Eutrophication of Tenkiller Reservoir, Oklahoma and Effects on Water Quality and Fisheries

Expert Report of Dr. G.D. Cooke and Dr. E.B. Welch

for

State of Oklahoma

in

Case No. 05-CU-329-GKF-SAJ

State of Oklahoma v. Tyson Foods, et al.

(In the United States District Court for the Northern District of Oklahoma)

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EXHIBIT
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Water residence time of a lake or reservoir is defined as the water bodies' volume divided by its annual outflow and is expressed in years. Water residence times, computed from total outflow (reservoir volume/outflow per half-year), ranged from about 0.7 to 2.5 half-years (HYs) over 11 years of data with a mean of 1.6 HYs. The unit HY was used in describing and explaining the water quality data, because the data were collected during April through September, which also encompasses the season of algal growth and thermal stratification. Residence time in years would be computed with roughly twice the flow, so half the HY value.

Tenkiller functions as a system of three zones, as is usual for large, run-of-river reservoirs (Thornton et al., 1990). Accordingly, Tenkiller was divided into zones that approximate riverine (LK-04), transition (LK-03), and lacustrine (LK-01 and LK-02), (lake-like) areas (Figure 1). Surface areas (in 10^6 m^2) representing the four stations are: LK-04, 6.76 (676 ha); LK-03, 11.26 (1126 ha); LK-02, 21.56 (2156 ha); and LK-01, 10.98 (1098 ha).

A comparison of Tenkiller to an unimpacted reservoir was chosen as another way to illustrate Tenkiller's condition. Two reservoirs, Stockton in Missouri and Broken Bow in Oklahoma were chosen as candidates due to their proximity to Tenkiller and therefore their potential similarity of soils, climate, and watershed vegetation, and due to their similar areas and depths. Stockton was rejected because there were no fish data, water quality samples had been taken only at the dam station, and the inflowing river had very high TP concentrations (CDM data; John Jones, University of Missouri, personal communication). Broken Bow had been sampled over several years by OWRB, the Army Corps of Engineers, and by CDM (2007) at stations along its length (Figure 2). Fishery data were available. The reservoir is found in a mainly (79%) forested watershed with few poultry houses and low TP concentrations in inflowing water.

Broken Bow reservoir (Broken Bow) was formed in 1970 on the Mountain Fork River. The reservoir is about 34 km long, has a surface area at normal pool of 56.8 km^2, a maximum depth of about 36 m and a mean depth of 19.7 m. The watershed-to-reservoir area ratio is 34:1 (Figure 2). Surface areas (in 10^6 m^2) representing the four stations are: BB-08, 4.80; BB-07, 4.38; BB-06, 15.63; and BB-03, 26.02.

IV. PROCEDURES AND METHODS

A. Water Sampling (Blue-Green Algae, Temperature, and DO)

Tenkiller was sampled by CDM at four sites during May-November in 2005, March-September in 2006, and June-September in 2007 (Figure 1). Samples were collected twice monthly during the first two years and monthly in 2007. A multi-parameter datasonde unit equipped with appropriate sensors was used to determine DO, temperature, conductivity, and pH at one-meter intervals with depth at the four sites. Water sampling procedures varied with depth and time for different constituents. Usually, a minimum of two samples was collected from the epilimnion (upper portion of the water column), two from the metalimnion (mid portion of the water column), and two from the

hypolimnion (lower portion of the water column) at each location and event in 2005 and 2006. Sampling depths for chl were generally at surface, 3 m, and 6 m. In 2006, sampling depths for phytoplankton alternated between every meter and every other meter from the surface to 15 m with occasional grab samples collected at additional depths. In 2007, samples were collected as 0-3 m composites and an additional sample for P collected at 1 m off bottom at each site.

Water transparency was determined with a standard Secchi disc at each site on each occasion.

Broken Bow was sampled twice in August 2007, with similar procedures at four sites distributed longitudinally similar to those in Tenkiller (Figure 2).

B. Analysis

Water samples for TP, soluble reactive phosphorus (SRP) and chl were kept cool during sample collection and shipped on ice to the analytical laboratory at the end of each sampling day. SRP was determined by the ascorbic acid method (EPA 365.1) following filtration in the laboratory. Unfiltered samples for TP were digested with persulfate prior to determining SRP. Sensitivity (detection limit) for P was to 2 μg/L.

Samples for chl were filtered when received in the analytical laboratory and analyzed spectrophotometrically according to Standard Methods (APHA, 1992).

Water samples for phytoplankton were preserved with Lugols solution in the field and enumerated in the laboratory. Results were reported as counts/ml and volumes in mm^3/L and in percent of total volume for each algal taxonomic group.

