A methodological framework for spatial distribution of small reservoirs

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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 is exacerbated by global warming, and 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 improvements 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 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 flood 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 systems of reservoirs and on mutual interactions among reservoirs based on their relative locations within the river network. I selected as study areas two HUCs subwatersheds (North Branch and Silver Creek) in the Turkey River basin in northeastern Iowa (Figure 2), where severe flood events have occurred in the past decades. The same methodology, however, can be applied in any watershed.

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To achieve flood protection (or other goals), there is 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. 3c), including source and minor reaches (low Horton order) and excluding major ones (high Horton order) where a reservoir would necessarily be large.

2. Designate 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 water in the reservoir. Given a certain dam orifice and spillway geometry, calculate discharge for different heights of water in the reservoir. Coupled with corresponding values of water volume in the reservoir to define the discharge storage function.

AIM #3: Generate reservoir models

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AIM #2: Find optimal spatial configurations

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

\[ \text{max} \sum_{i} V_{i} - h_{i} \text{ subject to:} \]

- \( \sum V_{i} \leq B \) (capacity budget)
- \( \sum h_{i} \leq H \) (height budget)
- \( \sum x_{i} \leq N \) (constraint on overall inundated area)
- \( x_{i} \leq \beta \) (topological constraint)

I use two established heuristic methods (multi-start and GRASP) and an original randomized search (GRIP). Performance of the three methods are reported in Tables 1b and 1c. Figure 4 shows the optimal configurations 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 watershed lies. The North Branch Surface (North Branch) is prevailingly 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 basal, as GRIP was able to find a better solution than the greedy one. However, result and algorithm performance may change if the same methodology is applied on other basins (budget value, etc...). In the future I will introduce two important improvements:

- Couple a hydraulic model to the optimization algorithm and maximize discharge reduction at outlet for a given flood event. The goal is to solve 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 specified Aim #4 to further understand which properties (geometry, locations, configurations) more effectively control water flow.