Leading the City of Baltimore into the 21st Century: Flexible Treatment Solutions and Integrated Raw Water Management

J. L. Manuszak*, M. MacPhee*, S. Liskovich** and L. Feldsher***

* Malcolm Pirnie Inc., 3101 Wilson Boulevard, Suite 550, Arlington, Virginia 22201, USA
(E-mail: jmanuszak2@pirnie.com)

** Gannett Fleming, Seton Business Park, Suite A, 4701 Mount Hope Drive, Baltimore, Maryland 21215, USA
(E-mail: sliskovich@GFNET.com)

*** City of Baltimore, 600 Abel Wolman Municipal Building, 200 North Holliday Street, Baltimore, Maryland 21202, USA
(E-mail: Larisa.Feldsher@baltimorecity.gov)

Abstract: The City of Baltimore, Maryland is one of many US cities faced with challenges related to increasing potable water demands, diminishing fresh water supplies, and aging infrastructure. To address these challenges, the City recently undertook a $7M study to evaluate water supply and treatment alternatives and develop the conceptual design for a new 120 million gallon per day (MGD) water treatment plant. As part of this study, an innovative raw water management tool was constructed to help model source water availability and predicted water quality based on integration of a new and more challenging surface water supply. A rigorous decision-making approach was then used to screen and select appropriate treatment processes. Short-listed treatment strategies were demonstrated through a year-long pilot study, and process design criteria were collected in order to assess capital and operational costs for the full-scale plant. Ultimately the City chose a treatment scheme that includes low-pressure membrane filtration and post-filter GAC adsorption, allowing for consistent finished water quality irrespective of which raw water supply is being used. The conceptual design includes several progressive concepts, which will: 1) alleviate treatment limitations at the City’s existing plants by providing additional pre-clarification facilities at the new plant; and 2) take advantage of site conditions to design and operate the submerged membrane system by gravity-induced siphon, saving the City significant capital and operations and maintenance (O&M) costs. Once completed, the new Fullerton Water Filtration Plant (WFP) will be the largest low-pressure membrane plant in North America, and the largest gravity-siphon design in the world.

Keywords: Raw water management; low-pressure membranes; gravity-siphon

INTRODUCTION

The City of Baltimore, Maryland is one of many US cities faced with challenges related to increasing potable water demands, diminishing fresh water supplies, and aging infrastructure. To address these challenges, the City recently undertook a $7M study to evaluate water supply and treatment alternatives and develop the conceptual design for a new 120 million gallon per day (MGD) water treatment plant. As part of this study, an innovative raw water management tool was constructed to help model source water availability and predicted water quality based on integration of a new and more challenging surface water supply. A rigorous decision-making approach was then used to screen and select appropriate treatment processes. Short-listed treatment strategies were demonstrated through a year-long pilot study, and process design criteria were collected in order to assess capital and operational costs for the full-scale plant. Ultimately the City chose a treatment scheme that includes low-pressure membrane filtration and post-filter GAC adsorption, allowing for consistent finished water quality irrespective of which raw water supply is being used. The conceptual design includes several progressive concepts, which will: 1) alleviate treatment limitations at the City’s existing plants by providing additional pre-clarification facilities at the new plant; and 2) take advantage of site conditions to design and operate the submerged membrane system by gravity-induced siphon, saving the City significant capital and operations and maintenance (O&M) costs. Once completed, the new Fullerton Water Filtration Plant (WFP) will be the largest low-pressure membrane plant in North America, and the largest gravity-siphon design in the world.

The following sections provide further detail on some of the project needs and objectives.
Addressing Capacity Issues
The City currently supplies treated water to approximately 1.8 million people within four regional jurisdictions, including the City of Baltimore, Baltimore County, Anne Arundel County, and Howard County. The City also supplies raw water to two additional counties. In total, the City provides an average of 250 MGD of potable water to the Baltimore distribution system. Maximum day demands approach 380 MGD. It is estimated that an additional 66 MGD of treatment capacity will be needed to meet anticipated growth projections over the next 40 years. However, system reliability and flexibility were also major factors in determining recommended capacity for the new Fullerton Plant, and those factors are discussed below.

