados online combinam com a análise laboratorial dentro de 5% para todas as medidas	Resultados online são > ± 5% dos resultados laboratoriais
Sensitividade	Cloro total: 0.1 mg/L Amonia: 0.01 mg/L Condutividade: 10µS UV_{254} : 0.001/cm OD: 0.1 mg/L Cloreto: 1mg/L	Sensitividade menor do que os valores listados
Variabilidade	Desvio padrão <10% da media durante o período de testes (máximo de 3 semanas)	Desvio padrão >10% da media durante o período de testes
Falsa Resposta	< 20% de mudança entre leituras consecutivas	>20% de mudança entre leituras consecutivas
Taxa falsa resposta	< 1 incidente por semana	> 1 incidente por semana
Alcance	Cobre os valores mínimo/máximo previsto	Não cobre os valores mínimo/máximo previstos
Facilidade de calibração	< 30min/semana	> 30min/semana
Frequência de calibração	< 1/semana	>1/semana
Frequência de manutenção	< 1/semana	>1/semana

Fonte: Adaptado de Skadsen adaptado, 2008

Skadsen *et al.* (2008) reportam que o custo de implantação, infraestrutura e comunicação foi de cerca de US$ 40.000,00 por localidade. Os resultados do monitoramento da água do sistema de ANN HARBOR no projeto piloto se encontram nos Anexos 4 ao Anexo 10, de forma gráfica.

A partir da análise do monitoramento dos cloretos na água tratada, foi constatada uma variação de mais de 100% nos valores medidos durante períodos de 24h, fazendo com que esse parâmetro fosse descartado da análise, visto que o máximo permitido para a variabilidade era 10%.

O critério de amônia também foi descartado por conta da sensibilidade da instrumentação adotada que não possuía a sensibilidade requerida.

Para o UV_{254} o projeto piloto demonstrou maiores variações tanto na rede de distribuição quanto na água tratada quando comparados com dados pontuais. Devido a esse resultado inesperado, que contrasta com a base de dados de coleta pontual, os autores salientam que isso seria mais uma razão para investir no monitoramento online.

Na análise do OD não foram utilizadas coletas pontuais, não permitindo assim a análise da acurácia do sistema implantado. Porém os valores obtidos pelos autores estão dentro dos valores usualmente observados.

Os autores também destacaram que, dentre os parâmetros monitorados, tanto na água tratada quanto no sistema de distribuição, o mais estável foi a condutividade. Porém a acurácia de um dos instrumentos foi baixa, e mostrou resultados que não conseguiram ser ajustados mesmo com calibração.

Para o cloro total foram utilizados sensores que não se utilizam de reagentes. Um dos instrumentos utilizados mostrou mais variabilidade do que o monitoramento tradicional que se utiliza de reagentes. Além disso, foram obtidas duas falsas respostas no monitoramento da agua tratada em 18 dias, em decorrência da formação de bolhas devido à vazão baixa.

Os autores concluíram que é necessário monitoramento da modelagem qualidade de água e dos sistemas de abastecimento para que a escolha dos pontos de análise seja feita eficientemente. Além disso os autores dizem que após a escolha dos locais de análise a partir das modelagens, é necessário que em casos críticos o tempo de resposta dos aparelhos sejam diminuídos, permitindo assim melhora no desempenho do monitoramento.

No projeto estudado por Skadsen, *et al* (2008), ocorreram variações significativas nos parâmetros da água tratada, o que os autores definiram como um possível fator para diminuição da sensibilidade do sistema de monitoramento

1.8 Caso 02 – Rede de sensores para monitoramento do abastecimento de água e redes de esgoto: lições de Boston (STOIANOV *et al.*, 2008)

Com o objetivo de criar um sistema alternativo aos sistemas SCADA, que, segundo os autores possuem custos elevados, os autores tomam como objetivo a utilização conjunta de sensores e modelagem para o monitoramento de qualidade da água e de transientes hidráulicos.

Os autores utilizam modelagem hidráulica e estimativa de estado para a modelagem de parâmetros de qualidade de água. Stoianov *et al* (2008) define estimativa de estado como o processamento do menor número possível de parâmetros para determinar as demais variáveis.

Em seu exemplo, o monitoramento da qualidade de água é usado para detectar, estimar e projetar em algum programa de SIG o fluxo que um evento de contaminação toma, possibilitando a interrupção do abastecimento em pontos específicos.

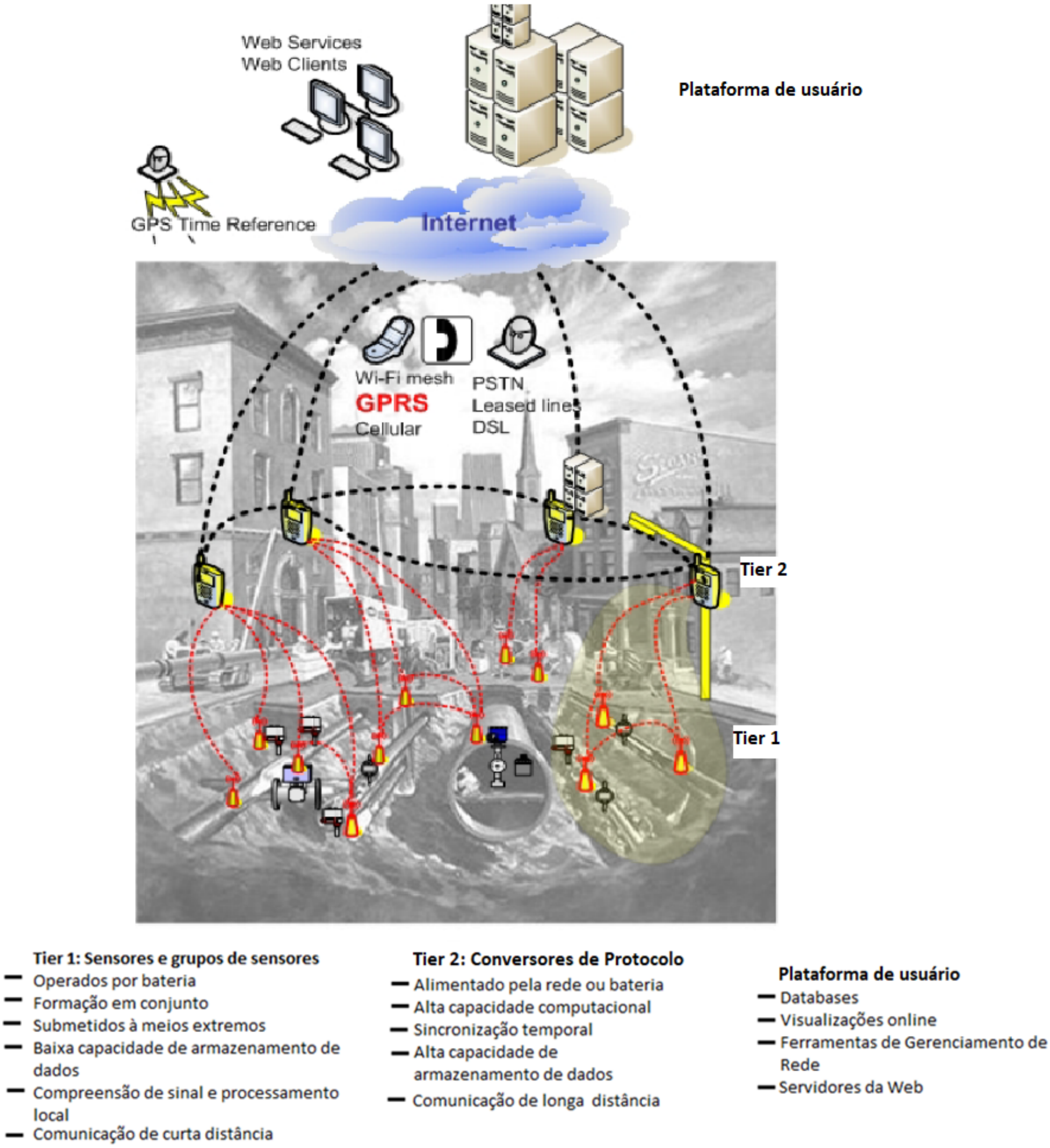
Nesse trabalho foi adotada a unidade S/s, que significa *Samples per Second*, que é uma unidade de frequência usada para captura de dados.

Os autores definem dois tipos de amostragem para os sensores de indicadores de qualidade da água: contínua, porém com leituras periódicas ou *burst mode.* No primeiro tipo, a amostragem é feita continuamente, com leitura a cada intervalo de tempo adotado (Exemplo: coletar por 5 segundos a cada 1 minuto). Além disso, o tipo contínuo também tem como parâmetro a taxa de amostragem e o tempo de comunicação com os conversores de protocolo (*Gateways*)

Já o *burst mode* é usado para análises mais sofisticadas, salienta o autor. Nele é adotada uma taxa de amostragem de 1000 S/s durante um período de 5 minutos. Esse modo tem como intuito realizar a transferência de uma grande quantidade de dados em um curto intervalo de tempo, reduzindo assim o consumo de bateria dos sensores.

Os autores desenvolveram um protótipo de hierarquia para sistemas de monitoramento sem fio. Tal sistema é representado por 3 camadas (*Tiers*): sensores, conversores de protocolo e a plataforma do usuário (*Back-end*).

Figura 7 - Representação esquemática dos tiers de desenvolvimento de um sistema de monitoramento



Fonte: Modificado de Stoianov *et al* (2008)

Para os sensores de Tier 1 (Figura 8), os autores escolheram transmissores via *bluetooth*, devido à pequena distância (10 a 100 m) a ser vencida. Os dados eram enviados via *burst mode* para os receptores de dados.

Os conversores de protocolo do Tier 2 foram instalados em postes de iluminação pública, garantindo o fornecimento de energia. A transmissão de dados era feita via rádio, com uso de protocolos para garantir confidencialidade.

O projeto contou com o uso de um sistema que permitia que os receptores do Tier 1 se comunicassem entre si, permitindo assim que, caso algum deles não conseguisse enviar seus dados ao Tier 2 diretamente, outro receptor seria usado como caminho alternativo para este envio.

Os componentes do Tier 2 utilizaram-se de conexão *online* para os envios dos dados para o servidor. Os autores utilizaram para o estudo de caso a plataforma desenvolvida pela Intel chamada de Stargate.

A análise foi feita em três grupos de monitoramento:

- Grupo 01 – Monitoramento de pressão e pH em uma rede de 12’’ de ferro fundido. Para o pH a coleta de dados era feita a cada 5 minutos por 30 segundos. Dentro desses 30 segundos, foi especificado que os 15 primeiros seriam para ligar o aparelho, enquanto apenas os 15 últimos coletariam os dados. Já a pressão era coletada por um período de 30s a cada 5 minutos com taxa de amostragem de 600S/s.
- Grupo 02 – Similar ao Grupo 01, com adição do monitoramento de pressão em tubulações de 8’’.
- Grupo 03 – Similar ao Grupo 02, com adição do monitoramento de nível da saída da rede de esgotamento sanitário.

Em 2005, um ano após a instalação inicial, houve mudanças nos controladores de protocolos. Foi adicionado um sistema que permite a reinicialização automática em caso de falha e também a cada 24h. Desde então estes equipamentos operam sem problemas.

A partir dos grupos de monitoramento, os autores estabeleceram quatro critérios para avaliar o desempenho: A habilidade de coletar e enviar dados para os conversores de protocolo, a eficiência da transferência dos controladores de protocolo para os servidores via rádio, a habilidade de recuperar de perda de dados e erros e o desempenho a longo prazo dos sensores.

Como resultado para a taxa recepção de dados para os grupos os autores obtiveram valores entre 65% e 85%. Já para os envios a partir dos controladores de protocolo via rádio, a eficiência variou de 78% a 90%. Porém, todos os dados coletados pelo controlador de protocolo são enviados posteriormente, caso haja alguma falha ou erro no envio.

As baterias que operam os sensores demonstraram vida útil de 50 a 62 dias, valor que foi justificado por Stoianov *et al* (2008), pela alta coleta de dados e ciclos de comunicação.

Os autores concluíram que o experimento superou suas expectativas. O uso de uma rede de sensores de baixo custo, que precisou do mínimo de manutenção e troca de baterias a cada 60 dias desempenhou o papel esperado no monitoramento da rede de distribuição.

1.9 Caso 03 – Monitoramento on-line e sistema de gerenciamento desenvolvido para a bacia do Rio Liming em Daqing, China (Yang, Nan e Sun, 2008)

Com o objetivo de manter a qualidade da água do manancial em níveis compatíveis com a região, foi desenvolvido um método de medição rápida da qualidade da água, permitindo respostas em tempo real para controle de poluição.

Neste estudo de caso foram usados equipamentos simples para a medição, utilizando-se de comunicação via *wireless* entre os sensores e os *data-loggers*, que por sua vez usavam de SMS para conexão com o centro de controle, que possuía conexão com a internet para publicar os resultados do monitoramento.

Os dados coletados diretamente por meio dos sensores foram: sólidos suspensos, vazão, pH e luz ultravioleta no espectro de 215 – 316 nm, especialmente em 254nm.

Para parametrizar a relação não linear entre dois parâmetros de qualidade da água (UV_{254} e pH) para obter como resultado valores de DQO, foi usado o conceito de rede neural artificial (RNA ou ANN).

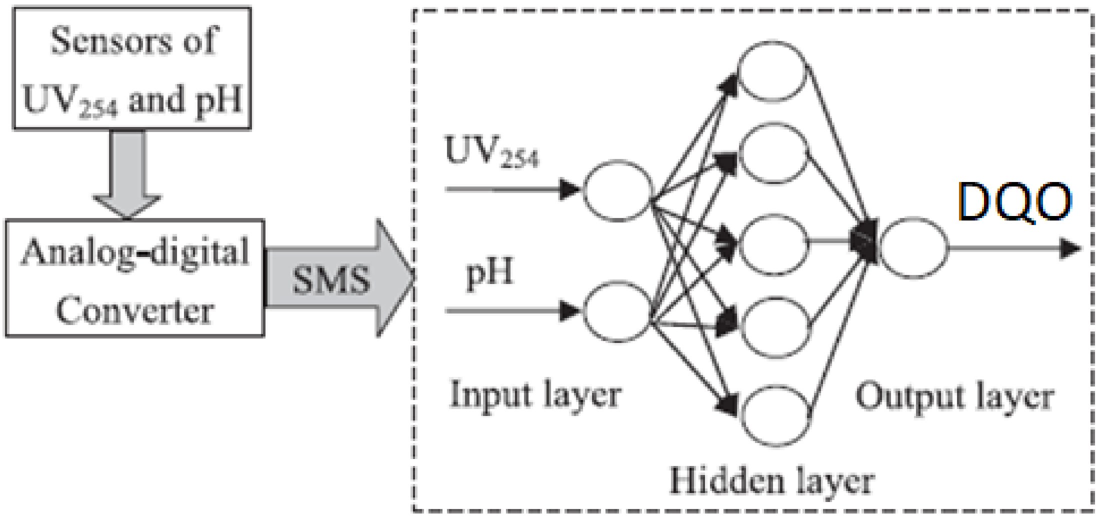
A concepção de rede neural abordada pelos autores pode ser entendida a partir do conceito de neurônios artificiais, que são funções matemáticas que tem como principal característica receber um ou mais parâmetros de entrada, somando-os para produzir um *output* (BONNIN, 2016). Além disso, a função que define o neurônio é sempre refeita, tanto em módulo quanto em direção e sentido. Os autores usaram a Equação 02 para exemplificar o processo de treinamento da rede neural usada:

$$x_{k+1} = x_k + a_k g_k \qquad (02)$$

Onde x_k é o vetor, x_{k+1} é o valor usado como entrada para a próxima iteração, g_k é o gradiente e a_k é a razão de aprendizado.

Os autores afirmam que quase toda matéria orgânica pode ser detectada a partir da absorbância do espectro de UV_{254}, permitindo a análise via instrumentação virtual da DQO da água. O processo é representado na 0.

Figura 8 - Ilustração do modelo de redes neurais artificiais utilizado para estimar a DQO em função do pH e dos valores de absorbância de luz visível e UV (UV_{254})



Fonte: Yang, Nan e Sun (2008)

Os valores de DQO obtidos a partir da instrumentação virtual quando correlacionados com valores medidos apresentaram boa correlação (0.924). Tal valor mostra que a combinação do modelo de Redes Neurais Artificiais e Instrumentação Virtual é possível para uma análise em tempo real de DQO de mananciais.

Por se tratar de sensores simples, porém de uma metodologia complexa, a viabilidade da aplicação da técnica usada por Yang, Nan e Sun (2008), está limitada apenas à adaptação da metodologia aos recursos e demandas do local em que se deseja fazer o monitoramento da qualidade da água.

CONSIDERAÇÕES FINAIS

O desenvolvimento do presente trabalho trouxe algumas conclusões a respeito da aplicação do sistema SIG para sistemas de abastecimento de água:

1. Há poucos trabalhos publicados na literatura internacional que reportem experiências do Brasil no tema. É possível que esse tipo de monitoramento seja feito por companhias de saneamento sem divulgação em revistas internacionais;
2. Os estudos de caso avaliados indicaram que a implantação de SIG para sistemas de abastecimento de água é possível, mas complexa e deve ser realizada em locais com acesso para manutenção de equipamentos e com disponibilidade de energia e rede para transmissão remota de dados;
3. No monitoramento de Ann Harbor, apresentada na revista *American Water Works Associations* em 2008, destacou-se a importância de se estabelecer um número coerente de locais de amostragem, bem como a influência na periodicidade da amostragem para a saúde pública;
4. No segundo caso, referente a Rede de sensores para monitoramento do abastecimento de água e redes de esgoto: lições de Boston, apresentado por Stoianov *et al*, no *Water Distribution Systems Analysis Symposium* em 2006, foi possível demonstrar o quanto o avanço nos sistemas de sensoriamento wireless podem proporcionar o aumento da resolução espacial e temporal do monitoramento da qualidade de água, mesmo com o uso de equipamentos simples
5. No terceiro estudo de caso, referente ao Monitoramento on-line e sistema de gerenciamento desenvolvido para a bacia do Rio Liming em Daqing, China, apresentado por Yang, Nan e Sun (2008), foi possível notar como a combinação de diferentes sensores, quando associados à metodologia correta pode estabelecer uma análise de qualidade de água dentro dos objetivos especificados.

A partir das conclusões positivas dos estudos de caso abordados, é possível notar que o desenvolvimento de metodologias para monitoramento de qualidade de água na realidade brasileira se encontra cada vez mais próximo. A disponibilidade de equipamentos e uma rede de infraestrutura bem consolidada (internet e energia, por exemplo) são essenciais para que o desenvolvimento e aplicação das tecnologias disponíveis para o monitoramento da qualidade da água se torne cada vez mais comum.

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ANEXO A - CONDIÇÕES E PADRÕES PARA ÁGUA DOCE – CLASSE 1, SEGUNDO RESOLUÇÃO N° 357 DO CONAMA (2005).

