Presentation for UNESCO conference on Sustainable Water Resources (4-6 Jun 98)

OPTIMIZING CONJUNCTIVE USE FOR SUSTAINABLE PRODUCTION:
TOOLS FOR THE MANAGEMENT SPECTRUM

By

Richard C. Peralta, Shengjun Wu, Fernando Chanduvi and H. J. Morel-Seytoux

1. Authors include Richard Peralta and Shengjun Wu from Utah State University (USU); Fernando Chanduvi from FAO, Rome, and myself. Dr. Peralta sends his regrets for not attending, but important family events were scheduled or became known after he proposed to present at the conference (two college graduations and a wedding between May 30 and June 6). Our topic concerns two simulation/optimization (S/O) models developed at Utah State University to aid managing aquifer and stream-aquifer systems.

2. An S/O model contains both simulation abilities and mathematical optimization algorithm(s). The S/O models discussed here are designed to compute mathematically optimal water management strategies for posed water management problems. The S/O model includes decision and state variables. In common parlance, decision variables are those which managers can control directly (such as groundwater extraction pumping). State variables are those which describe the physical systems response to the management decisions.

   The objective function is an equation that the S/O model will seek to minimize or maximize the value of (per user request). An example objective function is the sum of steady groundwater pumping rates from an area. Such an objective function is commonly used in S/O models seeking to maximize sustainable groundwater pumping.

   Bounds include upper and lower limits on decision or state variables, or even on the objective function value. One might place a lower bound on aquifer head to prevent a pumping strategy from causing unacceptably small saturated thickness near pumping wells.

   Constraints include equations that link decision and state variables, and other conditions that must be satisfied for a computed water management strategy to be acceptable. For example, constraint equations defining aquifer head or flow response to pumping are used in S/O models for computing optimal groundwater management strategies.
3. Here we primarily discuss CONJUS, a new S/O model designed primarily for use at the field level. It requires relatively little data input and so is suitable for relatively homogeneous and simple physical systems. We also mention REMAX, designed to address any aquifer system modelable by MODFLOW (the most commonly used USGS groundwater flow model), STR (the stream-routing package used with MODFLOW) and MT3D (the USGS groundwater contaminant transport model also used with MODFLOW).

4a. REMAX is extremely sophisticated and powerful. As preliminary simulators REMAX includes MODFLOW, STR, MT3D and an analytical solution. These provide input for REMAX to use to create surrogate simulation expressions that are used within the formal optimization process. The surrogate expressions include superposition equations (discretized convolution integral), regression equations, exponential and logarithmic expressions, and neural network(s).

4b. Either skip this or move it to after slide 5. This is what the REMAX main menu looks like. REMAX is very efficiently designed to minimize unnecessary computations. The four main processes are Simulation, Pre-optimization, Optimization and Analysis. Through these steps the user can cause REMAX to be computationally accurate even for nonlinear unconfined aquifer systems.

5. REMAX includes powerful and well tested optimization algorithms that perform linear optimization, nonlinear optimization, mixed integer optimization and MINLP optimization using gradient search or outer approximation methods. These techniques are suitable for most problems addressing sustainable groundwater supply. REMAX also uses genetic algorithm optimization to address groundwater contamination cleanup problems.

6. Thus, REMAX is very well suited for a wide range of management problems, including regional sustained yield planning, conjunctive water management and contaminant plume management. Again, REMAX is most suited for use by groundwater modelers, be they engineers or scientists.

7. Today we want to primarily discuss CONJUS, a new S/O that employs analytical expressions to develop influence coefficients and superposition equations for use in its optimization problems. Peralta and Wu of the Utah State University Irrigation Engineering Dept. developed CONJUS in response to an FAO desire to have tools better suited for use by field personnel that might not have the modeling experience or data to use REMAX.
8. This is the CONJUS front screen. The flow chart on the left illustrates the processing procedure and guides CONJUS usage. The shaded rectangles are buttons that the user presses to initiate certain tasks. The first task involves inputting the data that describes the physical system, including aquifer parameters, observation well, stream and recharge basin existence and potential pumping well locations. The second button causes CONJUS to develop influence coefficients suitable for the physical system.

CONJUS uses analytical equations to compute the influence coefficients. The analytical equations assume the physical system is homogeneous and isotropic...relatively simple. Sometimes field data shows that the physical system responds differently than the equations predict. In that case, as the top diamond shows, and third button show, the user can (guided by his field experience and records) manually change the influence coefficients. This can enable the CONJUS superposition equations to be more suitable, within certain ranges of stimuli and responses, for more complicated and nonlinear physical systems.

The lower diamond and fourth button permit the CONJUS user to select the weights and coefficients he desires for the objective function. This permits economic optimization, such as minimizing cost, and multiobjective optimization via weighting method. CONJUS can also perform multiobjective optimization via constraints.

Pushing the final button causes CONJUS to compute optimal pumping or stream/canal stage management strategies.

9. CONJUS can be used for normal simulation as well as to optimize management of simple systems for the following stress/response situations.
   - effect of gw pumping on stream depletion and gw head (this includes use of image wells)
   - effect of intentional stream(or canal) stage changes on gw head
   - effect of seepage from a line source on gw head
   - effect of recharge via field or basin on gw head

Generally these options are mutually exclusive. One can address only one of these situations at a time.

10. Time-varying variables that the CONJUS can place upper and lower limits on in formulating the optimization problem include gw pumping, head, and gradient; cumulative pumping volume; stream depletion rate and volume; and managed changes in stream/canal stage, seepage from a line source and recharge from a field or pond.