Improving Treatment of a Challenging Water Supply
The City currently utilizes raw water from a series of three highly pristine reservoirs. Combined, the reservoirs have an estimated capacity of about 74 billion gallons. However, these reservoirs have been drawn down drastically in recent droughts, and the City has been forced to use its secondary supply from the Susquehanna River. The river intake, pumping station, and raw water transmission main was developed in the 1960s; however, over the last 40 years this supply has remained largely untapped due to water quality and treatment concerns.

Raw water from Loch Raven Reservoir is conveyed to the City’s existing treatment plants by way of a single 12 FT tunnel, which was constructed in the 1940s and is in need of inspection and possible repair. In the event that this tunnel suffers a catastrophic failure, or must be taken out of service, the City must be able to operate on the Susquehanna River supply. At present, existing facilities cannot effectively treat Susquehanna River water when turbidity exceeds 40 NTU, and even under low turbidity conditions they must heavily blend the river water with raw water from Loch Raven to make it easier to treat. Furthermore, the City does not currently have any means of advanced treatment for removal of disinfection by-product (DBP) precursors, and future compliance with the Stage 2 Disinfectants and Disinfection By-products Rule (Stage 2 D/DBPR) is likely to be difficult if they are forced to treat any amount of Susquehanna River water. For these reasons, it is important that the City develop a better means of treatment for Susquehanna River water, in order to protect themselves against either: 1) a loss of raw water supply from their reservoir supplies; or 2) an inability to effectively meet EPA regulations when treating river water.

Addressing the Need for System Redundancy
The existing City system includes three water treatment plants. The Ashburton Plant has recently undergone both facility and treatment process upgrades. The two Montebello Plants, however, were both built in the early 1900s and are in need of major facility and process upgrades to be able to treat Susquehanna River water and address certain operating and hydraulic limitations. Unfortunately current system demands cannot be met if either one of the Montebello Plants are shut down for an extended period of time. Furthermore, it is very difficult to shut down a portion of either plant due to minimum flow limitations. Therefore, it was recommended that the Fullerton Plant be designed with enough capacity to meet demands and allow for systematic renovation to the Montebello Plants.

Drought Proofing the City’s Water Reserves
Having the capability to successfully treat Susquehanna River water will also allow the City to better firm its reservoir supplies. Baltimore has been approved by the Susquehanna River Basin commission (SRBC) to withdraw a maximum of 250 MGD from the river; however, during low flow periods their withdrawal is cut by almost 75%. This restriction directly conflicts with the City’s historical practice of using river water only when their reservoir supplies have been seriously depleted, which typically occurs during drought conditions when the river is also experiencing lower flows and withdrawal is thus restricted.
As discussed in the following section, the project team focused much attention on changing this way of thinking, and transitioning the City to a new operational strategy. This strategy is based on the principle of using river water more often, and under normal stream flow conditions, rather than waiting until the existing reservoirs become significantly depleted. Doing so will allow the City to maintain higher reservoir levels for a longer period of time, holding them in reserve for drought conditions when river water quality deteriorates and withdrawal is restricted by SRBC.

INTEGRATED RAW WATER MANAGEMENT

From a water quality perspective, the Susquehanna River is a less desirable source than the City’s other water supplies. Unlike their existing reservoirs, the river’s water quality varies frequently throughout a typical year. Low flow conditions, generally occurring in the summer and early fall, often produce the poorest water quality. During this time, total organic carbon (TOC), biological contaminants (e.g. coliforms and Cryptosporidium), taste- and odor-causing compounds, emerging contaminants, and hardness can become highly concentrated and may result in increased treatment costs. During drought conditions, this effect can become even more pronounced. During normal and wet-weather periods, concentrations of these parameters become more diluted, creating more favourable treatment conditions. However, after major storm events, turbidity (and suspended solids) levels can rise significantly from surface runoff. This can create additional operational challenges associated with residuals production and management.

To combat these challenges, the project team recommended that the City manage all of its water supplies on an integrated basis, to provide the best water quality possible to its customers while minimizing treatment and pumping costs. The new Fullerton Plant was therefore designed with the capacity to treat either Susquehanna River water or water from Loch Raven Reservoir. Switching between these two supplies will allow the City to avoid the river during unfavourable water quality conditions, and yet use it during normal periods to better firm their reservoir supplies.

