1996

Technical Appendix to Task III Report: Deficit Algorythm Methodology

J. Herman
University of Kentucky Water Resources Research Institute

L. Ormsbee
University of Kentucky Water Resources Research Institute

Repository Citation

Herman, J. and Ormsbee, L., "Technical Appendix to Task III Report: Deficit Algorythm Methodology" (1996). *KWRRI Research Reports*. 216.
https://uknowledge.uky.edu/kwrri_reports/216

KENTUCKY RIVER BASIN WATER SUPPLY ASSESSMENT STUDY

Technical Appendix to Task III Report: Deficit Algorithm Methodology

J. Herman
L. Ormsbee

Prepared for:
The Kentucky River Authority

By:
The Kentucky Water Resources Research Institute
University of Kentucky
Lexington, Kentucky

DECEMBER 1996
KWRRI 9606A

KENTUCKY RIVER BASIN WATER SUPPLY ASSESSMENT STUDY

Technical Appendix to Task III Report: Deficit Algorithm Methodology

J. Herman
L. Ormsbee

Prepared for:
The Kentucky River Authority

By:
The Kentucky Water Resources Research Institute
University of Kentucky
Lexington, Kentucky

DECEMBER 1996
KWRRI 9606A

1.0 Overview

This appendix contains a detailed description of the algorithm used by the KYBASIN model to quantify water supply deficits in the Kentucky River Basin. This document is an attachment to the report entitled **Task III Report - Deficit Analysis** (Ormsbee & Herman, 1996), which summarizes the water supply deficit results of Phase III of the KWRRI Kentucky River Basin Water Supply Assessment Study. The purpose of the study was to quantify water supply in the Kentucky River Basin during a severe drought for the existing supply system/resources under current and projected demand forecasts. The study was authorized by the Kentucky River Authority in a contract with the Kentucky Water Resource Research Institute dated April 1, 1995.

1.1 Introduction

Simulation of the Kentucky River Basin for the **Task III Report** (Ormsbee & Herman, 1996) was performed using a hydraulic river routing model developed for the study. The model, KYBASIN, simulates water movement in the basin over a 12-month period using a level-pool routing algorithm with an 8-hour calculation interval. River routing is performed on a pool-to-pool basis using pool stage-storage data and rating curves developed for the lock and dam structures. River routing is performed at the dam structures only and flow within a pool is not routed within the pool itself. Pool stage-storage data was obtained from the Kentucky Geological Survey and the Army Corps of Engineers. Lock and dam rating curves were developed from measured data at the lock and dam locations provided by the Unites States Geologic Survey.

In addition to simulating water movement through the river, water exchanges are modeled. These exchanges include municipal, commercial, and agricultural withdrawals, as well as, wastewater treatment plant discharges, and evaporation and transmission losses.

The primary output from the KYBASIN model is a summary of the daily water supply deficits occurring in main-stem river pools. Deficits are recorded by the model when daily water supply is insufficient to satisfy municipal demands. The following sections describe the methodology employed by the algorithm used in the KYBASIN model for quantifying deficits in the basin.

1.2 Deficit Definition

Water supply deficits are defined by the model as the sum of unmet municipal and commercial demands. Unmet demands are assumed whenever water supply in the river[1] is insufficient to satisfy the daily desired withdrawal. Deficits are quantified for permitted[2] surface water withdrawals from the main stem of the Kentucky River only. Water supply deficits are provided for each pool; deficits for individual municipalities within a pool are not disaggregated. Deficits are quantified on an 8-hour interval and summed to produce daily output.

1.3 Water Exchange Mechanisms

Figure 1 illustrates the components of the algorithm used by KYBASIN to determine pool deficits in the basin. There are eight components, or water exchange mechanisms, which occur in any given pool during a calculation interval. Three of these mechanisms occur as inflow into a pool. These pool inflow mechanisms are: upstream inflow, upstream dam leakage, and waste water treatment plant (wwtp) discharges. Upstream inflow is the flow that enters a pool as discharge over the upstream dam and is determined by the upstream pools' water level and dam dimensions/characteristics. Upstream leakage is the leakage through the upstream dam. Upstream leakage is a function of the water level in the upstream pool. Flows entering a pool from wwtp discharges are based on the magnitude of water withdrawn from the river by municipalities serviced by the wwtp and the consumptive loss. Water entering a pool from wwtp discharges reflects water withdrawn from the river on the previous day. For a more detailed explanation of how wwtp discharges are computed by the model refer to *3.8 Return Flows* in the **Task III Report** (Ormsbee & Herman, 1996).