11. CONJUS is very user-friendly and operates from within Microsoft EXCEL. After the user provides initial physical system and management problem characteristics, CONJUS automatically sizes the input data arrays...freeing the user from doubt about how little or much data is required. CONJUS can address a range of optimization problems fro the specified physical system.
12. CONJUS can address problems of any duration and number of stress periods (time steps) as long as each period is of the same duration. However, to aid practical usage, CONJUS also has special superposition equations that permit the user to employ two stress periods of non-uniform duration. These are especially useful in stream depletion studies.

The user can control the relative proportions of water being injected into the aquifer via wells and that being extracted by wells. Injection is most commonly used when groundwater contamination is being managed.

13. For example, a simple problem could have one pumping well located 2500 m from a stream and an observation well located somewhere between the two. Initially, one wants to know the most one can pump steadily for 12 weeks which will cause stream depletion by the end of 12 weeks to exceed a certain rate.

14. In the initial problem input one provides information on number and duration of stress periods, numbers of wells, gradient control locations, and general aquifer parameters.

15. This shows the first data input sheet. Here the user specifies the just-mentioned general problem information. One can only enter data in white cells. One cannot enter data in grey or blue cells. Based on the provided information CONJUS automatically provides the correct numbers of white cells for data entry in subsequent sheets.

16. The next sheet requires this input data specifically for wells and pumping.

17. Note that previously we indicated there would be one extraction well, no injection well, and one observation well. This transparency shows that CONJUS permits us to enter data for only that many wells. Had we specified two extraction wells, CONJUS would have provided white rows for two wells in the top part of the screen.

18. skip the slide, but mention that similarly one enters the lower and upper bounds on pumping rates and heads.

19-20. Skip these slides, but mention that ....Similarly one provides input for problems involving location and orientation of a stream, and a line source of seepage.

22. Skip these slides if you want, but mention that... One enters appropriate data for a recharge basins or fields providing recharge to an aquifer.

23. Skip
24. Here we enter the limit on acceptable stream depletion rate caused at the end of period 1 by pumping during period 1. For this example, we do not use time-varying pumping, although CONJUS easily does so. For problems involving more than two stress periods, all periods must be of equal duration. In that case, CONJUS will compute time-varying optimal water management strategies.

25. One can constrain cumulative pumping volume. This is used to address a problem I (H J M-S) solved in my 197 Groundwater Journal Paper on optimizing conjunctive use. One can determine the smallest size of reservoir needs to prevent unacceptable stream depletion. That example shows how to time one's pumping so as to make best use of the lag between stream depletion and groundwater pumping. Of course that means that pumping must change with time.

26. This shows the influence coefficients that CONJUS computes to describe aquifer head response to pumping, and the unit pumping rates employed to compute those. As specified by problem input, these are computed for the end of 12 weeks of steady pumping (end of period 1) and the end of a subsequent 4 weeks without pumping (end of period 2).

27. This shows the stream depletion rate and volume influence coefficients that CONJUS computes.

28. Here we see a graphic that CONJUS automatically prepares to illustrate the locations of specified wells, etc.

29. This shows part of the CONJUS output sheet. At the top it summarizes that CONJUS used linear programming optimization to maximize the value of the objective function (3,214 cubic meters per day). It summarizes the head that results at the extraction and observation wells at the end of period one, as well as the stream depletion rate at that time and the cumulative depletion volume by that time.

30. This shows the output for period 2, the four weeks during which there was no pumping. Note that although cumulative pumping has not changed from period one, the stream depletion volume and rate have increased.
31. In summary, there are available powerful S/O models to help management of stream-aquifer systems. These are suitable to address physical systems of a wide range of complexities by users having a wide range of experience. CONJUS is most suitable for relatively homogeneous and simple physical systems. One can manually adapt it for nonideal systems if one has sufficient field information. REMAX is suitable for study areas of whatever size and complexity one can simulate. Other simulation models can be used within REMAX than merely MODFLOW. For example, the SWIFT code (suitable for fractured flow) was used within REMAX in one project. REMAX has procedures for automatically adapting to nonlinear systems and correcting for nonlinearities in its computations.

32. Both CONJUS and REMAX are available from Dr. Richard Peralta, in the Biological and Irrigation Engineering (formerly Agricultural and Irrigation Engineering) Dept. at Utah State University. I have a few of Dr. Peralta's business cards. He can be reached via email at peralta@cc.usu.edu, phone at 435 797 2786 in the US, or FAX at 435 797 1248.
TRANSMISSION OK

TX/RX NO. 2969
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CONNECTION ID
START TIME 06/02 16:16
USAGE TIME 05'12
PAGES 7
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OPTIMIZING CONJUNCTIVE USE FOR SUSTAINABLE PRODUCTION: TOOLS FOR THE MANAGEMENT SPECTRUM

Richard C. Peralta
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S/O Model Has

- Variables
- Objective Function
- Bounds
- Constraints
SIMULATION/OPTIMIZATION (S/O) MODELS

- CONJUS...for small relatively simple physical systems, field engineers/scientists
- REMAX...for complex physical systems, groundwater modelers
REMEX
SIMULATION/OPTIMIZATION MODEL

- Analytical, Numerical, & Neural Simulation Expressions
- Superposition Equations
- Optimization Algorithms
REMEX

Simulation/Optimization Model for Optimally Managing Aquifer and Stream/Aquifer Systems by Response Matrix and Response Surface Methods
Version 2.70 \( \ast \) edition
Jan 1998

