Concentration of Minerals by Ice in Long Shallow Lakes

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Abstract

The concentration of minerals by ice growth in long shallow lakes can be readily assumed to be insignificant until there is consideration given to the volume of ice generation relative to mass of water. Current theory gives greater emphasis to the assumption that ground water is the major contributor to the increase of minerals in our streams and small in-channel reservoirs than to the effects of ice concentration. Investigation of the effects of ice on water quality, such as meeting drinking water standards, was carried out in a long pencil-lake to determine the reasons for changes in dissolved mineral levels or TDS and its associated impact on water supply. With the availability of significant water quality data for both upstream river and reservoir, water discharge data at critical locations and regulation criteria, it was found that the river and lake conditions were significantly affected by the natural growth of ice and its ability to increase dissolved minerals in the water column. The limited hydrologic record allowed for sufficient analyses to be carried out and prove that the effects of ground water intrusion was limited and that ice played the major role in the concentration of minerals during the ice growth period. In addition ice melt resulted in lake freshening to a greater extent immediately after the snow melt period. This observation has resulted in a re-evaluation of the conventional thinking that most of our winter mineral increases are caused by ground-water alone.

Résumé

La concentration des minéraux par la formation de glace dans les longs lacs et peu profonds est normalement considérée peu importante par rapport au volume de glace engendré à celui de la masse d'eau. L'hypothèse la plus souvent appliquée est d'assumer que l'augmentation des minéraux est directement reliée aux eaux souterraines dans les petits lacs et rivières. Une investigation des effets de glace sur la qualité de l'eau, telle que de rencontrer les normes d'eau potable, a été effectuée sur un long lac et mince pour évaluer les variances dans les minéraux dissous et l'impact des sources d'eau. Avec la disponibilité des données de qualité d'eau significative en amont et en aval du réservoir avec les débits nécessaires et le critère de régularisation du barrage, il était déterminé que la formation de glace était le facteur le plus dominant sur les augmentations des minéraux dissous. Même avec un historique limité, il a été possible d'effectuer une étude et de prouver que l'effet d'intrusion de l'eau souterraine était limité mais que la glace joue le rôle prédominant dans la concentration des minéraux lors de la formation de glace. De plus, la fonte de glace rafraîchie la masse d'eau dans lac après la fonte de neige. Cette observation a eu pour but de s'interroger sur l'hypothèse que l'eau souterraine est toujours responsable de l'augmentation des minéraux durant l'hiver.

1.0 Introduction and Problem Background

In general, transient water quality simulation or prediction on a continuous basis can be made extremely difficult with the lack of sufficient frequently monitored historical record of major water supply sources. In particular, water parameter predictions for smaller rivers and lakes can be significantly affected by variable surface and ground water supplies. In-order-to quantify these parameters, such as sulfates (SO_4) and total dissolved solids (TDS), it was necessary to determine the principal factors that contribute to changes that affect these parameters with time.

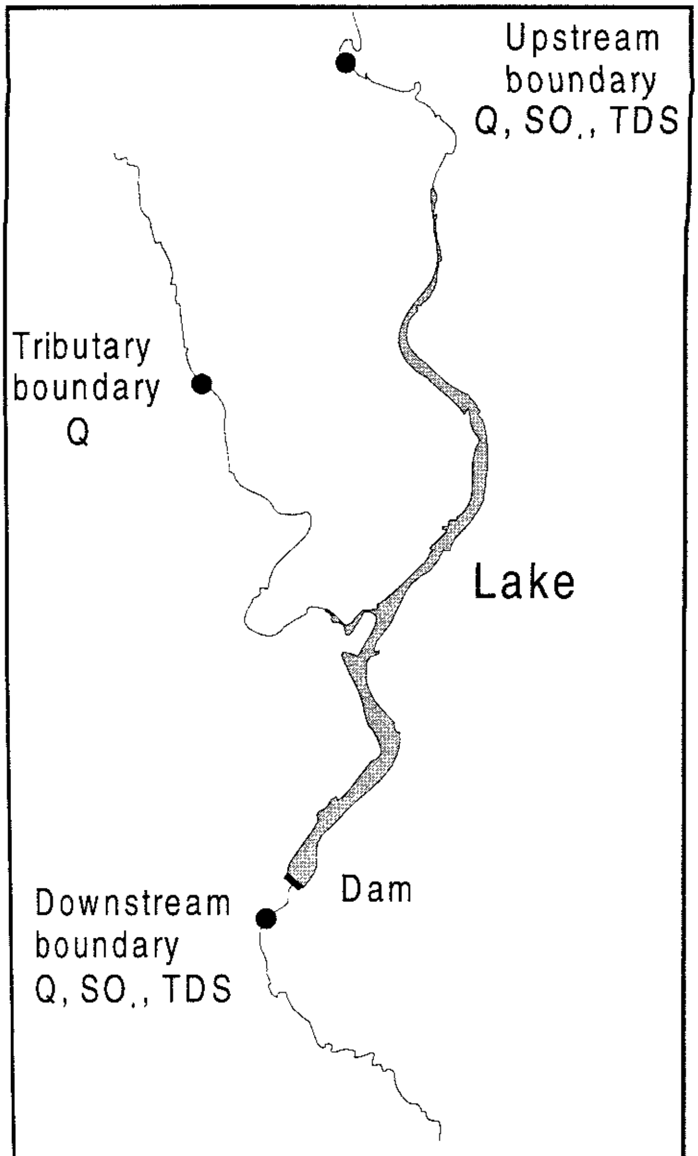

Figure 1 - Model Layout

Due to a variety of climatic conditions in central North America, open water body concentration of minerals are affected by summer evaporation, variable stream flow and seepage from ground water, evapotranspiration from aquatic plants and from less frequent assessments of concentration due to ice. Historically, the more common approach is to make the assumption that ground water contributes significantly to the changes in water quality during drier summers as well as the winter period. This assumption was tested but it was found that for shallow lakes, ice is probably the more likely major factor. Lack of ground water data makes it difficult to directly quantify the effects of water content mineral increases. It was through the following indirect method that the effects of ice to concentrate minerals in the water column were judged to be the most significant factor. The following system layout was modelled.

2.0 Methodology - Hydraulic and Water Quality Data Preparation

Historical data was collected and developed as input to the model. The data consisted of river and tributary daily discharges, daily monitored reservoir outflows, water samples of several parameters which included sulfates and provided on a monthly or seasonally basis. For water quality parameters, the lack of historical records make a water quality study more difficult as historical values are often provided as a single value per month and more often as low as one value per year.

A hydrologic flow budget, into and out of the reservoir including a small tributary into the middle of the lake, resulted in very small volumetric differences that proved that significant unmeasured sources were not present. There were only significant inflows from the mid-lake tributary area during the 1979 spring runoff period. A flow budget based upon all recorded flows was used to derive the local runoff and were used to satisfy the mass balance requirement for the entire study period.

The availability of sufficient water quality data measurements permitted a regression analysis to be made with flows that were later used to fill-in the remaining days. The daily data served as boundary input to both the main input flow channel as well it was assumed to apply to the mid-lake tributary flows. The results of the regression analysis are provided in Table 1. The regression based upon the reciprocal function, 1/Y = a + bx.

