Monitoring the Health of Water Treatment Plants

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Abstract. This paper describes analytical modeling of degradation of water treatment plants (WTP) during their extended operation; it also describes the algorithms for configuring such models on the basis of current WTP status readings so as to predict when the WTP deteriorates to the point it is no longer usable (time to failure). Model selection is based on analyzing and generalizing a bulk of experimental data on various WTPs. Configuration algorithms are model-agnostic, which means the proposed approach can be used universally to improve water treatment quality while also cutting its costs.

1. Introduction
As water pools continue to accumulate harmful substances and microorganisms [1] [2], water treatment plants (WTP) find ever greater use, whether stand-alone or in the cycle of clarification, deferritization, softening, disinfection, deionization, etc. [3]. The health of a WTP and its degradation are determined by the filters, sorbents, and other components [4], which might deteriorate during the plant’s life cycle and will need to be restored or replaced [5]. While manuals usually provide instructions for restoration, which might be done by washing, solution-based treatment, loosening, or other methods, the effective time to failure [6] [7](time to reach a point, beyond which a component will need replacement or regeneration) is case-specific [8]. The water pollutants are involved in a variety of physical and chemical processes such as adsorption, peptization, coagulation, polymerization, crystallization, and biological fouling, [9], which means that the general time to failure may vary from application to application even for the same WTP type. The existing documentation, e.g. [10] [11] [12], contains only generic statements that treated water must meet certain quality standards; enterprises, on the other hand, only run periodic preventive diagnostics at pre-specified WTP type-specific intervals. Even a household filter can operate beyond its rated time to failure (as defined in [13]) or fail faster than that. Large-scale water supply infrastructures face even higher degree of uncertainty, as their operating instructions rely on annual average water quality parameters [14] and only specify the lower treatment quality threshold per the design [15]. Lack of WTP degradation data might cause severe economic losses or environmental damage. 90% of the time, urban wastewater treatment plants are not repaired or maintained in due time, which jeopardizes natural water reservoirs [16].

Today, requirements to water quality and its monitoring become ever stricter; albeit a welcome change, it would be considerably more efficient if coupled with a WTP maintenance review program [17] [18]. Such a program could use a model approximating the WTP degradation processes on the basis of degradation kinetics.
2. Kinetic features of WTP degradation

The research team has analyzed the degradation of non-reagent natural and wastewater treatment plants. The observed WTPs varied in performance and treatment quality; some were designed for centralized water supply, others for local use. Data was sampled from waterline and sewerage stations, factories, and residential quarters, mainly in the Urals. Testing the degradation of several dozens of WTPs revealed that the desired kinetic functions were mostly nearly linear, which meant that the health indicator (treatment quality or performance) would be inversely proportional to the operating time. However, some graphs were not strictly linear. In some cases, a curve was expressly concave near the origin, then becoming convex. Often the curve was concave-convex across the entire range of the argument (operating time or total treated water volume). This led to an assumption that despite how diverse the water composition or the treatment methods/parameters could be, the WTP degradation model could well be described by a linear, a logistic, or an exponential (convex or concave) function.

Below are the algorithms for approximating the experimental data with these functions. Understanding that water users might be interested in a case study for such algorithms, the research team applied them to the case of extracting boron from a boron-containing hydrocarbon chloride sodium solution that imitated the groundwaters of Eastern Trans-Urals [19][20].

The experiments used laboratory stands for testing fillers and membranes described in [19], as well as a stand for making test solutions, which was based on a water treatment plant with pollutant dispensers; this stand was made under a Ministry of Health License No. 30-03/951 and had a performance of up to 200 dm$^3$/h.

The test solution that contained 5 mg of boron per dm$^3$ was treated by means of the following components synthesized as described in [10, 21]:

– $Y_2O_3$-stabilized ZrO$_2$-based sorbent that had an exchange capacity of 0.79 mg/g and was produced by the sol-gel method from a sol that in turn was produced by the deposition of oxychloride solutions;

– Al$_2$O$_3$-based sorbent that had an exchange capacity of 0.75 mg/g and was produced by the sol-gel method from a sol that in turn was produced by the deposition of aluminum oxychloride solution;

– reverse osmosis membranes produced by the chemical deposition of $Y_2O_3$-stabilized ZrO$_2$.

Treatment efficiency was evaluated by measuring the boron concentration in the samples of purified water at the Ural Center for Standardization and Metrology lab as well as at the Sverdlovsk Oblast Hygiene and Epidemiology Center lab. Besides, the experimenters would periodically test the performance of membranes or sorbents, which originally was either 55 dm$^3$/h or 34 dm$^3$/h.

It was found out that the membrane stand did not display a significant change in water treatment efficiency, while the adsorption stand did not change significantly in terms of performance. For membranes, performance was the limiting health indicators; for sorbents, the treatment quality.

Experimentation returned all of the above WTP degradation functions. As seen in Figure 1, the membrane-stand performance loss first (from 55 dm$^3$/h) followed a convex function (the solid line), then (from 24 dm$^3$/h) was nearly proportional to the operating time (the dash-dot line). Loss of water treatment quality by the adsorption stand followed a concave curve (the dotted line) in case of an aluminum-based sorbent, a concave-convex curve (the dash line) in case of a zirconium-based sorbent. Thus, the zirconium-based WTP degradation function was similar to a logistic S-shaped function; its aluminum-based counterpart had a concave exponential function; for membranes, the function was linear or exponential convex.

