reservoir management plan to maximize hydropower and irrigation benefits while maintaining storage

Six Months of Optimal System Allocations

Prepared by Joshua Ward

09/25/2020

Utah State University

CEE 5410/6410 | Dr. David Rosenberg, PhD

## Introduction

Even in an idealized world where water resources are measured in arbitrary volume “units” and economic inflation has yet to diminish the purchasing power of the dollar, reservoir management strategies are still essential in academic societies. A water manager in such circumstances asked the author to determine the optimal management strategy that maximized financial benefits, as well as the detail the recommended plan’s sensitivity to changes in constraints (Rosenberg 2020). This report details the methods and results of a linear programming (LP) model formulation. The primary findings include the maximized benefits of the recommended management strategy, the sensitivity of model parameters, and potential implications for the water manager when modeling larger time periods.

## Methods

A model was formulated and solved in the General Algebraic Modeling System (GAMS) software. The model incorporated decision variables (allocated water units) at several locations over a course of six months, giving a total of 30 decision variables to optimize. Similarly, all constraints location specific and dependent on time and produced many various constraints equations. Sensitivity analyses were performed to determine how marginal changes in variables or constraints affect the total benefits (Table 1) and at what point streamflow requirements would change the basis, or the set of non-zero decision variables; changes in the basis variables would indicate a major change in the optimal allocation plan. The model formulation is shown in Figure 1 and the code solution is available online in the [author’s GitHub repository](https://github.com/joshuatward/JTW_CEE5410_Repo/tree/master/HW4%20Reservoir) (Ward 2020).

## Results

The LP model projected maximum benefits of $51.6 in total. The water manager specifically requested an evaluation on how benefits change under the scenarios in Table 1, provided the solution basis remains the same. Table 2 shows the recommended water allocations by location and month.

Table 1. Sensitivity of total benefits to changes in model constraints and decision variables

|  |  |  |  |
| --- | --- | --- | --- |
| **Scenario** | **Marginal set by month ($/unit)** | **Change in Total Benefits ($)** | **Findings** |
| Reservoir capacity expanded +1 unit | [0, 0, 0, 0, 0, 0] | 0 | Reservoir capacity never bound. Increasing capacity does not change the model. |
| Streamflow requirements increase +1 unit | [-2.1, -2.0, -1.9, -2.0, -2.2, -2.2] | -12.4 | Streamflow requirements bind each month. Change in basis (+1 streamflow unit) decreases benefits by $0.4. |
| Irrigation increase +1 unit in months 1-3 | [-1.1, -0.8, 0, 0, 0, 0] | -1.9 | Only months 1-2 bind and decrease overall benefits. |

The water manager also requested information about when the streamflow requirements change the optimal solution. Increases in months 1-3 and months 4-6 by 1 unit and 3 units, respectively, would change the solution basis. Should streamflow requirements increase by even 1 unit, the model should be solved anew (Ward 2020).

## Conclusion

Despite its usefulness, the model has several potential drawbacks as the number of time periods increase that the water manager should consider:

* Future flows, prices, etc. are more accurate in the short-term than long-term. Introducing more time periods in the model may increase uncertainty in the model results.
* Each additional month modeled adds 5 decision variables, 1 inflow value, 2 objective function coefficients, and 6 constrain equations. Model maintenance could develop into a significant hassle.
* The model is based on maintaining existing storage, not planning for future growth.

That said, this information has significant potential for effectively managing this water resource system. The model determined that a maximum total benefit of $51.6 results from the allocation plan in Table 2, and beneficial uses are far more sensitive to streamflow requirements than reservoir capacity.

# References

Rosenberg, David E. 2020. "HW4 - Reservoir operation problem." *CEE 5410 Canvas Course.* September. Accessed September 25, 2020. https://usu.instructure.com/courses/612457/assignments/3066093.

Ward, Joshua Timothy. 2020. "HW 4 Reservoir." *JTW\_CEE5410\_Repo | GitHub.* September 25. https://github.com/joshuatward/JTW\_CEE5410\_Repo/tree/master/HW4%20Reservoir.

# Appendix A: Model Formulation and Output

Diagram

Description automatically generated

**Objective Function**

Maximize financial benefits ($) from hydropower generation and irrigation of farmland.

