Implementing Soft Constraints in Hydroelectric Decision Support Systems

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Powel-MiniMax

- Powel-MiniMax is a US-based energy software and services provider of stand-alone and integrated energy solutions.
- Powel has more than 250 employees based in Europe, USA, and Canada.
- Over 35 software modules used by more than 1000 customers worldwide covering
  - Transmission and Distribution Management
  - Trade and Risk Management
  - Customer Management
  - Geographic Information Systems (GIS)
  - Generation and Water Management
- Over 25 years of water management experience ranging from hydrological analysis and forecasting, water quality modeling, hydro systems, planning and operational analysis.

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Agenda

- Introduction
  - What is a soft constraint?
  - Why are soft constraints needed?
  - How are soft constraints modeled in DSS?
  - A few soft constraint examples in HYDROPS™
  - Implementation Issues
  - Conclusions and Future Developments

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Introduction

Constraint Satisfaction Problems (CSP)

$$Maximize \qquad f(x_{1,}x_{2,}\cdots,x_n)$$

$$Subject \quad to \qquad C_1: \quad g_1(x_{1,}x_{2,}\cdots,x_n) \cong 0$$

$$C_2: \quad g_2(x_{1,}x_{2,}\cdots,x_n) \cong 0$$

$$\cdots\cdots\cdots$$

$$C_m: \quad g_m(x_{1,}x_{2,}\cdots,x_n) \cong 0$$

$$x_i \in D_i \qquad i = 1,2,\ldots,n$$

$$Where \quad \cong \quad means \quad \geq, \leq or =$$

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Introduction

Hydroelectric DSS Model
(Nonlinear Objective Function with Linear Constraints)

$$Maximize \qquad f(x_1, x_2, \cdots, x_n)$$

$$Subject \quad to \qquad a_{11}x_1 + \cdots + a_{1n}x_n \cong b_1$$

$$a_{21}x_2 + \cdots + a_{2n}x_n \cong b_2$$

$$\cdots \cdots \cdots \cdots \cdots \cdots$$

$$a_{m1}x_1 + \cdots + a_{mn}x_n \cong b_m$$

$$l_i \le x_i \le u_i \qquad i = 1, \cdots, n$$

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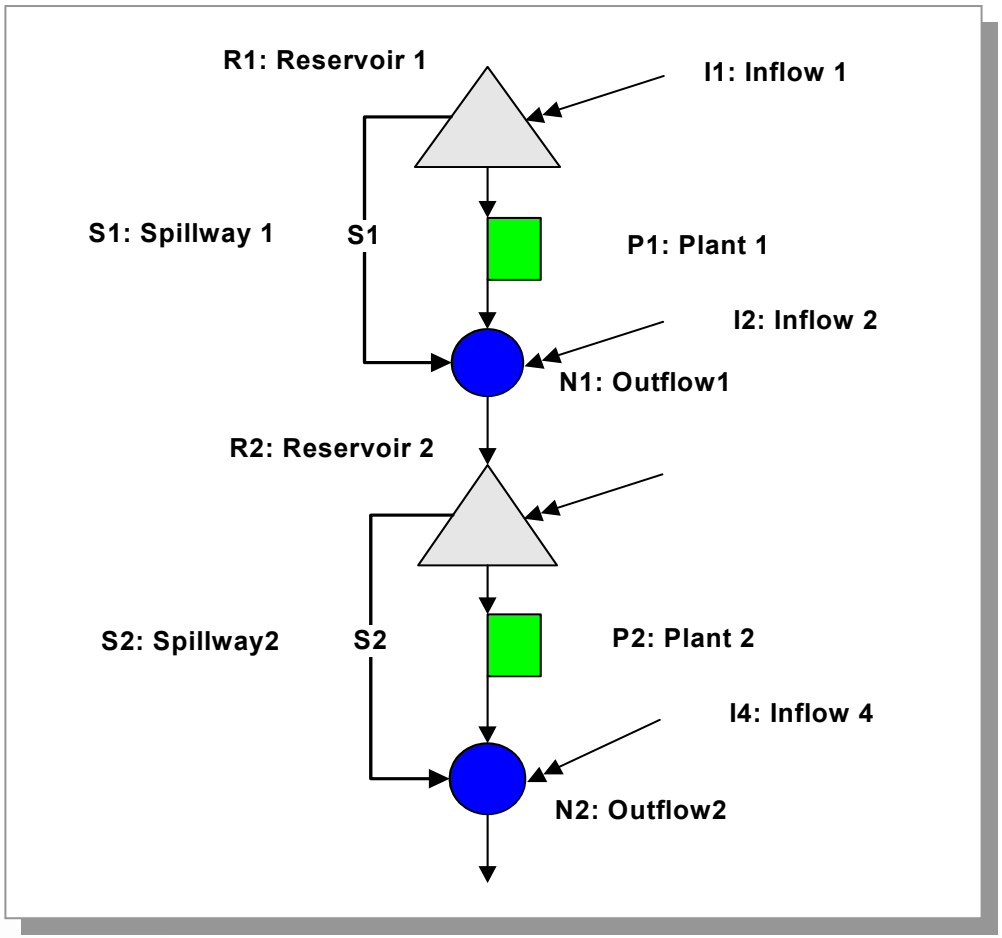
Schematic of a Two Reservoir System