Parâmetro	Classe 2
Salinidade	≤0,50 ‰
Efeito tóxico crônico	Não verificação de crônico
Materiais Flutuantes	Virtualmente ausentes
Substancias que comuniquem gosto ou odor	Virtualmente ausentes
Corantes provenientes de fontes antrópicas	Virtualmente ausentes
Óleos e Graxas	Virtualmente ausentes
Resíduos Sólidos Objetáveis	Virtualmente ausentes
Clorofila a	≤30 ug/l
Densidade de Cianobactérias	≤50.000 cel/mL
pH	6 a 9
OD	≥5 mg/L O_2
DBO_5 (20°C)	≤5 mg/L O_2
Cloreto total	≤250
Nitrogênio amoniacal total	3,7- pH≤7,5
	2,0-7,5<pH≥8,0
	1,0-8,0<pH≥8,5
	0,5-pH.>8,5
Fósforo total	lêntico≤0,030 mg/L
	intermediário e tributário de lêntico≤0,050 mg/L
Coliforme termotolerante	≤1000 em 80% de 6 amostra/ano
Sólidos Dissolvidos Totais	≤500
Cor Verdadeira	≤75mg Pt/L
Cloreto total	≤ 250
Turbidez	≤100 UNT
Nitrato	≤10
Nitrito	≤1,0
Ferro dissolvido	≤0,3
Cádmio total	≤0,001
Chumbo total	≤0,01
Cobre dissolvido	≤0,009
Cromo total	≤0,05
Manganês total	≤0,1
Zinco total	≤0,18
Níquel total	≤0,025
Mercúrio total	≤0,0002

Parâmetro	Classe 2
Fenóis totais	≤0,003

Fonte: Conselho Nacional do Meio Ambiente (CONAMA), 2005.

ANEXO B - QUADRO RESUMO DE SENSORES E SUAS PRINCIPAIS CARACTERÍSTICAS

Sensor	Tipo	Parâmetro (s) Medido (s)	Aplicação	Fabricante	Fonte
ATI	Parâmetro Único	Cloro Livre	Estações de Tratamen-to	ATI	Hall *et al* (2007)
Hach Model A-15 CI-17	Parâmetro Único	Cloro Livre e total	Estações de Tratamen-to	Hach	Hall *et al* (2007)
Hach 1720 D	Parâmetro Único	Turbidez*	Estações de Tratamen-to	Hach	Hall *et al* (2007)
GLI Model PHD	Parâmetro Único	pH*	Estações de Tratamen-to	Hach	Hall *et al* (2007)
GLI Model 3422	Parâmetro Único	Condutividade específica*	Estações de Tratamen-to	Hach	Hall *et al* (2007)
Hach Astro TOC UV Process Analyzer	Parâmetro Único	Carbono Orgânico Total	Estações de Tratamen-to	Hach	Hall *et al* (2007)
Dascore Six-Sense Sonde	Multiparâmetro	Condutividade específica, OD, Potencial Redox, pH, temperatura, cloro livre	Estações de Tratamen-to	Não Encontrado	Hall *et al* (2007)
YSI 6600 Sonde	Multiparâmetro	Condutividade específica, OD, Potencial Redox, pH, temperatura, amônia-nitrogênio, cloreto, nitrato-nitrogênio, turbidez	Estações de Tratamen-to	YSI	Hall *et al* (2007)
Hydrolab Data Sonde 4a	Multiparâmetro	Condutividade específica, OD, Potencial Redox, pH, temperatura,	Estações de Tratamen-to	Ott HydroMet	Hall *et al* (2007)

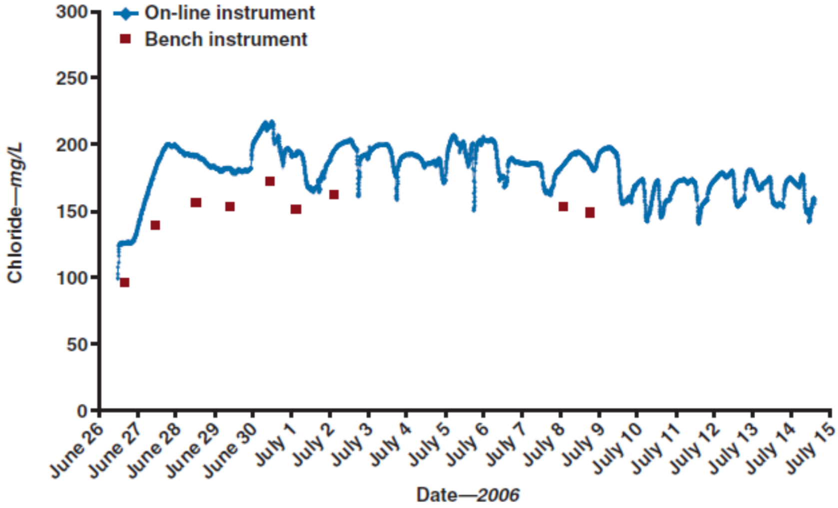
Sensor	Tipo	Parâmetro (s) Medido (s)	Aplicação	Fabricante	Fonte
		amônia-nitrogênio, cloreto, nitrato-nitrogênio, turbidez			
Aqua Troll 600	Multiparâmetro	Oxigênio Dissolvido, condutividade, turbidez, pH, potencial redox.	Água bruta	In-Situ	Chen e Han, (2018)
FCML 412 N	Parâmetro Único	Cloreto	Redes de Água	WTW	Xylem Analytics (2017)
SenTix® ML 70 combina-tion electrode	Multiparâmetro	pH, condutividade e potencial redox	Redes de Água	WTW	Xylem Analytics (2017)
Turb 2000	Parâmetro Único	Turbidez	Redes de Água	WTW	Xylem Analytics (2017)
Chlorine 3000	Parâmetro Único	Cloreto	Redes de Água	WTW	Xylem Analytics (2017)

ANEXO C – PARÂMETROS MAIS RELEVANTES DO PADRÃO DE POTABILIDADE DA ÁGUA SEGUNDO A PORTARIA Nº 2914 DO MINISTÉRIO DA SAÚDE (2011).

Parâmetro	Valor Máximo Permitido
Água para consumo humano	
Escherichia coli ou coliformes termotolerantes	Ausência em 100ml
Água na saída do tratamento	
Coliformes totais	Ausência em 100ml
Água tratada no sistema de distribuição (reservatórios e rede)	
Escherichia coli ou coliformes termotolerantes	Ausência em 100ml
Coliformes totais	Sistemas que analisam 40 ou mais amostras por mês: Ausência em 100ml em 95% das amostras examinadas no mês.
	Sistemas que analisam menos de 40 amostras por mês: Apenas uma amostra poderá apresentar mensalmente resultado positivo em 100ml.
Cloro Residual Livre	2mg/ L
pH	entre 6.0 e 9.0
Turbidez Pós filtração ou pré-desinfecção	
Desinfecção (para águas subterrâneas)	1,0 uT em 95% das amostras
Filtração rápida (tratamento completo ou filtração direta)	0,5 (3) uT em 95% das amostras
Filtração lenta	1,0 (3) uT em 95% das amostras
Padrões Organolépticos de Potabilidade	
Cor Aparente	15 uH
Sólidos Dissolvidos Totais	1000 mg/L
Gosto e Odor	Intensidade 06
Substâncias Químicas	
Nitrato	10 mg/L
Nitrito	1 mg/L
Ferro	0.3 mg/L
Cádmio total	0.005 mg/L
Chumbo total	0.01 mg/L
Cobre dissolvido	2 mg/L
Cromo total	0.05 mg/L
Manganês total	0.1 mg/L

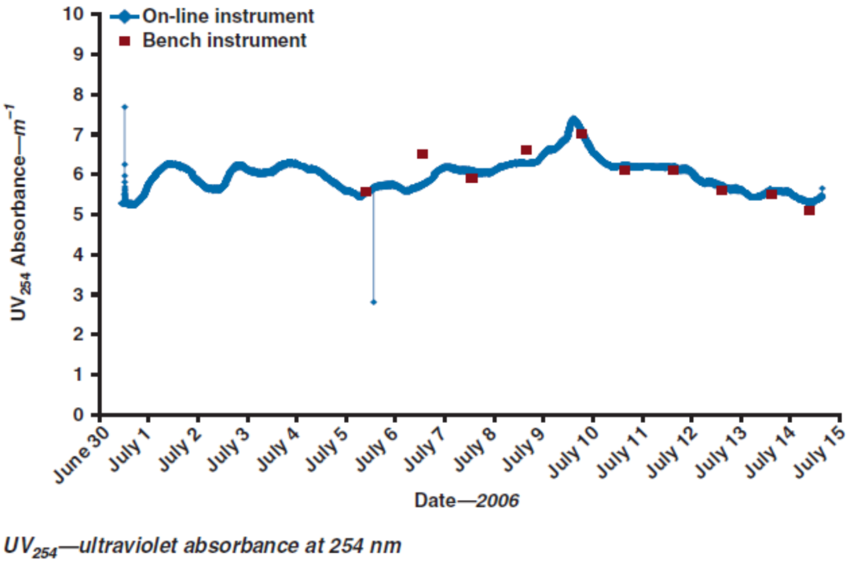
Parâmetro	**Valor Máximo Permitido**
Zinco total	5 mg/L
Níquel total	0.07 mg/L
Mercúrio total	0.001 mg/L
Cloreto	250 mg/L

ANEXO D – MONITORAMENTO DE CLORETOS EM ÁGUA TRATADA NO SISTEMA DE ANN HARBOR



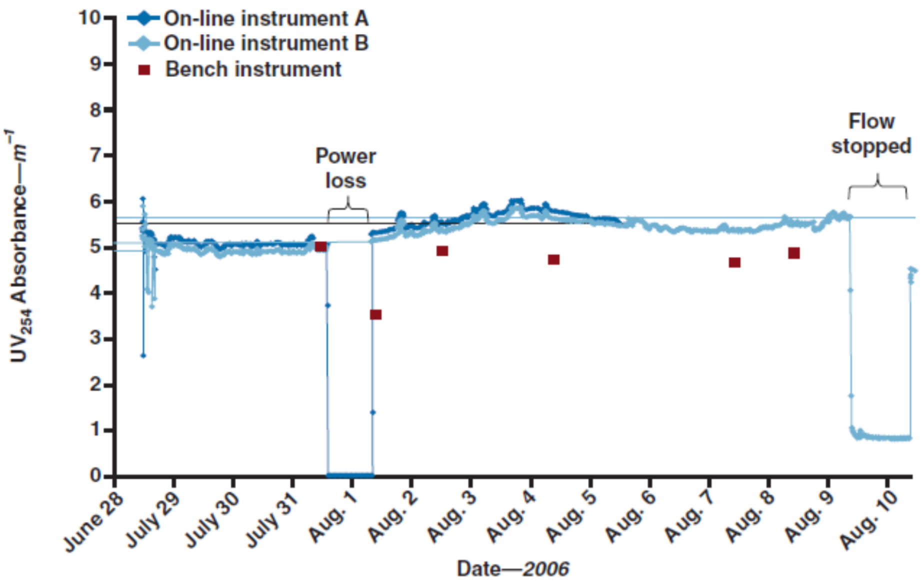
Fonte: Skadsen *et al* (2008)

ANEXO E – MONITORAMENTO DE UV254 EM ÁGUA TRATADA NO SISTEMA DE ANN HARBOR



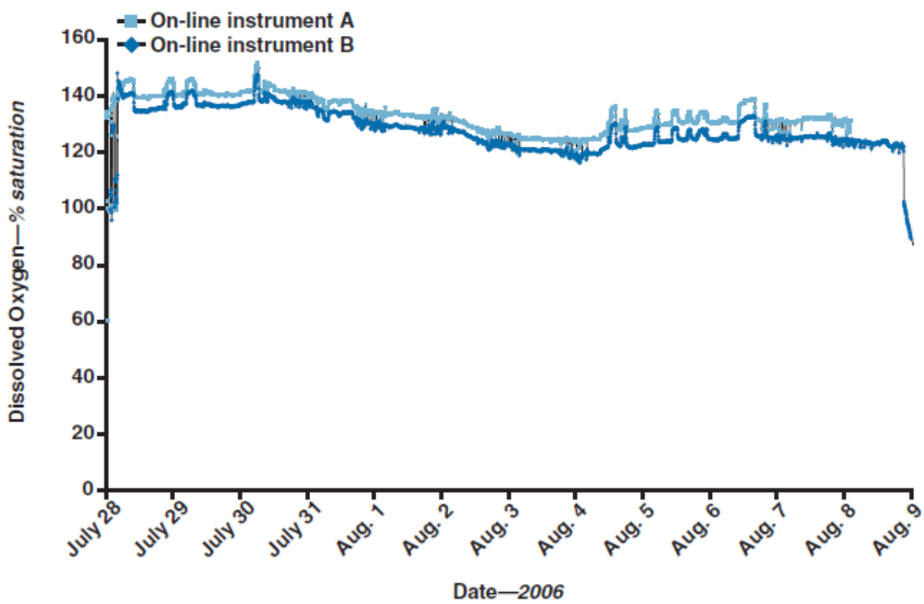
Fonte: Skadsen *et al* (2008)

ANEXO F – MONITORAMENTO DE UV_{254} EM UM PONTO DO SISTEMA DE DISTRIBUIÇÃO DE ANN HARBOR



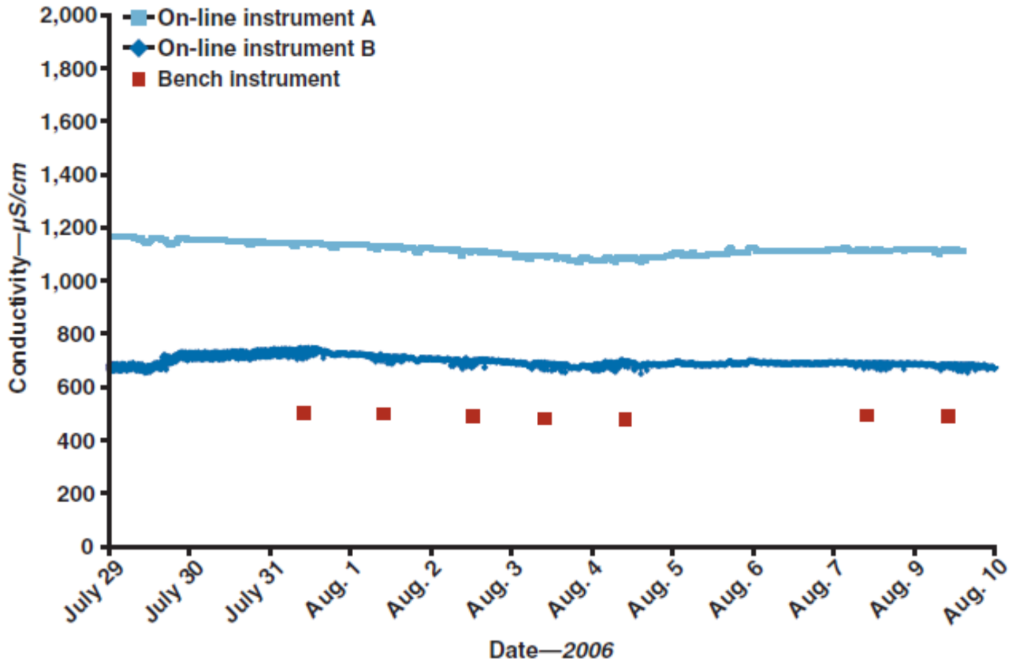
Fonte: Skadsen *et al* (2008)

ANEXO G – MONITORAMENTO DE OXIGÊNIO DISSOLVIDO NA DISTRIBUIÇÃO DE ANN HARBOR



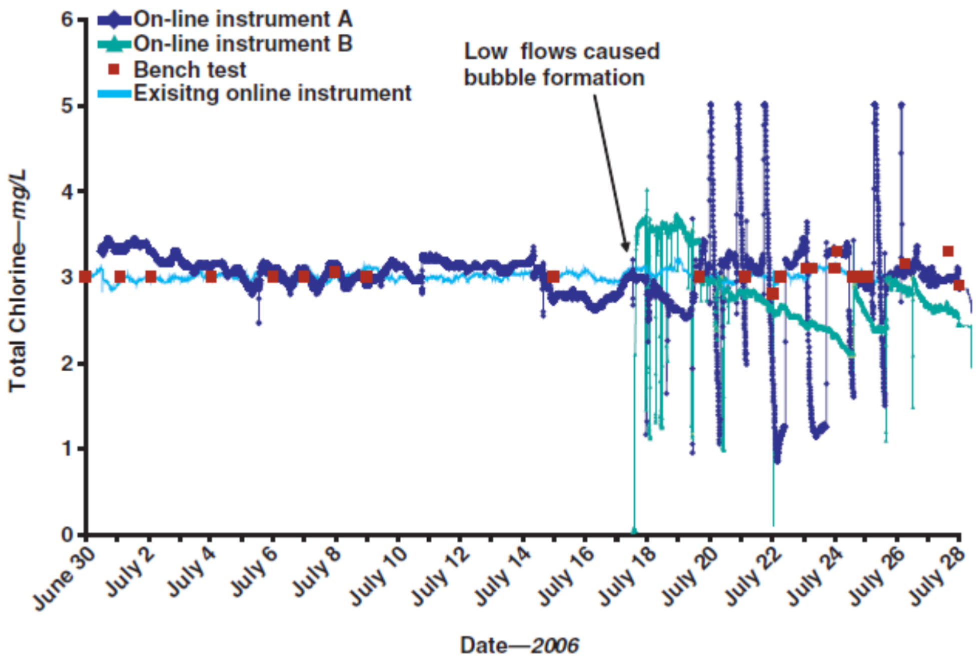
Fonte: Skadsen *et al* (2008)

ANEXO H – MONITORAMENTO DE CONDUTIVIDADE NA DISTRIBUIÇÃO DE ANN HARBOR



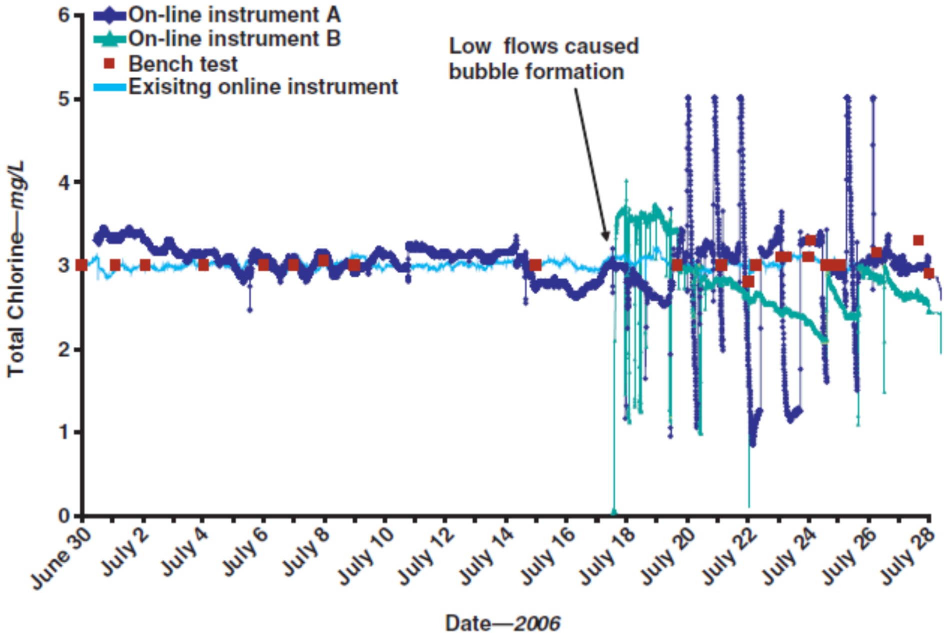
Fonte: Skadsen *et al* (2008)

ANEXO I – MONITORAMENTO DE CLORO TOTAL EM ÁGUA TRATADA NO SISTEMA DE ANN HARBOR



Fonte: Skadsen *et al* (2008)

ANEXO J – MONITORAMENTO DE CLORO TOTAL EM UM PONTO DO SISTEMA DE DISTRIBUIÇÃO DE ANN HARBOR



Fonte: Skadsen *et al* (2008)

ANEXO K – ARTIGO RELATIVO AO MONITORAMENTO DE ANN HARBOR

Concerns about water quality and possible intentional contamination of water distribution systems are making on-line monitoring an increasingly important priority for many water utilities. The city of Ann Arbor (Mich.) evaluated different water quality monitoring parameters, tested multiple manufacturers' monitoring equipment, and evaluated how to effectively locate monitoring equipment within the distribution system to address these two concerns. A suite of modeling tools was used in this case study. Total chlorine, ultraviolet absorbance at 254 nm, conductivity, and dissolved oxygen were selected for monitoring based on pilot testing. When balancing costs and benefits, four stations for monitoring water quality and four stations for monitoring contamination events were found to be sufficient for the city. Only one location was common between water quality and security sites, and the number of security monitors needed was not affected by system demands. It was confirmed that it is critical to minimize response time in order to mitigate the effects of a contamination event.