Coefficient	Y = SO4	Y = TDS
Intercept, a	0.00669181	0.00160266
Slope, b	0.00000598851	0.0000015982
R-squared	68.39%	72.56%

Table 1

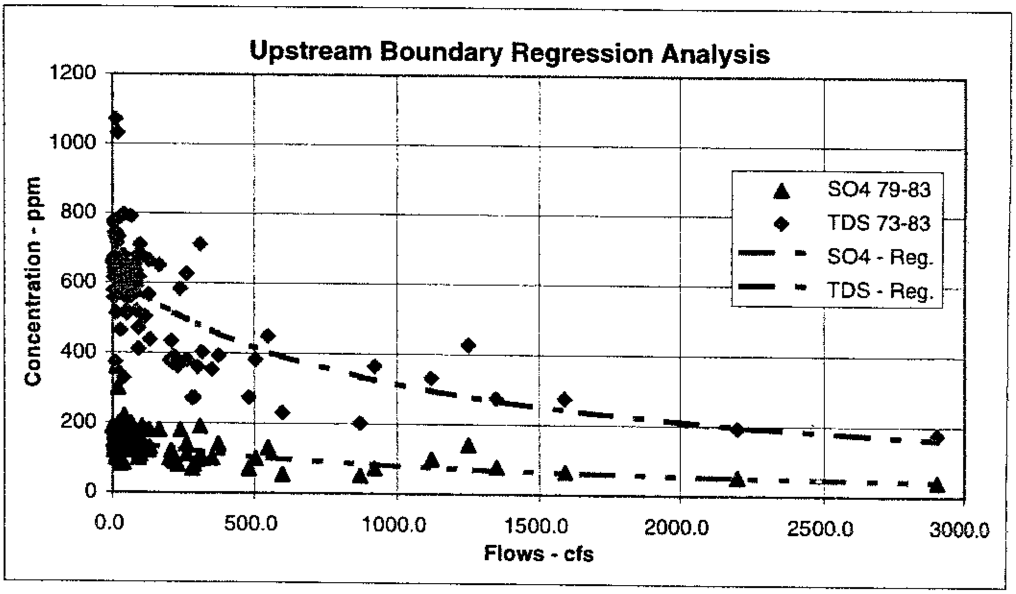

Figure 2: Upstream Boundary Regression

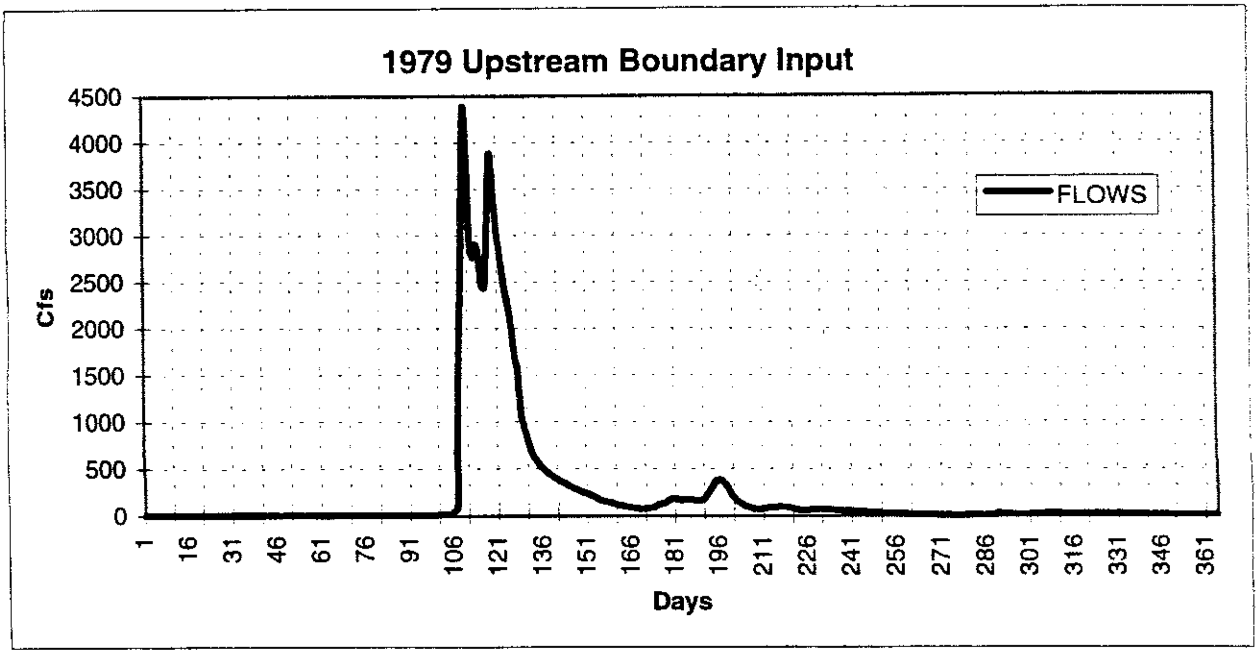

Figure 3: Typical Flow Input

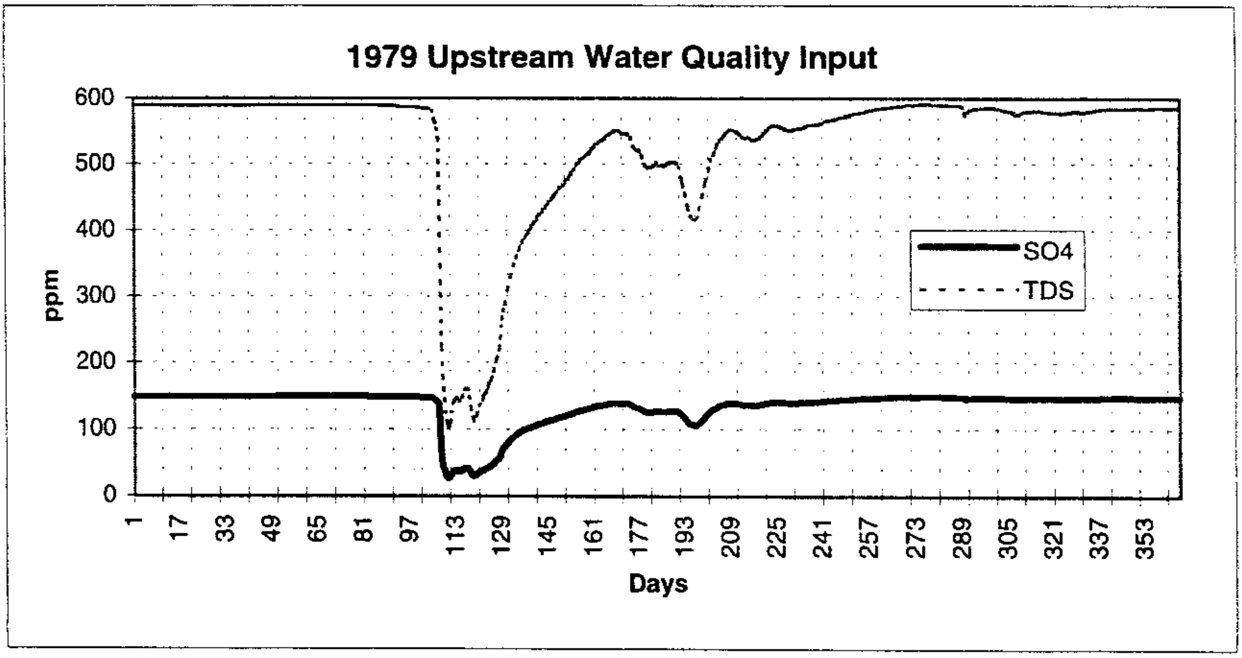

Figure 4: Typical Water Quality Input

3.0 Numerical Prediction of Transient Water Quality Parameters

The two-step procedure, calibration followed by verification, was undertaken to create a prediction model of the system leading into and including the lake itself. A series of numerical tests were used that would permit the continuous simulation of water quality parameters which closely followed the recorded data provided at the dam outlet. The initial component of the model study was to hydraulically simulate on a continuous basis based upon historical record data from both upstream and downstream reservoir outlet. The correlation data between flow and both sulfates and TDS were used in constructing continuous water quality daily record for the selected period of study.

