A methodological framework for spatial distribution of small reservoirs

Federico Antolini, *Department of Geographical and Sustainability Sciences and Interdisciplinary Program in Informatics, University of Iowa*

Problem overview and research objective

Riverine flood losses have been on the rise in the last decades, both in the US and globally. There is general agreement that this trend, exacerbated by global warming, will continue in the future. In addition to that, dams and reservoirs, which have been the main engineering measure of flood mitigation, are object of an ongoing process of removal, due to their high maintenance cost and adverse environmental impacts. In this context, the need for alternative, *cost-effective and environmentally sustainable strategies* for flood management becomes more pressing.

A **distributed system of reservoirs (DSR)** is a set of water storage impoundments distributed across a watershed for intercepting and controlling excess discharge during a flood event. Compared to large dam-based reservoirs, DSR impoundments have lower cost and a reduced ecosystem impact due to their small footprint. Flow control effects of DSRs depend on single element characteristics, like storage capacity and dam geometry, as well as on system characteristics, like number of reservoirs and their distribution within the river network. While there has been extensive research on how a single reservoir alters hydrology, little is understood about **how reservoirs work collectively** and **how their spatial distribution influences stream flow**. This work aims to fill this knowledge gap through a three-step methodology, illustrated in Figure 1. Efforts are concentrated on the **spatial dimension** of system of reservoirs and on mutual interactions among reservoirs based given their relative locations within the river network.

I selected as study areas two HUC12 subwatersheds (North Branch and Silver Creek) in the Turkey River basin in northeast Iowa (Figure 2), where severe flood events have occurred in the past decades. The same methodology, however, can be applied in any watershed.

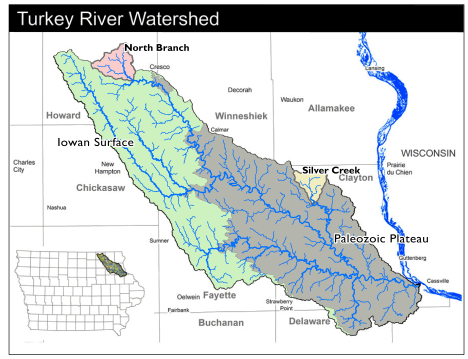


Figure 2. Locations of study areas in the Turkey River watershed.

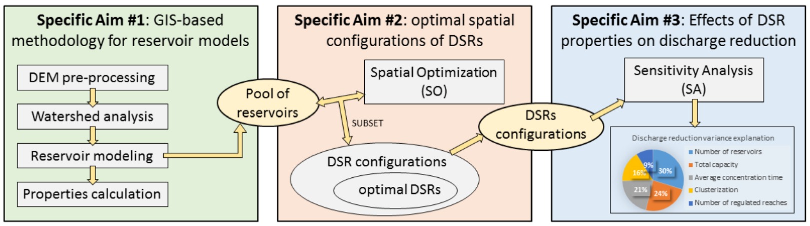
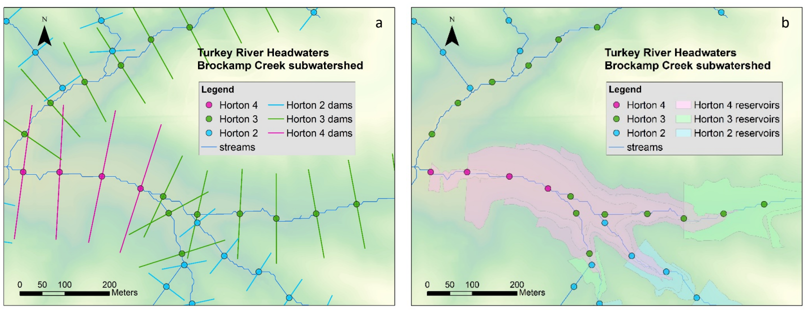


Figure 1. Methodological framework articulated in three specific aims:
#1 Generate reservoir objects on numerous potential locations across a watershed through a GIS-based methodology
#2 Find spatial configuration of reservoirs maximizing discharge reduction at outlet at minimal cost
#3 Identify via sensitivity analysis DSR properties that mostly influence discharge reduction



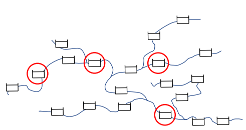
AIM #1: Generate reservoir models

To achieve flood protection (or other goals), there is no a priori information on where to locate the reservoirs of a system. A rigorous investigation must evaluate multiple configurations. Therefore, there is a need for reservoirs modeled in many potential locations. They will form a pool from which subsets can be selected.

1. Identify regularly spaced locations on each streamline (Fig. 3a), including source and minor reaches (low Horton order) and excluding major ones (high Horton order) where a reservoir would necessarily be large.
2. Delineate a transversal dam and the reservoir boundary upstream of the dam, corresponding to the contour line at the elevation of water level when the reservoir is full (Fig. 3b).
3. Calculate reservoir **volume** and **footprint area** for different heights of the water in the reservoir.
4. Given a certain dam orifice and spillway geometries, calculate discharge for different heights of water in the reservoir. Coupled with corresponding values of water volume in the reservoir to define the **storage-discharge function**.

Figure 3. Example of reservoir locations (a) and footprints (b).

AIM #2: Find optimal spatial configuration



Reservoirs are modeled on **n** locations.
How many possible configurations of **k** reservoirs exist?

If **k** is fixed $\binom{n}{k} = \frac{n!}{k!\,(n-k)!}$, otherwise 2^n

To find the most effective subset of reservoirs, I use **spatial optimization** and **heuristic search**.