Distribution system on- line monitoring for detecting contamination and water quality changes

BY JANICE SKADSEN,
ROBERT JANKE,
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MARK TENBROEK,
BRIAN STEGLITZ,
AND SUMEDH BAHL

One goal for this project was to provide the city of Ann Arbor (Mich.) with a monitoring program that could be used to minimize public health exposures after release of a chemical contaminant or biological agent into the distribution system. The other goal was to provide practical, real-time water quality monitoring to detect water quality degradation in the distribution system caused by naturally occurring processes such as nitrification, iron corrosion, and bacterial regrowth. It was hoped that both goals could be addressed in order to maximize the benefits of a new on-line monitoring system.

OVERVIEW OF THE ANN ARBOR SYSTEM

The city of Ann Arbor's water system, which provides treated water to approximately 130,000 customers, encompasses approximately 49 sq mi. The total population modeled in this study was based on current census information plus an estimate of the number of college students present in the city nine months of the year. The average system demand is 15 mgd, with a range of 7 to 30 mgd depending on the season. Plant capacity is 50 mgd.

The community straddles the Huron River, which bisects the city. The distribution system is divided into five major pressure districts with elevated tanks and storage reservoirs to adequately serve the varied topography. The pressure districts, which are typically operated independently, include interconnects that are sometimes used to control pressure and flow. The distribution system has an estimated average retention time of two and one-half days and includes some areas that can contain water that is

An on-line instrumentation test rack was developed by the city of Ann Arbor (Mich.) to evaluate different water quality monitoring parameters, test various equipment, and evaluate how to effectively locate monitoring equipment in the distribution system.

7 to 10 days old. This retention time can result in water quality degradation. Although distribution system piping consists primarily of cement-lined ductile iron, areas of unlined cast-iron pipe remain in service. These areas are often heavily tuberculated and have resultant rusty water problems. The utility's grab-sample program addresses distribution system water quality and regulatory concerns. This program includes sampling for Total Coliform Rule, Surface Water Treatment Rule, Lead and Copper Rule, and Disinfectants and Disinfection Byproducts Rule compliance as well as nitrification, iron corrosion, and bacterial regrowth.

Source water consists of surface water and well water. Source water is blended during the lime-softening split-treatment process. Treatment also includes ozone disinfection, phosphate stabilization, granular activated carbon/sand filtration, fluoridation, and final disinfection with chloramines.

Recently efforts have been directed at improving security of the distribution system against possible acts of intentional contamination. This project was undertaken to determine whether both objectives—an early warning system for contamination events and identification of water quality problems—could be developed and integrated into an improved distribution system monitoring program. Potential parameters for monitoring were evaluated, and an assortment of on-line instruments was pilot-tested.

DISTRIBUTION SYSTEM ANALYSIS

The study team used multiple simulation and optimization models in conjunction with expert input from city staff to design a distribution system monitoring program that included on-line instrumentation and grab samples.

Hydraulic model. The city of Ann Arbor developed a hydraulic model of its water distribution system in 1999. This all-pipes model was developed using EPANET (Rossman, 2000) and included every water main in the system. By incorporating each main into the model, detailed demands down to the parcel level could be used to determine localized capacity constraints throughout the system and better assess water quality concerns. The model represented an average-day–demand scenario of approximately 15 mgd.

Initially, the model was reviewed using a variety of system demands to make sure that it reflected the operational methodology used by staff for each condition. This process was necessary because the model was originally developed for average system demands. Exercising the model throughout the range of possible flow conditions (low-flow day of 10 mgd, average-flow day of 15 mgd, and maximum-flow day of 30 mgd) resulted in a more robust model for evaluation purposes.

In addition, the model was extensively reviewed with respect to its pressure-boundary valve configuration to ensure it was consistent with current field conditions and operations. This involved performing various water quality simulations to determine interconnections between pressure districts, including identification of any unintended connections, and then evaluating the results.

Using threat ensemble vulnerability assessment and sensor placement optimization toolkit (TEVA-SPOT) software, population-exposure impact plots were developed for various contaminant-release scenarios. Each contaminant-release scenario represented an extended-period hydraulic and water quality simulation. Each exposure impact plot depicted a model node release location for the contaminant and the corresponding receptor nodes that "witnessed" the contamination event and ber of sensors) were developed for each sensor network. Their effectiveness at protecting public health was evaluated as the principal component of a contamination warning system.

Selection of the best locations within a drinking water distribution system to monitor for a contamination event has been a well-studied optimization problem (Berry et al, 2005; Uber et al, 2004). When facing such a problem, an objective function is defined to measure the value of each solution, and the best solution is determined subject to a set of constraints. The TEVA-SPOT software includes a heuristic sensor optimization approach to determine and compare sensor network designs. The functionality of the sensor network design component has been previously described (Hart et al, 2006).

Concerns about water quality and possible acts of intentional contamination to distribution systems are making on-line monitoring an increasingly important priority for many water utilities.

The TEVA-SPOT software was used to find the best set of sensor locations when all possible locations in the network are considered and when the best set of locations from a smaller list of possible locations is determined to be preferable by the utility. The utility-preferred locations represented utility-owned facilities and/or facilities that were easily accessible for monitoring.

Sensor network monitoring designs were based on minimizing the mean number of health effects for a given number of sensor locations and an associated response-time delay. For these analyses, it was assumed that the sensors represented "perfect" sensors, i.e., each sensor would detect the contaminant at a concentration above zero and a corrective action would be taken within a user-specified response time, thereby eliminating any further exposures. Corrective actions could involve "do-not-drink-or-use" orders and/or shutdown of the system. The design of sensor networks based on contamination detectors, which detect any amount of contamination above zero, is unrealistic but provides an upper limit on sensor network performance. An imperfect sensor model has been described (Berry et al, 2006), and it is possible that its application would result in different sensor network designs.

The analysis was performed with response delay times of 0, 4, 12, 24, and 48 h to account for the time needed to validate that a monitor's reading represents an actual contamination event and to account for the time needed to notify the public or take necessary corrective actions to mitigate additional exposures. Two unnamed contaminants were modeled—a fast-acting chemical contaminant and a slow-acting biological contaminant. Other model inputs included each contaminant's mass release rate, the length of time each contaminant was released into the distribution system, and the contaminant's dose–response parameters, which make it possible to characterize the contaminant's effect on public health. Individuals were assumed to have a mass of 70 kg and to consume 2 L of water per day. Exposure to contamination was modeled to occur at every hour during each 24-h period, with the portion of the 2 L ingested at each time step proportional to the demand at the time step. Public health effects were estimated by calculating doses at each model node using a dose–response curve for each contaminant. Probit dose–response curves were developed using data from the literature (Holcomb et al, 1999). Additional parameters input into TEVA-SPOT for each contaminant included a latency period (time period from exposure to the contaminant to the onset of symptoms), a fatality time (time from onset of symptoms until death occurs), and a fatality rate (fraction of population exposed resulting in death). Using this information, the software identified optimal node locations for sensor placement in order to minimize the health effects of the average threat scenario. The software can also be used to find the best location or set of locations after first fixing a given number of monitoring locations. In this way, TEVA-SPOT can determine the near-optimal sensor network design and the best order in which to place the sensors given a phased, sequential implementation.

Water quality model. PipelineNet was used both for assessing the location of water security monitors and for placing water quality monitors (Bahadur et al, 2003). PipelineNet is a flexible, EPANET-based modeling and simulation tool that allows the user to define the objectives of a monitoring plan, e.g., to improve water quality or respond to contamination incidents, and then to design the monitoring plan to meet those objectives. PipelineNet was used to rank the different water mains in the system based on water velocity, age, and flow. The factors and their weighting criteria were selected by city personnel in conjunction with the study team as part of a facilitated group session to reflect the specific objectives being considered. To assess the relative value of the monitoring locations identified, each was ranked based on the numerical average of the PipelineNet water quality assigned index of all pipes at the monitoring location. In a more general way, this approach was also used to provide a grid-based output that predicted the locations throughout the city with the highest potential for water quality problems.

Staff expertise. The locations identified by TEVA-SPOT and PipelineNet were reviewed to determine similarity in location selection. The analyses from both models were overlaid with staff expertise and practical knowledge to determine the final proposed monitor locations.

PARAMETER SELECTION AND INSTRUMENT PILOT TESTING

The Ann Arbor project team initially evaluated six parameters for pilot testing to address both security and water quality concerns (Table 1). Although all parameters could potentially exhibit water quality changes, of primary interest for water quality parameter selection was identification of those parameters that would be most affected by distribution system processes and exhibit concentration changes indicating degradation. For each parameter selected, one or two manufacturers provided instruments.[1–6] Each instrument was challenged with four water sources—the city's raw water supplies (both river water and groundwater), finished drinking water, and water from one distribution system location. Pilot testing was performed on each water type for one to three weeks. Results were compared with the approved bench testing methods normally used by the utility.

In addition to chemical-based monitoring, Ann Arbor staff was also interested in radiation and biological detection. There are few radiation monitors available in an on-line format, and those that are available are costly. Consequently, it was determined that hand-held instruments and/or grab samples were better alternatives. Continuous biological monitoring for on-line toxicity screening using organisms such as fish, *Daphnia,* and mussels is available, although use of state-of-the-art technologies for finished water monitoring is still evolving. Major problems include limited range of microbes detected, sensitivity of the tests, and high rate of false positives. The utility staff determined that maintenance and interpretation of these biological monitors was beyond what they could support at the time.

RESULTS: DISTRIBUTION SYSTEM MODELING

Sensor network design. The TEVA-SPOT software was initially used to identify optimal monitoring locations by selecting from among the nearly 7,000 nodes in the distribution system model. Figure 1 provides the percentage reduction in health effects versus number of monitoring locations for the optimal sensor network designs.

The top 10 optimal locations selected using the software were subsequently evaluated and found to present various practical difficulties in terms of placing the monitoring equipment. These difficulties included lack of a suitable facility, utility access, and needed utilities, e.g., a sanitary sewer. As a result, the project team identified potential monitoring locations within the distribution system where utility access, utility infrastructure, and connections to the distribution system existed. The monitoring locations chosen by the TEVA-SPOT software from the list of feasible locations identified by utility staff were generally close to the locations that were optimally selected by the software considering no practical or logistical constraints on sensor placement. Private locations were only considered if city-owned sites were not available in sufficient number or located throughout the city.

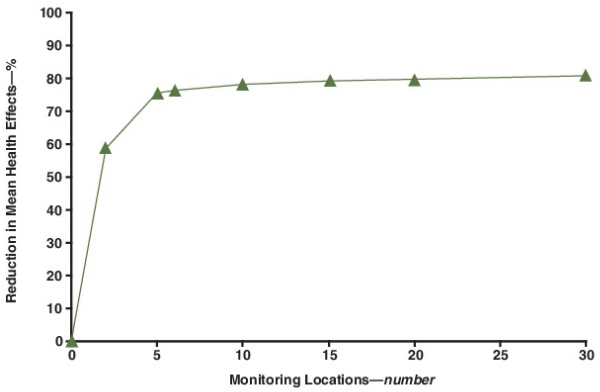
The final site list included water utility facilities (pump stations, reservoirs, tanks, and pressure monitoring locations), other city facilities (fire stations, parking structures), and a limited number of private sites. The potential number of monitoring locations was significantly reduced from thousands to 27 throughout the city. Using the TEVA-SPOT software, it was determined that the relative reduction in health protection afforded by limiting the potential number of monitoring locations was not significant given the overall uncertainties in the mod-

TABLE 1 Selected on-line monitoring parameters and their usefulness in identifying contamination events and/or water quality changes

Parameter	Usefulness	Security Information	Water Quality Information
Total (combined) chlorine	Key parameter identified by USEPA study	√	√
UV_{254}	General indicator of organics, surrogate for total organic carbon	√	
Ammonia (total and free)	Operational control parameter critical to nitrification and chloramine decomposition	√	√
Chloride	General ion indicator	√	
Dissolved oxygen	Indicator of corrosion and oxidant demand	√	√
Conductivity	General indicator for ionic composition	√	

USEPA—US Environmental Protection Agency, UV_{254}—ultraviolet absorbance at 254 nm

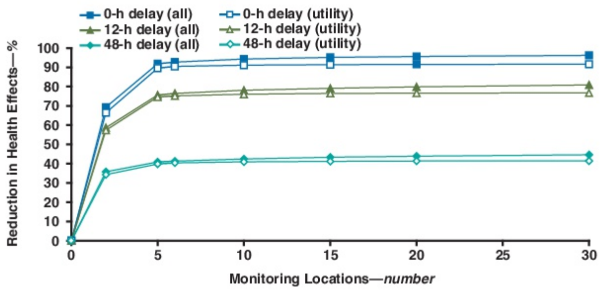
FIGURE 1 Percentage reduction in public health effects versus number of monitoring locations for the optimal sensor network designs using TEVA-SPOT software



TEVA-SPOT—threat ensemble vulnerability assessment and sensor placement optimization toolkit

Reduction in mean health effects applies to the baseline, no-sensors case.

FIGURE 2 Effect of restricting modeling to a limited number of sites versus all possible locations



eling process. Figure 2 shows relative public health protection versus the number of monitoring locations based on all candidate locations and the 27 utility-preferred locations. These plots demonstrate that the effect of using a limited number of sites is surprisingly small. Fully 95% of the potential benefit is achieved when the limited number of locations is used compared with the universe of all potential locations. This conclusion is likely to be utility-specific and influenced by the simplifying assumptions. For Ann Arbor, the preferred sites were distributed throughout the pressure zones, thus ensuring good distribution system coverage. Depending on other distribution system configurations and the availability of utility sites, such coverage may not always be possible.

Proper operation of a monitoring site is tied to its access for servicing. Also, the response time can be enhanced if good site access is available. Therefore, restriction of the monitoring locations to these limited sites was found to be beneficial based on site access while having little influence on monitoring effectiveness. Each field location was visited to determine its feasibility as a monitoring location. The sites were ranked based on site ownership and availability of connection to the distribution system, power, communications, and a sanitary sewer. Also, access and existing heating, ventilation, and air-conditioning were included in the assessment. The prioritization criteria and scale for ranking are given in Table 2. Sites were found to range from "perfect" (score of 30 points) to "significant work needed" (score of 14 points). This information was used in final site selection. Ultimately, four sites with scores of 30, 29, 26, and 23 points were selected for security-based monitoring. For water quality monitoring, sites were selected in different pressure zones with site scores of 27, 26, 26, and 14. The low-scoring location was retained because it had abundant historical water quality information and known degradation problems. Its historical value was deemed to outweigh the low site score. It was recommended that the availability of historical water quality data be considered in the future as an evaluation criteria.

To supplement the security analysis provided by TEVA-SPOT, the PipelineNet methodology was examined in order to evaluate potential sensor locations for protection of sensitive facilities, e.g., schools and hospitals, and high-population areas from contaminant attack. This was done for critical facilities by assuming that the principal and likely threat of contaminant injection could only occur within a certain distance of the critical facility. Contaminant injection distances of 0.1, 0.5, and 1.0 mi from the critical facility were then used to develop a database of pipes within the distribution system model for the area surrounding the critical facilities. Distances were determined using geographical information system tools contained within the PipelineNet program. Pipes were then ranked according to flow rate, i.e., pipes with higher flow rates received higher scores and therefore represented better locations at which to place sensors.

A similar approach was used to place sensors in and around densely populated areas. Not surprisingly, this resulted in PipelineNet clustering sensor locations around the largest of these facilities. Although this may result in increased protection for these sensitive facilities, the remainder of the potential target population was not protected to the extent provided by the TEVA-SPOT methodology used in this study because TEVA-SPOT considered contaminant attacks from anywhere in the distribution system. TEVA-SPOT provides the ability to quantitatively evaluate and compare different sensor network designs to a common objective, e.g., minimize effects on public health. In this way, alternative sensor network designs developed by the utility or another software program can be loaded into TEVA-SPOT and evaluated. However, PipelineNet was useful for determining potential areas of water quality degradation for monitoring. Although PipelineNet does not provide exact site locations, it does provide general areas where water age is predicted to be high. Combined with staff knowledge, water quality monitoring sites were specifically located.

Water system demands. TEVA-SPOT was applied to the Ann Arbor system considering several different water system demand scenarios. EPANET models were developed to represent average-day demands and annual low- and high-demand days. Four demand scenarios that reflected the utility's range of normal operations were tested—10, 15, 20, and 30 mgd. The results indicated that variations in total system demand did not result in significant variations in the number and location of monitoring locations using a response time of 12 h (Figure 3).