The study period chosen was to cover the complete years from 1978 to 1983 inclusive. This period of record was selected because it includes an extreme high flood event followed by and extreme low year and then an average flow period. It was also felt that a regression equation with daily flows would be more suitable for studying long synthetic flow periods when no water quality records exist.

The simulation hydraulic and water quality computations were carried out using a hydrodynamic one-dimensional finite-difference model that computes both stage, discharge and water quality as function of time and at computational cross sections located every 1,000 to 1,500 feet along the river and submerged river or lake channel. The computations were carried out every 15 minutes of real-time. Plotted computed results for specific points, Figures 5 through 16, located at the lake outlet and at a point 80% of the lake length, were provided on a daily basis and represent mid-day or noon values.

Lake regulation is carried out for the purposes of spring freshet storage, summer recreation, fishing and water supply. Daily data is available due to the fact that operational considerations are based upon the above factors as well as water conditions in the basin. Data was provided at a critical location upstream of the reservoir and at this gauge water quality samples were taken for analysis.

Modelling of both hydraulic flows and water quality must be given at the initial "time zero" step. These were based upon known quality parameters at that time as well as average water levels expected. The initial conditions were tested to assure that the model could properly predict the initial period of the simulation study. Year-to-year values are simply transferred to assure that the conditions are consistent for the following year. Hydraulic computations required physical input data included both river and lake cross sections, Manning roughness coefficients from previous HEC II model studies.

Water quality inputs provided to the model were initial concentrations values, dispersion coefficients, locations of water quality sections, normally assumed at the hydraulic sections and computational time-step of 15 minutes for slow varying transients. These were made consistent with results found in other studies such as that on the Hudson's River. Experience was gained in the application of the variation of coefficients in conjunction with the hydraulic conditions in the lake.

4.0 Calibration of "Ice Effects" As Both Lateral Outflows and Inflows

Simulating ice formation was not a parameter that was currently available in the numerical model but was reproduced by using a procedure that simply removed a specified quantity of flow along the length of lake. This specified flow rate was removed along with the water quality element that was set at the expected ice mineral concentration of 10 ppm level. Ice melt, or the return of removed flow, was simply the same process but in reverse. Ice formation and its effect on concentration changes according to this study was found to be very similar to that produced through actual field *measurements by Daniel E. Canfield et al., Department of Animal Ecology, Iowa State* University. He concluded that his study "not only confirmed the earlier findings of Mortimer (1941) that 94% of the dissolved salt content of lake (ice) water was removed during ice formation, but also supported one of the major assumptions of the freeze-out model".

In the current modelling work, the assumption was made that ice contains only 4% mineral content or roughly 10 ppm of sulfate when frozen which is later returned during the spring ice melt. To achieve the historical levels of sulfates during each year, a specific but differing quantity of water was removed and returned to the lake distributed along its entire length.

The following table provides the equivalent quantity of water removed, as a function of depth, that was later returned in the spring thaw year by year (differences taken at the dam outlet location of the lake).

Simulation	Year	Spring - Ft	Fall - Ft	Total Winter
1	1978	2.50	0.05	2.5+
2	78 - 79	2.21	-0.01	2.26
3	79 - 80	4.35	0.90	4.34
4	80 - 81	4.05	0.36	4.95
5	81 - 82	2.84	2.25	3.20
6	82 - 83	1.91	1.74	4.16

Table 2

5.0 Simulation Results - Model Verification Using TDS Conditions

The unique feature of the study results is that the concentration levels in the lake could be properly simulated once the ice was used as a water quality concentrator. It was assumed that ice can reject salts at a level of about 94 to 98%. In the current modeling work, the assumption was made to remove water containing 4% or roughly 10 ppm of sulfate during freeze-up and then return it during the spring ice thaw. Since the same dispersion coefficients used to simulate TDS were used in the verification runs and still reproduced historic data confirms that the model adequately represents both water quality parameters.

After making the verification runs using the total dissolved solids data as input, it would appear that excess ice formation was simulated in the lake during the years 1980, 1981 and possibly 1983 since these produced simulated TDS values higher in the spring than that which were recorded. Calibration using the TDS data, and comparable reductions in ice thickness, could likely have produced a slightly better fit for the sulfate simulations.

The graphical results, Figures 5 to 16, confirm that the calibration runs can adequately define the change of minerals in the water column with time. The water quality calibration input includes basically two terms that help define the movement of salt. These are the dispersion parameter that accounts for the convective force of water motion in the river or lake and the added dispersion due to a concentration gradient differences. Once the model was calibrated to the sulfate concentrations, the verification TDS simulation runs were made by replacing sulfate by respective TDS concentrations. The graphical results, presented at two locations in the lake, the outlet of the dam (R56-END) and a location at approximately 80% of the length of the lake (R51-MID). Historical data, from measurements taken at the dam outlet, are provided.

It would appear that if more data was available for the winter period, perhaps from water treatment plants downstream of the dam, then it may be possible to further improve upon these calibrations. Even with only two data points per year, it was evident that a trend does exist that can be associated with ice formation. Closer examination of the water quality graphs reveals that significant increases in TDS occur in the latter winter period and generally result in levels that exceed the current drinking water standard of 500 ppm. In dry years, 1981 for example, TDS levels are consistently at or near the drinking water limit. It is also evident that pre-flood storage releases from the reservoir helps to reduce the concentration of salts in the lake. Further dilution from melting ice provides for the reduction of salts in the coming summer period. It is at the mid-February to March period that the highest concentrations of TDS are found which would inevitably impact on water supplies for consumptive users located at or downstream of the dam.

6.0 Conclusions

A result of the modelling effort is that one-dimensional models can adequately predict the transient concentration of dissolved minerals in long shallow lakes using ice as a concentrator. It is also clear that sufficient water quality data must be present to make this assessment possible to extend the data or "fill in" the remaining days with adequate confidence that they reflects reality. Even with the limited water quality dataset currently available, it is possible to produce results that could be used to assess changes in water quality throughout the year and more specifically during winter periods.

Most of the knowledge gained in this study was to more clearly understand the role of ice and ground water during this winter period. Even when ground water and ice thickness were not measured, indirect methods can be used to compute the impact of both in contributing to water quality changes in smaller rivers and long shallow lakes.