Richard C. Peralta and Ali H. Aly

Touch S for Simulation
P for Pre-optimization
Q for Optimization
A for Analysis

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Copyright (c) Utah State University
Telephone: (435) 797-2786
Fax: (435) 797-1249

Data Directory
EX1
Not Cycling
REMEX Optimization Options

- Linear Optimization
- Nonlinear Optimization
- Mixed Integer Nonlinear Optimization
- Evolutionary Optimization
Regional sustained yield groundwater management strategies

Conjunctive water management strategies (quantity & quality goals)

Groundwater contaminant plume management strategies (containment & cleanup goals)
CONJUS
SIMULATION/OPTIMIZATION
MODEL

- Analytical Simulation Equations
- Superposition Equations
- Optimization Algorithms
CONJunctive Water Management Utility Software and Simulation/Optimization Tool

Richard C. Peralta and Shengjun Wu

Software Engineering Division
Systems Simulation/Optimization Laboratory
Dept. of Biological and Irrigation Engineering
Utah State University
Logan, UT 84322-2105

Phone: (435) 797-2785/6
Fax: (435) 797-1248
CONJUS Simulation Abilities

- Stream depletion due to gw pumping
- Gw head response to gw pumping (extraction or injection)
- Gw head response to stream stage changes
- Gw head response to line source
- Gw head response to field/basin recharge
Transient Variables

- groundwater pumping rate
- groundwater head & gradient
- cumulative pumping volume
- stream depletion rate & volume
- stream stage change
- line source seepage rate
- field or pond recharge rate
CONJUS Attributes

- User-friendly interface (VBA & Excel 97-based spreadsheet model)
- Automated input array sizing
- Option for manually changing influence coefficients
- Optimization options (linear, quadratic, nonlinear, goal programming, MiniMax, MaxiMin)
CONJUS Attributes

- Ability to use two nonuniform stress periods as well as many uniform stress periods
- Ability to constrain the ratio (total injection / total pumping)
Example Problem

- One extraction well having 15 cm radius, 2500 m from stream
- One observation well between the extraction well and the stream
- Aquifer: 10 m thick, 0.1 storativity, 100 m/day conductivity
- Pump for 12 weeks; stop for 4 weeks

WANTED:
Determine maximum steady pumping during first 12 weeks which will not cause stream depletion by the end of 12 weeks to exceed 0.002 m³/sec (172.8 m³/day)
General CONJUS Input

- Number of stress (time) periods
- Number of extraction, injection, & observation wells
- Number of gradient control pairs
- Aquifer storativity
- Aquifer hydraulic conductivity
- Bounds on (injection / total pumping)
- Stress period duration
### General Management Problem Information

<table>
<thead>
<tr>
<th>No. of periods</th>
<th>No. of extraction wells</th>
<th>No. of injection wells</th>
<th>No. of observation wells</th>
<th>No. of gradient control pairs of observation wells</th>
<th>Simulate stream depletion response to pumping and use image well(s) to compute aquifer head (yes / no)</th>
<th>Simulate aquifer head response to stream stage change without image well(s) considered (yes / no)</th>
<th>Simulate aquifer head response to line source without image well(s) considered (yes / no)</th>
<th>Rectangular recharge areas, generally only one recharge area considered (yes / no)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>yes</td>
<td>no</td>
<td>no</td>
<td>no</td>
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### Additional Problem Information

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<tr>
<th>Storativity</th>
<th>Minimum ratio of injection to total pumping for every period</th>
<th>Maximum ratio of injection to total pumping for every period</th>
<th>Unit period 1 [T]</th>
<th>Unit period 2 [T]</th>
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<td>100</td>
<td>0.1</td>
<td>84</td>
<td>28</td>
</tr>
</tbody>
</table>
Input Concerning Wells & Pumping

- Location
- Aquifer thickness
- Ground surface elevation
- Radius
- Unit pumping rate
- Transient unmanaged groundwater head
- Transient bounds on optimal managed head, pumping, & cumulative pumping
### Extraction Well Information

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<thead>
<tr>
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<tbody>
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<td>10</td>
<td>0.1524</td>
<td>100</td>
<td>2592</td>
<td>100</td>
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### Injection Well Information

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### Observation Well Information

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<td>100</td>
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### Gradient Control Pairs of Observation Wells
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<tbody>
<tr>
<td>100</td>
<td>0</td>
<td>n/a</td>
<td>0</td>
<td>n/a</td>
<td>100</td>
<td>0</td>
<td>n/a</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>100</td>
<td>0</td>
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<td>100</td>
<td>0</td>
<td>100</td>
<td>0</td>
<td>200</td>
<td>100</td>
<td>0</td>
</tr>
</tbody>
</table>
Input for Stream Depletion Problem

- Well information
- Pumping information
- Aquifer information
- Stream location
- Stream orientation
Input for Line Source Problem

- Location and orientation
- Unit seepage rate
- Bounds on seepage rate for each period
### General Stream and Stream Stage Change Information

<table>
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### Line Source Information

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</table>

### Rectangular Recharge Area Information
Input for Rectangular Recharge Problem

- Location
- Orientation
- Size
- Unit seepage rate
- Bounds on seepage in each time period
Input for Stream Depletion Problem

- Well information
- Pumping information
- Aquifer information
- Stream location
- Stream orientation
### Rectangular Recharge Area Information

