Chapter 17

Water Quality Modelling of a Proposed Reservoir

Lawrence H. Woodbury and G. Padmanabhan
Department of Civil Engineering
North Dakota State University
Fargo, North Dakota 58105

This chapter introduces modelling techniques that have been found to be successful in evaluating future water quality conditions in proposed reservoirs. An example of an actual reservoir modelling study is used to illustrate the approach.

17.1 Introduction

Reservoirs are valuable surface water resources formed by the construction of dams or other hydraulic structures. These facilities demand minimum standards of water quality in order to attain desired benefits for recreation, water supply, irrigation, fish and wildlife uses. Since reservoirs generally become semi-permanent facilities, careful planning is required to insure that they do not become long-term liabilities to society. Once constructed and filled, reservoirs offer little opportunity for water

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resource professionals to manage water quality degradation. All natural and artificial lakes (reservoirs) undergo a natural process of aging called eutrophication. Eutrophication is essentially an increase in biological productivity, and is usually measured by changes in certain water quality parameters. It is essential that any proposed reservoir planning study include an assessment of potential water quality conditions within the reservoir.

Too often, reservoir projects are sold during the planning stage with overly optimistic estimates of future water quality conditions, which are based on little or no rational technical analysis. This in turn has resulted in inflated benefit-cost ratios and flawed economic studies. Decision makers deserve much better information on projected water quality conditions, which in turn translates into realistic estimates of benefits to be realized over the project life.

The following discussion uses an actual water quality planning study for a proposed run-of-the-river reservoir in a case study approach to describing a successful modelling technique. The problem is approached by first conducting a water quality data collection program. The water quality data base is then used as input to one of two different water quality models. The first is a computer program called FLUX, to simulate nutrient loadings. The output of FLUX (nutrient loadings) is then used as input to the second model, BATHTUB, which produces trophic state indices as output. The trophic state indices are then used to assess and estimate future eutrophication potential of the proposed reservoir. Modelling results are easily comprehended by laymen and professionals for decision making purposes.

17.2 Background Information

Winger Dam and Reservoir is a proposed water resources development project in northwestern Minnesota, USA. The project, which is to be located just south of the City of Winger on the Sand Hill River, consists of a permanent pool for recreation and a temporary surcharge pool capacity for flood storage. The permanent pool extends in a northeasterly direction upstream from the proposed dam site for a distance of approximately six miles.

During the course of project development, the Minnesota Department of Natural Resources (MDNR) prepared a Draft Environmental Impact Statement (DEIS) which was published in June of 1987. This document contained the first preliminary assessment of anticipated water quality conditions in the proposed reservoir, based upon field data collected by MDNR personnel at various times between the months of April and September of 1986. This data included water temperature, dissolved oxygen, biochemical oxygen demand (BOD), fecal coliform bacteria, total suspended solids, total dissolved solids, total alkalinity, total phosphorous, and sulfate.

After completion of the DEIS, the U. S. Environmental Protection Agency (USEPA) and the Minnesota Pollution Control Agency (MPCA) raised several water quality and wetland protection concerns to the project sponsor, the Sand Hill River Watershed District. In order to adequately address the water quality issues raised by USEPA and MPCA, the District commissioned a modelling study to investigate the issues and develop a suitable response.

There are several water quality models available which could be utilized for assessing the long-term water quality response of the proposed Winger reservoir. All of these models vary with many degrees of sophistication. Some require only regionalized data estimates, while others require detailed water quality sampling for data input. The water quality modelling effort conducted by the District essentially consisted of three phases:

1. development of a water quality and flow rate data base;
2. modelling of reservoir nutrient loadings; and
3. modelling of reservoir response with respect to water quality.