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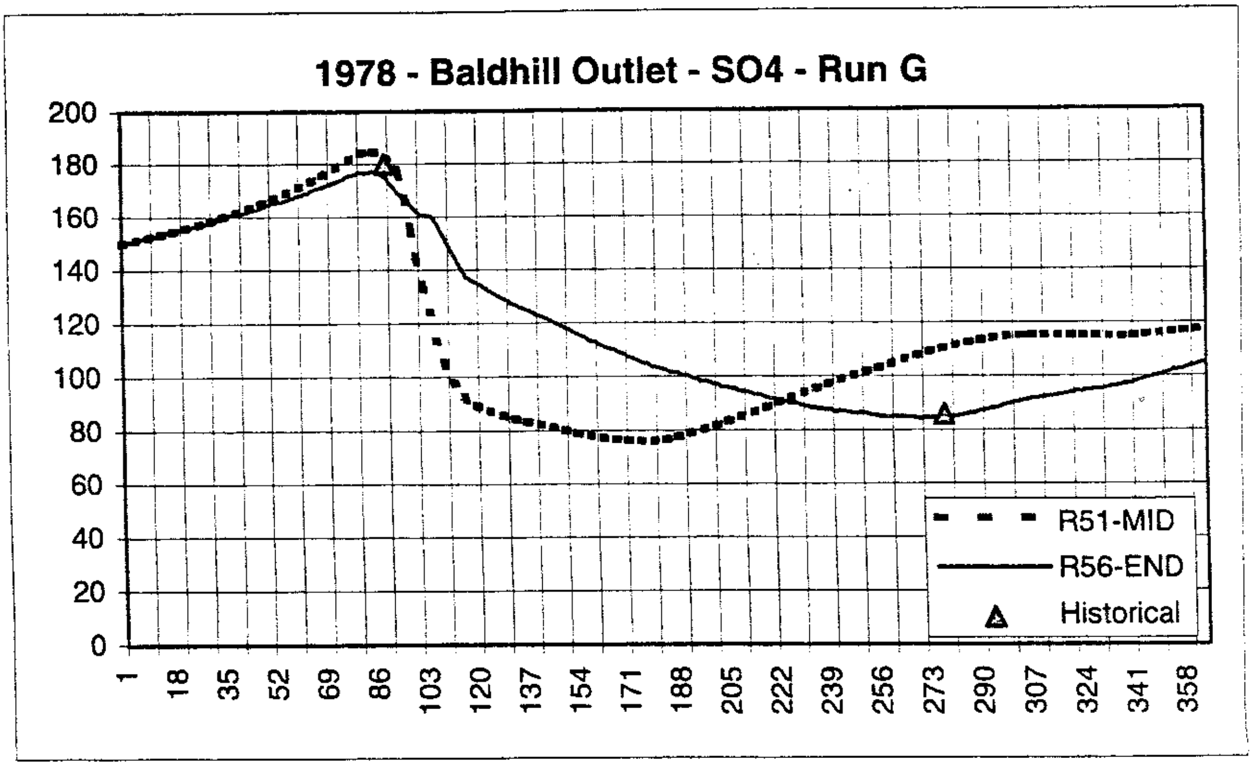

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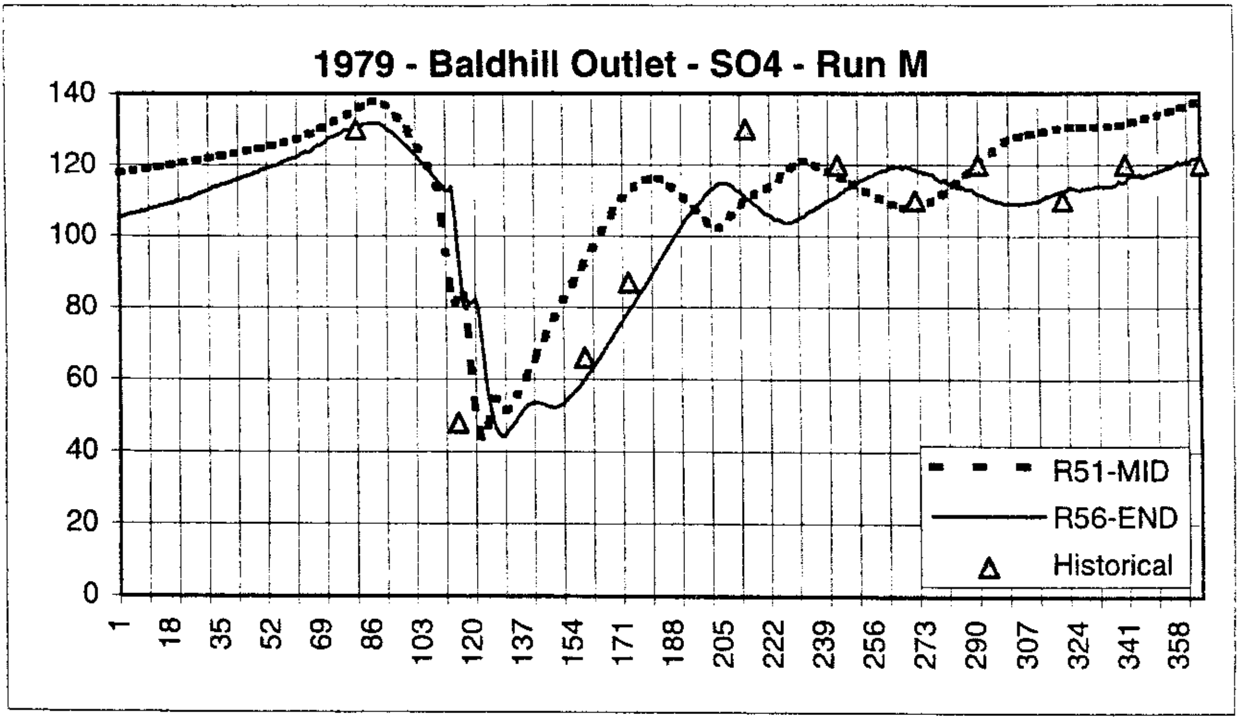

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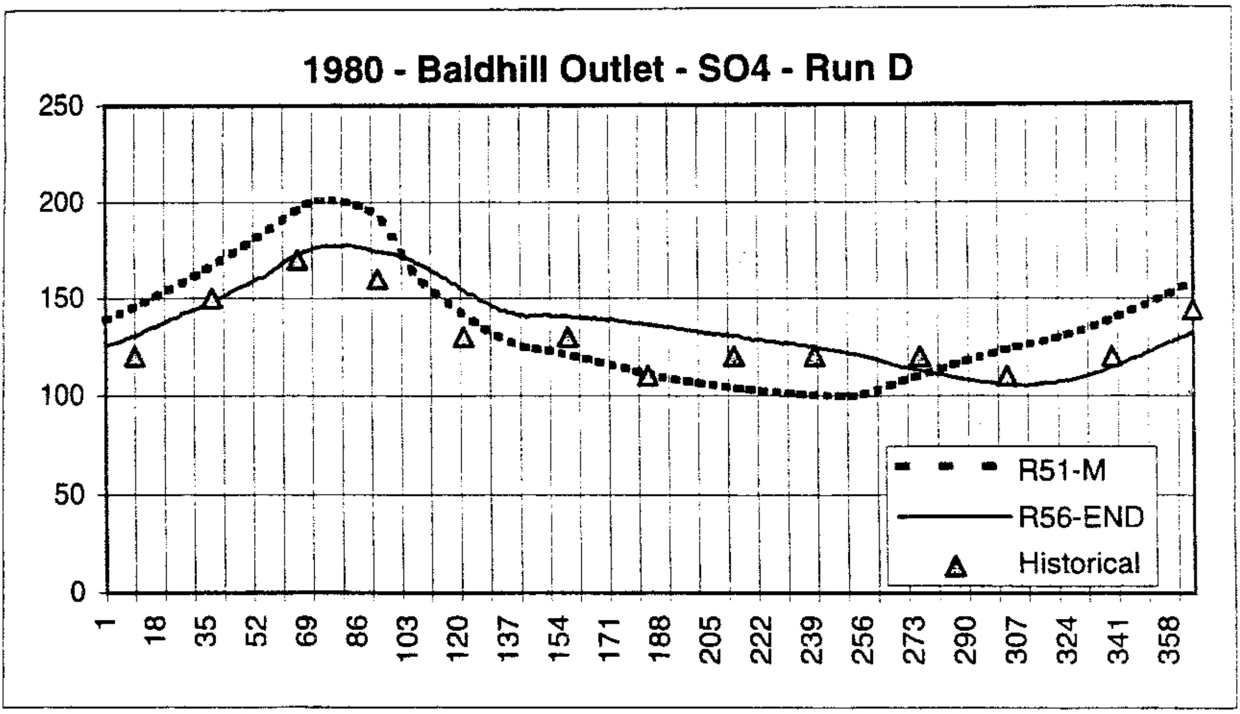