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Formula of a Two Reservoir System

$$\textit{Maximize} \quad \textit{Generation}$$

$$\textit{Subject to} \quad Q_1^1 + S_1^1 + V_1^1 = I_1^1 + V_0^1 \qquad t = 1$$

$$-Q_1^1 - S_1^1 + N_1^1 = I_1^2$$

$$-N_1^1 + Q_1^2 + S_1^2 + V_2^1 = I_1^3 + V_0^2$$

$$-Q_1^2 - S_1^2 + N_1^2 = I_1^2$$

$$-N_t^1 + Q_t^1 + S_t^1 + V_t^1 - V_{t-1}^1 = I_t^1 \qquad t > 1$$

$$-Q_t^1 - S_t^1 + N_t^1 = I_t^2$$

$$-N_t^2 + Q_t^2 + S_t^2 + V_t^1 + V_{t-1}^2 = I_t^3$$

$$-Q_t^2 - S_t^2 + N_t^2 = I_t^4$$

Where $Q_t^1 = \text{discharge}; \quad S_t^1 = \text{Spill}; \quad N_t^1 = \text{outflow}$

$V_t^1 = \text{storage}; \quad I_t^1 = \text{inflow}$

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Formula of a Two Reservoir System (Concluded)

$$\underline{Q}_t^k \le Q_t^k \le \overline{Q}_t^k;$$

$$\underline{S}_t^k \le S_t^k \le \overline{S}_t^k;$$

$$\underline{N}_t^k \le N_t^k \le \overline{N}_t^k;$$

$$\underline{V}_t^k \le V_t^k \le \overline{V}_t^k; \quad and$$

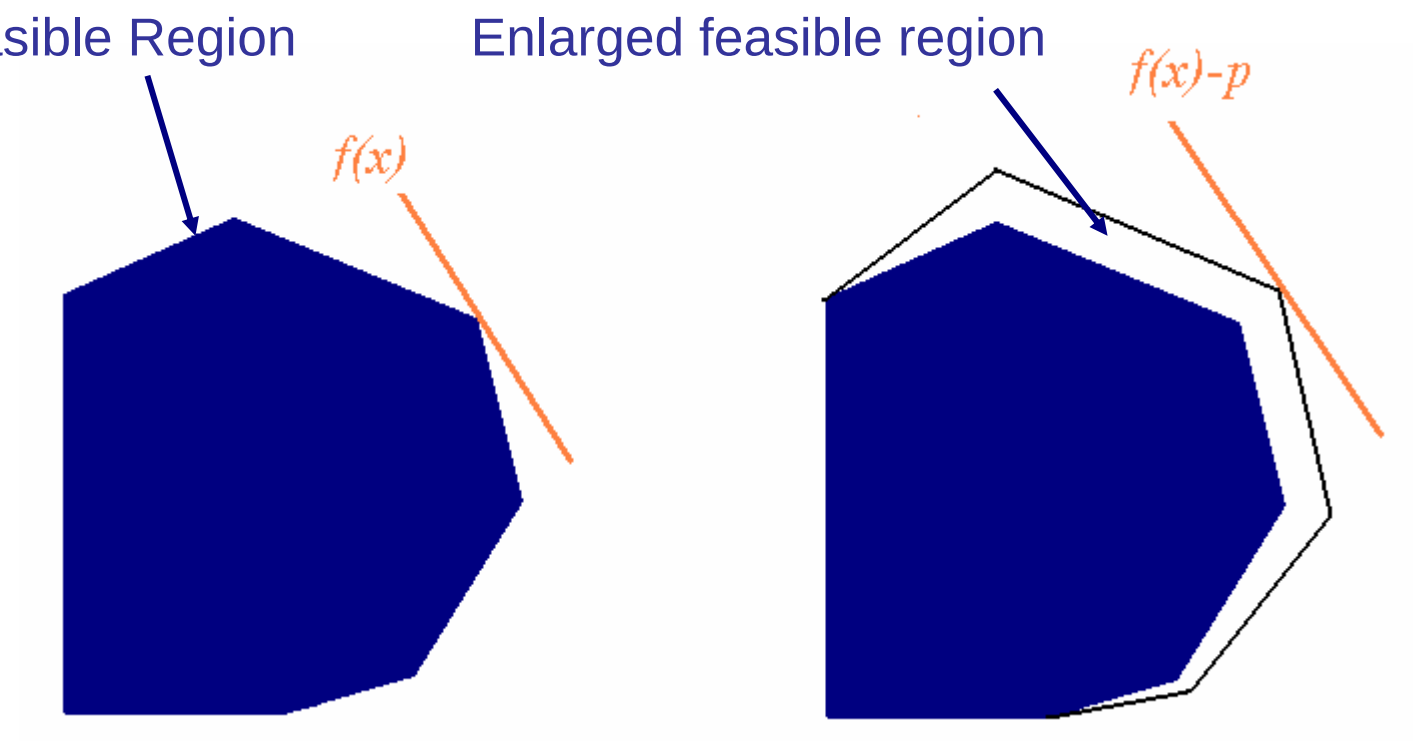
$$V_n^k = ending \quad storage;$$

$$t = 1, \cdots, n \qquad k = 1, 2$$

What is a Soft Constraint?

- Soft constraint is a term used in Constraint Satisfaction Problems (CSP) that allows constraints to be partially satisfied without making a solution unacceptable.

Soft Constraint: Geometry



Why are Soft Constraints Needed?

- Soft constraints represent the real-world operations better than traditional hard constraints.
  - Given higher flexibility to the DSS model and Solve infeasible issues in optimization computations