In the following version of the problem, the objective is to maximize the total capacity of the DSR, while respecting constraints on budget, total inundated area and making sure there is no overlap between any two selected reservoirs.

$$\max \sum_{i=1}^{m} V[x_i]\,, \quad x_i \in X$$ Maximization of capacity

$$s.t. \sum_{i=1}^{m} C[x_i] \leq b\,, \quad x_i \in X$$ (1) budget constraint

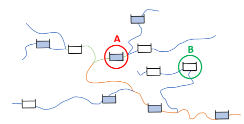
$$\sum_{i=1}^{m} A[x_i] \leq f\,, \quad x_i \in X$$ (2) constraint on overall inundated area

$$x_i \notin F[x_j]\,, \forall\, x_i, x_j \in X, i \neq j$$ (3) topological constraint

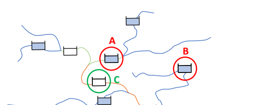
I use two established heuristic methods (multi-start and GRASP) and an original randomized search (GRIP). Performances of the three methods are reported in Tables 1b and 1c. Figure 4 shows the optimal configurations found by GRIP.

- **Multi-start** Procedure
  - Start from an empty solution
  - Randomly pick a reservoir
  - If feasible, add it to the solution
  - Repeat as long as the solution is feasible
  - 1 solution is produced
  - Repeat *k* times to produce *k* solutions
- **GRASP** (Greedy Randomized Adaptive Search Procedures)
  - Rank reservoirs by a property (e.g. capacity-to-area V/A)
  - Randomly add one of the *m* best reservoirs to solution
  - Repeat as long as the solution is feasible
  - Repeat *k* times
  - *k* solutions are produced
  - Update best solution during the process
- **GRIP** (Greedy Randomized Improvement Procedures)

DOWN move
- Start from a (random) solution
- Randomly select a **reservoir A** to replace
- Consider candidates of lower or equal Horton
- Build a list of feasible improving candidates for replacement
- Replace **A** with one of the best candidates **B**
- 1-to-1 replacement



UP move
- Start from a (random) solution
- Randomly select 2 reservoirs **A** and **B** to replace
- Consider candidates of higher or equal Horton
- Build a list of feasible improving candidates for replacement
- Replace **A**, **B** with one of the best candidates **C**
- 2-to-1 replacement



Results

Horton order	Reservoir cost (US$)
2	5,000
3	10,000
4	20,000
5	40,000
6	70,000

(a)

Watershed	Greedy attribute	α = 0.01	α = 0.05	α = 0.1	α = 0.2
North Branch (budget = 600k, maxFloodArea = 500k)	V	382326	424170	435210	461238
	V/A	422038	473979	526770	624503
	V/C	402031	426445	446945	493976
	V/AC	509391	548539	587945	598301
	A	621127	636029	632108	605927
	Best multi-start solution: **695899**				
Silver Creek (budget = 600k, maxFloodArea = 500k)	V	848863	875458	856274	853289
	V/A	742719	824628	867259	865472
	V/C	630765	630231	649395	674922
	V/AC	726850	787787	830629	909920
	A	943303	**973925**	970480	933957
	Best multi-start solution: 967773				

(b)

# GRIP search	North Branch (budget = 600k, maxFloodArea = 500k)	Silver Creek (budget = 600k, maxFloodArea = 500k)
0 (from greedy sol.)	**713316**	1044012
1	704676	1051680
2	619672	1050408
3	665941	936504
4	633003	1045185
5	587362	1043153
6	636912	986856
7	706488	**1089747**
8	699349	1082453
9	709210	1050093
Average	**667592.9**	**1038009.1**
Std dev.	45452.02	44935.35

(c)

Table 1a. Cost estimate based on stream size.

Table 1b. Max capacity found by GRASP and multi-start.

Table 1c. Max capacity found by GRIP.

Conclusions

In North Branch watershed, most of the total capacity is due to a single reservoir much larger than the others. In Silver Creek, the optimal DSR is made of many small reservoirs and only a few larger ones. This discrepancy is mostly due to the different geologic formations on which the watersheds lie. The Iowan Surface (North Branch) is prevalently flat and reservoirs on small reaches are harder to model.

Improvement-oriented search proposed **(GRIP) performs better** than other standard algorithms, as it found solutions with higher capacity in less time.

The problem formulated here is not banal, as GRIP was able to find a better solution than the greedy one. However, result and algorithm performance may be influenced by constraints (budget value, etc…). In the future I will introduce two important improvements:

1) Couple a **hydrologic model** to the optimization algorithm and maximize discharge reduction at outlet for a given flood event;
2) Redefine the problem from single to **multi-objective** optimization, so to produce a Pareto-optimal frontier of solutions.

A variety of optimal (good) solutions will then be analyzed in Specific Aim #3 to further understand which properties (geometry, locations, configurations) more effectively control water flow.

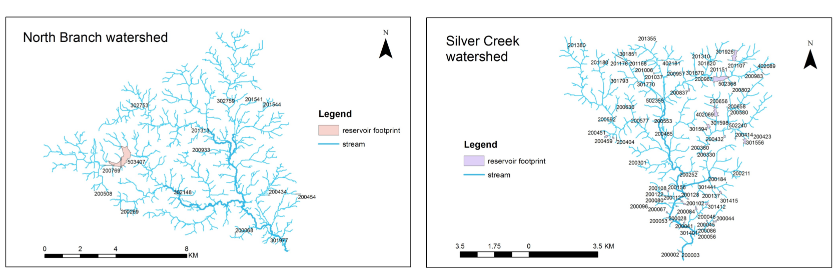


Figure 4. Optimal configurations found by GRIP on North Branch and Silver Creek watersheds. Reservoir ID first digit indicates stream order.