C. Sampling for Benthic Macroinvertebrates

Benthic macroinvertebrates were collected near each of the four sampling sites in Tenkiller and Broken Bow in October 2007 using a petite-ponar dredge (15 X 15 cm) (Figures 1 and 2). Three composite samples were collected along an approximately 50 m longitudinal transect adjacent to each site. Each composite sample consisted of three separate sediment grab samples, which were composited prior to sieving. Once sieved, the samples were picked and all macroinvertebrates visible on the surface of the sieve were collected and stored in isopropyl alcohol. Samples were transported to the laboratory for identification.

D. Sediment Cores

Cores were taken in August 2005 at four sites distributed longitudinally through the lacustrine and transition zones (Figure 1). In the lower lacustrine areas, cores were inserted by a SCUBA diver to the depth of pre-reservoir sediment (LKSED-1 and LKSED-2), but only the core for LKSED-1 recovered pre-reservoir sediments. The depth of post-dam sediment was deeper and pre-dam sediment was not reached at the two upper sites (LKSED-3 and LKSED-4) (Fisher, 2008).

The cores were sectioned at 2-cm intervals to depths of 38-54 cm within 24 hours of collection. Sections were analyzed for water content and TP according to EPA methods 3050 and 6020 (Fisher, 2008).

Sedimentation rates were determined over an approximate 50-year period, from reservoir construction until 2005, by dating each sediment section using ^{137}Cs and ^{210}Pb procedures. Analyses were performed by Prof. F. M. Soster, DePauw University, who used the Constant Initial Concentration (CIC) Model for unsupported ^{210}Pb (Fisher, 2008).

Deposition of P over time was calculated from the dry matter content of TP (mg/kg), the fraction of dry matter in each time-depth interval, and corrected for TP retention (0.83), based on whole reservoir TP concentrations observed during 2006, to approximate annual TP loading.

The data used in this report are considered adequate to support the conclusions. A complete description of all field and laboratory sampling and analytical procedures and methods is provided in Sections 2.11 and 2.12 of Olsen (2008).

V. RESULTS AND DISCUSSION

A. Disinfection By-Products in Tap Water from Utilities along the Illinois River and Shores of Tenkiller [1]

Disinfection by-products (DBPs) are formed as raw reservoir or river water is disinfected with chlorine (Teaf, 2008). DBPs occur when chlorine reacts with dissolved organic molecules (e.g. lignins, humics, algal extracellular products) in the untreated water. These organic molecules in the untreated water are called DBP precursors. Trihalomethanes (THMs; e.g. chloroform, bromodichloromethane) and haloacetic acids (HAA5s; e.g. dichloroacetic acid, trichloroacetic acid) are among the most common DBPs. The term HAA5 means that there are 5 haloacetic acids that are combined into one value for reporting. DBP precursors in reservoirs are directly linked to the eutrophication process through total and dissolved organic carbon (TOC and DOC) drainage from the watershed and TOC-DOC production by algae in the river and reservoir.

The U.S. Environmental Protection Agency (USEPA) established threshold concentration values for DBPs in finished tap water (USEPA, 2005, 2007) because DBPs pose human health risks. DBPs are linked to cancers of the bladder, rectum, and colon, and to increased incidences of stillbirths (USEPA, 2003; King et al. 2000). The increased risks of bladder and rectum cancers are well-documented (Morris et al. 1992; Villaneueva et al. 2007). Presently, the threshold concentrations are 80 µg/L for THMs and 60 µg/L for HAA5s. Tap waters with concentrations above these thresholds are in violation of USEPA standards. Because health risks may be dose-dependent, "near-violations" (a

[1] Dr G.D. Cooke is the primary author of this section.

term developed for this report) are considered to be DBP concentrations 10 percent or less below the USEPA thresholds. Thus THM concentrations of 72-79 μg/L in tap water, are "near-violations" of the guidelines, and may pose human health risks near that of the threshold violation value of 80 μg/L.

Utilities may employ pre-chlorination or post-chlorination treatments of water to lower precursor concentration or formed DBPs. These treatments include aluminum sulfate coagulation of raw water and/or sand or activated carbon filtration of chlorinated water. Costs per unit of finished tap water are high for smaller (number of customers) utilities (Walker, 1983). Because of its potential cost-effectiveness, the American Water Works Association Research Foundation, as well as many other scientists (e.g. Stepczuk et al. 1998 a, b), advised utilities to attempt to lower DBP precursors in raw water by reducing precursor production in the watershed (e.g. wetland and agricultural runoff) and by reducing algae production in eutrophic reservoirs (e.g. Cooke and Carlson, 1989; Graham et al. 1998). Algae production is strongly linked to P loading from the watershed and P concentration in the reservoir water (see Section C, Reservoir Trophic State).