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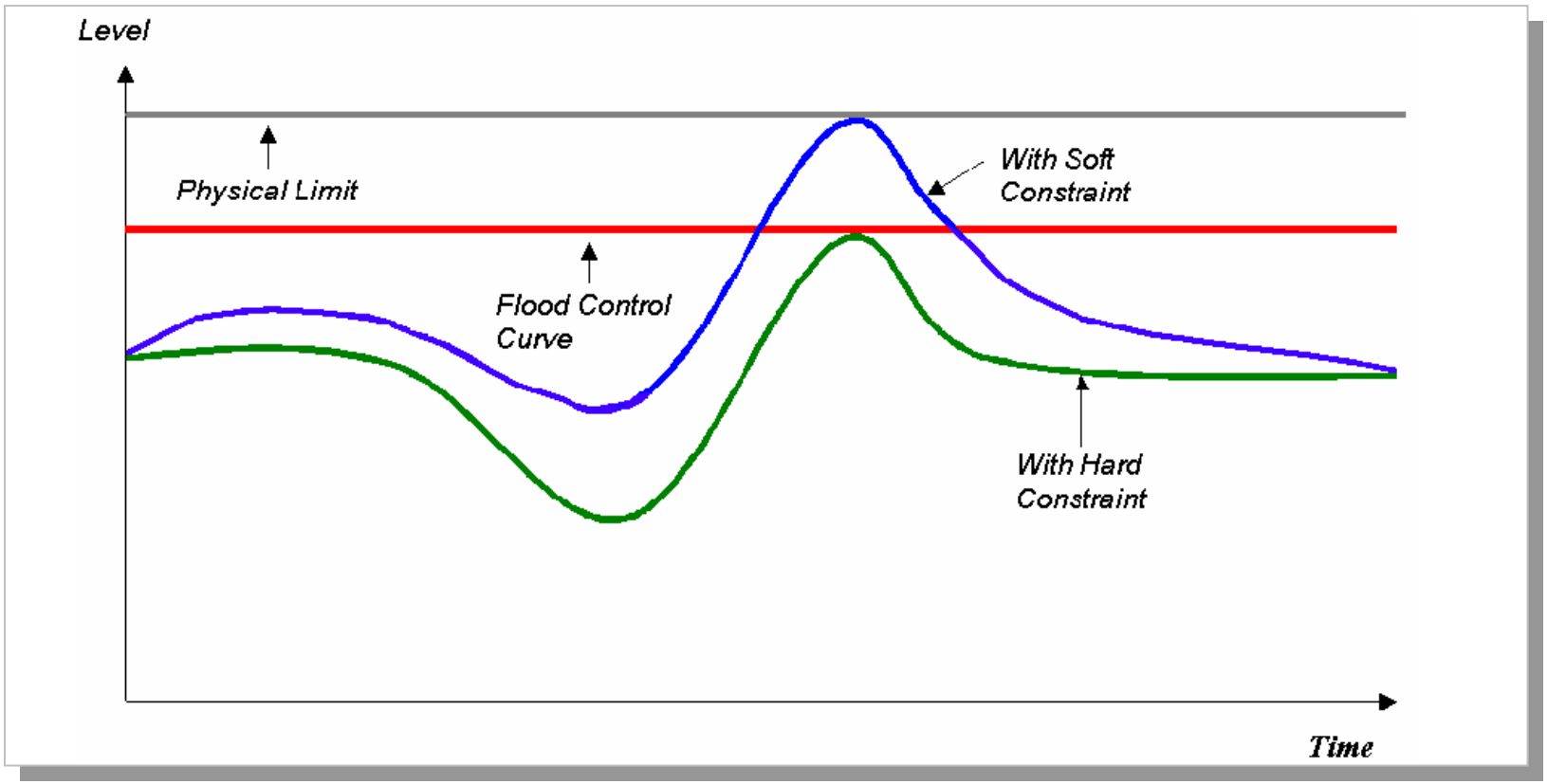
Reality: Flood Control vs. Generation



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Flexibility: Infeasible Issues

- Infeasible means the feasible region is an empty set. In this case, no solution is possible.
- Infeasible may come from data errors, input errors, or unrealistic scenarios, etc.
- Soft constraint give the flexibility to produce useful results

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How Are Soft Constraints Modeled?

- Any constraint may be “softened.”

$$x \leq 10$$

$$x - u \leq 10 \qquad u \geq 0$$

  - Penalty methods.