Response time. Response time is defined as the interval between when the first monitoring instrument alarm (deviation from expected value) is received and when action is taken by the utility to protect public health and mitigate any further exposures. TEVA-SPOT analyses were performed to review the effects of different response times. Figure 4 shows these different response times, which include 0, 4, 12, 24, and 48 h. Although there is no industry standard for what constitutes an acceptable response time, minimization is critical. For this project, a response time of < 12 h was considered acceptable and achievable.

Based on the results shown in Figure 4, as response time increases, monitoring becomes less effective. This is reflected in achievable public health protection (i.e., reduc-

TABLE 2 Prioritization criteria used to select final monitoring location

Site-ranking Criteria	Ranking Scale: 1 (low)	Ranking Scale: 5 (high)
Site ownership	Private	City owned
Distribution connection	None existing	Existing with easy access
Electricity	None existing and difficult to connect	Easily available
Drain/sewer	None existing and difficult to connect	Easily available
Communication	None existing	Sufficient capacity and availability
Access	Confined space, no access	Easy access

FIGURE 3 Effect of water system demands on sensor network design performance as determined by reduction in mean health effects and with a 12-h response delay

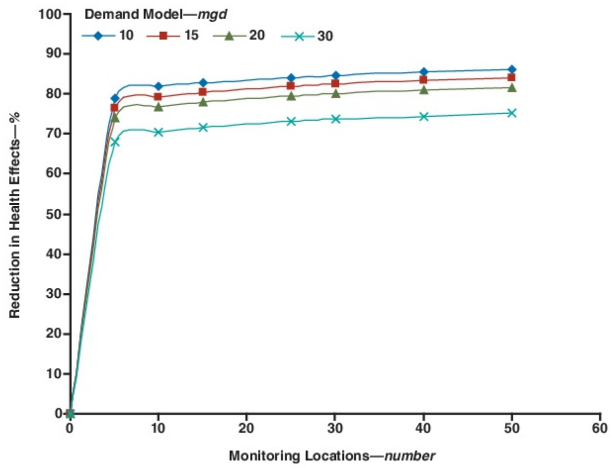


FIGURE 4 Effects of response time delays

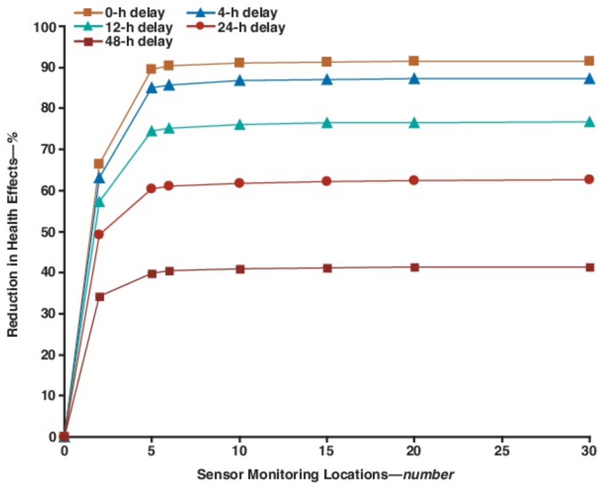
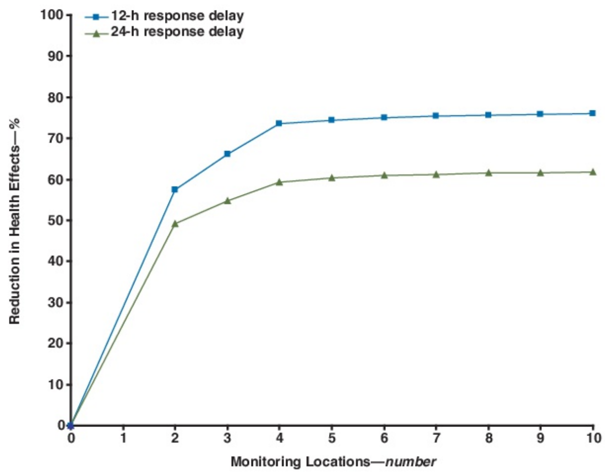


FIGURE 5 Optimal number of monitoring locations needed to provide public health protection



tion in health effects), which decreases significantly with longer response times. If response times cannot be reduced to an acceptable level, alternative or supplementary methodologies may prove to be more effective at detecting contamination. Such methods include customer and medical facility feedback. These methods will only be effective if they can provide significantly faster detection and response times. Combining on-line monitoring with additional feedback mechanisms will provide the most complete information on the probability of an event being real and may therefore reduce confirmation time.

Number of monitors. The TEVA-SPOT modeling found that a small number of monitors provided significant benefits as measured by the percent reduction in public health effects. It was found that four monitoring locations would be the most cost-effective for detecting contamination (Figure 5). Only small incremental benefits were observed with more than four locations. The costs for equipment, installation, and operation are discussed later in this article. Each community must determine the trade-off between cost of additional monitoring locations and the incremental increase in public health protection provided. This conclusion assumes that these are "perfect" monitors that perform reliably and accurately all of the time. Increasing the number of monitors beyond four seemed to provide only minor incremental benefits, considering the assumptions stated. Given the size of Ann Arbor's distribution system (130,000 people over a 49-sq mi area), this low number of monitors was a surprising outcome. However, the percentage reduction in health effects plateaus at about 75 to 80% protection. Therefore, with four monitors, more than 20% of the population could still be affected on average.

Water quality. The PipelineNet model was used to determine areas in which water quality concerns were the highest based on the criteria established by Ann Arbor staff. These areas were matched against the available monitoring locations. It was found that areas where water quality was affected clustered along the edges of the system and along pressure boundaries, consistent with predictions of areas of high water age and previous tracer studies.

Final monitoring location selection for water quality and contamination events. Results of the TEVA-SPOT analyses, PipelineNet results for water quality, and staff knowledge of the system were integrated. Four sites were selected for security monitoring, and four locations were selected for water quality monitoring. One site selected for security was the same as a site selected for water quality. This general lack of co-located sites was predicted because the driver for security monitoring (protect as much of the population as possible) was not the same as that used for water quality monitoring (find the areas of high water age usually associated with remote or isolated parts of the distribution system). This was considered to be an important finding, suggesting that security monitoring locations may not show significant dual benefit in a system in which operational concerns are based on water quality effects such as nitrification. The project team was originally interested in achieving efficiency in operations and cost savings if the water security and water quality locations overlapped. However, Ann Arbor was willing to implement the recommendations even in the absence of this dual benefit. If utilities have limited finances, the investigation of dual benefits is recommended.

RESULTS: MONITOR SITE AND PARAMETER SELECTION

Using a variety of information, including data from USEPA's Test and Evaluation Facility in Cincinnati, Ohio, other research studies, and utility surveys, a workshop was hosted by the city of Ann Arbor staff in order to evaluate the data and information and determine the set of monitoring parameters (Hall et al, 2007). Chorine and total organic carbon (TOC) were the most highly recommended parameters for use when addressing water security concerns. TOC was ultimately not selected because of instrument cost and complexity of operations. Ultraviolet absorbance at 254 nm (UV_{254}), which is also used to measure organic content of water, was selected as an alternative for TOC. Because combined chlorine is used for final disinfection, the utility wanted a total chlorine monitor that did not use reagents. Prior experience with analyzers that require reagents revealed that they worked well at the treatment plant but that routine maintenance in the distribution system proved to be a challenge. Other parameters selected for testing included ammonia, chloride, dissolved oxygen (DO), and conductivity (Table 1). Ammonia was selected as an indicator of water quality, because chloramine decomposition results in the release of free ammonia, which leads to nitrification. Chloride was recommended as a general indicator ion of potential contamination. DO was deemed useful for detecting nitrification, corrosion, and contamination; conductivity was selected as a general parameter for detecting contamination events.

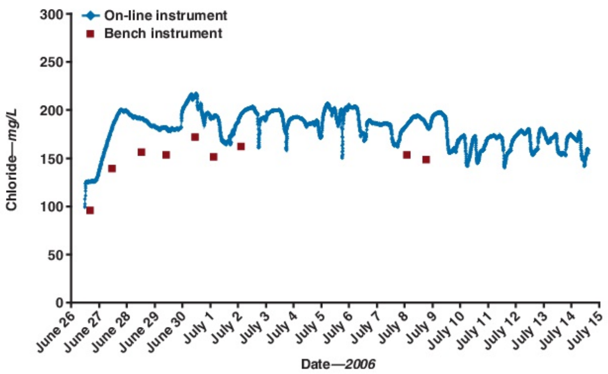
It was recognized that a contamination warning system must have the capability to rapidly and accurately detect a significant change in water quality as it occurs within the distribution system. Because contaminant-specific on-line sensors do not currently exist, the city is hoping to initially rely on single-parameter on-line water quality sensors to signal a change in water quality. Work in identifying techniques for detecting changes in water quality using laboratory data sets has been reported (Byer & Carlson, 2005; Cook et al, 2005). More recent work has focused on automated detection of water quality changes (Klise & McKenna, 2006a). The key to detecting changes in water quality is to separate anomalous conditions from normal background operating conditions with accuracy and repeatability. Ultimately, the purpose of monitoring is to notify the operator that a change in water quality has occurred in order to initiate an appropriate response. Establishment of alarm limits based on decision algorithms will be critical to the successful use of on-line

TABLE 3 Instrument evaluation criteria for pilot testing

Measurement	Acceptability Criteria	Unacceptability Criteria
Accuracy	On-line results match bench analysis within 5% for all measurements	On-line results are > ± 5% of lab results
Sensitivity	Total chlorine: 0.1 mg/L	Sensitivity exceeds listed values
	Ammonia: 0.01 mg/L	
	Conductivity: 10 µS	
	UV_{254}: 0.001 cm^{-1}	
	Dissolved oxygen: 0.1 mg/L	
	Chloride: 1 mg/L	
Variability	Standard deviation < 10% of the mean over the test period (maximum of three weeks)	Standard deviation > 10% of the mean over the test period
False response	< 20% change between consecutive readings	> 20% change between consecutive readings
False response rate	< 1 incident/week	> 1 incident/week
Range	Range covers anticipated minimum/maximum values	Range does not include potential minimum/maximum values
Ease of calibration	< 30 min/week	> 30 min/week
Calibration frequency	< 1/week	> 1/week
Maintenance frequency	< 1/week	> 1/week

UV_{254}—ultraviolet absorbance at 254 nm

FIGURE 6 Chloride monitoring on finished water



factors. Other factors such as calibration ease, frequency, and maintenance were also important; however, a unit's ability to deliver useful data was deemed the most critical function. All criteria were considered for initial planning purposes and will likely be refined based on further operating experience.

instrumentation for water security and water quality monitoring. Variability in monitoring results will affect the usefulness of parameters for both water quality and security monitoring. The higher the normal variations in concentrations, the lower the probability that the measured parameter will detect an "out-of-range" value.

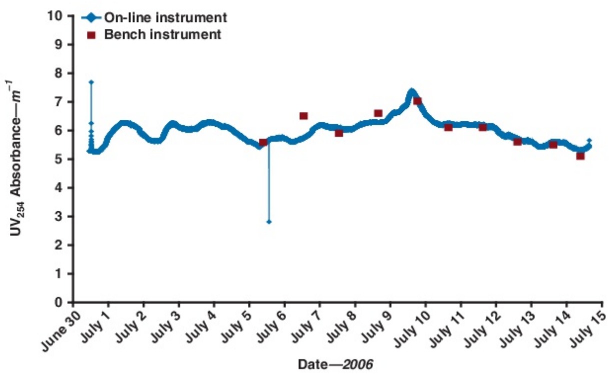
Various criteria were developed to assess instrument performance and acceptability. Key criteria are listed in Table 3. Of these, accuracy (agreement between lab testing and on-line instrument results), sensitivity (low-level measurement ability), and variability (presumed normal fluctuation in water quality) proved to be the most important factors. Other factors such as calibration ease, frequency, and maintenance were also important; however, a unit's ability to deliver useful data was deemed the most critical function.

On the basis of outcomes of the on-line instrumentation pilot testing, chloride and ammonia were eliminated as monitoring parameters. Chloride exhibited large and regular fluctuations in concentration in the finished water (Figure 6). The values more than doubled and then rapidly decreased by more than 100% over a 24-h period on numerous occasions. The project team established a maximum 10% deviation around the mean as the acceptable criteria. Because of these fluctuations, chloride values were believed to be too variable for chloride to serve as a reliable security parameter.

Ammonia was not recommended as a water quality parameter because the instrumentation tested was not sensitive enough to measure the low levels of ammonia typically observed in the system. Ammonia in the finished water is controlled at < 0.10 mg/L in order to prevent nitrification. With decomposition of chloramines in the distribution system, ammonia concentrations of 0.2–0.4 mg/L have been observed, but even these concentrations were too challenging for routine, reliable measurement. Comparison with bench-scale testing revealed that the on-line ammonia results varied by more than 5%, often up to 100%. The instrument produced flat-line results at about 0.10 mg/L, indicating that the desired sensitivity of 0.01 mg/L was not achieved.

Other instruments provided detailed information not available from the normal grab-sample analyses. For example, UV_{254} exhibited significant but slow change in values, typically between 5.2 and 7.7 m^{-1} in the finished water (Figure 7). These fluctuations appeared to dampen in the distribution system, where absorbance typically ranged from 4.8 to 6.0 m^{-1} (compare Figure 8 with Figure 7). This dampening

FIGURE 7 UV_{254} monitoring on finished water

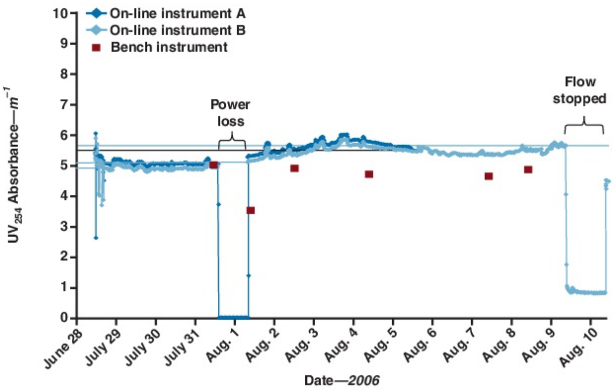


UV_{254}—ultraviolet absorbance at 254 nm

of variability in the distribution system was observed for most parameters monitored. Pilot-testing results showed larger variations in plant performance and finished water quality than were typically observed with grab samples. The grab-sample approach provides too few data points to capture the fluctuations occurring in water quality. This additional knowledge gained from more detailed data collection and interpretation regarding treatment plant performance was unexpected. It had been assumed that data collected from grab samples over many years would present an accurate picture of water quality variability. However, this database never indicated the breadth and rapidity of water quality variations. This conclusion provided an additional reason to invest in on-line monitoring beyond the original goals.

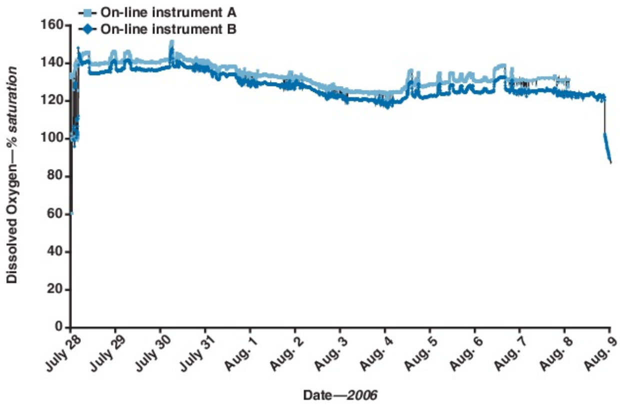
DO on-line monitoring results for the finished water are given in Figure 9. DO fluctuated somewhat in both finished water (145 ± 6% saturation with instrument A and 140 ± 6% saturation with instrument B) and distribution system water (124 ± 13% saturation with instrument A and 133% saturation ± 7 with instrument B). This is likely caused by operation of the ozone treatment process, which results in supersaturated finished water. Because a limited number of grab samples of the finished water were collected and no samples were collected from the distribution system, accuracy of the on-line instruments could not be compared. The DO values observed were typical of the system.

FIGURE 8 UV_{254} monitoring at one distribution system location



UV_{254}—ultraviolet absorbance at 254 nm

FIGURE 9 Dissolved oxygen monitoring in the distribution system



Of all parameters measured, conductivity appeared to be the most stable in the finished water and in the distribution system (Figure 10); results for both finished water and distribution system water were similar. However, the two conductivity instruments tested differed greatly in their accuracy when compared with bench testing. Only one on-line instrument (instrument B) provided results that were close to the bench instrument results in the finished water. Instrument A provided results that were nearly double those of the bench results. This was not resolved by recalibration.

Total chlorine was of particular interest in terms of both security and water quality. A new technology that allows measurement of combined chlorine without use of reagents was tested. One instrument was found to perform better than the other (Figures 11 and 12). Although this instrument exhibited more variability than the traditional reagent-based on-line instrument used at the water treatment plant, it was thought to be acceptable for distribution system monitoring. In the finished water, the average and standard deviations for total chlorine were 3.11 ± 0.13 mg/L for instrument A

FIGURE 10 Conductivity monitoring in the distribution system

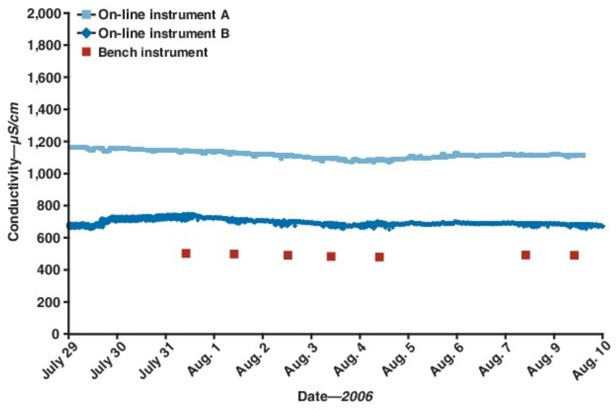
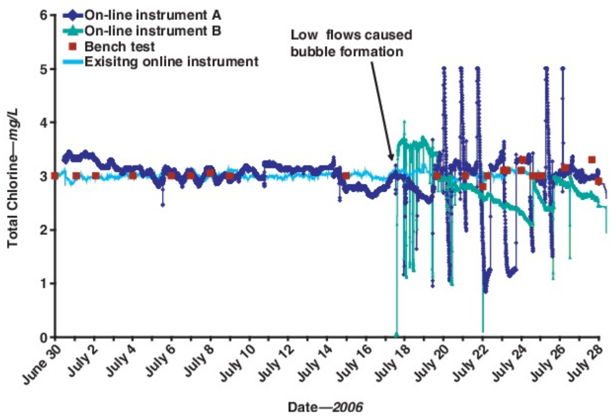


FIGURE 11 Total chlorine monitoring on finished water



chlorine residual of 2.14 ± 0.29 mg/L compared with instrument B with an average and standard deviation of 1.70 ± 0.35 mg/L. Grab samples measured at 2.19 ± 0.15 mg/L. Instrument A was more accurate than instrument B; however, both instruments exhibited greater variability than the grab-sample results. This may be related to the lower frequency of grab-sample analysis compared with on-line data collection. Because of the variability in readings from the distribution system, the false-response rate was not numerically assessed. Both on-line instruments tested were very sensitive to flow. Maintaining a minimum flow is critical to proper operation. A minimum of 6–10 L/h was required depending on the instrument, and it was important that this flow remain stable.