Sources of DBP Data for Tenkiller and Illinois River Utilities

There are 4 potable water supply utilities along the streams of the Oklahoma portion of the Illinois River watershed and 14 along the shores of Tenkiller. Some of them have less than 200 customers. The largest utilities are the towns of Tahlequah, OK (18,431 customers), located on the Illinois River, and Sequoyah County Water Association (15,719 customers), located near the reservoir's dam and reservoir sampling station LK-01 (Figure 3).

The small treatment plants (< 200 customers) reported DBP concentrations to the Oklahoma Department of Environmental Quality (ODEQ) from a single yearly sample. The larger utilities reported DBPs to ODEQ on a quarterly basis. These reports to ODEQ (Appendix A; compiled by HSWMR Inc.) are the basis of the following description of DBPs in the tap water of the utilities along the Illinois River and Tenkiller.

CDM sampled DBP concentrations within the communities served by the Gore PWA, Cherokee County RWD #2, and Tahlequah PWA, during summer 2006. These data are described separately from the ODEQ data. The CDM samples were taken by CDM personnel, accompanied by each water plant manager, at locations that correspond to locations regularly sampled by plant personnel. Each location was confirmed to have no interfering processes operating at the time of sampling (e.g. aerators, water purifiers), and samples were taken after allowing faucets to run for periods consistent with each plant manager's sampling techniques. Samples were sent to Alpha Woods Hole Laboratory, priority overnight, packed in ice, under chain of custody.

Results of the Tap Water Disinfection By-Products Survey

Locations of the 18 drinking water treatment plants in the Oklahoma portion of the Illinois River watershed streams and along the shores of Tenkiller are shown in Figure 3. These utilities are also listed in Table 1 and Appendix A, along with the period of

sampling and reporting record at ODEQ, the number of samples, and the number of violations and near-violations for the period of record. Table 2 is a list of the DBP data obtained by CDM in 2006 for Cherokee County RWD #2, Gore PWA , and Tahlequah PWA.

Fin and Feather Resort (Tenkiller), Adair Co. RWD #5, and Flint Ridge (Illinois River) did not report DBPs in their tap water over an 8 year span (Table 1).

The other 15 utilities reported DBPs (THMs and HAA5s) in tap water, with THM violation and near violation frequencies ranging from 0 percent of samples (LRED Wildcat) to 33 percent of samples (Burnt Cabin RWD). The highest numbers of HAA5 violations and near-violations were at GORE PWA (8) and Tahlequah PWA (11) (Table 1).

Utilities with 15 or more reports to ODEQ over the 8 to 10 years of reporting may give a more accurate picture of DBP violation frequency. Flint Ridge (17 reports), had no THM or HAA5 violations or near-violations. At the other utilities, THM violation frequencies of 10 percent to 20 percent of samples were common, ranging up to 36 percent (Tenkiller Water Utility Company, Burnt Cabin RWD). When occurrences of HAA5s in tap waters of the utilities with higher reporting frequencies are included, violations and near-violations of 20-30 percent or more were found (Table 1).

The Sequoyah County Water Association (15,719 customers) has a raw water intake located near reservoir sampling station LK-01 and the dam (Figure 3). With 64 reports between September 1999 and January 2008, 25 percent of tap water samples were contaminated with THMs, above or near the violation threshold. There were 13 percent actual THM violations and no HAA5 violations or near-violations (Table 1).

The Cherokee County RWD #2 had two THM violations and one near violation during summer 2006 (samples from a grocery store and a home), and Gore PWA had 2 near-violations in tap water during that summer (CDM data, Table 2).

The City of Tahlequah, OK (18,431 customers) obtains its raw potable water from the Illinois River. Tahlequah PWA reported an increasing frequency of THM and HAA5 violations to ODEQ (Table 3). Between February 1997 and December 2007, 148 tap water samples were analyzed. Three dates were sampled by CDM in 2006 (Table 2). There were 4.7 percent to 6.7 percent violations and near-violations of the THM and HAA5 thresholds over the almost 11 year span of reporting by Tahlequah PWA. In the 8 year period from February 1997 to March 2005, THM and HAA5 violations and near-violations were lower (1.8 percent to 5.4 percent) than the 11 year frequency. There was a rate of 0.97 THM violations and near-violations per year during this 8 year period. Violations and near-violations increased between June 2005 and December 2007 (Figure 4). There were THM violations in 16 percent of the 50 samples in that period, a rate of 5.3 THM violations and near-violations per year. All violations occurred during June and August (Table 3). The CDM samples of the Tahlequah tap water during summer 2006 found 40 percent THM violations or near-violations and 27 percent HAA5 violations or near-violations. The CDM samples were taken at sites in the distribution system,

including grocery stores and the wastewater treatment plant water fountains (WPC Plant) (Table 2).