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- Penalty methods.

$$\max \quad f(x) + \lambda u$$

$$\lambda < 0$$

Penalty Methods for Linear Constraints (≤ ≥ =):

$$\sum_{i=1}^{n} a_j x_j \le b$$

$$\sum_{i=1}^{n} a_j x_j - u \le b \qquad u > 0$$

Add a penalty term λu to the objective.

$$\sum_{i=1}^{n} a_j x_j \ge b$$

$$\sum_{i=1}^{n} a_j x_j + v \ge b \qquad v > 0$$

Add a penalty term λv to the objective.

$$\sum_{i=1}^{n} a_j x_j = b$$

$$\sum_{i=1}^{n} a_j x_j - u + v \le b \qquad u > 0, v > 0$$

Add a penalty term $\lambda (u + v)$ to the objective.

A few examples of Soft Constraints in HYDROPS™

- Soft ending level constraints.
- Soft Soft minimal stream flow soft constraints.
- Soft ramping constraints.
- And many more ……

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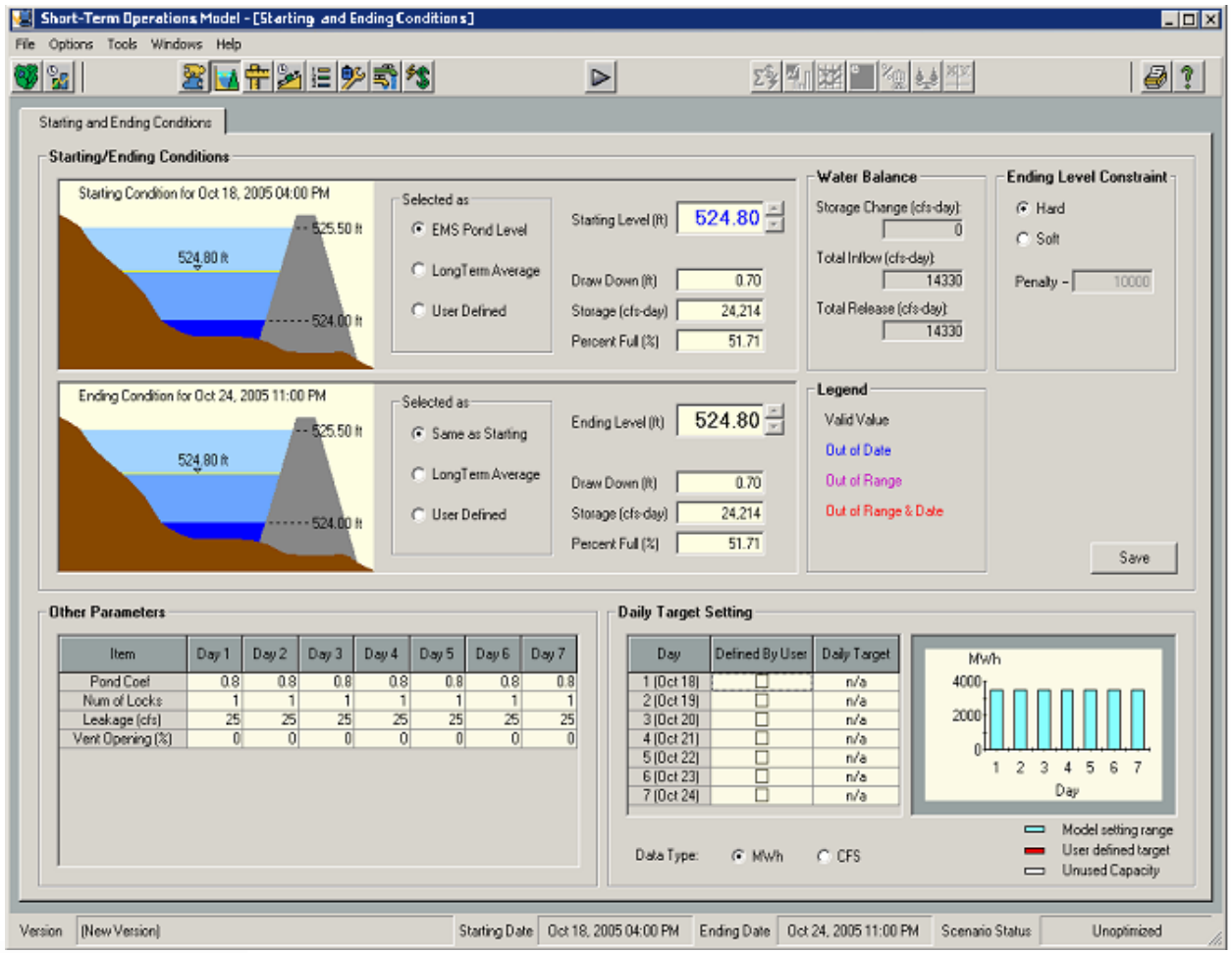
Example 1: Reservoir Soft Ending Constraints