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</table>

### Stream Depletion Constraints

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</thead>
<tbody>
<tr>
<td>0</td>
<td>172.8</td>
<td>0</td>
<td>n/a</td>
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<td>n/a</td>
<td>0</td>
<td>n/a</td>
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</tbody>
</table>

### Constraints on Cumulative Pumping Volume

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<tr>
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<th></th>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>172.8</td>
<td>0</td>
<td>n/a</td>
<td>0</td>
<td>n/a</td>
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### End of Input Data

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<thead>
<tr>
<th>Level</th>
<th>Minimum</th>
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<tr>
<td>L42</td>
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<td>n/a</td>
</tr>
<tr>
<td>L43</td>
<td>n/a</td>
<td>n/a</td>
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</tbody>
</table>

### Constraints on Cumulative Pumping Volume

<table>
<thead>
<tr>
<th>Level</th>
<th>Minimum</th>
<th>Maximum</th>
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</thead>
<tbody>
<tr>
<td>L42</td>
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<td>n/a</td>
</tr>
<tr>
<td>L43</td>
<td>1.0</td>
<td>2.0</td>
</tr>
</tbody>
</table>

---

**Return to main sheet**
### Influence coefficients

Unless you have changed them, the below coefficients were created by CONJUS using your input data. CONJUS will use these coefficients to calculate the optimal water management strategy.

Influence coefficients describing drawdown for two nonuniform periods:

<table>
<thead>
<tr>
<th>Observation location</th>
<th>Excitation location</th>
<th>pumping during Period 1; observe at the end of period 1</th>
<th>pumping during Period 1; observe at the end of period 2</th>
<th>pumping during Period 2; observe at the end of period 2</th>
<th>Unit pumping</th>
</tr>
</thead>
<tbody>
<tr>
<td>extraction well #1</td>
<td>extraction well #1</td>
<td>3.75663E+00</td>
<td>2.85823E-01</td>
<td>3.53004E+00</td>
<td>2.59200E+03</td>
</tr>
<tr>
<td>observation well #1</td>
<td>extraction well #1</td>
<td>1.24681E-01</td>
<td>1.40059E-01</td>
<td>2.41506E-02</td>
<td>2.59200E+03</td>
</tr>
</tbody>
</table>

Uniperiod(1) = 8.40000E+01

Uniperiod(2) = 2.80000E+01
Depletion rate influence coefficients for two nonuniform periods:

<table>
<thead>
<tr>
<th>Excitation location</th>
<th>pumping during Period 1; observe at the end of period 1</th>
<th>pumping during Period 1; observe at the end of period 2</th>
<th>pumping during Period 2; observe at the end of period 2</th>
<th>Unit pumping</th>
</tr>
</thead>
<tbody>
<tr>
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<td>2.43669E+02</td>
<td>2.16558E+00</td>
<td>2.59200E+03</td>
</tr>
</tbody>
</table>

Depletion coefficients describing volume of river depletion for nonuniform period:

<table>
<thead>
<tr>
<th>Excitation location</th>
<th>pumping during Period 1; observe at the end of period 1</th>
<th>pumping during Period 1; observe at the end of period 2</th>
<th>pumping during Period 2; observe at the end of period 2</th>
<th>Unit pumping</th>
</tr>
</thead>
<tbody>
<tr>
<td>extraction well #1</td>
<td>3.09183E+03</td>
<td>8.46879E+03</td>
<td>7.82103E+00</td>
<td>2.59200E+03</td>
</tr>
</tbody>
</table>
Optimization option: Linear
Maximize precision: 0.001 convergance: 0.002 tolerance: 5%
Use linear model to perform optimization

Objective solution:

Period 1

Optimal pumping and injection rate(s) \([ \text{L}^3/\text{T}]\):
  - pumping of extraction well #1: 3.21447830E+03

Optimal head at extraction and injection well(s) \([ \text{L}]\):
  - head at extraction well #1: 9.53412009E+01

Optimal head at observation well(s) \([ \text{L}]\):
  - head at observation well #1: 9.98453770E+01

Optimal stream depletion rate \([ \text{L}^3/\text{T}]\):
  - 1.72800000E+02

Optimal stream depletion volume \([ \text{L}^3]\):
  - 3.83434145E+03

Cumulative pumping volume \([ \text{L}^3]\):
  - 2.70016177E+05

Ratio of injection to extraction: n/a
Period 2

Optimal pumping and injection rate(s) [L^3 / T]:
  pumping of extraction well #1  0.00000000E+00

Optimal head at extraction and injection well(s) [L]:
  head at extraction well #1  9.9645352E+01

Optimal head at observation well(s) [L]:
  head at observation well #1  9.98263057E+01

Optimal stream depletion rate [L^3 / T]:
  3.02187473E+02

Optimal stream depletion volume [L^3]:
  1.05026053E+04

Cumulative pumping volume [L^3]:
  2.70016177E+05

Ratio of injection to extraction:  n/a
SUMMARY

- Powerful stream-aquifer S/O models
- Suitable for physical systems of a range of complexities
- User-friendly for range of users
- Adaptable to nonlinear systems
- Compute optimal strategies
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Utah St. Univ., Logan, Utah

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OPTIMIZING CONJUNCTIVE USE FOR SUSTAINABLE PRODUCTION:
TOOLS FOR THE MANAGEMENT SPECTRUM

By

Richard C. Peralta, Shengjun Wu, Fernando Chanduvi and H. J. Morel-Seytoux

1. Authors include Richard Peralta and Shengjun Wu from Utah State University (USU); Fernando Chanduvi from FAO, Rome, and myself. Dr. Peralta sends his regrets for not attending, but important family events were scheduled or became known after he proposed to present at the conference (two college graduations and a wedding between May 30 and June 6). Our topic concerns two simulation/optimization (S/O) models developed at Utah State University to aid managing aquifer and stream-aquifer systems.