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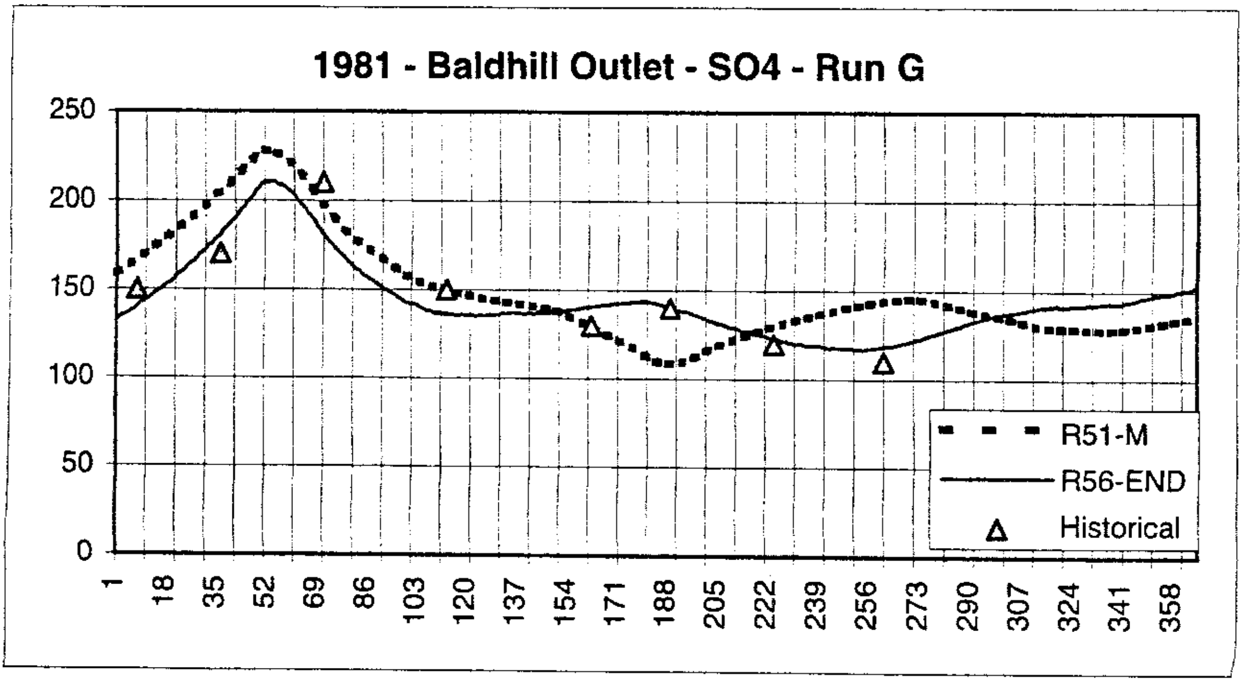

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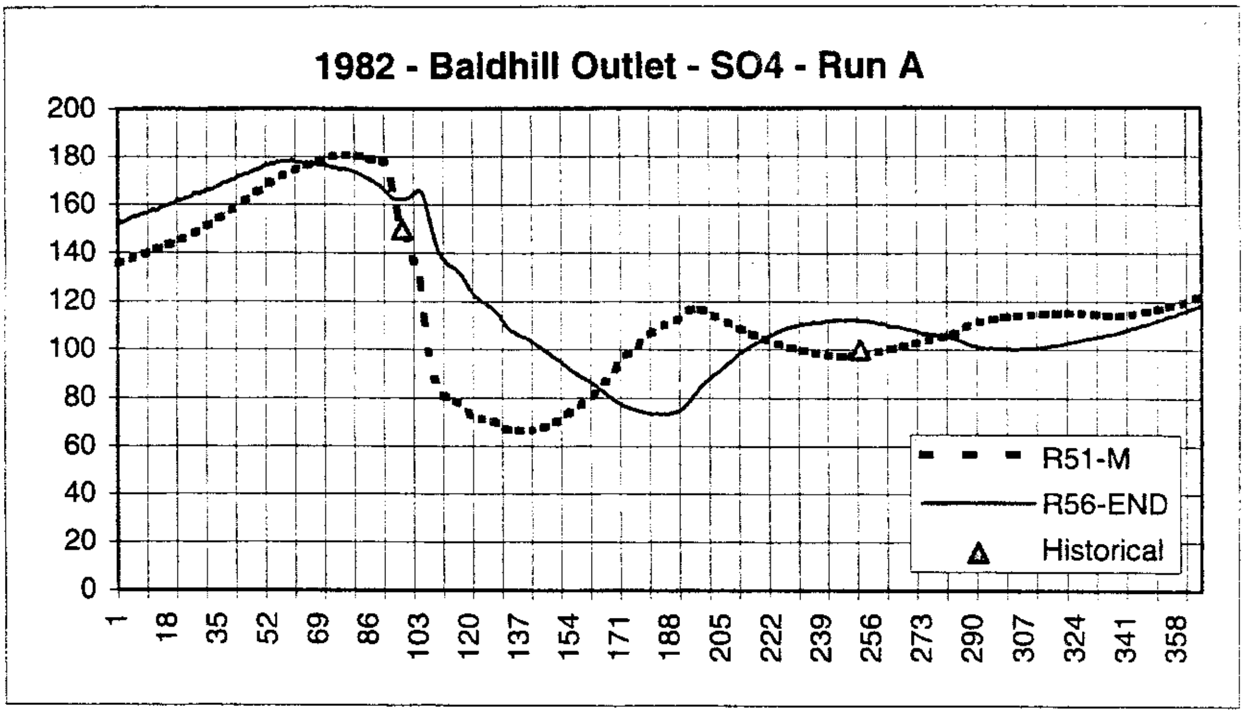