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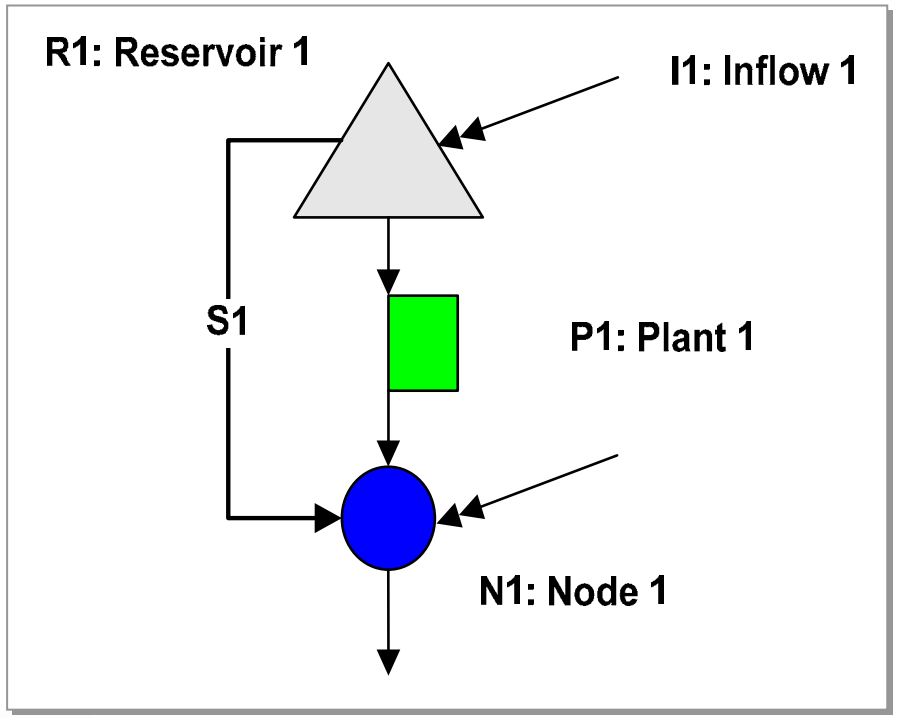
Implementing Soft Constraints in Hydroelectric Decision Support Systems