2. An S/O model contains both simulation abilities and mathematical optimization algorithm(s). The S/O models discussed here are designed to compute mathematically optimal water management strategies for posed water management problems. The S/O model includes decision and state variables. In common parlance, decision variables are those which managers can control directly (such as groundwater extraction pumping). State variables are those which describe the physical systems response to the management decisions.

The objective function is an equation that the S/O model will seek to minimize or maximize the value of (per user request). An example objective function is the sum of steady groundwater pumping rates from an area. Such an objective function is commonly used in S/O models seeking to maximize sustainable groundwater pumping.

Bounds include upper and lower limits on decision or state variables, or even on the objective function value. One might place a lower bound on aquifer head to prevent a pumping strategy from causing unacceptably small saturated thickness near pumping wells.

Constraints include equations that link decision and state variables, and other conditions that must be satisfied for a computed water management strategy to be acceptable. For example, constraint equations defining aquifer head or flow response to pumping are used in S/O models for computing optimal groundwater management strategies.
3. Here we primarily discuss CONJUS, a new S/O model designed primarily for use at the field level. It requires relatively little data input and so is suitable for relatively homogeneous and simple physical systems. We also mention REMAX, designed to address any aquifer system modelable by MODFLOW (the most commonly used USGS groundwater flow model), STR (the stream-routing package used with MODFLOW) and MT3D (the USGS groundwater contaminant transport model also used with MODFLOW).

4a. REMAX is extremely sophisticated and powerful. As preliminary simulators REMAX includes MODFLOW, STR, MT3D and an analytical solution. These provide input for REMAX to use to create surrogate simulation expressions that are used within the formal optimization process. The surrogate expressions include superposition equations (discretized convolution integral), regression equations, exponential and logarithmic expressions, and neural network(s).

4b. Either skip this or move it to after slide 5. This is what the REMAX main menu looks like. REMAX is very efficiently designed to minimize unnecessary computations. The four main processes are Simulation, Pre-optimization, Optimization and Analysis. Through these steps the user can cause REMAX to be computationally accurate even for nonlinear unconfined aquifer systems.

5. REMAX includes powerful and well tested optimization algorithms that perform linear optimization, nonlinear optimization, mixed integer optimization and MINLP optimization using gradient search or outer approximation methods. These techniques are suitable for most problems addressing sustainable groundwater supply. REMAX also uses genetic algorithm optimization to address groundwater contamination cleanup problems.

6. Thus, REMAX is very well suited for a wide range of management problems, including regional sustained yield planning, conjunctive water management and contaminant plume management. Again, REMAX is most suited for use by groundwater modelers, be they engineers or scientists.

7. Today we want to primarily discuss CONJUS, a new S/O that employs analytical expressions to develop influence coefficients and superposition equations for use in its optimization problems. Peralta and Wu of the Utah State University Irrigation Engineering Dept. developed CONJUS in response to an FAO desire to have tools better suited for use by field personnel that might not have the modeling experience or data to use REMAX.
8. This is the CONJUS front screen. The flow chart on the left illustrates the processing procedure and guides CONJUS usage. The shaded rectangles are buttons that the user presses to initiate certain tasks. The first task involves inputing the data that describes the physical system, including aquifer parameters, observation well, stream and recharge basin existence and potential pumping well locations. The second button causes CONJUS to develop influence coefficients suitable for the physical system.

CONJUS uses analytical equations to compute the influence coefficients. The analytical equations assume the physical system is homogeneous and isotropic...relatively simple. Sometimes field data shows that the physical system responds differently than the equations predict. In that case, as the top diamond shows, and third bottom show, the user can (guided by his field experience and records) manually change the influence coefficients. This can enable the CONJUS superposition equations to be more suitable, within certain ranges of stimuli and responses, for more complicated and nonlinear physical systems.

The lower diamond and fourth button permit the CONJUS user to select the weights and coefficients he desires for the objective function. This permits economic optimization, such as minimizing cost, and multiobjective optimization via weighting method. CONJUS can also perform multiobjective optimization via constraints.

Pushing the final button causes CONJUS to compute optimal pumping or stream/canal stage management strategies.

9. CONJUS can be used for normal simulation as well as to optimize management of simple systems for the following stress/response situations.
- effect of gw pumping on stream depletion and gw head (this includes use of image wells)
- effect of intentional stream(or canal) stage changes on gw head
- effect of seepage from a line source on gw head
- effect of recharge via field or basin on gw head

Generally these options are mutually exclusive. One can address only one of these situations at a time.

10. Time-varying variables that the CONJUS can place upper and lower limits on in formulating the optimization problem include gw pumping, head, and gradient; cumulative pumping volume; stream depletion rate and volume; and managed changes in stream/canal stage, seepage from a line source and recharge from a field or pond.

11. CONJUS is very user-friendly and operates from within Microsoft EXCEL. After the user provides initial physical system and management problem characteristics, CONJUS automatically sizes the input data arrays...freeing the user from doubt about how little or much data is required. CONJUS can address a range of optimization problems fro the specified physical system.
12. CONJUS can address problems of any duration and number of stress periods (time steps) as long as each period is of the same duration. However, to aid practical usage, CONJUS also has special superposition equations that permit the user to employ two stress periods of non-uniform duration. These are especially useful in stream depletion studies.