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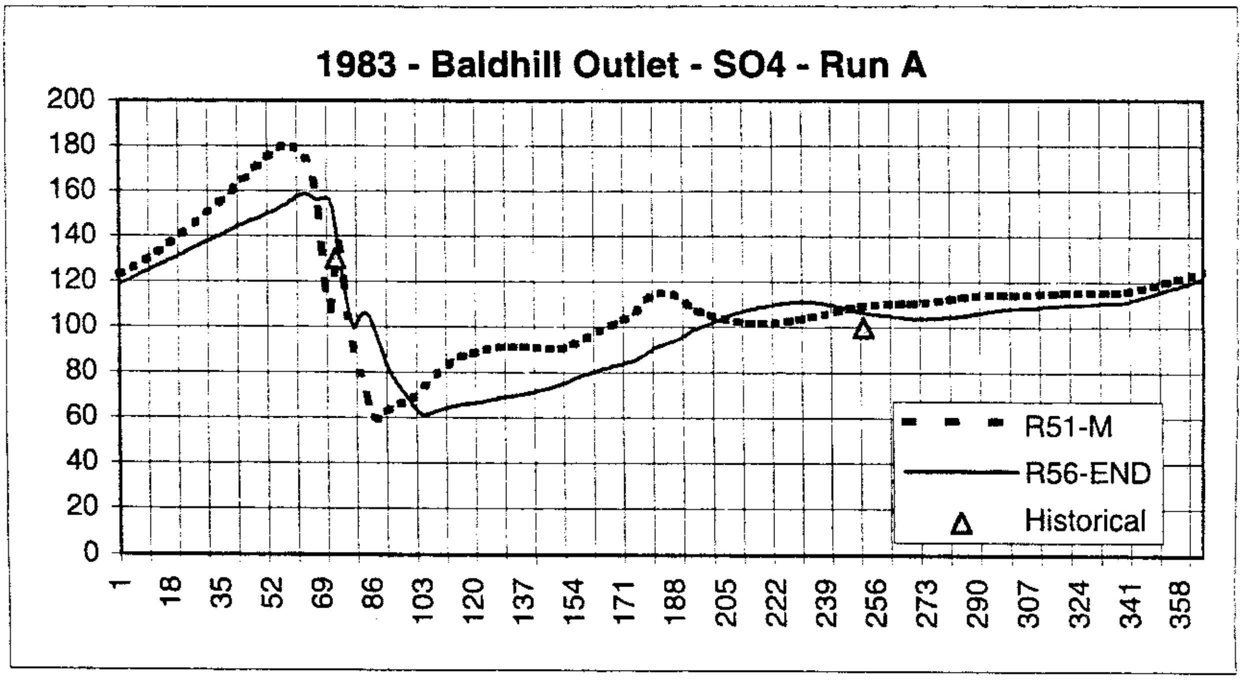

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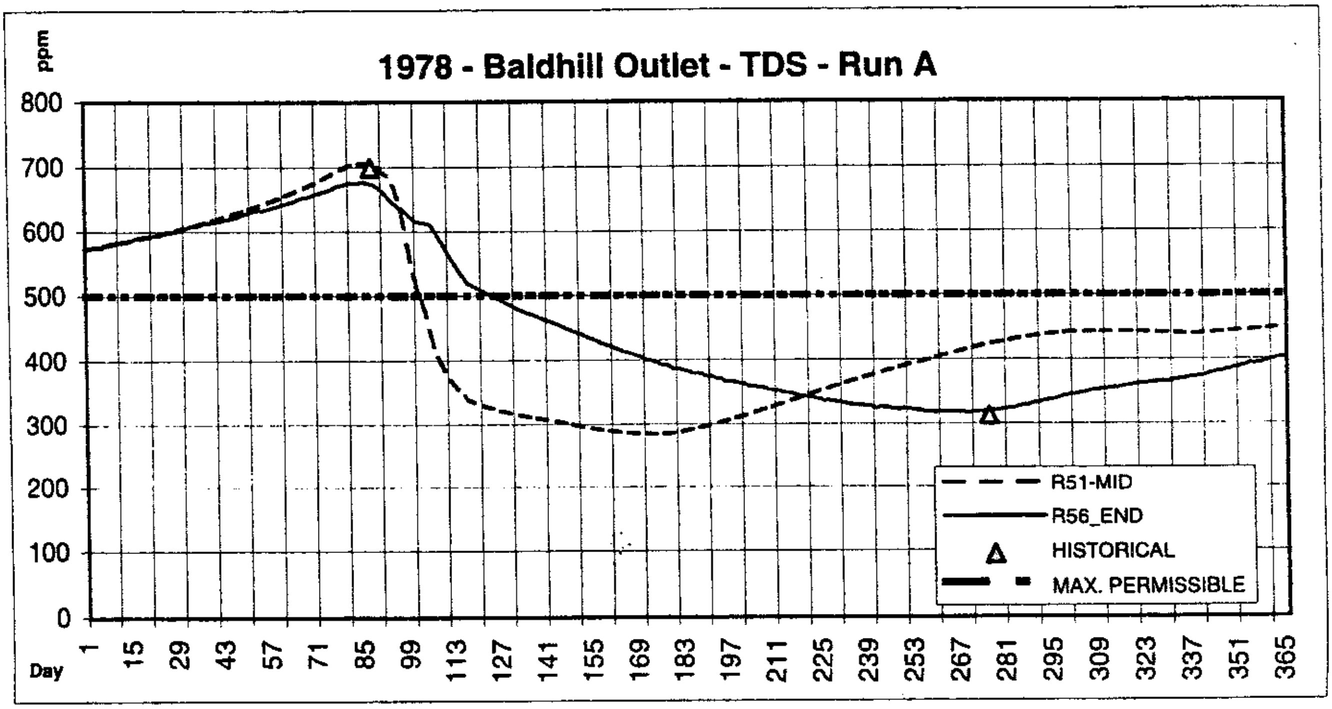