A water quality monitoring plan was developed and approved by the MPCA for implementation in 1989. The data base generation was conducted on a continuous basis between the months of August 1989 and July 1990. The data base served as input for modelling reservoir loadings of various nutrients having water quality ramifications. For this purpose, the District utilized the computer program FLUX (U. S. Army Corps of Engineers, 1987). The reservoir loadings, as modeled with FLUX, then served as input data to the reservoir water quality response model BATHTUB (U. S. Army Corps of Engineers, 1987). The BATHTUB model produces results which serve as an aid in predicting the eutrophic status of the proposed reservoir.

17.3 Reservoir Hydrology

17.3.1 Watershed Characteristics

The Sand Hill River is a major tributary of the Red River of the North, which flows north into the Canadian Province of Manitoba. The Sand Hill River basin, which can be characterized as long and narrow, has an average width of about eight miles and a length of approximately 55 miles. The total size of the watershed is about 426 square miles at the river's outlet at Climax, Minnesota. In comparison, the drainage area of the proposed reservoir at Winger is about 91.9 square miles, or 21% of the total basin drainage area.

The Sand Hill River originates in Sand Hill Lake, located about four miles south of the City of Fosston, Minnesota. In the most easterly portion of the watershed, the elevation rises to nearly 1,350 feet above sea level. The river flows generally in a westerly direction, but zigzags north and south over a range of five to seven miles. At the proposed dam site, the flood line elevation is proposed to be 1165 feet above sea level. This represents a drop from the highest point of the upstream watershed of about 185 feet.

The contributing watershed of the proposed reservoir is glacial in origin and its soils support agricultural uses. It is mostly gently rolling terrain with numerous potholes, the majority of which have been drained. A large portion of the watershed has been cleared of original tree growth to allow farming. The soils for the contributing drainage area exhibit rather complex relief, in which slopes range from gently sloping to steep. The soils are mostly loam.

17.3.2 Climate

The watershed is located near the center of the North American continent and has a continental climate. Characteristics of the climate are warm summers and cold winters. The mean temperature for winter months is 10.0 F, and 68.0 F for the summer months. On the average, there are 15 days above 90.0 F in the summer, and 55 days below 0.0 F in the winter. The average annual precipitation for the Sand Hill River basin is 22 inches with extremes varying from a minimum of 10 inches to a maximum of 34 inches. About 75%, or nearly 17 inches, of the annual precipitation falls during the period of April through September. Approximately 15% of the precipitation normally occurs as snow.

Drought can be a problem in July and early August in the entire basin, especially in the center portion where soils are thin and light. Rainfall is normally adequate in May and June for agricultural purposes. Heavy rainfall during the spring and early summer months contributes to flooding problems in the basin (Houston Engineering, Inc., 1991).

17.3.3 Reservoir Morphometry

For the purposes of this discussion, the reservoir morphometry will be described by mean reservoir depths, water residence or flow-through characteristics, and stratification potential. Taken as a whole, the reservoir at a permanent pool elevation of 1190 feet above mean sea level (MSL) is about 5.75 miles long. At its peak flood pool elevation of 1196 MSL, the reservoir is 6.8 miles long. The permanent pool surface area 1217 acres and its volume is 11,131 acre-feet. The maximum permanent pool depth at the dam site is 24.8 feet and the overall mean depth throughout the reservoir is 9.1 feet. As was indicated previously, the watershed area contributing to the reservoir is 91.9 square miles. Average annual precipitation over the contributing basin is 22 inches, and the average annual evaporation is 32 inches (Houston Engineering, Inc., 1991).

The proposed Winger reservoir is typical of most manmade impoundments. The long, narrow configuration of the reservoir reflects the existing river valley topography. For the purposes of water quality modelling, the reservoir can be divided into three separate and distinct segments. The lower segment, just upstream from the dam, can be thought of as a relatively deep water basin with a very narrow littoral zone along its periphery. If there is any chance for stratification within the proposed reservoir, it will occur within this lower segment.