The comparison of finished water to distribution water for all parameters did not cover the same time intervals. Because only one set of instruments was available, the waters tested were run sequentially. This lack of direct comparison over time limits the conclusions from this study and will be addressed in future phases of the project.

To monitor water quality on-line, Ann Arbor staff selected total chlorine and DO for on-line instrumentation. To monitor for contamination, the utility selected total chlorine, UV_{254}, conductivity, and DO. Biological activity (both adenosine triphosphate and heterotrophic plate count) and several other parameters, e.g., nitrite, ammonia, and nitrate, will continue to be monitored using grab samples.

and 3.03 ± 0.11 mg/L for grab samples, indicating consistency of the on-line instrument results (standard deviation < 10% of the mean). Two false responses occurred in the finished water over an 18-day period for instrument A prior to the occurrence of flow problems. A false response was defined as a change of more than 20% between sequential readings. Because instrument B was not available during this interval, its accuracy (comparison with grab samples), variability (standard deviation), and false-response rate on the finished water could not be assessed. In the distribution system, instrument A had an average and standard deviation for total

MONITORING SYSTEM COST ESTIMATES

The costs of monitor acquisition, installation, operation, and maintenance will be utility-specific. For Ann Arbor, the costs for monitor acquisition were estimated at $25,000 per installation, assuming that each location had four instruments: total chlorine, DO, conductivity, and UV_{254}. Installation costs, including infrastructure and communications, averaged $40,000 per location. However, this figure could vary greatly depending on the extent of services available. Installation may include building a suitable structure, tapping a water main, and installing electrical, sanitary, and other support features. Operations and maintenance (O&M) costs were estimated at $7,000 per installation per year. This estimate did not factor in the time to provide initial data handling and interpretation to develop response protocols. This component consisted primarily of staff time to visit the site and perform routine maintenance and calibration.

A 10-year life span was assumed for the equipment. Based on these estimates, the utility's plan includes an initial capital investment of approximately $500,000 for eight sensor locations, with an annual operating budget, including replacement costs, of $106,000. These costs do not include the costs of initial design and pilot testing, which are approximately $200,000. These figures are important when the cost–benefit ratio compared with the number of monitors installed is considered. Figures are given for planning purposes only.

CONCLUSIONS

On the basis of TEVA-SPOT results, PipelineNet water quality results, and staff knowledge, eight monitoring locations were selected—four sites for potential contamination events and four sites for water quality. With one location coincident, seven sites were recommended. This lack of overlap between security-based sites and water quality–based sites is not surprising given the differing nature of the goals. Monitoring at the water treatment plant, including assessment of water quality variations and the resulting effect on distribution system parameters, was also recommended to establish a baseline. Water quality monitoring is performed to evaluate deterioration that results from age (such as nitrification) and typically occurs in distant areas of the distribution system where low flow and/or dead ends occur. Security monitoring is based on population protection, and monitors are likely to be located in areas of high flow or high demand.

The following conclusions were reached based on this work:

• An extended-period hydraulic and water quality model that is representative of normal water distribution system operations is critical in order to optimally select locations for monitor placement.

• The TEVA-SPOT modeling methodology provides a means for assessing contaminant threats to distribution systems and uses the information gained to optimally locate contaminant monitors.

• Use of the TEVA-SPOT software to select optimal sensor locations from the list of utility-preferred locations provided the best balance between the costs of installation and sensor maintenance and the protection of public health and water security. The PipelineNet modeling software proved useful in identifying locations for water quality monitoring.

• Having a reduced set of monitoring locations to choose from, i.e., utility-owned or accessible locations, did not markedly reduce the potential protection afforded by a security monitoring system.

• Minimization of response time once a threat is detected is critical to reducing public health effects.

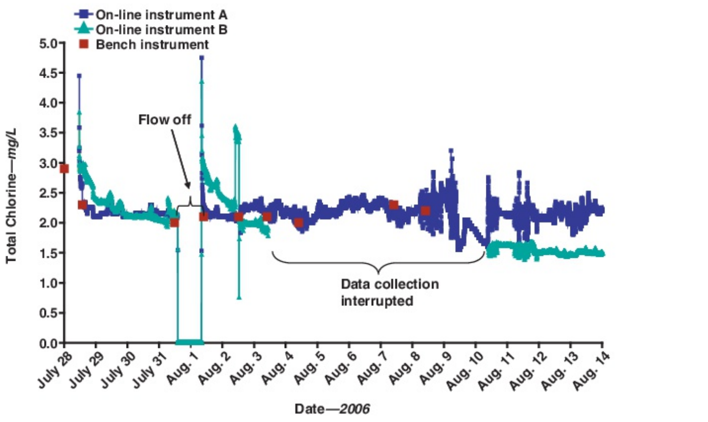
• Ann Arbor staff determined that four monitors for measuring water quality changes and for warning of potential contamination were implementable, considering both capital costs and O&M costs. The additional public health protection afforded by adding more than four security-based monitors in the distribution system was minimal.

• There was limited overlap between optimal security and water quality monitoring locations.

• Variability in concentrations of the parameters that were pilot-tested for monitoring was higher than expected in the finished water. This may influence the distribution system data and likely decrease the alarm system's sensitivity. Adding a monitor to the finished water will provide benefits for understanding variation in treatment processes and for comparing analytical results from the distribution system.

• Parameters selected for monitoring included total chlorine, DO, conductivity, and UV_{254}. The city will implement the project in multiple phases to facilitate

FIGURE 12 Total chlorine monitoring in the distribution system



longer-term assessment of monitor performance and O&M costs.

- Not all instruments that were pilot-tested performed the same for the selected analytical parameters. Therefore, instrument selection is important and may be specific to the water matrix.

All conclusions presented here are specific to the Ann Arbor system and its model of operation.

ACKNOWLEDGMENT

The authors thank the personnel at USEPA's National Homeland Security Research Center, TEVA Research Program, for use of their distributed computing facilities and water security research tools and the Science Applications International Corp. for assistance on the PipelineNet water quality analysis. The authors also thank the manufacturers that supplied instruments for the pilot-testing effort and to utility staff at the city of Ann Arbor.

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FOOTNOTES

[1]UVAS sc, Hach Co., Loveland, Colo.
[2]Depolox 3 Plus, USFilter (Siemens), Vineland, N.J.
[3]MCL-99, Rosemont Analytical, Irvine, Calif.
[4]Spectro::lyser™, S::can, Cincinnati, Ohio
[5]Troll 9500, In-Situ Inc., Fort Collins, Colo.
[6]6920 V2-2, YSI Environmental, Yellow Springs, Ohio

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ANEXO L – ARTIGO RELATIVO AO MONITORAMENTO DA REDE DE ABASTECIMENTO DE BOSTON

SENSOR NETWORKS FOR MONITORING WATER SUPPLY AND SEWER SYSTEMS: LESSONS FROM BOSTON

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Abstract

Recent developments in wireless sensor networks (WSN) promise to have significant impact on a broad range of applications relating to environmental monitoring, structural health monitoring, security and water safety. The convergence of the Internet, telecommunications, and novel information technologies with techniques for miniaturisation now provides vast opportunities for the application of low-cost monitoring solutions which could drastically increase the spatial and temporal resolution of environmental data.
The paper describes the development of a prototype monitoring system which bridges advances in wireless sensor networks with advances in hydraulic and water quality modeling. The prototype monitoring system was deployed at Boston Water and Sewer Commission (BWSC) in December 2004, and it has been successfully collecting and charting near-real time hydraulic and water quality data as well as water levels in combined sewer outflows (CSO). The remote monitoring system has unique functionalities in terms of sampling rates (up to 1000 S/s), time synchronization (up to 1 ms) and in-network processing. These features create novel opportunities for wirelessly collecting data for applications such as hydraulic pressure transients, remote acoustic leak detection together with low-duty cycle applications such as monitoring water quality parameters and water levels in CSOs.
The trial with BWSC has been tremendously useful to prototype hardware and software tools, and to identify deployment and operational challenges in using sensor networks for monitoring and management of large scale water supply systems.

Keywords
Industrial application of sensor networks, Water supply systems, Real-time monitoring and embedded systems

1. INTRODUCTION

Monitoring large scale urban infrastructure such as water supply and sewer networks for detecting leaks, changes in water quality and preventing water contamination caused by sewer overflows has the potential to save municipalities millions of dollars a year and bring significant social benefits by reducing public health hazards. In the US alone, there are approximately 160,000 public drinking water systems that comprise around 700,000 miles of water distribution mains (EPA 2005b). A recent study carried out by the US Environmental Protection Agency estimates that community water systems need $277 billion over the next 20 years (2003-2023) to install, upgrade, and replace infrastructure (EPA 2005a). Transmission and distribution projects represent the largest category of this estimate with $184 billion in needs. The problems of aging and failing infrastructure have been further exacerbated with the threat of contaminant intrusion due to leaking pipes (Friedman et al. 2005) or malicious human actions. These operational challenges and public health threats are major incentives encouraging the development of new technologies for in-line monitoring systems that can optimize operation of the large scale supply networks, prolong service life, evaluate performance and improve the security of water supply to customers. The integration of near real-time data with accurate analytical models can be used in a variety of applictions ranging from optimization of pump scheduling (efficient power management), to the detection and quantification of leaks, and the implementation of an early warning system for contaminant intrusion. To implement these critical applications, the water utilities require a large number of spatially distributed measurement points to represent accurately the complex, highly non-linear temporal and spatial processes that occur in water supply and sewer systems.

In current practice, continuous data collection is limited to a small number of high-risk, high-cost measurement locations that collect hydraulic data, and control the status of pumps and valves. The acquired flow data are used for billing purposes (e.g. data from Automatic Meter Readers, AMR) and are hardly ever integrated into monitoring systems which dynamically model the stochastic processes that occur in water supply and sewer systems. Water quality sampling in distribution networks is generally done through grab samples (i.e., single point in time) that are either analyzed on-site or returned to a laboratory. Water quality can also be monitored remotely through recent developments of multi-parameter sensors which measure surrogate parameters such as pH, redox, conductivity and DO (e.g., Censar; http://www.censar.com/; and Hach, http://www.hach.com/) which are interfaced to a logger with wireless communication capabilities. The main reason for the limited level of continuous monitoring is the prohibitively high price of traditional telemetry systems and in some case the high cost of ownership.

In this paper we present the development and field validation of a generic monitoring solution tailored to the specific needs of the water industry which builds upon recent advances in wireless sensor networks. We have chosen two major applications for the development and evaluation of our monitoring solution. These are (i) hydraulic and water quality monitoring of water transmission and distribution systems which also includes capturing fast pressure transient events; and (ii) monitoring the water level in sewer collectors and combined sewer outflows. Recent laboratory experiments carried out at MIT further extended the list of applications by demonstrating how the system could be used for remote acoustic leak detection (Tokmouline, 2006). A key challenge was the integration of these different applications in terms of bandwidth and sampling regimes within a generic wireless data collection network. To the best knowledge of the authors, this is the first deployment of a monitoring solution in the water industry that is capable of remotely capturing hydraulic pressure transients and displaying raw high-frequency data in near real-time.

We formulate the technical requirements and develop a complete solution which includes sensors, wireless data collection system, middleware and back-end applications for data analysis. As this was a proof-of-concept, we were primarily interested in the following objectives:

- Outline of the requirements for the wireless data collection system. The applications which we cover are the most demanding ones within the water industry in terms of sampling rates, bandwidth and operational environment. Therefore, we are confident that the presented system can satisfy wide scope of monitoring needs within the water industry and beyond;
- Evaluate the cost of deployment, maintenance and ownership;
- Assess the reliability and robustness of sensors and wireless sensor nodes under extreme environmental conditions (e.g. in sewer collectors);
- Evaluate the performance of the deployed platform in terms of reliable data transfer, processor speed and network bandwidth in dense urban environment;
- Learn from operating the data collection network over a long period of time (15 months) in collaboration with Boston Water and Sewer Commission (BWSC) under real-life conditions.

The remainder of this paper is organized as following. Section 2 presents an overview of current data acquisition practice within the water industry. Section 3 outlines the applications and the motivation for applying wireless sensor networks. Section 4 outlines the architecture of the monitoring system and describes the critical components. In Section 5, we describe the deployment at Boston Water and Sewer Commission and present the results of our preliminary data analysis. In Section 6, we summarize the lessons learned.

2. CURRENT DATA ACQUISITION PRACTICE

There is a variety of telemetry solutions which the water utilities are using and frequently these solutions are integrated into SCADA systems (Supervisory Control and Data Acquisition). The schematic of a typical SCADA system is shown in Figure 1, and it has four major components that are interconnected via a network: (i) remote telemetry and automation devices, such as outstations, data-loggers and PLCs (Programmable Logic Controller); (ii) data gatherers which acquire and manage the telemetry data; (iii) data server providing telemetry data for users and other applications; and, (iv) workstations which provide a user interface.

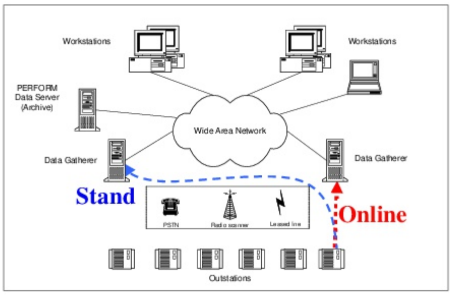

Figure 1: Schematic of a SCADA system

The outstations are connected to the data gatherers via a range of different media including telephone lines (PSTN lines, cell phone modem), leased lines, radio (UHV, VHF, spread spectrum), private networks, fieldbuses (e.g. Profibus), and satellite. The workstations communicate with the data gatherers via local and wide area networks as appropriate, such as X25, Ethernet or asynchronous links. Communications interfaces between workstations, data gatherers and corporate systems are provided through Industry Standard Protocols such as TCP/IP or OSI standards. The data gatherers (DGs) provide the data collection service at the heart of the system by scheduling and executing telemetry polling, managing and distributing the real time database, and serving the workstations. The outstations are grouped into sets (clusters) and then each set is interfaced to two DGs: a *primary* and a *secondary*, to minimize the risk of failure. During normal operation, the primary DG polls the set's outstations and collects the corresponding data. This data is forwarded to the secondary DG where a further copy of the set's database is maintained.

Current SCADA systems are expensive and their deployment within the water industry is limited to critical sites. Many SCADA protocols are vendor specific and proprietary as the legacy of the early low-bandwidth protocols remains. In general, SCADA systems serve low-data rate applications (e.g. collecting data once every 15 minutes; or only when the DG polls the outstation) and provide little flexibility in terms of changing sampling regimes, adaptive sampling, local processing and remote (over-the-air) software update. Many SCADA protocols now contain extensions to operate over TCP/IP, although many utilities prefer not to connect SCADA systems to the Internet for security reasons.

There is a growing need for monitoring solutions that can be deployed at much lower cost and faster using in-house expertise while providing much higher spatial and temporal density. These novel monitoring solutions are expected to complement traditional telemetry and SCADA systems while generating a high level of monitoring redundancy. As an illustration of this trend, many sensor vendors have started to offer embedded cellular connectivity in their products. For example, ABB provides GSM/SMS connectivity to its FieldIT AquaMaster water meters, enabling information to be remotely collected via SMS messaging (www.abb.com). The AquaMaster flowmeters can be remotely configured by sending an SMS message. Data are being recorder at predefined intervals of 15minutes; with an option for a high resolution one minute sampling rate. The data are transmitted once every 24 hours for battery operated units which have a projected battery life of 5 years. Data can also be pulled on demand by dialling an individual sensor and collecting sensor data (flow rate, pressure, total water consumption, alarms) and status information such as battery level. The battery life is reduced to two months for a data collection and communication of once every 5 minutes; and to approximately 6 months for data collection and communication every 15 minutes. Using commercially available SMS Gateway solutions, the automated SMS meter readings can then be received, decoded and exported to an existing billing application or database to provide near real-time usage information via Internet. Wireless communication is also supported via packet switched (e.g. 1xRTT) or circuit switched (e.g. CDMA) cellular (http://www.telog.com/).

The wide-scale adoption of these communication solutions illustrates that the water industry is actively looking for novel low-cost monitoring solutions. The bandwidth however remains limited as the data are primarily used for billing with limited use for near real-time monitoring. Capturing high-frequency data is exclusively done via manual data collection.

3. APPLICATIONS

The applications which we selected for the development and evaluation of our monitoring solution include (i) hydraulic and water quality monitoring of water transmission and distribution systems (this also includes capturing fast pressure transient events); (ii) remote acoustic leak detection including remote cross-correlation; and, (iii) monitoring the water level in sewer collectors and combined sewer outflows. The reasons we concentrated on these applications are as following:

- the monitored infrastructure, water transmission, distribution and sewer pipes, share the same spatial distribution. Figure 2 shows the complexity and density of underground infrastructures for a street in London, UK. All large cities worldwide face the same challenges in using the streets as conduits for utilities to transport water, gas, electricity and telecommunication services;
- water distribution and sewer pipes are frequently located within close proximity. Figure 3 shows a broken sewer pipe located on top of a leaking water pipe. Under certain hydraulic (pressure) conditions, the leak can become an entry point for the intrusion of contaminants which might introduce significant public health hazards;
- the pipeline infrastructure is generally operated by a single company (water utility) and having the opportunity to address all these applications within a generic monitoring system provides excellent opportunities to enable an integrated modelling and management approach while keeping the cost for the monitoring solution low; and,
- the lead author has significant expertise in modelling and operational control of water supply systems. A number of problems were identified through extensive field deployments using custom built data loggers for time synchronized data collection of hydraulic transients (Stoianov *et. al.* 2003a). Extensive research was carried out to address these problems. The practical implementation of these solutions, however, was hindered by the costly manual data collection and the technological limitations of current telemetry solutions.

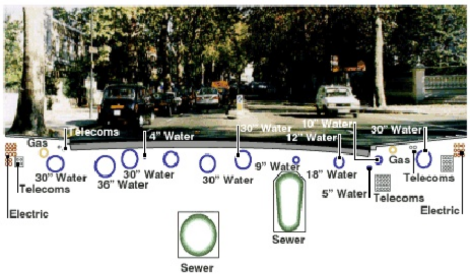

Figure 2: Underground infrastructure in urban environment. (*Courtesy of Thames Water Ltd*).