Below is the test of these hypothesis on the kinetics of degradation from $t$ the initial value $Z_0$ to 100% degradation.
3. Testing the approximation of the ZR-based WTP degradation kinetics by a logistic model for the given experiment

The S-shaped logistic model of degradation is written as

\[ Z(t) = \frac{Z_0}{Z_0 + (1-Z_0)\exp(-\lambda t)} \]

where \( Z_0 \leq Z(t) \leq 1 \), \( Z(t) = \frac{Y(t)}{100} \), \( Y \) is the value of the monitored health indicator, \( \lambda \) is the parameter describing the WTP degradation rate.

For periodic degradation monitoring, a convenient option is a discrete stepwise \( \lambda \) estimation model:

\[ Z_i = \frac{Z_{i-1}}{Z_{i-1} + (1-Z_{i-1})\exp(-\lambda \Delta t)} \]

This recurrent model is transformed into a linear one:

\[ \ln \left( \frac{Z_i}{1-Z_i} \right) = \ln \left( \frac{Z_{i-1}}{1-Z_{i-1}} \right) + \lambda \Delta t \]

\( \Delta t = (t_i - t_{i-1}) \). Thus, the desired parameter equals:

\[ \lambda = \frac{\ln \left( \frac{Z_i}{Z_{i-1}} \cdot \frac{1-Z_{i-1}}{1-Z_i} \right)}{\Delta t} \]  

(1)

\( \lambda \) is now easy to estimate by the least squares method using the right side of (1) as a result of equivalent measurements. To that end, write the least squares equation for the constant parameter as

\[ \sum_{i=1}^{n} \left[ \ln \left( \frac{Z_i}{Z_{i-1}} \cdot \frac{1-Z_{i-1}}{1-Z_i} \right) \right]^2 \to \min \lambda \]  

(2)
Thus, \( \bar{\lambda} = \frac{1}{n} \sum_{i=1}^{n} \ln \left( \frac{Z_i \cdot 1-Z_{i-1}}{Z_{i-1} \cdot 1-Z_i} \right) \frac{\Delta t}{\Delta t} \), i.e. the least-square estimate is an arithmetic mean.

Table 1 presents experimental and modeled degradation (as shown by the water treatment quality, %) of the Zr-based WTP, see Figure 1. Here the desired parameter is estimated at \( \bar{\lambda} \approx 0.045 \); \( \Delta t = 20 \) hours, \( \exp(\bar{\lambda} \Delta t) \approx 0.4 \).

Table 1. Zr-based WTP degradation: experimental data vs logistic modeling.

| i   | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  | 11  | 12  |
|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| \( t_i \), h | 0   | 20  | 40  | 60  | 80  | 100 | 120 | 140 | 160 | 180 | 200 | 220 |
| \( Z_i, \text{exp} \) | 0.003 | 0.007 | 0.04 | 0.11 | 0.24 | 0.45 | 0.85 | 0.90 | 0.94 | 0.97 | 0.98 | 0.98 |
| \( Z_i, \text{model} \) | 0   | 0.008 | 0.02 | 0.10 | 0.26 | 0.44 | 0.67 | 0.85 | 0.93 | 0.96 | 0.98 | 0.99 |

Thus, the time to failure is \(~140\) hours. Apparently, the experimental data and the model output match well. However, this is not always apparent; let us therefore describe an algorithm for evaluating the conformity error for such data series.

The arithmetic mean (2) is barely sensitive to deviations of its components from the Gaussian distribution. Besides, the least squares method can estimate variance in terms of the residual sum of squares (point \( i=1 \) is excluded as it is not calculated):

\[
S^2 = \frac{1}{n-2} \sum_{i=2}^{n} (Z_{i, \text{calc}} - Z_{i, \text{pacy}})^2 = 0.00025.
\]

Thus, \( S = 0.016 \); assuming normality given that table quantile of normal distribution \( \mu_{0.95} = 1.64 \), the average estimation error at a confidence probability of 0.9 is \( \pm S \cdot \mu_{0.95} \approx 0.026 \) or 2.6%.

4. Testing other models for approximation of WTP degradation kinetics

Similar calculations have been run for other models: the concave exponential model for the Al-based WTP; the concave exponential model and the linear model for a variety of membrane WTPs. Table 2 summarizes the results.

Table 2. Estimated values for a 80% degradation in terms of treatment quality or performance for WTPs of different types.

| Model           | Estimated LSM parameter | Average accuracy of degradation estimate, % | Estimated time to failure, h |
|-----------------|-------------------------|---------------------------------------------|-----------------------------|
| Concave exponent | \( z_i = z_{i-1} \exp\{-\lambda \Delta t_i\} \) | \( \bar{\lambda} = -\frac{1}{n} \sum_{i=1}^{n} \ln \frac{z_i}{z_{i-1}} \) | 2.25 %                     | \(~200\)                        |
| Convex exponent | \( z_i = 1 - (1-z_{i-1}) \times \exp\{-\lambda \Delta t_i\} \) | \( \bar{\lambda} = -\frac{1}{n} \sum_{i=1}^{n} \ln \frac{1-z_i}{1-z_{i-1}} \) | 10 %                        | \(~100\)                       |
| Linear function | \( z_i = z_{i-1} + \lambda \Delta t_i \) | \( \bar{\lambda} = \frac{1}{n} \sum_{i=1}^{n} \frac{z_i - z_{i-1}}{\Delta t_i} \) | 7 %                         | \(~300\)                       |
Thus, in any case the experiment/model divergence is within 10%, which means the approximation error is within statistical spread.

Analytical modeling of WTP degradation coupled with the described recurrent algorithms for configuring such models helps extrapolate current WTP status readings to unobserved time domains in order to prevent failure.

The authors hereof monitored WTPs of varying performance and treatment quality, designed for both centralized and local water supply networks; they hope the proposed approximation models will be applicable in a wide range of non-reagent water treatment methods.

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