Four of the water exchange mechanisms illustrated in Figure 1 result in a loss of pool storage. These pool loss mechanisms are: agricultural withdrawals, municipal / commercial withdrawals, downstream flow, and dam leakage. Agricultural withdrawals occur in the summer months as riparian farmers withdraw water for the purpose of irrigating crops. The location of municipal and commercial withdrawals from the river are determined by the Division of Water (DOW) surface water withdrawal permits. The magnitude of these withdrawals are based on the demand forecast used in the analysis. Downstream flow is the flow over the dam at the downstream end of the pool. Downstream flow is determined by the pool water level and the dam dimensions/characteristics. Downstream flow for a pool is the upstream flow for the downstream pool. Dam leakage reflects the flow exiting a pool through or around the

---

[1] Permitted withdrawals from pool #9 of the river may also utilize available storage in Jacobson Reservoir. Deficits are not recorded for withdrawals from pool #9 unless both river and reservoir supplies are insufficient for satisfying the daily desired withdrawal.

[2] "Permitted" withdrawals refers to river withdrawals regulated by the Division of Water (DOW) via surface water withdrawal permits.

dam structure and lock chamber. Water lost as dam leakage becomes inflow into the downstream pool.

The final water exchange mechanism, lateral inflow, can be either a pool inflow or loss. Lateral inflow is a lumped parameter which is defined as the sum of the inflow into a pool from runoff or groundwater (baseflow) and the natural losses in a pool occurring from evaporation, groundwater recharge, etc. Lateral inflows are typically negative (a loss) during drought periods, due to the lack of rainfall and ground moisture. Further discussion of lateral inflows and their calculation appears in *3.4 Lateral Inflows* in the **Task III Report** (Ormsbee & Herman, 1996).

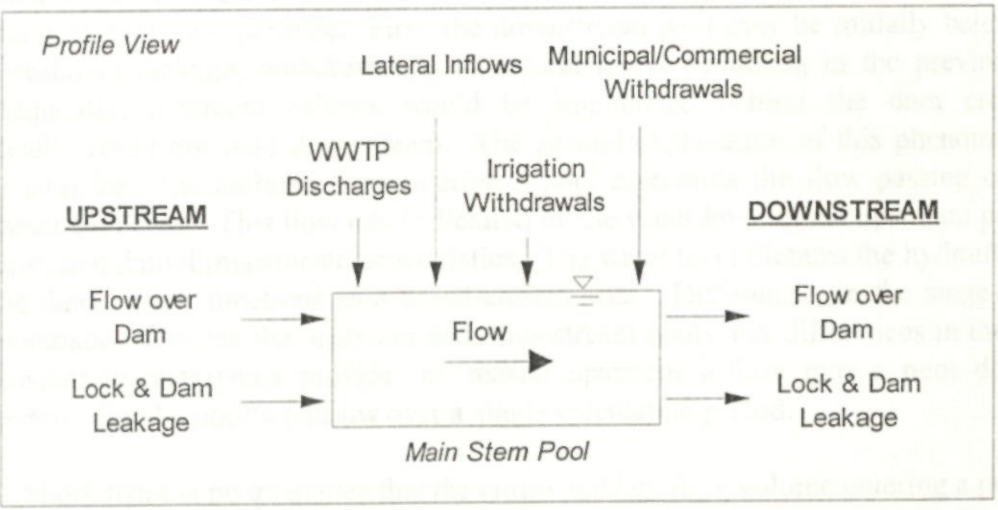

Figure 1: Water exchange mechanisms in river pools

1.4 Impact of Minimum Flow Requirement

The Division of Water (DOW) enforces a minimum flow requirement at all Kentucky River lock and dam locations. This requirement mandates that a pre-specified flow must be permitted to pass through the river at select river locations. Minimum flows on the river are used to preserve river biota by ensuring there is sufficient flow in the river to prevent stagnation and provide adequate dilution for incoming pollution. Permitted demands on the river are contingent upon the river passing minimum flow requirements. Withdrawals which will prevent passage of the minimum flow requirement are prohibited[3]. When inflow into a pool is less than the minimum flow requirement at that location, the flow entering the pool, termed ambient flow, must be permitted to pass downstream.

---

[3] Legislation exists in which the Governor of Kentucky may declare a state water emergency. In this event, the DOW is authorized to relax minimum flow requirements and can allocate water amongst users at its discretion. The deficit algorithm does not consider the possibility of the declaration of a state water emergency and assumes the original policy is strictly enforced.

The DOW minimum flow requirement policy has a profound impact on the water available for municipal withdrawal. Effectively, this policy can prohibit municipal withdrawals when the ambient flow into a pool is less than the minimum flow requirement, since withdrawal from the pool may draw down the pool and prohibit passage of the ambient flow over the downstream dam. Recall flow over the dams is dependent upon the water level in the pool and the dam dimensions/characteristics. In addition to lowering the hydraulic head on the dam crest, it is possible that municipal withdrawals could draw down the pool below crest, prohibiting all flow over the dam.