The middle segment of the reservoir, approximately 2.35 miles in length, has a maximum depth of 13 feet and mean depth of 7.7 feet. It is assumed that this portion of the lake will maintain a polymictic, or a completely mixed state. As such, no stratification is anticipated. The littoral zone around the periphery of the middle segment can be considered to be more extensive than the lower segment.

The upper segment is approximately 1.25 miles in length. With a maximum depth of 7 feet and a mean depth of 3 feet, this reservoir segment can only be characterized as a completely mixed shallow lake. In fact, this can be considered to border on wetland status in consideration of its extensive littoral and vegetative zones.

A last item to be discussed with respect to reservoir morphometry concerns hydraulic residence time. From the standpoint of water quality modelling, there are two types of residence times. The first type of residence time is a long-term, steady-state residence time which is established after the reservoir has filled and reached maturity. Using an average annual flow rate (28 cubic feet per second), a steady-state hydraulic residence time of 0.55 years was determined for the proposed Winger reservoir. Since residence time is simply the reservoir volume divided by average annual flow rate, and since reservoir volume is relatively constant, the annual average volumetric flow rate becomes of prime importance. The lower the flow rate, the higher the residence time, and vice versa. Therefore, when flows are extremely low, residence times can be expected to increase dramatically. Flow data recorded at the Winger site between August 1989 and July 1990 resulted in an average annual flow of 7.3 cubic feet per second (CFS), corresponding to a residence time of 2.1 years.

Residence times are also affected by precipitation, evaporation, and ground water inflow/outflow from the reservoir. Assuming a negligible ground water inflow contribution, it is noted that average annual evaporation exceeds average annual precipitation by about 10 inches per year. The resulting net deficit to the reservoir water budget can significantly increase the hydraulic residence time. For the 1989-90 data period at the Winger site, the average annual flow would be reduced to 5.9 CFS, with a corresponding residence time of 2.6 years.

From the standpoint of water quality and the ability of in-lake nutrients to support aquatic growth, it can generally be assumed that a lake with a very high residence time will enhance the eutrophication process. On the other hand, when assessing the impact of a lake's mixing characteristics on eutrophication, it can be assumed that a well mixed lake (polymictic) will enhance internal recycling of nutrients, resulting in higher nutrient values and accelerated eutrophication. Only the lower segment of the proposed Winger reservoir seems to have any potential for reducing mixing and maintaining a dimictic or stratified state. The middle and upper segments can be expected to be polymictic and enhancers of the eutrophication process.

17.4 Water Quality Monitoring Program

The purpose of the water quality monitoring plan was to develop additional water quality data on watershed inflow to the proposed reservoir area. This data can then be used as input to the reservoir water quality models, which in turn can provide estimates of future reservoir states of eutrophication and water quality. The objective of the water quality monitoring program was to collect enough data to enable the mathematical modelling of the proposed Winger reservoir.

In order to insure that the effects of seasonal variation are included in the samples, it is usually recommended that the sampling period be conducted over at least a three year period (Minnesota Pollution Control Agency, 1990). However, in the case of the Winger project, time constraints dictated a one year sampling period. Sampling frequency was designed to be more intense during spring runoff and summer storm runoff events. The intent of the increased sampling frequency during peak runoff events was to capture the water quality parameter variation in relation to the flow rate variation.

The Sand Hill River Watershed District and the MPCA mutually agreed on a specific set of parameters to be included in the water quality monitoring plan. These parameters are ones normally utilized as input to the FLUX and BATHTUB models. Seven of the parameters are water quality related, and one is a hydraulic parameter. The parameters include: total phosphorous, ortho phosphorous, total suspended solids, total volatile suspended solids, total Kejedahl nitrogen, nitrate, nitrite, and instantaneous flow rate (hydraulic parameter).

17.5 Water Quality Modelling

17.5.1 Model Formulation

The procedures utilized for conducting a water quality modelling study of the proposed Winger reservoir involved the following steps:

1. problem definition;
2. data collection and compilation;

3. model implementation of reservoir loadings;
4. model implementation of reservoir response to loadings; and
5. interpretation of results.