The user can control the relative proportions of water being injected into the aquifer via wells and that being extracted by wells. Injection is most commonly used when groundwater contamination is being managed.

13. For example, a simple problem could have one pumping well located 2500 m from a stream and an observation well located somewhere between the two. Initially, one wants to know the most one can pump steadily for 12 weeks which will cause stream depletion by the end of 12 weeks to exceed a certain rate.

14. In the initial problem input one provides information on number and duration of stress periods, numbers of wells, gradient control locations, and general aquifer parameters.

15. This shows the first data input sheet. Here the user specifies the just-mentioned general problem information. One can only enter data in white cells. One cannot enter data in grey or blue cells. Based on the provided information CONJUS automatically provides the correct numbers of white cells for data entry in subsequent sheets.

16. The next sheet requires this input data specifically for wells and pumping.

17. Note that previously we indicated there would be one extraction well, no injection well, and one observation well. This transparency shows that CONJUS permits us to enter data for only that many wells. Had we specified two extraction wells, CONJUS would have provided white rows for two wells in the top part of the screen.

18. skip the slide, but mention that similarly one enters the lower and upper bounds on pumping rates and heads.

19-20. Skip these slides, but mention that ....Similarly one provides input for problems involving location and orientation of a stream, and a line source of seepage.

22. Skip these slides if you want, but mention that... One enters appropriate data for a recharge basins or fields providing recharge to an aquifer.

23. Skip
24. Here we enter the limit on acceptable stream depletion rate caused at the end of period 1 by pumping during period 1. For this example, we do not use time-varying pumping, although CONJUS easily does so. For problems involving more than two stress periods, all periods must be of equal duration. In that case, CONJUS will compute time-varying optimal water management strategies.

25. One can constrain cumulative pumping volume. This is used to address a problem I (H J M-S) solved in my 197__ Groundwater Journal Paper on optimizing conjunctive use. One can determine the smallest size of reservoir needs to prevent unacceptable stream depletion. That example shows how to time one's pumping so as to make best use of the lag between stream depletion and groundwater pumping. Of course that means that pumping must change with time.

26. This shows the influence coefficients that CONJUS computes to describe aquifer head response to pumping, and the unit pumping rates employed to compute those. As specified by problem input, these are computed for the end of 12 weeks of steady pumping (end of period 1) and the end of a subsequent 4 weeks without pumping (end of period 2).

27. This shows the stream depletion rate and volume influence coefficients that CONJUS computes.

28. Here we see a graphic that CONJUS automatically prepares to illustrate the locations of specified wells, etc.

29. This shows part of the CONJUS output sheet. At the top it summarizes that CONJUS used linear programming optimization to maximize the value of the objective function (3,214 cubic meters per day). It summarizes the head that results at the extraction and observation wells at the end of period one, as well as the stream depletion rate at that time and the cumulative depletion volume by that time.

30. This shows the output for period 2, the four weeks during which there was no pumping. Note that although cumulative pumping has not changed from period one, the stream depletion volume and rate have increased.
31. In summary, there are available powerful S/O models to help management of stream-aquifer systems. These are suitable to address physical systems of a wide range of complexities by users having a wide range of experience. CONJUS is most suitable for relatively homogeneous and simple physical systems. One can manually adapt it for nonideal systems if one has sufficient field information. REMAX is suitable for study areas of whatever size and complexity one can simulate. Other simulation models can be used within REMAX than merely MODFLOW. For example, the SWIFT code (suitable for fractured flow) was used within REMAX in one project. REMAX has procedures for automatically adapting to nonlinear systems and correcting for nonlinearities in its computations.

32. Both CONJUS and REMAX are available from Dr. Richard Peralta, in the Biological and Irrigation Engineering (formerly Agricultural and Irrigation Engineering) Dept. at Utah State University. I have a few of Dr. Peralta's business cards. He can be reached via email at peralta@cc.usu.edu, phone at 435 797 2786 in the US, or FAX at 435 797 1248.

Dear Prof. Peralta,

I am pleased to inform you that your paper mentioned below has been selected by the Conference Organizing Committee for presentation at the Conference and publication in the Proceedings:

Accepted paper: "Optimizing conjunctive Water Use for Sustainable Production: Tools for The Management Spectrum"

You are kindly invited to prepare the full text of your paper and submit it to the Division of Water Sciences before the deadline which is 1 March 1998. All papers submitted before the deadline will be published in the Conference Proceedings and distributed at the Conference.

Please read the attached information note and follow the layout of the example when preparing your text which should be submitted on diskette (Word 6) as well as on hard copy.

I look forward to receiving your contribution.

Yours sincerely

H. Zebidi
Water Sciences Specialist

Prof. Richard C. Peralta
Department of Biological and Irrigation Engineering
Utah State University
Building EC-216
Logan, Utah
84322-4105 USA
Email: peralta@cc.usu.edu
Fax: +1 801 274 3536; Tel: +1 801 797 2786
Participants are invited to submit papers or posters on the themes of the Conference, for presentation both at the plenary sessions and during the working group sessions.

Abstracts of no more than one page are to be sent to the Division of Water Sciences, UNESCO, Paris, before 15 September 1997.

An International Organizing Committee will select the papers to be presented at the Conference and the related authors will be notified by the end of December 1997; the deadline for submission of the full papers is the end of April 1998.

Articles of the Conference will be published after the Conference and will include the papers presented and recommendations.