Discussion of Disinfection By-Product Survey Results

Total trihalomethane formation potential (TTHMFP) is a measure of the potential of a reservoir or lake water sample to form THMs when chlorinated. It is a method to evaluate raw (untreated) drinking water for the presence of THM precursor molecules such as those that are produced by algae or transported to the reservoir from land runoff or from synthesis by river algae. The water sample is treated with enough chlorine to achieve a chlorine residual of at least 3 mg/L at the end of a seven day incubation period under standard conditions. At this point, the sample is tested for THMs (APHA, 1992; USEPA, 1998). TTHMFP samples from Tenkiller were taken at a 3 meter depth near raw water intakes.

The appearance of DBPs in tap water is causally linked to eutrophication of the water supply. Palmstrom et al. (1988) demonstrated that THMFP increased as water moved along the length of a eutrophic Ohio water supply reservoir. Not only were DBP precursors added to this reservoir by the river, but one-third of the total precursors entering the potable water supply treatment plant were produced in the reservoir itself. Their studies, along with those of Wachter and Andelman (1984), Sondergaard et al. (1985), and many others, demonstrated that algae in the reservoir (live cells and algal extracellular products, ECPs), were significant sources of THM precursors.

These observations and conclusions strongly supported the detailed study of the origins of THM precursors in the reservoir waters that supply New York City (NYC). THMFP was significantly correlated with TP and TOC concentrations in the reservoir, and algal blooms were significantly correlated with TP concentrations. Blue-green (Cyanobacteria) blooms were associated with the highest THMFP. The NYC water supplies were strongly and adversely affected by non-point runoff, including livestock operations (Stepzcuk et al. 1998 a, b).

High TOC and DOC concentrations in the water are strong indicators of the presence of THM precursors (Walker, 1983). The sources of TOC and DOC in Tenkiller are inflowing river water and production by algae and microbes in the nutrient-rich waters of the river and reservoir. TOC in the reservoir averaged 2.5 mg/L, vs. 1.5 mg/L in the inflowing water (Olsen, 2008). The additional TOC in the reservoir was produced by its algae. As shown in the Trophic State Section of this report (Section C), production of algae and thus the production of TOC and DOC is driven by the inflows of TP into Tenkiller from the watershed (Engel, 2008; Wells, 2008). The major sources of TOC and DOC in the Illinois River are from algal production in the river itself, driven by the high TP concentrations in its water, as well as from land runoff from poultry waste land applications and from domestic waste. The TOC concentration in water draining off poultry waste-amended pastures had a median value of 10 mg/L, versus the median concentration in runoff from the non-amended pastures of 1.0 mg/L (Olsen, 2008). The area of wetlands on the watershed is < 1 percent (Homer et al. 2004), indicating that wetlands are not important watershed sources of TOC and DOC.

TOC and DOC concentrations in Tenkiller surface waters were determined in summer 2006 by CDM (Table 4). Average DOC concentrations were between 2.35 and 2.47 mg/L at the four sampling stations in Tenkiller, with a range of 1.0 to 5.5 mg/L. The relationship between TOC and THMFP in Tenkiller (summer 2006 and 2007 CDM data; Table 5) is significant ($r = 0.59$, $p < 0.05$) (Figure 5). As TOC increased in Tenkiller, the risk by utilities along it to produce THMs in tap water increased.

Table 6 is a list of the results of the TTHMFP survey at 9 potable water utilities along Tenkiller's shores (see map, Figure 3). Results are presented as maximum, minimum, and average TTHMFP, along with the number of samples. Cherokee County RWD #2 and #13 and Gore PWA had between 1000 and 2000 customers, whereas the other utilities in Table 6 were much smaller (see Table 1 for customer numbers).

All nine utilities had a THMFP in excess of the THM violation standard of 80 μg/L set by the USEPA. This means that their untreated Tenkiller water had to be treated (e.g. flocculation, filtration, activated carbon) to remove THM precursors found in the DOC of the reservoir water. Their successes at removal are listed in Table 1. Of the nine utilities in this study, only LRED (Wildcat) and Fin & Feather reported 0 percent THM in finished tap water. In the others, 11 percent to 33 percent of the finished tap water samples (Table 1) were contaminated with carcinogenic THMs above the USEPA violation threshold. They were incompletely successful in removing THM precursors prior to chlorination.