Example 2: Minimal Flow Soft Constraints



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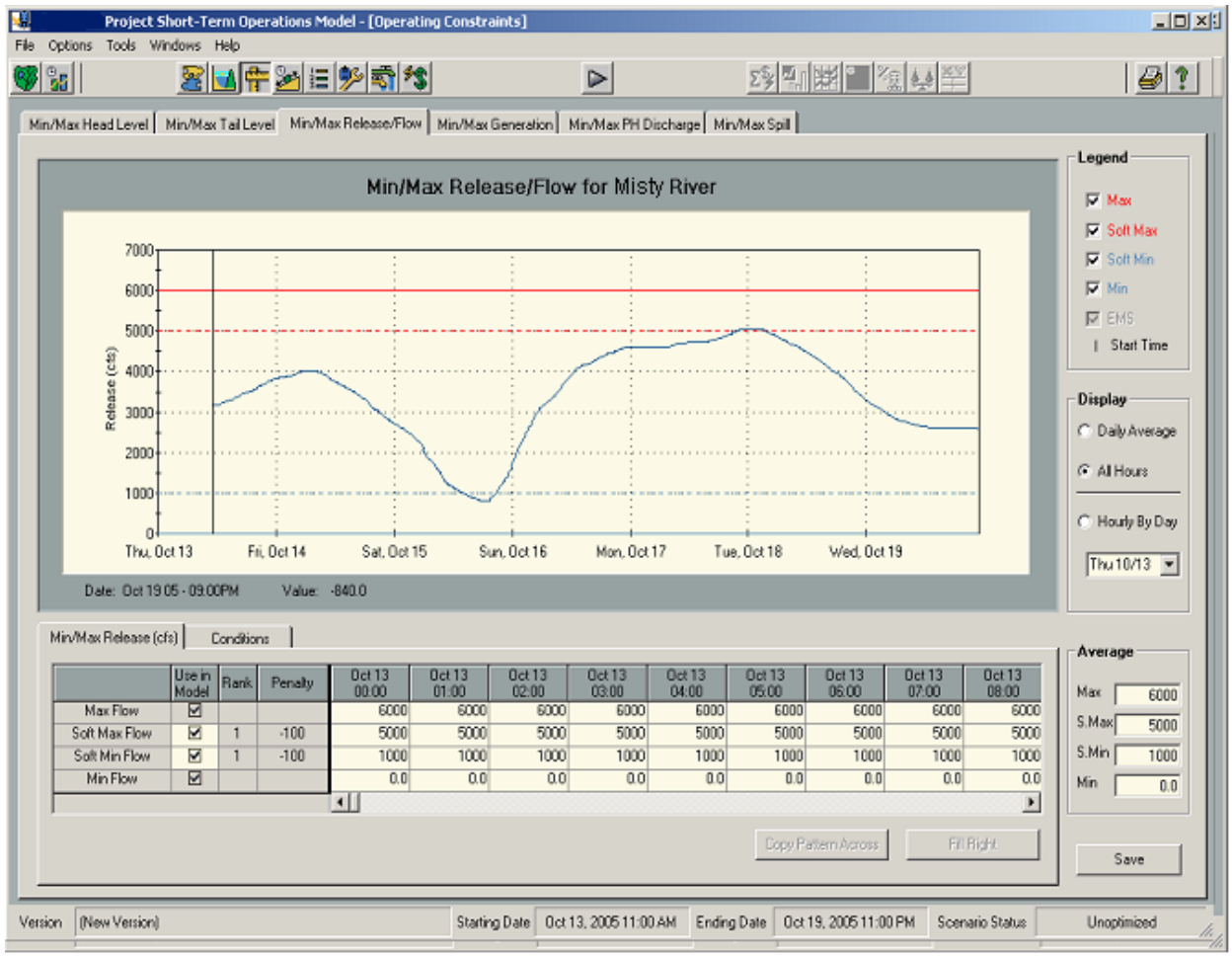
Example 2 : Minimal Flow Soft Constraints (concluded)