All those interested in taking part in the Conference and/or presenting papers or posters are invited to complete this form and to return it as soon as possible by post or by fax to:

UNESCO
Division of Water Sciences
1 Rue Miollis
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Utah State University
Biological and Irrigation Engineering
Logan, UT 84322-4105 USA

FAX Number: (801) 797-1248
Telephone: (801) 797-2785

To:
Dr. Kanniah
Phone 396 570 54033

FAX Number:

From: R. Pealth.

Date: 30 Sep 97.

Pages (Including this sheet):

Message: Here is the paper abstract I submitted in the UNESCO conference. It will include a summary of tools in the conjunctive use. Please report I an preparation. Please let me know if you want to be a co-author & whether you will be able to attend.

R.L.

[The report is coming soon. I plan to complete it soon. Software is also... for field level use.]
At the end of the century, concern about the availability of water resources to meet the needs of future economic and social development is increasing. Awareness of the importance of this vital resource heightens daily. Countries situated in the arid and semi-arid regions will face a water crisis in the years to come; sharing of transboundary rivers or groundwater systems may bring about conflict in others. What is the present situation with regard to the availability of water resources in the world and what are the problems to be encountered in the future?

The publication by UNESCO, in the framework of the International Hydrological Programme, of the monograph *World Water Resources at the beginning of the 21st Century* gives an opportunity to the international scientific community to review and discuss the knowledge gathered to date on the water resources of the world and to identify the problems to be faced in the next century.

**Objectives**

- To take stock of the present knowledge of water resources of the world considering both the quantitative and qualitative aspects;

- To identify water problems to be faced in the next century due to the increased demand for water for human water supply, irrigation and industry;

- To make recommendations to the international scientific community for dealing with future challenges.

**Themes of the Conference**

- State of knowledge of the water resources of the world (both quantitative and qualitative aspects);

- Data and improvement of Water resources assessment;

- Water quality and environmental impact;

- Impact of human activity on water resources;

- Scarcity of water resources;

- Economic and social aspects of water resources.

The Conference takes the place of the 4th IAHS/IHP Kovacs Colloquium. The programme is as follows:

**Day 2: Plenary session**

Presentation and discussion of:
- the IHP monograph on *World Water Resources at the beginning of the 21st Century*;
- other monographs and synthesis of the regional and/or global assessment of water resources.

**Day 2 and 3: Working group activities**

Five working groups will be established to consider the main themes of the conference and to work in parallel.

**Day 4: Plenary session**

Presentation, discussion and adoption of the main conclusions and recommendations submitted by the working groups.

**Languages**

*Plenary sessions:* English, French, Spanish and Russian with interpretation.

*Working groups:* English and French without interpretation.
Pre-Registration Form

Title: Professor (decrease as appropriate)
Name: Richard C. Peralta
Institute/Organization/Company: Utah State University
Postal Address: USU/DBIE
Bldg. EC-216
Logan, UTAH 84322-4105, USA
Fax: 801-797-1248
E-Mail: peralta@cc.usu.edu
Tel: 801-797-2786
Telex: 

I Plan to attend the Conference
I wish to present a paper/poster on the following topic:

Optimizing conjunctive water use for sustainable production: tools for the management spectrum

Date: 30 May 97
Signature: __________________________

All those interested in taking part in the Conference and/or presenting papers or posters are invited to complete this form and to return it as soon as possible by post or by fax to:

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To: D. of Water Sciences, UNESCO
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From: Richard Peralta (E-mail: peralta@cc.usu.edu)
(Phone 801 797 2786)

Date: 15 Sep 97

Pages (Including this sheet):

Message: Please accept/consider the attached abstract for the UNESCO conference scheduled for 3-6 June 98 in Paris (Water... a looming crisis?).

Please send me the preregistration or registration materials. Can you also please confirm to me that you received this fax?

I have not seen an announcement for this conference, but was told about it by Dr. H.J. Morel-Seydoux. I & my wife (French ancestry) would like to come very much.

Abstract submitted for presentation at conference "Water: a looming crisis?"

"Gestion intégrée optimale des eaux de surface et souterraines dans un grand bassin".

par
H.J. Morel-Seytoux
Hydrology Days Publications
57 Selby Lane
Atherton, CA 94027
Etats-Unis d'Amérique
tel. et fax (650) 365 4080
email: morels@nsge.gov

Massé dans ses deux volumes (1946) discute le problème de la gestion optimale des lachures dans le cas d'un seul réservoir de surface quand le bénéfice est dérivé de la production d'énergie hydroélectrique. Massé obtint ses résultats à la fois par un raisonnement économique et par une généralisation du Calcul des Variations. Sa méthode lui permit de fournir la preuve rigoureuse de la méthode graphique de Varlet (1923), dite du "fil tendu". Dans cet article on généralise la procédure de Massé au cas où (1) le bénéfice est réalisé bien en aval du point de lachure, (2) il y a plusieurs "point-cibles" (points où un certain objectif doit être assuré), (3) il y a plusieurs réservoirs, et (4) les rivières sont en connection hydraulique avec la nappe alluviale. Massé avait trouvé que la gestion optimale est celle qui maintient la valeur marginale du bénéfice constante dans le temps, pourvu que la gestion soit en régime libre, c'est à dire tant que le réservoir ne fonctionne ni à plein ni à vide. On montre de manière rigoureuse dans le cas général que pour une gestion optimale ce qui doit rester constant dans le temps c'est la somme des valeurs marginales futures des bénéfices en tous les point-cibles tant pour les lachures des réservoirs de surface que pour les débits de pompage dans la nappe aquifère. Les "bénéfices" sont réalisés par la réduction des inondations et par la fourniture des besoins pour l'alimentation d'eau potable. On donne des exemples (simplifiés) d'application pour un bassin illustratif dont les caractéristiques reflètent celles du bassin de la Seine jusqu'à l'aval immédiat de Paris.
Hotels located near UNESCO