Figure 3: Leaking water and sewer pipes (*Courtesy of AWWARF*)

3.1. Hydraulic and Water Quality Monitoring. Sampling requirements.

Near real-time hydraulic and water quality monitoring in water supply and transmission systems are essential for detecting failures (such as leaks and bursts), optimizing operational control, pump scheduling, chlorination and chlorine residual and implementing an early warning system for contaminant intrusion. The monitoring process is highly dependant upon the density of the measurements and the accuracy of the simulation model. The hydraulic model which solves a system of non-linear equations approximates the network behaviour by calculating pipe flows, velocities, head-losses, pressures and heads, reservoir levels and reservoir inflows. State estimation techniques are well suited for the purpose of on-line monitoring as they allow tracking the time varying flows and pressures. These techniques are frequently used in the electrical and gas industries, but the scarce number of monitoring points precludes their use in the water industry. State estimation is defined as the computation of the minimum set of values necessary to completely describe all other pertinent variables in a given system from some measurement data. The state estimator algorithm maps the available new information from measurements into a state-space using an over-determined set of equations. This is typically formulated as a projection resulting in a minimization problem. The principles of hydraulic modelling and state estimation can be extended for modelling water quality parameters. Figure 4 outlines a monitoring system that is designed to use near real-time data coupled with accurate hydraulic and water quality models for detecting and tracing a contamination event. In this example, simulations were carried out to demonstrate how hydraulic data from pressure sensors and flow meters can be combined with water quality data obtained from multi-parameter water quality sensors such as pH, dissolved oxygen, conductivity and free chlorine. The developed model simulated the spatial spread of an introduce contaminant at time 0, 2 hours, 4 hours and 24 hours. The data are then projected over the GIS (Geographical Information System) and used for minimizing the effects of contamination.

The sampling regimes are split into a ***continuous*** (periodic) mode and ***burst*** mode. The sampling regimes and rates that were defined for this application can be summarized as following:

- **Continuous mode**: Collect for ***A*** seconds (e.g. 5, 10, 15 seconds specified remotely by the user) every ***B*** minutes (e.g. 1, 5, 15 minutes specified remotely by the user) with a SR of ***C*** S/s (e.g. 1, 10, 100, 1000, 2000 S/s specified remotely by the user). The outputs include average, minimum, maximum, and standard deviation;
- The acquired data are communicate to gateway once every ***D*** minutes (e.g. as collected, 1, 5, 15, 30, 60 minutes, 6 hours, 12 hours, 24, hours or when a threshold is exceeded – these options are specified remotely by the user and can be changed in near real-time);

- Complete remote control (bi-directional) to change the collection regime, sampling rate and communication frequency;
- Adaptive sampling for a particular parameter. If the data exceeds a pre-determined threshold then sampling rate is increased while the communication intervals are decreased. For example, if pH goes above 9.5, then collect data every ***E*** minutes (e.g. 1 minute) and communicate data to a data gatherer every ***F*** minutes (e.g. 5 minutes);
- **Burst Mode**: sampling rate of 1000 S/s burst mode over a period of 5 minutes. This will be performed under burst demand request from the server at a pre-defined *Start Time*. Minimum 15 minutes will be allowed for the server to send the *Start Time* for the burst data collection mode to the sensor nodes. The acquired data are used for a sophisticated analysis and modelling of hydraulic transients for detecting failures in air valves and large bursts, and fine tuning of control valves in large diameter transmission pipelines (Stoianov et al. 2003b);
- The acquired high-frequency data are compressed in near real-time using lossless data compression algorithms to reduce communication time and power consumption as the sensor nodes are battery operated;
- The acquired burst mode data will be time synchronized between sensor nodes located in separate clusters to 1ms; and,
- The remote sensor nodes are re-programmed remotely (software/firmware update over the air).

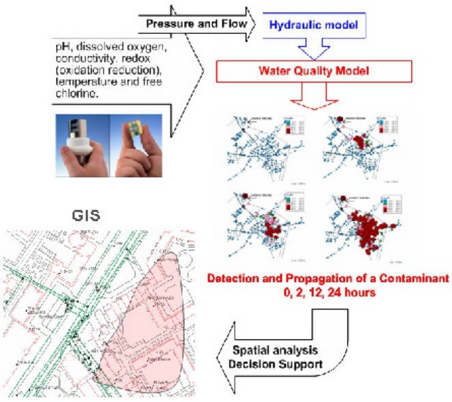

Figure 4: Simulation of the spread of a contaminant over time

3.2. Remote Acoustic Leak Detection. Sampling requirements.

Acoustic Emission and vibration signals have been widely used as a non-destructive testing (NDT) technique for detecting and locating leaks in pipes. Generally, a leak generates noise due to the rapid release of energy which results into a transient elastic wave. To perform leak detection, vibration or acoustic signals are manually acquired at two access points using sensors such as accelerometers or hydrophones on either side of the location of a suspected leak (Figure 5).

If a leak exists, a distinct peak may be found in the cross-correlation of the two signals $s_1(t)$ and $s_2(t)$. This gives the time delay τ_{peak} that corresponds to the difference in arrival times between the signals at each sensor. The location of the leak relative to one of the measurement points, d_1, can be calculated using a relationship between the time delay τ_{peak}, the distance d between the access points, and the propagation wavespeed c in the buried pipe

$$d_1 \frac{d - ct_{peak}}{2}$$

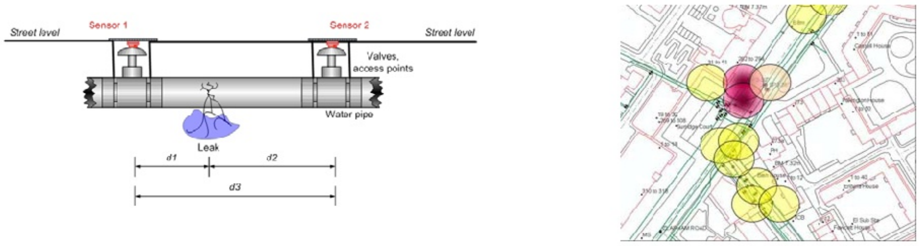

Figure 5: Acoustic leak detection (fixed point remote monitoring)

If $s_1(t)$ and $s_2(t)$ are two stationary random signals with zero mean, the cross-correlation function is defined by (Gao et al. 2006; Oppenheim et al. 1986)

$$R_{s_1 s_2}(\tau) = E[s_1(t)s_2(t+\tau)]$$

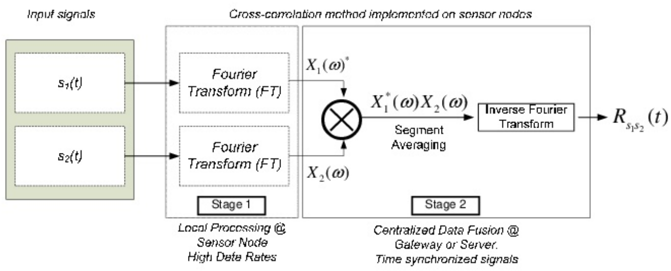

Figure 6: Procedure for calculating the cross-correlation function

where τ is the time lag and E is the expectation operator. The value of τ that maximizes the equation provides an estimate τ_{peak} of the time delay. A procedure to calculate the cross-correlation function using sampled data is illustrated in Figure 6. The cross-correlation estimator can be obtained from the inverse Fourier transform of $X_1^*(f)X_2(f)$ and scaled appropriately for normalization, $X_1(f)$ and $X_2(f)$ are the Fourier transforms of $s_1(t)$ and $s_2(t)$ (and $*$ denotes complex conjugation).

Commercial products such as MLOG offered by Flow Metrix Inc (http://www.flowmetrix.com/) and Phocus2 offered by Primayer (www.primayer.co.uk) provide functionalities for remote and drive-by data acquisition. Various processing algorithms are used to locally analyze the noise characteristics to provide status information which is defined as leak, possible leak, and no-leak. While these products facilitate unattended night time data collection (during hours of low background noise) and approximate identification of leaking areas, they still require manual intervention for accurately pinpointing leaks (the cross-correlation).

The data collection system presented in this paper can provides functionalities that go beyond the listed commercial systems by enabling both local processing of status information and centralized pair-wise data processing of high-frequency time synchronized data. The developed data collection and processing system can provide significant benefits for monitoring high-consequence pipelines and areas. The sampling regime requirements for the remote acoustic leak detection can be summarized as following:

- **Burst data** collection is carried out ***G*** times per 24 hours (e.g. ***G*** = 4, specified remotely by user);
- Collect data for ***H*** minutes (e.g. ***H*** = 5 specified by user) with a SR of 1000 S/s (2000 S/s is supported in the new version of the hardware);
- Process data to identify a status (*Leak, Possible Leak, No Leak, DoNotKnow*). The local data analysis includes time-frequency algorithms together with a classification algorithm. The processing algorithms perform real-time processing on the sensor node (mote). This requires the development of middleware for plugging computational routines which can be remotely queried and updated (over-the-air software update);
- Time-synchronize (time stamp) acquired data with accuracy of 1 ms; and,
- Communicate status information. If status information differs from *NoLeak* status, then transfer high-frequency data to a central server and carry out pair-wise cross-correlation.

3.3. Monitoring Combined Sewer Outflows. Sampling requirements.

Combined sewer systems are sewers that are designed to collect rainwater runoff, domestic sewage, and industrial wastewater in the same pipe. Most of the time, combined sewer systems transport all of their wastewater to a sewage treatment plant, where it is treated and discharged to a water body. During periods of heavy rainfall, however, the wastewater volume in a combined sewer system can exceed the capacity of the sewer system or treatment plant. For this reason, combined sewer systems were designed to overflow and discharge excess wastewater directly to nearby streams, rivers, or other water bodies. These overflows, called combined sewer overflows (CSOs), are among the major sources for water quality impairments as the discharge contains not only storm water but also untreated human and industrial waste, toxic materials, and debris. They are a major water pollution concern for 772 large cities in the U.S. (typically older communities) that have combined sewer systems (EPA 2006).

Combined sewer systems could greatly benefit from real-time control (RTC) which is a custom-designed computer-assisted management system that is activated during a wet-weather flow event. Though uses of RTC systems had started in the mid 60s (EPA 1974), recent developments in wireless sensor networks, telecommunication, instrumentation, and automation are turning RTC into a viable solution. RTC management provides a cost-effective solution in comparison to construction projects designed to separate combined sewers in urban areas. RTC systems are designed to perform a variety of management functions in a given sewerage system such as routing flows to a treatment plant, or other designated points; control flooding, overflows, or surcharges; maximize storage space; optimize treatment plant capacity; prevent operational problems; and, protect receiving waters. Field (2000) defines the basic components of RTC systems as sensors, automated gates and strategies. The RTC equipment includes measurement devices for water level, flow, rainfall intensity and sometimes pollutant concentration, and regulators for pumps, gates and weirs. The reliability of the RTC equipment, calibration and maintenance present significant challenges as the monitoring equipment is subjected to extreme fouling, corrosion and frequently placed in not easily accessible locations. Furthermore, the equipment needs to be intrinsically safe as it could potentially cause ignition of gases in the sewer atmosphere.

In this study, we only demonstrate measuring reliably water level in sewer collectors. The equipment is generic to allow the interface of additional sensors. The sampling regime requirements for monitoring combined sewer outflows can be summarized as following:

- Use multiple sensors to create hardware redundancy for reliable monitoring and sensor fault identification;
- Periodic mode of data collection: Collect data for ***I*** seconds (e.g. ***I*** = 10s specified remotely by user) every ***J*** minutes (e.g. ***J*** = 5mins specified by user) with SR of 1 S/s (outputs include average, minimum, maximum, and standard deviation);

- Communicate acquired data to gateway every K minutes (e.g. K = 15 mins);
- Adaptive sampling: If the collected data exceeds a user-specified threshold, then start collecting data once every minute and communicate the data at 5 minutes intervals until the level drops below the threshold;
- Use radar-measured precipitation and/or data from rain gauges to change the sampling regime;
- All data collection and communication parameters are specified remotely by the user.

4. WIRELESS MONITORING SYSTEM: SYSTEM ARCHITECTURE

The application specifications listed in Section 3, place demanding requirements for the wireless monitoring system in terms of bandwidth, long-distance communication and accurate time synchronization across a wide spread monitoring system, and local data processing. Furthermore, many of the sensor locations do not have access to power, and rely on battery operation. Therefore, the major challenge in developing the wireless monitoring system is how to balance the conflict between long-distance communication, bandwidth, local data processing and the constraints for low-power consumption.

To better address these challenges, a prototype hierarchical wireless monitoring system was developed. The schematic of the system with its main components (sensors, communication, middleware and back-end) are presented in Figure 7. The system consists of a three-tier (subsystems) communication structure which utilizes a cluster-based power management protocol, and a reliable bulk transport. In this way, the subsystems work together to coordinate periodic and burst data collection across a large number of sensing points while maximizing sleep time. The first tier contains energy-constrained sensor nodes with low transmission range which form clusters. The data from the sensor nodes are transmitted to local data gatherers which compose the second tier. The data gatherers are not energy constrained as these can be installed at street lights, illuminated street signs and bollards, or equipped with solar panels. This setup eliminates the need of digging up the pavements and maintaining power cables which is costly and risky particularly in dense urban environment. The data gatherers combine cluster head nodes which control the sleep schedule of each sensor node and a gateway (an industrial single board computer – SBC). The gateway initiates and controls the long-range communication to a central server via TCP/IP over GPRS (General Packet Radio Service). Secure Shell network protocol SSH-2, (Barrett et al. 2005) is used to establish a secure tunnel between the gateway and the server for bi-directional communication. The SSH protocol guarantees confidentiality and integrity of the data exchanged between the gateway and the server using public-key cryptography and message authentication codes. A data control center on the back-end stores and process data on a server at MIT, and displays the acquired data via a web browser (http://db.csail.mit.edu/dcnui/). The application is built on open source web technology, deploying Linux/Apache/PostgreSQL/PHP stack in a client-server model. Google Maps Programmer's toolkit (API) was used to build geospatial viewing tools for the deployed monitoring locations (Figure 8). This open source framework facilitates a rapid application development at low cost. As the user interface is just a common browser window, it runs on any computer and on a hand-held device which enables quick data interrogation and validation by office and field engineers. A basic set of additional functionalities were added to the control center such as charting near real-time data and status information, alarm notification via email and SMS messages based on thresholds, executing pre-defined queries on historical data and account management to authorize users to view acquired data, and interface between PostgreSQL database and Matlab.

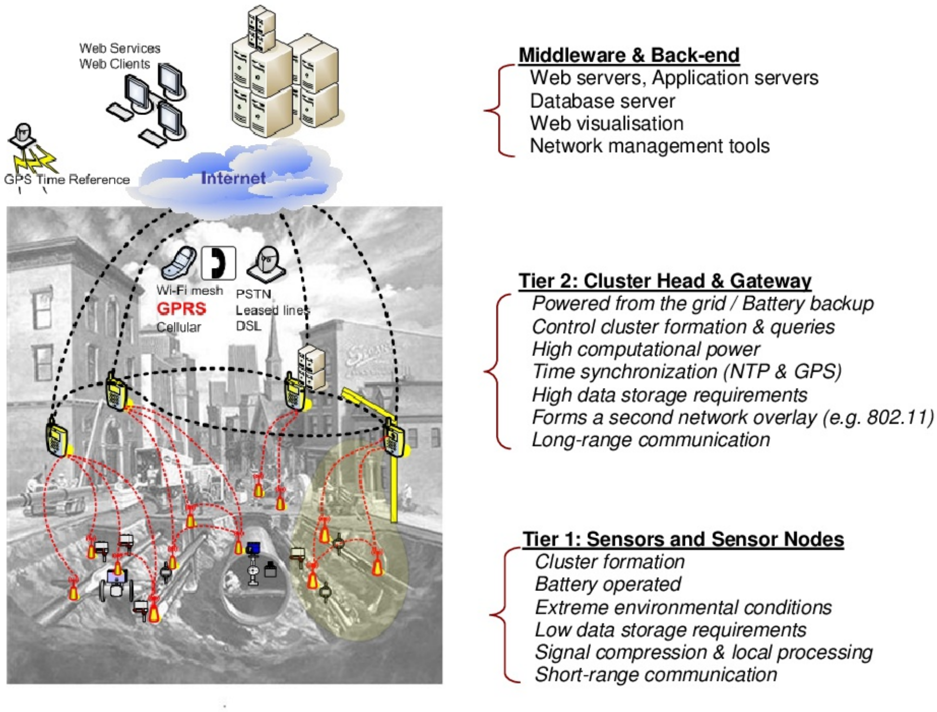

Figure 7: Schematic of the three ties of the developed monitoring system

The following sub-sections provide a brief overview of the system components and operation of the first two tiers of the data collection network.

4.1. Tier I: Sensor Nodes

In the proposed two-tier monitoring setup, the transmission range requirement of the sensor units is within 10-100m distance as they communicate with the data gatherer. At this initial stage of our development, we decided to use Bluetooth (2.4 GHz license-free ISM band) as a choice for short-range communication within a cluster because of the RF-method of FHSS (Frequency Hopping Spread Spectrum) which makes it more robust in outdoor environment, the high transfer data rate (1 Mbps), low cost and the application/cluster requirements. The cluster formation includes small number of nodes with one to two hops exchanging periodic or burst data over relatively short periods of time. The choice of the radio is particularly important as it impacts not only energy consumption, range and reliability of data transmission (quality of service) but also the software design (e.g., network self-assembly, multi-hop routing, time synchronization and in-network processing).

The applications under consideration relied on the implementation of computationally intensive real-time processing of high-frequency data which required more advanced microprocessor architectures for the sensor nodes while maintaining low power consumption. These requirements were successfully addressed by a novel sensor node platform developed by Intel Research (Kling 2003). The first version of the Intel Mote which we deployed in the Boston Water trial is built on a 3x3cm circuit board that integrates a wireless microcontroller module (32-bit ARM7TDMI processor running at 12MHz, 64kB of Ram, 512 kB of FLASH and a CMOS Bluetooth radio) and various digital I/O options using stackable connectors. The connectors expose two UART ports (up to 960 kb/s) which support very high sampling rates, e.g. 16 bit data at 20kHz, USB client, GPIOs and power. The radio's range is approximately 30 meters with the built in antenna, however, we were able to extend the range up to a 100 meters using a custom-built external antenna. We used TinyOS (http://www.tinyos.net/) as an open source operating system for the Intel Mote. The OS and radio stack leave about 11 KB of free SRAM to be used by the application. Another advantage of the Intel Mote is its modularity which allows custom sensor boards, interface boards and debug boards to be attached to the system in a flexible manner.