The first step in any modelling process is problem definition. In the case of the proposed Winger reservoir, it was necessary at this stage to describe the reservoir and watershed characteristics. It was also appropriate at this stage to determine the study type and model type. In the case of this project, the study type was determined to be predictive in nature and the model type selected was a eutrophication response model.

17.5.2 Modelling Reservoir Loadings - FLUX

In the data reduction phase, tributary water quality data are reduced or summarized in a form which can serve as model input. Since the models generally deal with conditions averaged over a growing season within defined reservoir areas (segments), data reduction involves the averaging or integration of individual measurements, sometimes with appropriate weighting factors. The FLUX computer program is designed to facilitate reduction of tributary inflow monitoring data. Using a variety of calculation techniques, FLUX estimates the average mass discharge or loading that passes a given tributary monitoring station, based upon grab-sample concentration data and a continuous flow record. In the case of the proposed Winger reservoir, FLUX made possible the estimation of average mass loadings for a variety of chemical/nutrient parameters. The results of the FLUX analysis for the 1989-90 data at the Winger site are given in Table 17.1.

17.5.3 Modelling Reservoir Responses - BATHTUB

Given the reservoir mass loadings for various nutrient constituents, the model implementation phase proceeds with

Table 17.1: Winger Reservoir Loadings - FLUX.

Parameter	Flux (kg/yr)	Conc. (ppb)
Ortho Phosphorous	447.7	68.84
Total Phosphorous	722.8	111.13
Total Kejedahl Nitrogen	25348.2	3897.16
Nitrate	8829.0	1357.42
Nitrite	308.9	47.49
Total Suspended Solids	78196.9	12022.40

developing reservoir responses from accumulated mass loading. The BATHTUB computer program permits application of empirical eutrophication models to morphometrically complex reservoirs. The program performs water and nutrient balance calculations in a steady-state, spatially-segmented hydraulic network which accounts for advective transport, diffusive transport, and nutrient sedimentation. Eutrophication related water quality conditions (expressed in terms of total phosphorous, total nitrogen, chlorophyll-a, transparency, organic nitrogen, particulate phosphorous, and hypolimnetic oxygen depletion rate) are predicted using empirical relationships previously developed and tested for reservoir applications. In addition, BATHTUB calculates Carlson's Trophic State Indices (TSI), including the phosphorous TSI, the chlorophyll-a TSI, and the secchi disc TSI.

A key option of the BATHTUB computer program allows the modeller to reduce a given reservoir into a selected number of segments for more detailed analysis on a segment-by-segment basis. Figure 17.1 shows various types of possible segmentation schemes provided for in BATHTUB. In the case of Winger reservoir, this capability was put to good use because of the unique nature of various portions of the reservoir. As was previously described, the Winger reservoir was divided into three unique segments, similar to Scheme 3 in Figure 17.1. The specific hydraulic and geometric characteristics of each segment are compiled in Table 17.2.