The high algal productivity of Tenkiller, and the associated production of THM precursors by the algae, was caused by the high P concentration in Tenkiller water, which in turn was caused by the high inflow of P into Tenkiller from the watershed. This has led to a human health risk in drinking water of many residents along Tenkiller's shores. Three of the nine utilities (Cherokee Co. RWD #2, LRED Woodhaven, and Tenkiller Aqua Park) have reported problems with algae to ODEQ (Tenkiller Lake Watershed Survey, 2002).

A five variable model (season, source of water, treatment methods, ecological region of the reservoir, and DOC concentration) was developed to aid in the prediction of the probability of exceeding DBP violation thresholds in tap waters of Quebec, Canada. DOC alone was the most important variable. Based on this model (Milot et al. 2000), the probability of exceeding a THM concentration of 80 μg/L (the USEPA threshold) with a DOC of 2.5 mg/L is 50 percent (using data from Table 4). Using this model, the probability of exceeding the USEPA threshold when treating water from Tenkiller in summer 2006 ranged from 40 percent to 65 percent. Thus, the DOC in Tenkiller surface water was high enough in 2006 to pose substantial and ongoing risks to water supply utilities for producing DBPs, a fact which poses human health risk and the possibility of increased costs to lower the risk. Utilities along the shore of Tenkiller commonly have 30 percent DBP frequencies (Table 1 and Appendix A).

There are other factors, in addition to the P-driven production of algae in Tenkiller, that are involved in an increase in THM formation when eutrophic raw water is used to produce tap water. Photosynthesis by algae, stimulated by increased P concentrations, increases the pH of reservoir surface waters as CO_2 is withdrawn by the cells. The yield

of THMs at chlorination increases as the pH of raw water increases (Trussel and Umphres, 1978; Wachter and Andelman, 1984). Utility operators who withdraw water from Tenkiller indicated that they often increase the chlorine dose in an attempt to offset tastes and odors in tap water (telephone interviews between operators and HSWMR Inc). While this treatment may be effective in oxidizing taste and odor molecules, increased chlorine and chlorine contact time in the plant and distribution system will lead to increased THMs in the tap water (El-Dib and Ali, 1994; Graham et al. 1998). Chlorine also breaks up algae cells, releasing DOC, including toxins in blue-green algae cells. Like increased pH, the use of additional chlorine and chlorine contact time to decrease tastes and odors is a direct result of the algal blooms in Tenkiller, which in turn are due to increased P concentrations in the water and thus to increased P loading from the watershed.

The increases in the DBP violations at Tahlequah may be due to plant operation problems, to increases in DBP precursors in the Illinois River, or both. About 26 percent of water samples from Tahlequah were in violation or near violation of the USEPA THM standard (Table 3). Thus more than 18,000 customers experienced excessive and chronic exposure to a known carcinogen in their drinking water.

In summary, a substantial fraction of the drinking water supplied to customers from the treatment of Illinois River and Tenkiller raw water contained DBPs above or nearly above the USEPA thresholds. The production of these DBPs is directly linked to the eutrophication process occurring in these waters, primarily from the disposal of P rich poultry waste on the watershed. A smaller fraction of the P loading to Tenkiller (15.5%) is from the wastewater treatment plants located on the river (Engel, 2008). Reduction of the concentrations of DBPs in the tap waters produced by the utilities requires the reduction of P loading to the river and reservoir (Hoehn et al. 1984; Cooke and Carlson, 1989; Stepzcuk et al. 1998 a, b).

DBPs in tap water are strongly linked to human health risks, including bladder cancer. Villanueva et al. (2006) found a doubling of bladder cancer risk with exposure to DBP levels of 50 μg/L or higher. DBP concentrations of 50 μg/L and higher were commonly found in tap water from the Illinois River and Tenkiller (Table 2, Appendix A). The appearance of molecules linked to human health risks from tap water produced from Illinois River and Tenkiller waters was caused by high P concentrations in the water and the ensuing eutrophication of those waters. Engel (2008) reported that 59 percent of the load of P to Tenkiller was from poultry waste. These conditions violate Oklahoma's water quality standards relating to public and private water supply. The standard requires that waters of the state designated as public or private water supplies (such as the Illinois River, and Lake Tenkiller) be maintained "...so that they will not be toxic, carcinogenic, mutagenic, or teratogenic (OAC 785:45-5-10(5))."