Water Quality Correlation Analysis

As part of this study, a water quality correlation analysis was performed to determine whether any statistical correlation exists between Susquehanna River stream flow and certain water quality parameters of interest. If such a correlation could be found, then the City could use stream flow (which is monitored regularly by the USGS) as an indicator for when to use river water and when to avoid it because of water quality concerns.

As expected, significant correlations were observed as a result of the regression analysis between Susquehanna River stream flow and concentrations of turbidity and hardness. During storm events, surface runoff transports sediment and other material into the river, causing higher turbidity with increasing stream flow. Therefore high stream flow can be used as an indicator of when to expect high raw water turbidity events. In contrast, raw water hardness increases as river flow decreases. During these periods, a higher percentage of flow in the river is from groundwater. Because groundwater is typically harder than surface water, this results in higher hardness levels. While either adequate data did not exist or significant correlations could not be established for other parameters of interest, turbidity and hardness were viewed as good “indicator parameters” for other compounds which might be affected by runoff and concentration effects.

The regression equations developed between stream flow and turbidity and hardness were then used to investigate the occurrence of less desirable water quality periods, when it would be preferable not to use water from the river. To aid this analysis, different classifications of water quality were developed and used as “triggers”, indicating when to stop pumping from the river and switch to higher quality reservoir sources. Table 1 summarizes the water quality classifications for turbidity and hardness.
Table 1: Initial Classifications of Water Quality.

<table>
<thead>
<tr>
<th>Parameter of Interest</th>
<th>Fully Acceptable</th>
<th>More challenging, or &quot;Marginal&quot; Conditions</th>
<th>Most challenging, or &quot;Poor&quot; Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbidity</td>
<td>&lt; 50 NTU</td>
<td>50-200 NTU</td>
<td>&gt; 200 NTU</td>
</tr>
<tr>
<td>Hardness (as CaCO₃)</td>
<td>&lt; 100 mg/L</td>
<td>100-150 mg/L</td>
<td>&gt; 150 mg/L</td>
</tr>
</tbody>
</table>

It is important to note that “marginal” and “poor” water quality designations do not represent any kind of regulatory criteria or treatment constraints, rather these triggers indicate generalized guidelines for when to expect the cost of treatment, residuals production, and/or consumer satisfaction to be affected. Trigger values may be further refined by the City as they begin to implement these new operational strategies and understand what impact water quality has on operational costs.

Looking back at the last 60 years of Susquehanna River stream flow data, it was determined that approximately 99% of the time stream flow was less than 252,000 cfs, which corresponds to turbidity values of less than about 50 NTU. Likewise, 75-80% of the time stream flow was greater than 12,500 cfs, which corresponds to hardness levels of less than 100 mg/L.

Water Supply Utilization Simulation Tool
The results of the water quality correlation analysis were then used to develop a Water Supply Utilization Simulation Tool, which is an Excel-based worksheet that allows the user to evaluate different operational scenarios for managing the City’s raw water supplies. As discussed, the City has historically relied on the Susquehanna River only after its reservoirs have become substantially depleted. This Simulation Tool allows the user to consider turning on the Susquehanna River supply earlier, when flows are higher, to treat river water when its quality is better and withdrawals are not restricted, which will in turn keep the existing reservoir system full for a longer period of time. Likewise, the Simulation Tool can be used to identify periods when the river should not be used, due to increased cost of treatment or poor water quality conditions.

The hydrologic time-series water balance tool is capable of simulating various Susquehanna River pumping criteria, demand scenarios, water quality “triggers”, and other user inputs such as:
- The total system demand and how it varies throughout the year
- Percentage of demand to be met by each reservoir
- Total system volume triggers to start and stop pumping from the Susquehanna River
- Treatment and transmission capacities
- Reservoir volumes and target volume curves

Figure 1 provides a screenshot of the Water Supply Utilization Tool input screen.

Raw Water Management Recommendations
The results of these water supply utilization simulations indicated that:
1. In the near term, the City should plan to begin using Susquehanna River water when total storage in their three reservoirs drops below about 70%. River use could then be discontinued when reservoir storage returns to 80%.
2. During the year 2050, when the Fullerton Plant is online and demands have increased, these “storage triggers” for starting and stopping river use may have to be increased to about 80% and 90% respectively.
3. To minimize operating costs, the Susquehanna River supply need not be operated during periods when stream flow is >250,000 cfs, which is an indicator that turbidity may be >50 NTU.
4. To avoid other undesirable water quality contaminants, the Susquehanna River supply need not be operated during periods when stream flow is <3,000 cfs. During these periods many inorganic, biological, and pharmaceutical constituents in the river’s base flow can become concentrated, and hardness is estimated to be >120 mg/L.