Key components in the tiered communication structure are the cluster-based power management protocol and the reliable bulk transport of high-bandwidth data. These elements work together to coordinate periodic data collection across the nodes within a cluster while minimizing power consumption and utilizing Bluetooth master/slave and piconet/scatternet operation. Subsequently, the network is self-organizing on start-up by employing a distributed node discovery and connection procedure (Nachman *et. al* 2005). After establishing the basic network, routing information is exchanged between the nodes to permit automatic network repair in the event of node or link failures, while a low power mode maintains network connectivity. The nodes in a cluster wake up based on a *Wake_UP* parameter communicated by the cluster head at the end of a previous period. Once the cluster nodes are awake, the cluster head initiates metric-based single-destination-DSDV routing (Yarvis*, et.al,* 2002) to allow all nodes to find a path to the cluster head. Next, each node sends periodic *TraceRoute* packets to the cluster head, allowing the cluster head to discover the nodes in its clusters. The cluster head waits a predefined period, to allow all nodes to report. Once discovery is complete, the cluster head sends a data capture and transfer request to each node. The resulting data is transferred using the bulk transfer protocol (Nachman *et. al* 2005). Once data collection is complete, the cluster head sends beacons indicating a start time and duration of the sleep phase. The sensor nodes then go to sleep for the requested duration.

4.2. Tier II: Data Gather and Gateway

The second tier acts as a cluster head, data gatherer and a gateway which manages the cluster, controls the long-range communication with the remote server and sends time beacons for time synchronization using PPS (pulse-per-second) signal provided by an embedded GPS. These functions generally could be performed by many single board computers (SBC). For our field trial we used a research platform developed by Intel called Stargate (http://platformx.sourceforge.net/). The Stargate platform is a 400MHz, PXA55 XScale processor, 64 MB SDRAM, 32 MB Flash with Ethernet, Serial, JTAG, USB, PCMCIA, Compact Flash connectors, Bluetooth and 802.11 (through the CF or PCMCIA slot) running Linux OS Kernel 2.4.19. We used General Packer Radio Service (GPRS) for long-range communication which is available worldwide via GSM cellular networks. For this purpose, we interfaced a Sierra Wireless A750 GPRS modem with the Stargate platform. Furthermore, we added 802.11b (WiFi) connectivity via Netgear MA401 card (CF slot) so that we can locally access the gateway for drive-by data collection and software upgrade. We used Motorola GPS engine M12+ specifically optimized for timing applications.

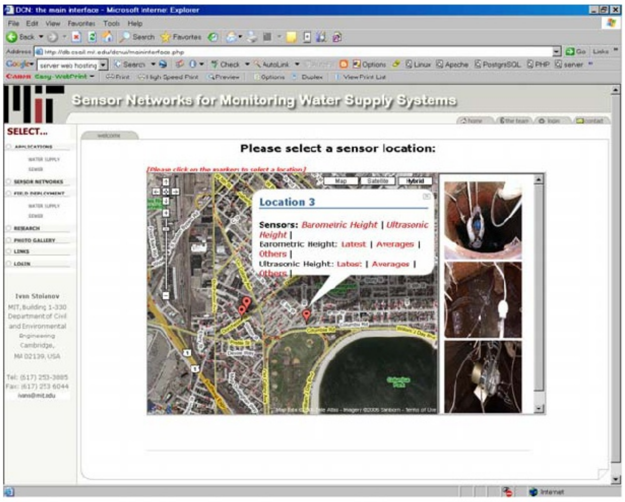

Figure 8: Web interface including Google MAP API for geospatial viewing of sensor data

5. BOSTON WATER DEPLOYMENT

In December 2004, in collaboration with Boston Water and Sewer Commission we deployed three monitoring clusters as a proof-of-concept (http://db.csail.mit.edu/dcnui/PhotoAlbum/index.html presents a series of photos detailing the installation). The trial which is still running aims to answer a wide range of technical and economic questions such as ease of deployment, cost of installation and maintenance, reliability of data communication, reliability of sensors, and packaging.

5.1. Installation

The three monitoring clusters were selected to represent the applications listed in Section 3. For all three clusters, the gateways were installed at neighbouring lamp posts which provide direct access to power (110V ac power lines). In addition, the gateways have back-up battery with re-charging circuitry which allows one week operation in the case of a power failure. A number of additional design challenges had to be overcome which included packaging ,temperature control via heat sinks and water proof ventilation (temperature measured in the gateway enclosure on a sunny hot day reached 140F), sensors, and antenna design and its installation in the road surface.

Cluster 1 includes monitoring pressure and pH in a 12” cast-iron pipe which supplies potable water. Data are collected at 5 minutes interval for a period of 30 seconds. The pH probe is warmed up (powered) for a period of 15 seconds, and then readings are taken once per second for 15s. The data are communicated to the data gatherer and the server every 5 minutes. We used a pH glass electrode with Ag/AgCl reference cell for which an immersion apparatus was developed to lower the probe in the pipe through a 1” access point. We also developed a signal conditioning circuitry to condition the output signal to 0.5-4.5 Vdc which corresponds to a pH range of 3-11. The signal conditioning circuitry for the pH probe consumed less than 10mW of power. Significant amount of time and effort were spent on the selection and modification of the pressure sensor. We needed a low-cost sensor (less than 200 USD) with good accuracy (+/-0.3%FS) and long term stability. The most critical parameters however were the start-up time, the dynamic response for capturing pressure transients and the sensor performance under aggressive power cycling. In order to address this challenge, we used an OEM piezoresistive silicon sensor for which an advanced ASIC compensation technology was developed to achieve accuracy better than +/-0.2%FS including effects of non-linearity, hysteresis and repeatability; start-up time of less than 20ms; fast dynamic response and power consumption of less than 10mW. Pressure data are collected at 5 minutes intervals for a period of 30s with a SR of 600S/s. The raw data are communicated to the data gatherer every 5mins where the data are compressed and send to the server.

Figure 9: Cluster 1: Installation of pH probe; Antenna embedded in the road surface

Cluster 2 (Figure 10) includes monitoring pressure in a 8" cast iron pipe. Data are collected in a similar way to Cluster 1;

Cluster 3 (Figure 11) includes monitoring the water level in a combined sewer outflow collector. As this is an aggressive environment, we decided to use hardware redundancy and implement a voting algorithm which identifies sensor failures or drifts. This information will optimize maintenance and increase the reliability of data. For this purpose, we implemented three sensors, two pressure transducers at the bottom of the collector and an ultrasonic sensor on the top. The pressure sensors are low-power devices consuming less than 10mW while the ultrasonic sensor is a high-power device consuming around 500-600 mW. Therefore, we used the pressure sensors for continuous (periodic) monitoring while the ultrasonic sensor was only used to verify the readings from the pressure sensors when their difference exceeded a threshold or when the water level exceeded the weir height. Data from the pressure sensors are collected at 5 minutes interval for a period of 30 seconds. Sensors are powered for 10s before readings are taken with a sampling rate of 1S/s. Both raw data and average data are transmitted to the data gatherer after every data collection

5.2. Performance

The performance of the data collection network is being evaluated on four criteria: (i) the ability to collect and deliver data to the gateway; (ii) the ability to transfer the data from the gateway to the server via the GPRS link; (iii) the ability to recover from loss or errors; (iv) the long-term performance of the deployed sensors.

During the initial stage (December, 2004 – July, 2005) we observed a series of problems with the gateways ranging from strange GPRS modem power modes to corruption of the Linux kernel. Detail analysis of these problems identified design faults with voltage regulators and the watchdog timer on the Stargate platform. An external watchdog and automated reset feature were added to the gateway nodes to monitor gateway performance. The gateway is rebooted if the application software halts. In addition, the external watchdog timer reboots the gateway once every 24 hours. Adding these features eliminated the observed problems and reduced the risk of unforeseen problems in the gateway software that would require manual intervention by an operator.

Figure 10: Cluster 2: Installation of the pressure sensor node

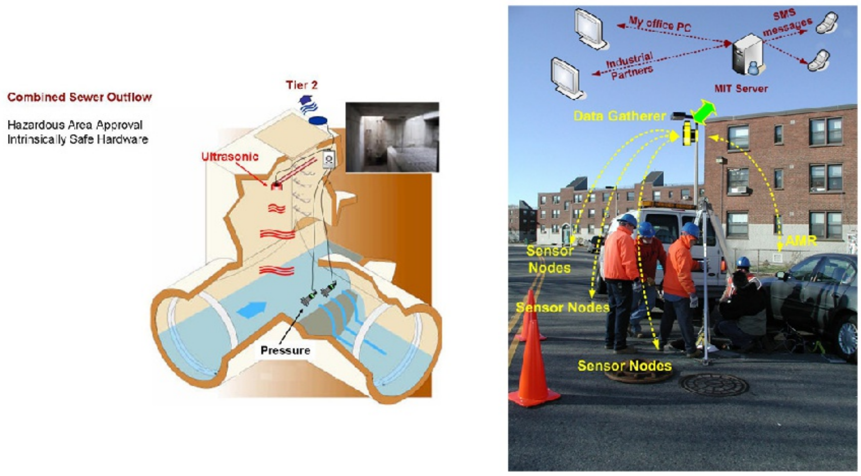

Figure 11: Figure: Schematic of Cluster 3, CSO monitoring

The modified gateways were installed in July 2005 and they have been operating since which is nearly one year of continuous trouble-free operation. The Intel motes have been operating successfully without hardware failures so far.

The communication performance is variable. The packet reception rate for the cluster ranges between 65-85%. The GPRS packet reception rate is within 78-90%, however, all collected data are transmitted from the gateway to the server as the gateway archives the data if a connection to the server cannot be established. The sensor node however does not currently have the functionalities to separate data acquisition from communication and if a connection to the cluster head cannot be established then data are not acquired. A newer version of the hardware (Intel Mote v2) has already addressed this limitation. We are also in the process of logging weather conditions to correlate humidity and rainfall to the packet reception rate. Surprisingly, the packet reception rate was high (82%) in January 2005 which was the snowiest month on record in Boston with snow accumulation of greater than 1.5 m.

The battery life (6V 12Ah battery) has been consistent with a duration of around 50-62 days. The Intel mote consumes 2 mA in sleep mode; 16 mA for Intel mote plus pressure sensor and A/D board; around 30 mA for Intel Mote plus radio, sensor and A/D board. This short battery life is due to the very aggressive data acquisition and communication cycles. Separating the acquisition from communication and adopting communication intervals of 15 mins with adaptive data acquisition and storage will increase the battery life beyond one year.

The performance of the pressure sensors exceeded our expectations. The sensors have been operating since December 2004 under extreme environmental conditions. The pH sensor however has required frequent maintenance and replacement ranging from a couple of weeks to six months. The replacement of the pH sensor is under consideration with a micro non-glass ISFET probe.

The monitoring system was successful in accurately capturing several critical events such as the emergency failure of the power supply for the Deer Island Sewage Treatment Plant in Boston on the 15th of October (Figure 12) when approximately 25 million gallons of untreated sewage were released into Quincy Bay (Boston Globe, 17th October, 2005: Untreated Sewage released into bay).

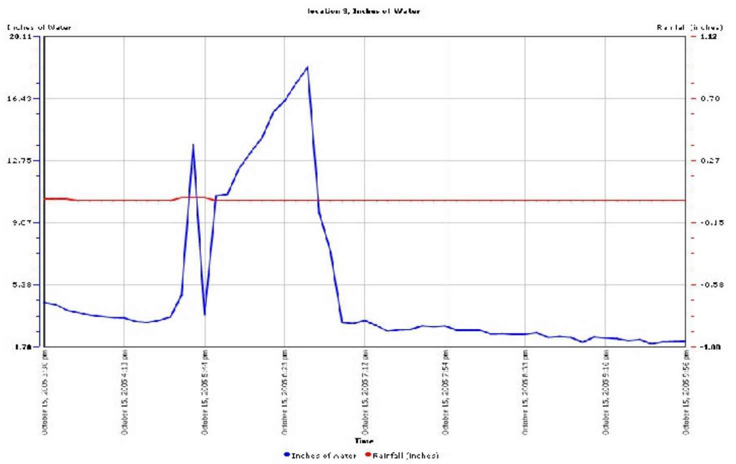

Figure 12: Sewage release on the 15th of October, 2005

The availability of a larger number of monitoring stations such as the one we deployed could have provided near real time information for utilising the spare buffer capacity of the system thus significantly reducing the discharge volume.

6. CONCLUSIONS

In this paper, we demonstrated how advances in wireless sensor networks, communication and sensing technologies could provide much needed increase in spatial and temporal resolution of hydraulic and water quality data for better understanding and monitoring large scale water supply and sewer systems. The developed prototype enables us to remotely acquire, view and process both high and low-frequency time-synchronized data from large scale water supply systems. The field trial with Boston Water and Sewer Commission has provided invaluable information about the performance of sensors, sensor nodes, data collection network, radio, hardware and software tools. This information is critical for the current upgrade of the monitoring system in terms of radio, network protocols and application layer.

Finally, we demonstrated the use of a sensor network to meet almost one year of continuous operation requirement with a minimum technical support of replacing batteries every 60 days under extreme outdoor conditions. Several techniques including careful protocol design, external watchdogs and periodic resets of system state enabled sufficient reliability for completely unattended operation. The data collection in this trial was primarily focused on the proof of concept for the communication, reliability of hardware and sensors. We are in the process of extending the trial so that we can acquire data of sufficient quality and quantity to demonstrate the advantages of using the data with much enhanced analytical models.

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ANEXO M – ARTIGO RELATIVO AO MONITORAMENTO ON-LINE DA BACIA DO RIO LIMING

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An online water quality monitoring and management system developed for the Liming River basin in Daqing, China

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Abstract

This paper describes an online water quality monitoring and management system that was developed by combining a chemical oxygen demand sensor with an artificial neural network technology and a virtual instrument technique. The system was used to model the hydrological environment of the Liming River basin in Daqing City, China, in an effort to maintain the water quality in this basin at a level compatible with the status of Daqing City as a scenic resort. Operation of the system during the past 2 years has shown that an optimal allocation of water (including water released from an environmental reservoir to mitigate pollution events) could be achieved for the basin using the information gathered by the system; using mathematic models established for this system, the quantity of water released from the reservoir is adequate to improve the overall water environment. The results demonstrate that the system provides an effective approach to water quality control for environmental protection.

Keywords: Online monitoring; Water environment management; Hydrological environmental modeling; One-dimensional advection–diffusion

1. Introduction

Many urban rivers in China, and particularly scenic rivers, have been polluted by overland runoff from point and non-point sources (Xu et al., 2004; Dong et al., 2004; Deng, 2003). Accidental pollution has often occurred, and sometimes identification of water pollutants and polluters was not possible because water samples could not be obtained in a timely manner (Chai et al., 2004). For example, fish mortality occurred overnight in one incident and was only detected the next morning, after the contaminated water had already disappeared (Bode and Nusch, 1999). In China, online monitoring installations have been constructed for several large rivers, including the Huanghe River (Zhao, 2004), the Huaihe River (Chen et al., 2003), and the Haihe River (Meng, 2002), to provide real-time information to guide environmental protection decision-makers. Although considerable progress has been made in recent years to develop an online water quality monitoring capability, these installations still only complement laboratory testing, which is not yet a fully viable alternative (Drage et al., 1998).

For most medium and small rivers, few of the hydrological stations are well-equipped, and the apparatus that are being used are outdated and cannot satisfy the requirements of detecting and responding to pollution events. Some researchers have investigated integrated water quality models (Richards et al., 1996; Ning et al., 2001; Beck, 2005; Lindenschmidt et al., 2005) and environmental management systems based on hydrologic modeling (Chau et al., 2002; Mujumdar and Saxena, 2004; Zacharias et al., 2005), but these systems are not connected with any online monitoring system. Even in emergency cases of water pollution, no feasible management scheme can be worked out in a timely manner (Thoms and Swirepik, 1998; Rauch and Harremoës, 1999; Huang and Xia, 2001; Quinn, 2003). These problems justify the development of an online water quality monitoring and management system that can provide an early warning of water-pollution events. In recent years, the Chinese government has paid much

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attention to monitoring and management of the country's water environment. The online water quality monitoring and management system that has been implemented for the Liming River basin in Daqing is one example of the resulting government-funded programs.

This paper describes the Liming online water quality monitoring and management system, which uses modern data transmission and artificial neural network (ANN) techniques to monitor the river's water environment and hydrological–environmental models to forecast the potential environmental water demand. This combination of techniques allows optimal allocation of water using information acquired from the monitoring system and estimates from the water environment models.

2. Background information on the Liming River basin

Fig. 1 illustrates 37 km of the Liming River in the eastern part of Daqing City of China's Heilongjiang province. It is one of the six major streams in this area that are managed for flood prevention and scenic purposes. In recent years, different sources of contamination have caused deterioration of the water quality in the river and other bodies of water, including lakes and reservoirs: oil-contaminated soil (from which oil is leached into the river by overland runoff and percolation through the soil), domestic sewage, and wastewater produced by oil-extraction plants. Many measures have been taken to improve water quality, including the construction of a wastewater treatment plant for the removal of oil pollutants from surface runoff and accidental oil spills, and the construction of an underground sequencing batch reactor with aerated sludge facilities used to treat domestic sewage concentrated from several geographically distinct locations. These measures have effectively controlled pollutant sources to some degree, but organic pollutants and a lack of clean water in the Liming River are both responsible for poor water quality. To help resolve this problem, an environmental reservoir with a capacity of $0.74 \times 10^8\,m^3$ has been built north of Daqing City to provide a source of clean water. Water can be released from this environmental reservoir to improve water quality in the Liming River as a result of dilution and flushing effects. However, it was necessary to develop an online monitoring and management system for the Liming River basin to coordinate the release of water from seasonal lakes and reservoirs and to assess the assimilative capacity of the river and thus, improve our ability to manage water quality.

3. Water quality monitoring

3.1. Configuration of the water quality monitoring system

In order to provide an early warning when water quality in the river drops below an acceptable level, five monitoring stations were installed along the river, and one central control station was established at the Daqing Flood Prevention Distribution Center (Fig. 1). Water management software was installed on a computer at the Center to monitor such parameters as flow rate, total organic matter, total petroleum hydrocarbons, and total suspended solids. In this paper, we have chosen chemical oxygen demand (COD) as the water quality parameter used to represent total organic matter, since COD data are available from the online monitoring stations.

3.2. Data transmission process

Fig. 2 illustrates the existing signal-transmission network for data from the monitoring stations. The system at each

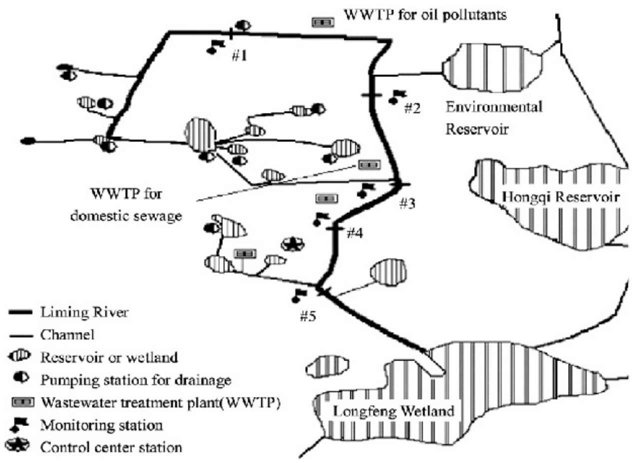

Fig. 1. Schematic diagram of the Liming River basin.