It is of interest to note that there is no guarantee that the ambient flow will be passed downstream even in the event municipal withdrawals are prohibited. Two explanations of this occurrence are possible. First, the downstream pool may be initially below crest as a result of leakage, withdrawals, and natural losses occurring in the previous day. Consequently, upstream inflows would be impounded behind the dam crest and physically could not pass downstream. The second explanation of this phenomenon is more complex. The ambient flow entering a pool represents the flow passing over the upstream dam crest. This flow rate is dictated by the water level in the upstream pool and the upstream dam dimensions/characteristics. The water level dictates the hydraulic head on the dam, which functions as a broad-crested weir. Differences in the stage-storage characteristics between the upstream and downstream pools and differences in their dam dimensions/characteristics provide the reason upstream inflow into a pool does not necessarily equal a pool's outflow over a single calculation period.

In short, there is no guarantee that the entire ambient flow volume entering a pool will exit the pool over a single calculation period, due to a portion of the ambient flow being retained behind the weir structure.

In recognition of the above phenomena, the minimum flow requirement was modeled at the downstream end of a pool. When flow over the dam in a pool was less than the minimum flow requirement for the dam location, municipal withdrawals were prohibited. This stipulation guarantees that the minimum flow requirement is passed before municipal withdrawals are permitted. Enforcing the minimum flow requirement at the upstream dam, whereby municipal withdrawals from the downstream pool are contingent upon flow over the upstream dam exceeding minimum flow values, does not guarantee the incoming minimum flows will be passed over the downstream dam.

1.5 Deficit Algorithm

The algorithm used by KYBASIN to compute pool deficits is based on assigning priority to the eight water exchange mechanisms described earlier. These priorities are internal to the model and can not be changed by the user. By prioritizing the water exchanges in a pool, the model can determine whether water is available for municipal withdrawal. Water is only available for municipal withdrawal when all natural losses, irrigation withdrawals, and minimum flow requirements have been satisfied.

Deficit calculations for river pools must begin with the most upstream pool, since flow exiting one pool becomes inflow to the adjacent downstream pool. For brevity the algorithm for a single pool is examined. The calculation process for all pools is identical with the exception of the most upstream pool (pool #14). For this pool their is no upstream leakage and the upstream inflow is simply the sum of the flows in the three forks (e.g. the North, South, and Middle Forks).

The following steps summarize qualitatively the algorithm used to quantify the water supply deficit for a single pool.

1. Identify the initial pool level and corresponding storage volume.
2. Compute the *intermediate storage* by adding the upstream flow, upstream leakage, lateral inflow, and all wwtp discharges in the pool to the initial storage.
3. The *critical storage* is the storage in a pool below which municipal and commercial withdrawals are prohibited. Use the stage-discharge data to determine the storage value in the pool at which the minimum flow requirement value is passed over/through the dam. Compare this value with the storages corresponding to the dam crest and the highest municipal/commercial withdrawal intake in the pool. The largest of these three storage volumes is the *critical storage* for the pool.
4. Convert all desired municipal/commercial demand withdrawals in the pool to a single withdrawal volume over the calculation interval. Repeat for the desired irrigation demand.
5. Compute the water supply deficit for the pool according to the following rules.

```
If (intermediate storage - irrigation w/d - municipal w/d) >= critical storage
    Then deficit = 0.

ElseIf (intermediate storage - irrigation w/d) <= critical storage
    Then deficit = municipal w/d

Else
    deficit = municipal w/d - (intermediate storage - irrigation w/d - critical storage)
```

where:

irrigation w/d is the total desired irrigation withdrawal volume from step 4 *and* **municipal w/d** is the total desired municipal/commercial withdrawal volume from step 4

6. Perform the routing algorithm (see *1.6 Routing Algorithm*)

7. Repeat steps 1 - 6 for each calculation interval.

The deficit algorithm above ensures that municipal withdrawals cease whenever either: 1) municipal/commercial withdrawal intakes are exposed, 2) minimum flow requirements are not met, or 3) the dam crest becomes exposed. The third requirement is necessary to ensure that municipal withdrawals will not mine the pools. Mining the pools would cripple the river's ability to meet minimum flow requirements in the next calculation interval. Note that the third requirement is redundant when minimum flow values are greater than the dam leakage estimates, since minimum flows would not be met at water levels below the dam crest. In addition, for pools with withdrawal intakes located below the dam crest, the first requirement is also redundant.

1.6 Routing Algorithm

Once municipal withdrawals are made and the deficit, if any, is quantified for the calculation interval, the remaining water in the pool is routed through the dam. A single stage-discharge function is used in the model to determine the flow over the dam crest and through the lock and dam as leakage. A separate stage-discharge function was developed for each lock and dam structure based on USGS measured data.