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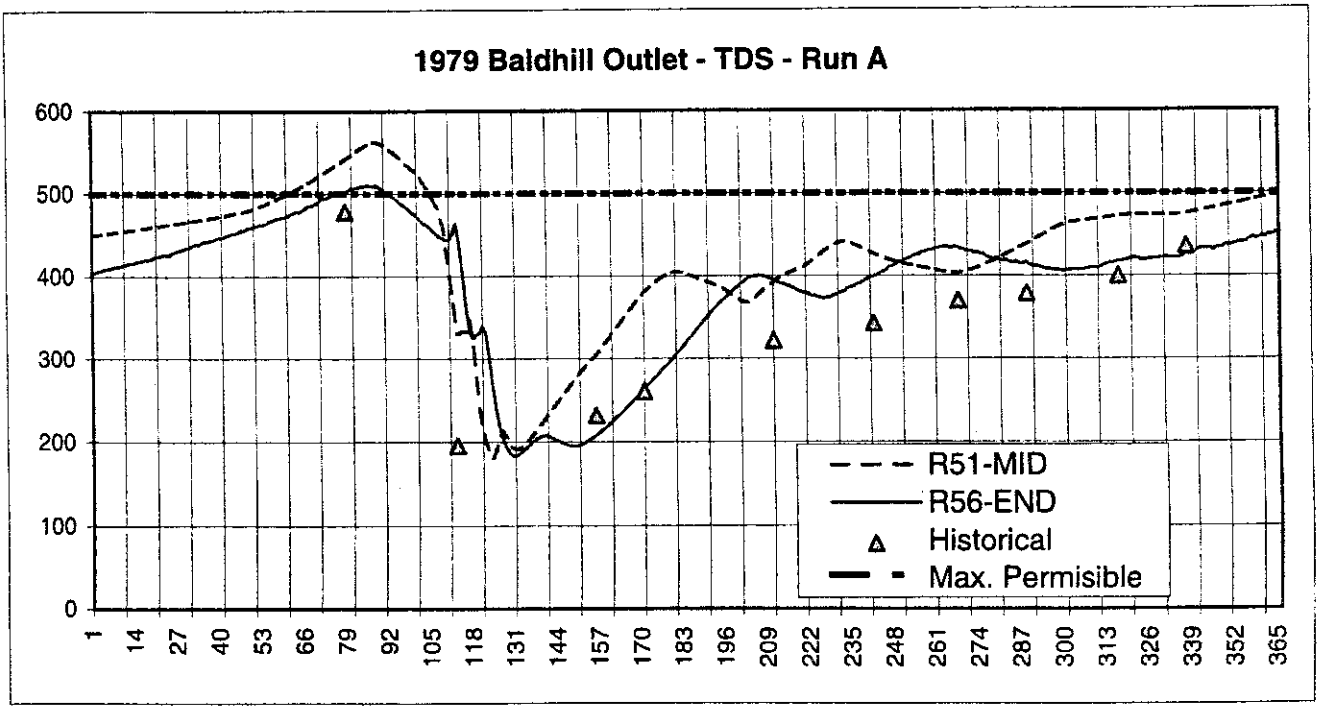

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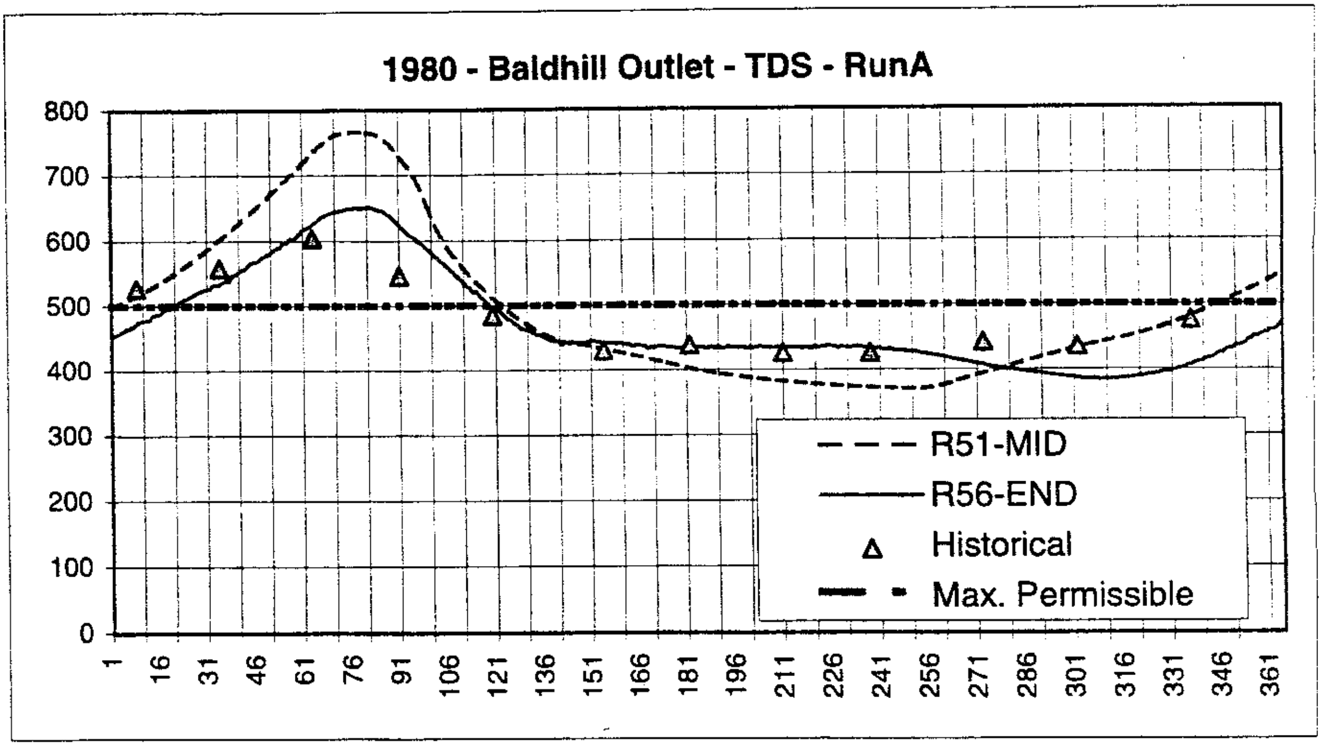

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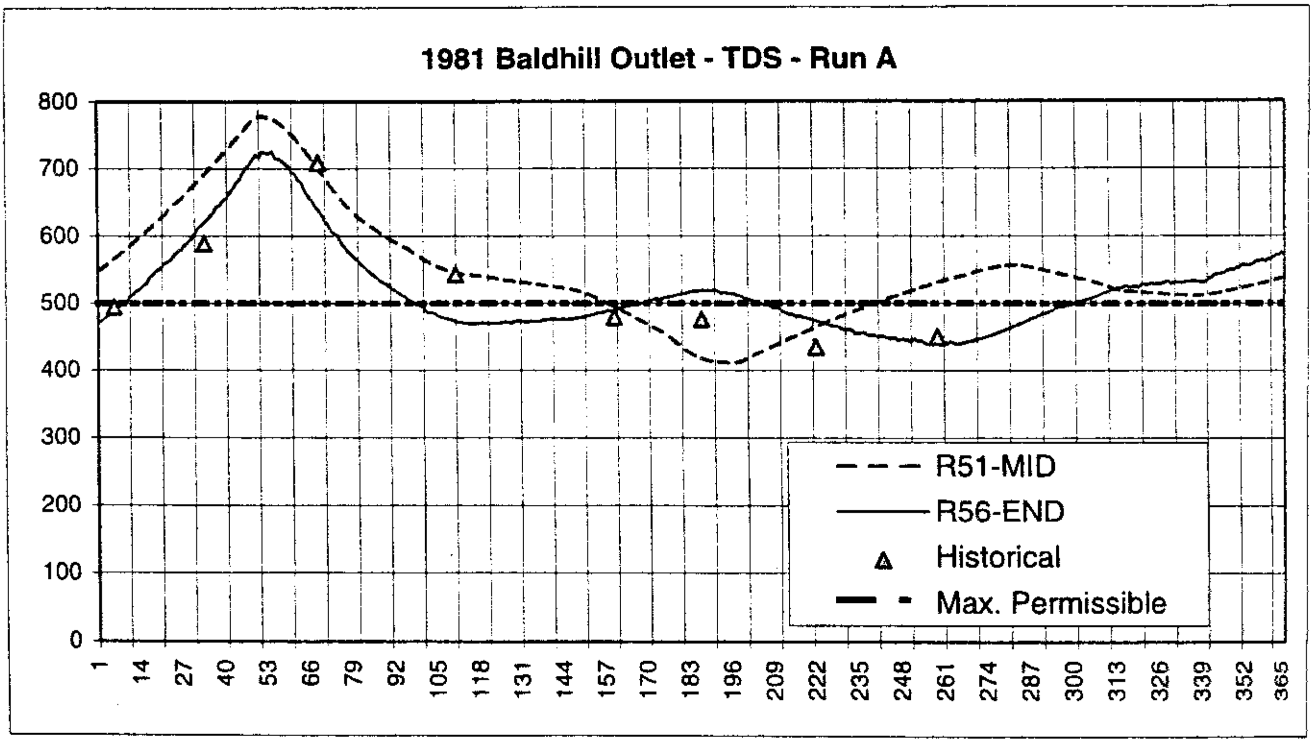