5. Once the Fullerton Plant is placed into service, the Susquehanna River will be needed approximately 30% of the time to meet system demands, while better preserving reservoir storage volumes. By the Year 2050, river water will be needed approximately 50% of the time.

<table>
<thead>
<tr>
<th>Total System Demand</th>
<th>275 mgd</th>
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<tbody>
<tr>
<td>LIBERTY (initial target without Susquehanna Pumping)</td>
<td>40%</td>
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<tr>
<td>LOCH RAVEN (initial target without Susquehanna Pumping)</td>
<td>60%</td>
</tr>
<tr>
<td>Minimum Demand to be Met by LIBERTY RESERVOIR</td>
<td>50 mgd</td>
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<tr>
<th>Reservoir Volumes</th>
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<tbody>
<tr>
<td>LIBERTY RESERVOIR</td>
</tr>
<tr>
<td>LOCH RAVEN RESERVOIR</td>
</tr>
<tr>
<td>PRETTYBOY RESERVOIR</td>
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<tr>
<th>Water Treatment Plant and Raw Water Transmission Capacities</th>
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<tbody>
<tr>
<td>Ashburton Filtration Plant Treatment Capacity</td>
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<tr>
<td>Loch Raven to Montebello Raw Water Transmission Capacity</td>
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<tr>
<td>Deer Creek Pump Station Capacity</td>
</tr>
<tr>
<td>Maximum Pumping Capacity During Low Flow</td>
</tr>
<tr>
<td>Minimum Release from Prettyboy to Loch Raven Reservoir</td>
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<table>
<thead>
<tr>
<th>Susquehanna Water Quality Triggers (Stop Susquehanna Pumping)</th>
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</thead>
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<tr>
<td>Low Flow WWQ Protection Trigger Using Hardness as a Surrogate</td>
</tr>
<tr>
<td>Turbidity (Exceeded when Flow &gt; Trigger)</td>
</tr>
</tbody>
</table>

**Scenario 1B (Default Tool Conditions)**

| Total System Demand (mgd) | 275 |
| Deer Creek Pumping Station Capacity (mgd) | 137 |
| Avg System Volume Susquehanna Start Pumping Trigger | 80% |
| Avg System Volume Susquehanna Stop Pumping Trigger | 90% |
| Low Flow Water Quality Protection Trigger (cfs) | 6,000 |

**Figure 1:** Snapshot of Simulation Tool Control Panel

**CHOOSING A FLEXIBLE TREATMENT TRAIN**

As discussed, utilizing the Susquehanna River as a source of supply presents several challenges; both in terms of regulatory compliance and secondary (aesthetic) standards. Thus the treatment processes for the new Fullerton Plant were carefully developed, so as to provide adequate capabilities for complying with current and future water treatment rules, as well as producing water with superior aesthetic characteristics.

Numerous technologies were considered and a rigorous process selection approach was applied to help navigate the alternatives and varying viewpoints of project stakeholders. Using an analytical hierarchy process (AHP), process selection was conducted in a logical, defensible, and well-documented manner. For the purposes of the Fullerton Plant evaluation, the following seven criteria were selected:

- Finished Water Quality
- Process Reliability
- Operational Sensitivity
- Product Availability
- Footprint
Relative importance of the decision criteria was established, and the results for the above-listed criteria are shown in Figure 2. Once the decision criteria were identified and ranked, treatment alternatives were scored in each category. Short-listed technologies were subsequently demonstrated in a year-long pilot study, the results of which are not presented in this paper.

![Figure 2: Fullerton Decision Criteria & Rankings](image-url)

Based on the evaluation of non-economic decision criteria and pilot testing results, it was decided to proceed with low-pressure membranes as the preferred filtration mechanism. This decision was based on the City’s desire to have a robust treatment process that would produce consistent and high-quality finished water, regardless of source water quality. Membranes provide a physical barrier to solids and pathogens, resulting in lower and more consistent filter effluent turbidities and reduce the risk of filter breakthrough (provided that there are no fiber breaks). To address DBP precursors and other contaminants of emerging concern (CECs), post-filter granular activated carbon (GAC) adsorbers were included in the treatment train. GAC provides a robust barrier to many dissolved pathogens, and the City is thus well positioned to meet potential future regulations. Additionally, GAC provides a removal mechanism for CECs, whereas other treatment technologies simply breakdown these contaminants into other, and less understood, compounds.