The steps below indicate, qualitatively, the algorithm used to perform the hydraulic routing of river flow over dam crests. This algorithm computes the flow over the dam crest for the 8-hour calculation interval and the storage at the end of the interval. For brevity only a single pool is examined. These steps are performed immediately after the deficit algorithm.

1. Compute the *storage after demands* for the calculation interval. The *storage after demands* is equal to the *intermediate storage* minus irrigation, municipal, and commercial withdrawals. To determine the *storage after demands* use the following logic.

```
If (intermediate storage - irrigation w/d - municipal w/d) >= critical storage
    Then storage after demands = intermediate storage - irrigation w/d - municipal w/d

ElseIf (intermediate storage - irrigation w/d) <= critical storage
    Then storage after demands = intermediate storage - irrigation w/d

Else
    storage after demands = critical storage
```

where:

critical storage is the storage in the pool below which municipal withdrawals are prohibited, as calculated in step 3 of deficit algorithm

intermediate storage is the storage in the pool after all inflows have been added, as calculated in step 2 of the deficit algorithm

irrigation w/d is the total desired irrigation withdrawal volume from step 4 of the deficit algorithm

municipal w/d is the total desired municipal/commercial withdrawal volume from step 4 of the deficit algorithm

2. Compute the *pool inflow minus demands* for the calculation interval. The *pool inflow minus demands (pimd)* is the remaining inflow into a pool after all losses and withdrawals have been subtracted. The *pimd* is negative when losses and withdrawals exceed inflows. Pool inflows are the sum of the flow over the upstream dam, lateral inflows, upstream dam leakage, and wwtp discharges into the pool. To determine the *pimd* use the following logic.

```
If (intermediate storage - irrigation w/d - municipal w/d) >= critical storage
    Then pimd = pool inflows - irrigation w/d - municipal w/d

ElseIf (intermediate storage - irrigation w/d) <= critical storage
    Then pimd = pool inflows - irrigation w/d

Else
    pimd = pool inflows - irrigation w/d - (intermediate storage - irrigation w/d -
           critical storage)
```

where:

pool inflows is the sum of the flow over the upstream dam, lateral inflows, upstream dam leakage, and wwtp discharges into the pool for the interval

3. Determine the *initial pool outflow* for the interval. The *initial pool outflow* is equal to the sum of the flow over the downstream dam and the downstream dam leakage from the previous calculation interval. The *initial pool outflow* represents the flow out of a pool through the lock and dam structure at the beginning of the calculation interval.

4. Use the storage after demands, pool inflow minus demands (pimd), and initial pool outflow calculated in the previous steps with the level-pool routing table developed for the pool[4] to determine the flow over the dam over the calculation interval and the storage in the pool at the end of the interval.

---

[4] The individual stage-discharge rating curves for each main stem pool were used to develop a level-pool routing table for each pool. These tables are used to facilitate level-pool routing calculations by the model. The tables appear in the KYBASIN model and are dynamic to reflect user-defined parameters.

From the above steps, it can be seen that the routing algorithm has several key assumptions imbedded in its logic. First, irrigation demands are always withdrawn regardless of the water level in a pool or minimum flow requirements. Furthermore, irrigation demands are given a higher priority over municipal/commercial demands. These assumptions contribute to conservative deficit predictions and were included in the algorithm to reflect the largely unregulated nature of irrigation withdrawals.

Water supply priority is also established in the routing algorithm. Water supply priority denotes the "pecking order" among water uses; the use with the highest priority has first access to river water. Natural losses are given the highest priority for river water. Recall that losses from evaporation, groundwater recharge, etc. are included in lateral inflow estimates for the pool. After natural losses, irrigation demands are given the priority. Minimum flow requirements are assigned the next priority, followed by municipal/commercial demands. Flow over the downstream dam (river routing) is given the lowest priority. Note that water priority only establishes the order of *access* to river water and other criteria may, as in the case of municipal/commercial withdrawals (see *1.5 Deficit Algorithm*), prohibit withdrawal/use.

A third assumption included in the routing algorithm is that the flow over the dam crest for the interval is assumed to be the instantaneous flow at the beginning of the calculation interval. This assumption was made in order to model river flow mechanics within a reasonable computation time. While this assumption over-predicts the actual flow volume over the dam crest for the interval, the rather small calculation interval (8 hours) reduces its impact on results.

The above algorithm demonstrates the methodology used by the KYBASIN to perform a level-pool routing of the Kentucky River. Typically, level-pool routing is used for reservoir routing. Since the Kentucky River is divided into a series of contiguous pools, or reservoirs, by the lock and dam structures, it was applied. The methodology and theoretical basis of the level-pool algorithm itself is not addressed here. This information may be found in most general hydrology/hydraulics textbooks.

REFERENCES

Ormsbee, L. and J. Herman, 1996, Task III Report - Deficit Analysis.