**Decision Variables**

Water allocations X(L, t) at each location in each time step

**Sets**

* Locations (L): res “Reservoir”, sp “Spillway”, hyd “Hydropower”, irr “irrigation”, riv “Streamflow at A”
* Months (t): M1- M6

**Constraints**

1. Obey reservoir continuity:
2. Obey continuity at diversion node:
3. Reservoir capacity (9 units) must not be exceeded:
4. Turbine capacity (4 units) must not be exceeded:
5. Ending reservoir storage must equal or exceed beginning storage:
6. Streamflow at A must be greater than or equal to 1 unit:

Figure 1. Model schematic (Rosenberg 2020) and model formulation (Ward 2020)

Table 2. Recommended system allocations by month

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Month** | **Reservoir (units)** | **Spillway (units)** | **Hydropower (units)** | **Irrigation (units)** | **River (units)** |
| 1 | 6 | 0 | 1 | 0 | 1 |
| 2 | 7 | 0 | 1 | 0 | 1 |
| 3 | 8 | 0 | 2 | 1 | 1 |
| 4 | 8 | 0 | 4 | 3 | 1 |
| 5 | 7 | 0 | 4 | 3 | 1 |
| 6 | 5 | 0 | 4 | 3 | 1 |

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Category**  **(Max. Score)** | **No Evidence** | **Doesn’t Meet Standard** | **Nearly Meets Standard** | **Meets Standard** | **Exceeds Standard** | **Self- Score** | **Instructor Score** |
| **Title**  **(1)** | Absent  0 | Evidence of two or less  0 | Evidence of three  0 | Evidence of four  1 | Title – can assess main point from title alone; Name, Instructors’ Names, Course, Date, Neatly finished 1 | 1 |  |
| **Introduction**  **(3)** | Absent, no evidence  0 | There is no clear introduction or main topic.  1 | Introduction states the main topic but either:   1. Does not give a full overview, Or: 2. Too detailed, leading to annoying repetition later. 2 | The introduction states the main topic and previews the structure of the report.  2 | The introduction states the main topic and previews the structure of the report. Good overview of the problem and solution approach. Gives enough detail to motivate the reader to continue reading.  3 | 3 |  |
| **Organization and structural development of the idea: procedure, results, conclusions**  **(10)** | No content provided.  0 | Paragraphs fail to develop the main idea. No section headers or guide to help the reader understand how material is organized.  1 – 5 | Organization of ideas not fully developed. Paragraphs lack supporting detail sentences. No transitions and/or ineffective section headers.  6 - 7 | Paragraph development present but not perfected. Each paragraph has sufficient supporting detail sentences. Few transitions.  8 | Writer demonstrates logic and sequencing of ideas through well-developed section headers, paragraphs, and transitions. The first sentence of each paragraph is the summary sentence.  9 - 10 | 9 |  |
| **Technical Correctness**  **(70)** | Questions not addressed.  3 – 42% | The writer has no clue what they are talking about.  45 – 58% | Sketchy: left out required design points. Did not work on this as much as you should have, and it shows. Many important answers are incorrect.  61 – 79% | Discussion lacks adequate detail, but all the necessary points are covered and nearly all answers are correct.  82 – 88% | Provides what was explicitly asked for. The function of each piece is demonstrated to the reader in adequate, but not overwhelming, detail. Answers are correct and reasonable.  91 – 100% |  |  |
| 1. Problem formulation (15) and solution (10) | | | | | 25 |  |
| 1. Sensitivity of net benefits (30) | | | | | 30 |  |
| 1. Allowable increase of in-stream flow requirement (10) | | | | | 10 |  |
| 1. Manager concerns as model time period increases (5) | | | | | 5 |  |

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Category**  **(Max. Score)** | **No Evidence** | **Doesn’t Meet Standard** | **Nearly Meets Standard** | **Meets Standard** | **Exceeds Standard** | **Self- Score** | **Instructor Score** |
| **Word Usage and Format**  **(10)** | Not applicable | Numerous and distracting errors in punctuation, capitalization, spelling, sentence structure, word usage, significant figures, tables, and figures. Data vomited onto page(s). Unacceptable / unprofessional at the graduate level. 1 – 5 | Misspelled words, poor English grammar and word choice. Main body of report is either longer or significantly less than one page. Figures are too small and/or under-labeled, although they are usually of acceptable quality and focus. Tables incoherent or not cohesive. Bad font sizes. Too much or too little data in appendices. Could be improved by being more meticulous.  6 - 7 | Almost no errors in punctuation, capitalization, spelling, sentence structure, word usage, significant figures, and presentation of figures, tables, and appendices. Main body of report is one page or less  8 | Punctuation, capitalization, spelling, sentence structure, word usage, and significant figures all correct. Main body of report is one page or less. Clear, consistent fonts. Good word processing skills. Figures have adequate contrast. Informative figure and table titles and legends. Figures have appropriate axis tick spacing, labels, units, and legends. Table columns cohesive, labeled, and specify units. Document is stapled. Appendices, if provided, are separated by topic, and each have a title, discussion, and proper formatting and display of information 9 - 10 | 9 |  |
| **Conclusion**  **(4)** | Absent  0 | Incomplete and/or not focused. 1 | The conclusion does not adequately restate the main results. 2 | The conclusion restates the main results. 3 | The conclusion restates the main results, and is an effective summary. 4 | 4 |  |
| **References**  **(0)** | Absent  0 | Numerous errors, off-the-wall sources used. 0 | Some errors in citing format; more sources should be cited.  1 | Prior work cited with few errors.  2 | All prior work and data sources are cited in the correct format with no errors.  2 | 0 |  |
| **TOTAL** (98) |  | | | | | 96 |  |