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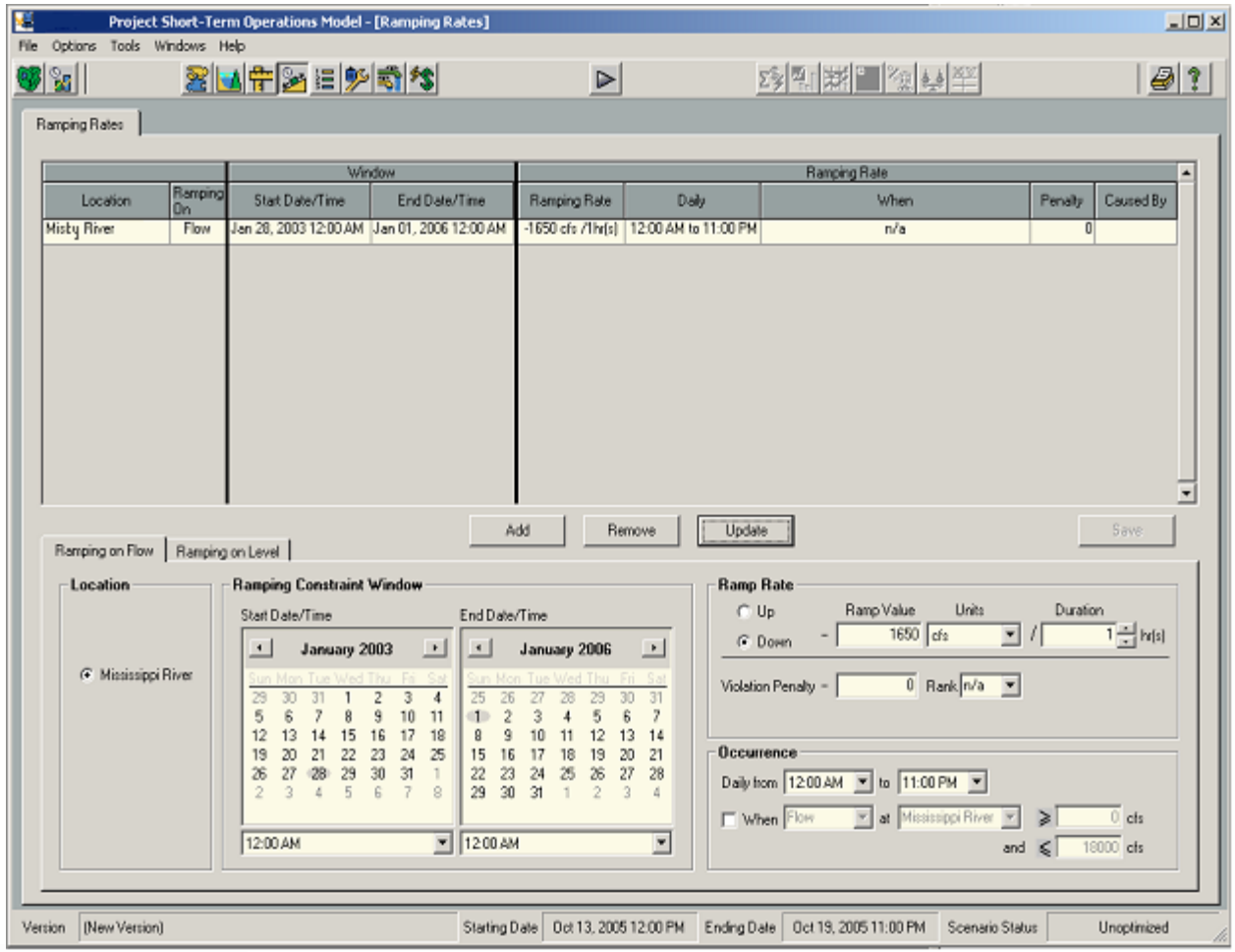
Example 3: Soft Ramping Constraints



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Implementation Issues

- Defining penalty coefficients.
  - When applying multiple soft constraints in a system, it's not easy to find the relationship between the penalty coefficients, especially when the variables have different units.

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Conclusions and Future Development:

- Soft Constraints are a useful tool in Hydroelectric DSS modeling, allowing a model to more closely reflect real-world operations.
- Soft Constraints allow operators to avoid the infeasible caused by data, operator error, etc.
- Soft Constraints are used successfully in HYDROPS™ DSS.
- Under Development: Quantify penalty co-efficiencies, especially for multiple soft constraints.

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Thank You!

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