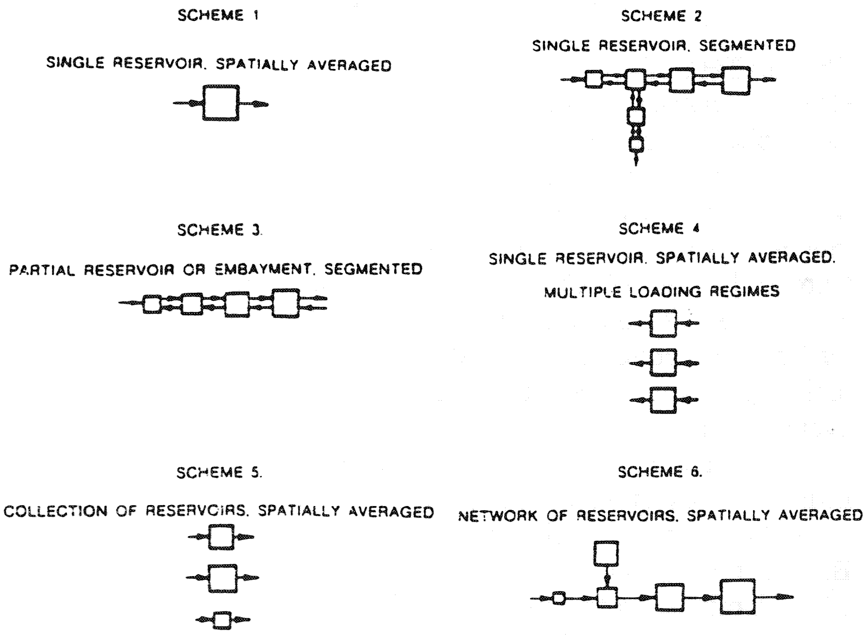

Figure 17.1: BATHTUB segmentation schemes.

Table 17.2: Reservoir Segment Characteristics.

Length (mi.)	Area (ac.)	Surface Volume (AF)	Max. Depth (ft.)	Mean Mix Depth (ft.)	Hypo Depth (ft.)
	Upstream Segment				
1.25	196	584	7	3	NA
	Middle Segment				
2.35	404	3107	13	7.7	NA
	Lower Segment (Near Dam)				
2.15	617	7440	24.8	12.1	NA
				4.66	10.5

17.6 Water Quality Modelling Results

The BATHTUB computer model was utilized to examine the effects of nutrient loadings on in-lake nutrient concentrations for data collected between August of 1989 and July of 1990. The hydrologic conditions during this year resulted in a low flow year by any standard of measurement. Therefore, the results of this modelling exercise are on the conservative side. Flow rates vary from as low as 0.6 CFS to a high of about 35 CFS. The mean annual flow for the year was about 7.3 CFS, averaged over the whole data collection period. The corresponding hydraulic residence time was about 2.6 years, which includes net evaporation losses.

Using the FLUX output as input to the BATHTUB model, in-lake values of various parameters were predicted for each of the three segments of the proposed reservoir. A summary of the BATHTUB output is reproduced in Tables 17.3, 17.4, 17.5, and 17.6. Units for each parameter value are defined as follows:

$$\begin{aligned} \text{Total P TSI} &= 4.2 + 33.2 \log P \\ \text{Secchi TSI} &= 60 - 33.2 \log (\text{Secchi}) \\ \text{Chl-a TSI} &= 30.6 + 22.6 \log (\text{Chl-a}) \end{aligned}$$

where:

ppb = parts per billion or mg/m^3	m = meters
TSI is dimensionless	P is in ppb
Secchi is in m	Chl-a is in ppb

In reviewing the predicted in-lake total phosphorous concentrations for each segment of the reservoir, it is noted that values range from 88 mg/m^3 in the upper segment, 79 mg/m^3 in the middle segment, to 58 mg/m^3 in the lower segment near the dam. Total phosphorous concentrations appear to decrease with distance from the upper end of the reservoir to the lower end of the reservoir at the dam. This could be substantiated by increased total phosphorous entrapment within the shallower vegetated areas of the reservoir. Nevertheless, all total phosphorous values predicted are significantly higher than the minimum threshold concentration of 50 mg/m^3 used as a guideline by the Minnesota

Table 17.3: BATHTUB output - upper segment.

Parameter	Units	Value
Total Phosphorous (Total)	ppb	87.71
Total Nitrogen (Total N)	ppb	2108.79
Organic Nitrogen (Org. N)	ppb	1498.01
Chlorophyll-a (Chl-a)	ppb	55.51
Secchi Disk (Secchi)	m	0.55
Chl-a TSI	-	70.0
Secchi TSI	-	68.7
Total P TSI	-	68.7

Table 17.4: BATHTUB output - middle segment.