Additional levels of treatment may be required in the future. Therefore, this conceptual design considered and included where appropriate, provisions for additional advanced treatment processes which can easily be implemented if ever needed. UV facilities could be phased in, based on changing raw water quality conditions, Bin classification associated with the Long-term 2 Enhanced Surface Water Treatment Rule (LT2ESWTR), changing regulations, or the setting of more aggressive treatment goals by the City. Likewise, hydrogen peroxide facilities could be added to form advanced oxidation processes (UV-AOP) for additional emerging contaminant control.

**CONCEPT OF PRETREATMENT FOR EXISTING PLANTS**

Because water from the Susquehanna River has been historically more difficult to treat than that from Loch Raven Reservoir, this project considered the option of building additional clarification facilities at the new plant and “pretreating” water for conveyance to and further treatment at the City’s existing Montebello Plants. Under this scenario, raw river water would be intercepted and diverted to the new plant, where it would benefit from oxidation, treatment with powder activated...
carbon (PAC), and coagulation/flocculation/sedimentation, before being sent back into the raw water pipeline for conveyance to the conventional Montebello Plants. Figure 3 shows the relative orientation of and piping between the new and existing City treatment plants. Providing “pretreatment” of river water would allow the Montebello Plants to treat river water regardless of its quality; eliminate the need for raw water blending; reduce the plant’s dependence on filter aid polymer; improve filter run times; and prevent the City from having to reduce filter loading (production) rates. While the City does intend to eventually renovate these facilities; it’s unclear how quickly that may proceed. Raw water management studies show that the City will need to increase its use of river water in the near term, and providing “pretreatment” at the new plant will provide a short-term solution to the many of the existing system’s treatment challenges.

Figure 3: Orientation of Loch Raven and the Susquehanna River source water supplies, and the Montebello and Fullerton Filtration Plants

DESIGN CONSIDERATIONS

In conducting the conceptual design for the new Fullerton Plant, it was determined that adequate elevation existed onsite to operate the membranes by gravity-siphon, with limited pumping by filtrate (vacuum) pumps. Table 2 presents the estimated capital and O&M costs for a submerged membrane system operating by gravity-siphon, compared to an encased positive-pressure membrane system. During the design phase, further evaluation is planned for examining options for staggered GAC replacement and/or implementing seasonal use only.

Table 2: Membrane Cost Comparison

<table>
<thead>
<tr>
<th>System Configuration</th>
<th>Submerged (Vacuum-driven) membrane system&lt;sup&gt;3&lt;/sup&gt;</th>
<th>Encased (positive-pressure) membrane system</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capital Cost&lt;sup&gt;1&lt;/sup&gt;</td>
<td>&lt; 50 NTU</td>
<td>50-200 NTU</td>
</tr>
<tr>
<td>Annual Power Costs&lt;sup&gt;2&lt;/sup&gt;</td>
<td>$528,000</td>
<td>$1,174,000</td>
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<sup>1</sup> All costs presented in 2008 dollars.
<br>
<sup>2</sup> Power costs based on rate of $0.11 per kilowatt-hour
<br>
<sup>3</sup> Assumes that submerged membranes will operate by siphon approximately 70% of the time
CONCLUSIONS

To meet the source water availability and water quality challenges of the future, the City of Baltimore is in the process of implementing several programmatic, operational, and facility design changes, including:

- Transitioning to new raw water management strategies, which encourage more proactive use of alternative water supplies, so that the capacity of existing reservoirs can be reserved for drought conditions
- Planning for and implementing more flexible water treatment processes, that are suited to address a variety of water quality challenges and meet potential drinking regulations in the future
- Investigating opportunities to creatively position new treatment facilities, taking advantage of site elevation and reducing in-plant pumping costs
- Considering the entire treatment and conveyance system when planning for a new plant, and looking for opportunities to incorporate facilities that will benefit the system as a whole