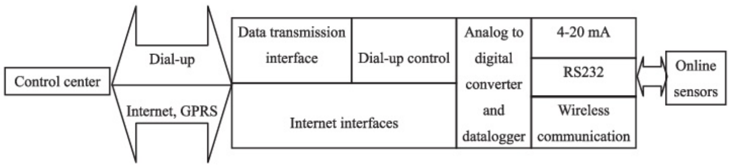

Fig. 2. Schematic diagram of the communication pathways in the monitoring system.

monitoring station includes data links using 4–20-mA power cables, RS232 connections, and wireless communication. Real-time analog signals carried by the power cables are obtained from each monitoring station through a series of water quality sensors. A programmable logic controller is used to convert the analog signals into digital signals, and then dataloggers at each monitoring station read these signals through an RS232 interface. In addition, general packet radio service was adopted; this service relies on retransmission and data integrity protocols to ensure that data packets transmitted by radio do not deteriorate or become lost. This technique can be used to greatly improve the reliability of data transmission (Lindemann and Thummler, 2003). Communication between dataloggers, the monitoring stations, and the control center is mainly carried out by means of the short-message service (SMS) technology complemented by a dial-up connection for use when this service is unavailable. The control center sends out a request to each station every 30 min. The station packages its monitoring data once per 30 s and transfers a compilation of this data to the control center when it receives the request from the control center. In addition, the control center can be connected to the Internet by means of a dial-up connection at any time to publish information and share it with the public.

3.3. Online monitoring using an ANN

The online water quality monitoring system that was developed for the Liming River basin used standard techniques for monitoring flow rate, total suspended solids, and total petroleum hydrocarbons, using instruments that are readily available on the market (Hu and Yang, 2004). A "soft" measurement technique for COD was used to overcome the drawbacks encountered with traditional online instruments. In this approach, multiple sensors are combined to evaluate COD in terms of changes in ultraviolet (UV) and visible (Vis) spectra and in pH. Because almost all organic matter exhibits characteristic absorbance in the range of 215–316 nm (especially in 254 nm), UV–Vis absorbance spectroscopy is widely used to characterize dissolved organic matter in water. In addition, pH, which is affected by dissolved substances, can sensitively indicate variations in water quality (Benjathapanun et al., 1997; Grattan, 1998). The most commonly used computational algorithm, back-propagation, was used in an ANN model to parameterize the non-

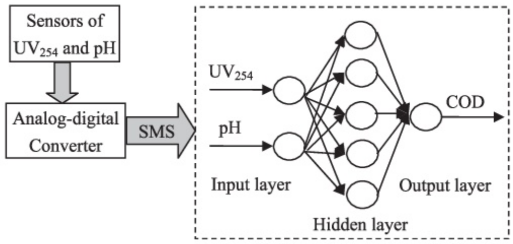

Fig. 3. Illustration of the ANN model used to convert absorbance of UV and Vis light (UV_{254}) and pH into an estimated COD value.

linear relationship between two water quality parameters (UV_{254} and pH) and COD. With UV_{254} and pH used as the inputs for the ANN and COD used as the output, a two-layer feed-forward neural network was created (Fig. 3).

In the process of training, one iteration of this algorithm can be written as follows:

$$x_{k+1} = x_k - \alpha_k g_k, \quad (1)$$

where x_k is a vector array of current weights and biases, x_{k+1} is the value used as the input in the next iteration, g_k is the current gradient, and α_k is the learning rate.

Starting with an initial learning rate ($\alpha_k = 0.1$), an initial momentum constant ($m_c = 0.9$), five hidden neurons, and an error rate of 0.01, the weights and biases are iteratively adjusted using the momentum method to evaluate the network performance (Hill et al., 1993), and the goal is to minimize the mean squared error (MSE) between the network outputs and target outputs during the training process. If the MSE becomes smaller than the training goal and stable at the end of each learning epoch by adjusting α_k and m_c, then the parameter set can be determined and post-processing can be carried out.

This algorithm is realized in a virtual instrument layer. In the process illustrated in Fig. 3, analog signals (data from the UV_{254} and pH sensors) are directly converted into initial digital signals using an analog to digital converter, and then the digital signals are transferred through SMS to the virtual instrument layer to quantify COD. The virtual instrument layer was simulated in hardware (a VXI bus card with an IEEE1394 bus controller) that was selected for its high performance. The required software was developed using version 7.0 of the LabVIEW software (National Instruments, Austin, Texas), which facilitates the

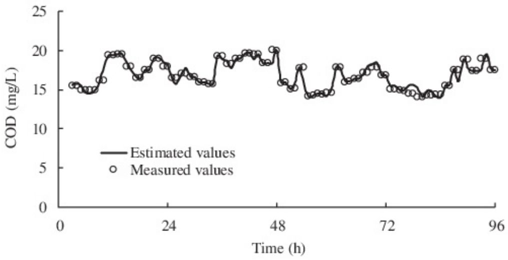

Fig. 4. Results of the training and learning stages for the ANN used to estimate COD (with pH in the range of 4.3–6.2).

development of virtual instruments and produces software that can be run on several types of computers and operating systems without changing the source code (Tanner and White, 1996; Torán et al., 2004). The complete virtual instrument was designed using the G language.

Once the models have been embedded in the computation software, the computers and instruments used for measurement and control are integrated through the virtual instrument layer. During the learning and training stage, data obtained from historical records (2004–2005) provided by the Daqing Flood Prevention Distribution Center was used. During the application stage, Fig. 4 shows that the estimated COD values were in good agreement with the observed values for pH values ranging from 4.3 to 6.2. The calculated values and measured values were fitted using version 11.5 of the SPSS software (SPSS Inc., Chicago, Illinois). The correlation coefficient was 0.924, which suggests that the model was acceptable for application in the Liming River basin and that the determination of COD values using UV_{254} and pH data could be used to rapidly perform online real-time measurements.

4. Hydrological–environmental modeling

4.1. Water quantity submodel for the river

In this paper, submodels for the environmental water requirements and of rainfall-runoff forecasting are included in the overall water quantity model. The environmental water requirements include modeling of the water required for assimilation of polluted river water, for evaporation, and for conservation of groundwater.

4.1.1. Quantity of water required for assimilation of polluted river water

The assimilative capacity of a river is defined as its capacity to "digest" pollution by means of biological activity and physical purification, both of which depend on the uses of the body of water and the quality standards adopted by the management agency (Lee and Wen, 1996). Calculation of the quantity of water needed for assimilation of polluted river water requires calculation of the inverse of assimilative capacity; that is, it represents the minimum quantity of water needed to permit self-purification and dilution of the pollutants, including the quantity of water diverted from other water conservation projects when the river water has been badly polluted. The quantity of water needed for assimilation of polluted water in the Liming River can be calculated as follows:

$$Q_1 = \frac{(q_1 c_1 + Q_0^* C_0)\exp(-kv/x_1) - (Q_0^* + q_1)C_N}{C_N - C\exp(-kt)}, \quad (2)$$

where Q_0^* is the flow rate from upstream ($m^3 s^{-1}$), C_0 is the concentration of pollutants from upstream ($mg L^{-1}$), q_1 is the flow rate from the pollutant sources ($m^3 s^{-1}$), c_1 is the concentration of pollutants from the pollutant sources ($mg L^{-1}$), Q_1 is the flow rate released from the environmental reservoir ($m^3 s^{-1}$), C is the concentration of pollutants from the environmental reservoir ($mg L^{-1}$), C_N is the standard for water quality ($mg L^{-1}$), k is a degradation coefficient (1/day), x_1 is the length of the river (m), and v is the average flow velocity ($m\,day^{-1}$).

4.1.2. Quantity of water needed for evaporation

Evaporative losses are an important part of a river's environmental water demand, especially during the summer. Evaporation of river water decreases the quantity of river water, without greatly affecting the quantity of pollutants in the river. Thus, evaporative losses should be compensated for by water diversion from other bodies of water using the following formula:

$$Q_2 = \begin{cases} 0.1A(E-P), & E > P, \\ 0, & E \leqslant P, \end{cases} \quad (3)$$

where Q_2 is the water demand created by evaporation ($10^4 m^3$), A is the average surface area of the water (km^2), P is the monthly rainfall (mm), and E is the monthly evaporation (mm).

4.1.3. Quantity of water needed for conservation of groundwater

Leakage from the river occurs when the water table is lower than the river water, and can be another important environmental water demand. Leakage losses can be calculated using the following equation:

$$Q_3 = k_1 A, \quad (4)$$

where Q_3 is the annual loss of river water to leakage ($m^3 yr^{-1}$) and k_1 is the leakage coefficient ($m\,yr^{-1}$).

4.1.4. Calculation of runoff from precipitation

The Soil Conservation Service curve number (CN) runoff-estimation approach (Soil Conservation Service, 1972) was used, with some modifications, to calculate the runoff from precipitation. This method uses the following equation (Smith and Williams, 1980):

$$Q_4 = (P - 0.2S)^2/(P + 0.8S), \quad (5)$$

where Q_4 is the runoff amount (mm), P is the rainfall depth (mm), and S is the maximum retention estimated for dry-soil antecedent moisture condition I (AMC-I), and can be calculated using the following equation:

$$S = (25\,400/CN) - 254, \tag{6}$$

where CN is the curve number used for the AMC-I soil moisture condition.

To compute the runoff amount from rainfall depth as a function of these initial abstractions and soil water storage, S is estimated from the actual water content in the upper soil layers and from the CN that characterizes the soil and its vegetation or other cover. To further improve accuracy, CN is calibrated from the observed data for wet, average, and dry antecedent soil moisture conditions. When rainfall data is used, the CN parameter is calibrated by combining the analysis of observed runoff hydrographs with the rainfall breakthrough curves for the same runoff events. As long as a suitable CN (here, one that falls within the 90% confidence interval for the calibration data, Bhunya et al., 2003) is obtained, runoff can be forecasted with considerable accuracy.

4.2. Hydrodynamic submodels

The motion of bodies of water in open channels can be described using the Saint-Venant equations, which express the conservation of mass and momentum (Luis and José, 2004). Conservation of mass leads to a continuity equation, which establishes balances between the rate of rise in the water level and the wedge and prism storage components (Singh and Woolhiser, 2002). Conservation of momentum leads to a dynamic equation that establishes balances between inertia, diffusion, gravity, and frictional forces. The governing continuity and momentum equations can therefore be written as

$$\frac{\partial Q}{\partial x} + \frac{\partial A_1}{\partial t} = q, \tag{7}$$

$$\frac{\partial Q}{\partial t} + \frac{\partial(\alpha Q^2/A_1)}{\partial x} + gA_1\frac{\partial h}{\partial x} + \frac{gQ|Q|}{C_2 A_1 R} = 0, \tag{8}$$

$$h(x)|_{\zeta} = h_1, \tag{9}$$

$$Q(x)|_{\zeta} = q_1, \tag{10}$$

$$h(t), Q(t)|_{t=0} = h_0, Q_0, \tag{11}$$

where Q is the flow rate ($m^3\,s^{-1}$), A_1 is the cross-sectional flow area (m^2), x is the horizontal distance (m), t is the time (s), q is the lateral inflow or outflow (positive for inflow and negative for outflow; $m^3\,s^{-1}\,m^{-1}$), α is the momentum correction coefficient, g is the gravitational acceleration ($m\,s^{-2}$), h is the water surface elevation above datum (m), $R = A/P_w$ is the hydraulic radius (m), P_w is the wetted perimeter (m), C is the de Chezy resistance coefficient, ζ denotes the boundary, h_1 is the water surface elevation above the datum at the boundary (m), q_1 is the flow rate at the boundary ($m^3\,s^{-1}$), h_0 is the initial water surface elevation above the datum (m), and Q_0 is the initial flow rate ($m^3\,s^{-1}$).

Eqs. (7) and (8) are described in mathematical terms as a pair of one-dimensional non-linear hyperbolic partial differential equations. The solution of any system of differential equations generally depends on the existence, uniqueness, and stability conditions. For many applications, it is not possible to solve the Saint-Venant equations analytically, but it is possible to solve them numerically using the Preissmann implicit scheme with the model boundaries represented by flow–time, stage–time, or stage–flow relationships (Crossley and Wright, 1997).

This model can also be used to generate the necessary input data for simulating water quality.

4.3. Water quality submodels

The transport of pollutants is modeled using a finite-difference approximation to the one-dimensional advection–diffusion equation (Siegel et al., 1997):

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial x^2} - v\frac{\partial C}{\partial x} - kc + S_0, \tag{12}$$

$$C(x)|_{\zeta} = c_1, \tag{13}$$

$$C(t)|_{t=0} = c_0, \tag{14}$$

where C is the pollutant concentration ($kg\,m^{-3}$), v is the cross-sectional average flow velocity ($m\,s^{-1}$), D is the diffusion coefficient ($m^2\,s^{-1}$), S_0 is the source/sink term (representing decay, growth, erosion, deposition, and other processes; $kg\,m^{-1}\,s^{-1}$), and c_1 and c_0 are the boundary and initial concentrations in the river, respectively ($kg\,m^{-3}$).

Model boundaries are represented by concentration–time or concentration–flow relationships. Pollutants can also be added or removed from any point in the modeling process.

Water quality modeling can cover a wide range of values for the water quality parameters, including the concentrations of solutes and suspended sediments. All the variables in Eq. (12) represent cross-sectional average quantities. This equation is solved using a novel implicit scheme based on a finite-volume central-difference scheme and a highly accurate Ultimate Quickest scheme (Yang et al., 2002).

4.4. Modeling procedure

The three submodels comprise the hydrological–environmental model. The integrated modeling is capable of predicting the water surface elevations, velocity, distribution of water quality parameters along the river, the river's assimilative capability, and the quantity of environmental reservoir water allocated for the Liming River.

The hydrodynamic submodel can provide the water flow data needed for the construction of the water quality submodel and the water quality submodel can be used to simulate water quality so that the results of water quantity modeling can be verified and optimized in a timely manner. If water quality in the river does not comply with the management agency's water quality standard, the water quantity modeling would be continued until the amount of released water required to produce a satisfactory water quality is achieved.

5. Results and discussion

It is necessary to divert water to improve water quality when pollution levels exceed the limits defined by the management agency. The quantity of water that must be released from the environmental reservoir to maintain an appropriate water quality is determined by the results of the hydrological–environmental modeling. In addition, the decision-making process requires that, in order to reduce the pressure on the clean water resource, the quantity of water released from the reservoir must be as little as possible to bring water quality in the river into compliance with the standard. In the decision-making process, the model is only used to calculate the release of clean water when the river's water quality exceeds the defined limit, and the calculation continues until the water quality complies with the standard; the quantity of water released for dilution of the pollution is thus defined. Fig. 5 shows several examples that illustrate the monitored water quality in 2004 and 2005. Fig. 6 shows an example of a water release schedule based on the online monitoring information. Both figures show that the system can effectively analyze water quality. Fig. 5 shows that the measured water quality remained well below the warning line (i.e., the COD level at which additional water must be released to maintain water quality at an acceptable level) in 2004 and on 5/9/2005, but exceeded the warning line on 30/8/2005, which indicates that water released from the environmental reservoir during the first three periods was higher than the amount required, and that some clean water was wasted. The information provided by the water management system thus supported a decision to reduce the amount of water released, and the required reduction in water flow was thus obtained using hydrological–environmental modeling. Water quality remained acceptable (i.e., COD remained below the warning line) when water flow was reduced by $0.5\,m^3/s$. Soon after this change, the trend line for water quality produced by the simulation remained gentle and the water release rate remained steady, indicating that no new source of water pollution had been detected and that the assimilative capacity of the river remained satisfactory.

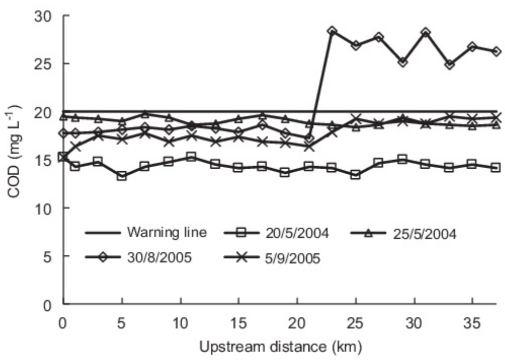

Fig. 5. Four examples of the water quality distributions along the Liming River after the release of water from an upstream environmental reservoir.

However, on 30 August 2005, there was a sharp increase in COD concentration in the river 20 km from the source of the Liming River. This suggests that a pollution incident occurred between monitoring stations #3 and #4 on the river. A survey revealed that this spike in COD was caused by an accident at the wastewater treatment plant in the upper reaches of the river; wastewater flowed directly into the river through a bypass valve. COD concentrations of the outflow from the wastewater treatment plant during the whole day are shown in Fig. 7. The accident lasted for 4 h, during which time raw wastewater flowed directly into the river. The results of the hydrological–environment modeling suggested that water flow should be increased by about

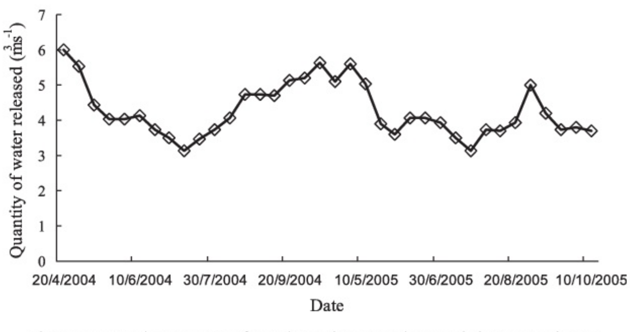

Fig. 6. Water release patterns from the environmental reservoir in 2004 and 2005.

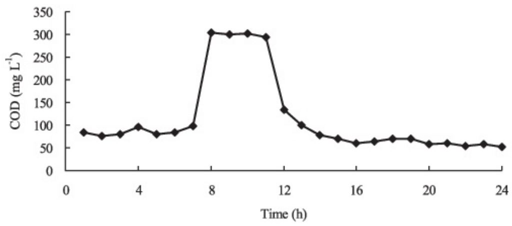

Fig. 7. COD concentrations in the outflow from the wastewater treatment plant on 30 August 2005.

$1.2\,m^3/s$, and water quality in the river was quickly improved by increasing the water flow to this level.

6. Conclusions

This paper describes an online water quality monitoring and management system developed for China's Liming River basin by combining an ANN-based model for sensing COD levels with a virtual instrument technique and using hydrological–environmental modeling to characterize the responses of the river to pollution loads and changes in the flow rate. The goal was to maintain the river's water quality at a level compatible with the status of Daqing as a scenic resort area of China. Using this approach, an optimal environmental water allocation was obtained, permitting a marked improvement in water quality and rapid responses to pollution incidents. The approach used a large quantity of real-time monitoring data as input for the hydrological–environmental model. The results of this approach show that the system provides an effective approach to control water quality for environmental protection purposes.

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