Parameter	Units	Value
Total P	ppb	78.50
Total N	ppb	1870.88
Organic N	ppb	1068.73
Chl-a	ppb	36.69
Secchi	m	0.65
Chl-a TSI	-	65.9
Secchi TSI	-	66.3
Total P TSI	-	67.1

Table 17.5: BATHTUB output - lower segment.

Parameter	Units	Value
Total P	ppb	58.40
Total N	ppb	1364.43
Organic N	ppb	752.40
Chl-a	ppb	22.81
Secchi	m	0.75
Chl-a TSI	-	61.3
Secchi TSI	-	64.2
Total P TSI	-	62.8

Table 17.6: BATHTUB output - reservoir.

Parameter	Units	Value
Total P	ppb	69.79
Total N	ppb	1652.41
Organic N	ppb	977.47
Chl-a	ppb	32.68
Secchi	m	0.68

Pollution Control Agency (MPCA,1990).

Another measure of recreational lake acceptability is the secchi disk reading, also known as transparency. The MPCA has indicated that it would be "desirable" for the secchi disk reading to remain at above 1.5 meters for at least 75% of the summer to avoid the perception of an "impaired" or "no swimming" lake. The MPCA has also correlated this secchi disk reading to an average summer surface-water phosphorous concentration of 40 mg/m^3. This correlation is apparently the basis for the recommendation that total phosphorous concentrations remain below 50 mg/m^3 (MPCA,1990).

From a review of the BATHTUB computed secchi disk readings, it is apparent that the transparency also increases with distance downstream from the upper end of the reservoir to the lower end. Specifically, the secchi disk values predicted varied from 0.5 meters in the upper end to 0.7 meters near the dam. These values seem to correlate quite well with total phosphorous predictions within each segment. However, again the predicted exceeded the standard suggested by this MPCA.

The BATHTUB modelling output also includes a calculation of Carlson's Trophic State Index for chlorophyll-a, secchi disk, and total phosphorous. All three TSI's register between 69 and 70 for the upper segment of the reservoir. Proceeding further downstream into the deeper waters of the reservoir, the TSI is reduced to a value between 66 and 67. The lower segment of the reservoir predicts TSI's ranging from 61 to 64. From the standpoint of predicting eutrophication, the following criteria have been established for establishing the trophic status of lakes and reservoirs (Reckhow, 1983):

Oligotrophic	TSI less than 40
Mesotrophic	41 < TSI < 50
Eutrophic	51 < TSI < 70
Hypereutrophic	TSI greater than 70

From reviewing the above criteria, it appears that the BATHTUB modelling effort has predicted eutrophic to hypereutrophic conditions in the upper more shallow segment of the reservoir. The middle and lower segments could be classified as eutrophic.

17.7 Summary

This study focused on predicting the water quality of a proposed reservoir. All indicators seemed to predict a reservoir with eutrophic characteristics. Hydraulic residence times are sufficiently long to insure significant entrapment of nutrients, such as nitrogen and phosphorous. Although it is feasible that the lower end segment of the lake could stratify and aid in controlling nutrient dispersion, the middle and upper segments will likely be polymictic and completely mixed, which will probably enhance internal cycling of nutrients. This would in turn result in higher nutrient concentrations in the upper two segments of the reservoir. By themselves, these physical characteristics of the reservoir would forecast a probable eutrophic condition.

Water quality modelling efforts utilizing both FLUX and BATHTUB have yielded predictions which again substantiate a potential eutrophic condition. Total predicted phosphorous levels in all segments of the reservoir significantly exceeded the MPCA suggested maximum value of 50 mg/m^3. In addition, the predicted secchi disk values also fall short of the MPCA 1.5 meter standard. All computed values of Carlson's Trophic State Index (TSI) predicted a reservoir with eutrophic characteristics.

17.8 References

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