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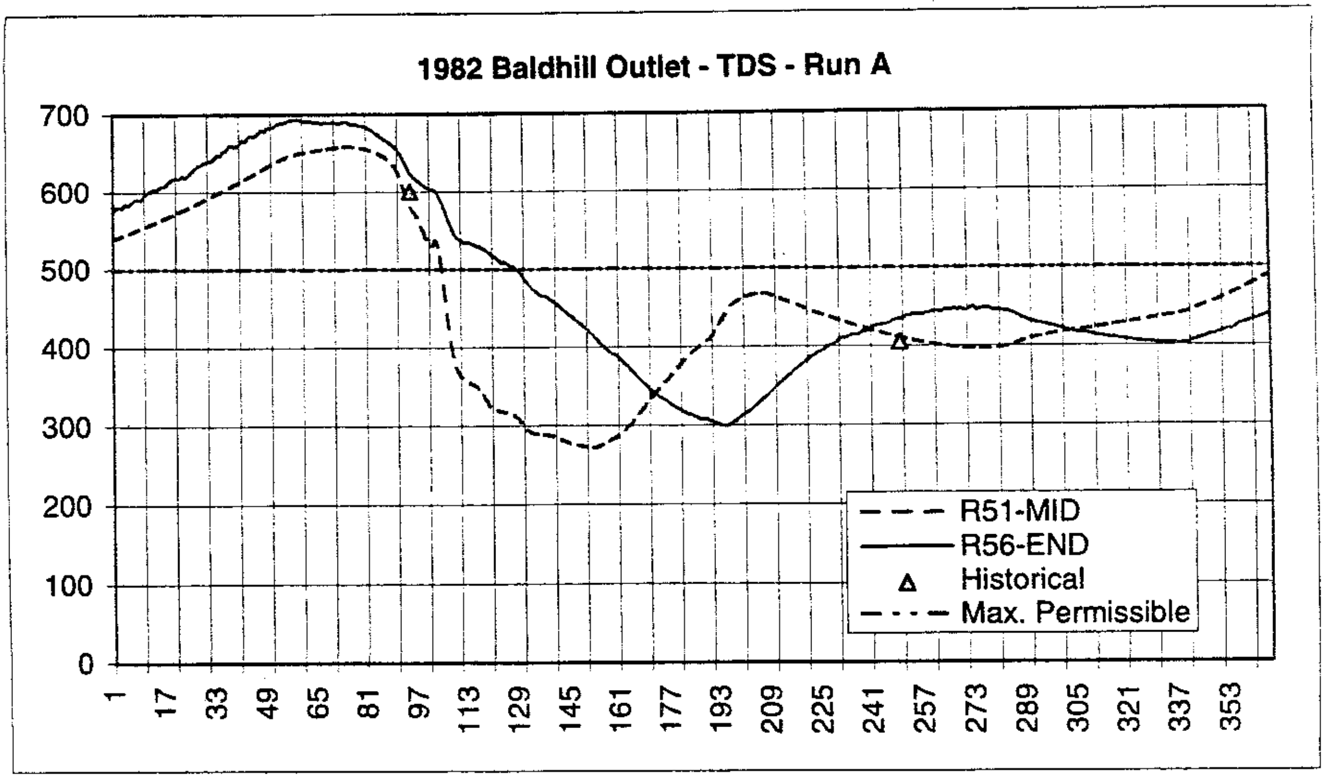

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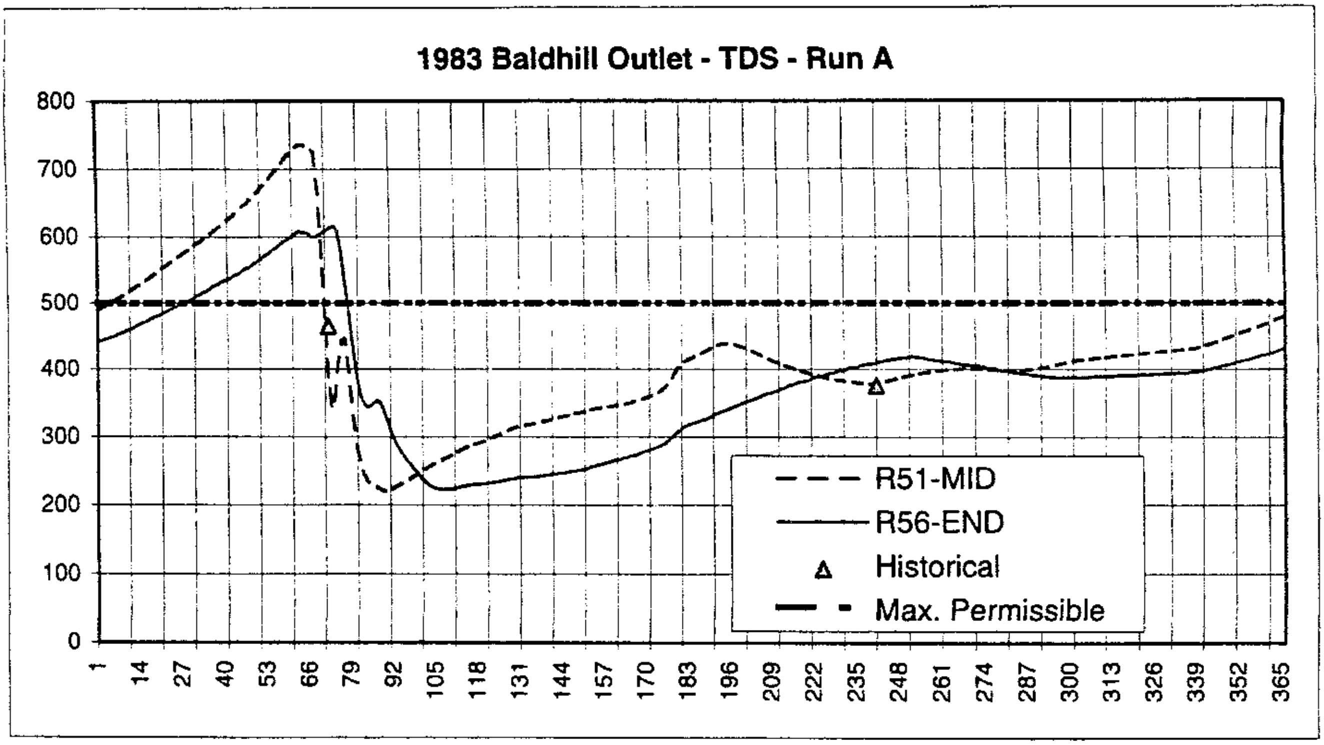

Figure 16