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28 May 98

TO: Dr. Hubert J. Morel-Seytoux (presenter)
     Mr. Zebidi (UNESCO conference organizer)

SUBJ: Transparencies and Presentation scheduled for 4 June 1998 at UNESCO Conference

'Optimizing Conjunctive Use for Sustainable Production: Tools for the Management Spectrum'

Because of a daughter's wedding and two daughters' graduations from college, I cannot attend the conference. Mr. Zebidi says my paper is scheduled for Thursday morning. I had earlier told Dr. M-S that I would send the transparencies for the presentation to the hotel he will be staying at. This message is to notify both of you that instead, I will today send them by Federal Express to Mr. Zebidi. I still hope that Dr. M-S will give the presentation, but if for any reason he cannot do so (conflict with another presentation, transportation strike, etc.) I hope Mr. Zebidi will arrange for the presentation to be given.

The paper, which includes Dr. M-S as a coauthor, is scheduled for Thursday morning. Because Mr. Zebidi is a conference organizer, he wanted me to mail the transparencies to him and he said he would get them to Dr. M-S. Federal Express said the shipment would arrive in Paris 2 days after shipping. I decided to send the mailing to Mr. Zebidi at UNESCO instead of to Dr. M-S at his future hotel in order to avoid the possibility that the hotel would not know what to do with the shipment (if it arrived before Dr. M-S), and also to avoid a problem in case Dr. M-S's main presentation is scheduled for the same time as this one. I hope Mr. Zebidi will get them to Dr. M-S quickly so Dr. M-S has time to prepare for the presentation.

In the shipment are 31 transparencies, a paper copy of all of these, and typed text to accompany the transparencies. One could read the text (except where I write that you could delete a transparency in the interest of time). One practice run will tell you whether to delete the transparency or not. The text can be copied and distributed, if desired.

I hope that you two will be able to contact each other so that Dr. M-S can obtain the transparencies as quickly as possible and prepare for the presentation. Your respective locations are:

Dr. Hubert J. Morel-Seytoux (arrival on 2 June); Hotel Segur
31 Boulevard de Garibaldi, 75015 Paris, FRANCE
ph 33-1-43 06 01 85, fax 33-1-43 47 34 30 82

Mr. Zebidi; International Hydrological Programme, Division of Water Sciences
1, rue Miollis, 75732 Pans Cedex 15
ph 45 68 39 98 or 45 68 10 00
FAX 33 1 45 68 58 11

Please confirm receipt

Hubert

OPTIMIZING CONJUNCTIVE WATER USE FOR SUSTAINABLE PRODUCTION: TOOLS FOR THE MANAGEMENT SPECTRUM

Richard C. Peralta, Professor, Dept. of Biological and Irrigation Eng., Utah State Univ., Bldg. EC-216, Logan Utah, 84322-4105, USA
ph (801) 797-2786, FAX (801) 797-1248, E-mail peralta@cc.usu.edu

Arumugam Kandiah, Senior Officer (Sustainable Water Development), Food and Agriculture Organization of the United Nations, Room B-727, Viale delle Terme di Caracalla - 00100 Rome, ITALY

Making best use of water resources requires coordinating use of groundwater and surface waters--conjunctive use. Conjunctive water management is important on the regional (watershed or aquifer), water district and field scales. Goals might differ for the different administrative levels. A regionally optimal water management strategy is not necessarily optimal for water district managers and individual farmers. Interactions between levels are affected by laws, regulations, traditions and public pressure.

To help each organizational level develop water management strategies that best achieve its goals, computer simulation/optimization (S/O) models are useful. Such S/O models couple water flow and transport simulation techniques with formal mathematical optimization algorithms. When properly calibrated, S/O models can be immensely valuable.

S/O models have long been used for managing reservoir releases and surface water resources. S/O model use for large-scale groundwater management and contaminant plume management is becoming more common. Advances in computer power and mathematical optimization procedures make it possible to address large problems previously impractical.

Likewise, increasing availability and power of PC computers and operating systems make it now practical for water district personnel and field engineers to develop optimal water management strategies. By exercising care appropriate for data and model accuracy, field-level S/O model users can develop better solutions for their management problems.

The use of S/O models at all water management levels makes it easier to negotiate compromise solutions when goals differ. S/O models are easily used to develop trade-off curves showing how much of one goal achievement must be forfeited to achieve more of another goal. Communication is enhanced when both negotiating parties have reliable trade-off information. Furthermore, S/O model and trade-off curve use highlights differences in data or understanding of data available to the parties--making it easier to resolve those differences.

This paper discusses robust S/O software available and useful for the spectrum of groundwater and surface water managers. This software promotes improved water management and goal achievement. Case studies illustrate benefits of S/O model use.
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To: Dr. Landish
Phone 396 5225 6278
FAX Number: 396 5225 6278

From: R. Peale, Jr.

Date: 30 Sep 97

Pages (including this sheet):

Message: Here is the paper abstract I submitted for the UNESCO conference. It will include a summary of tools in the Cooperative Use Report I am preparing. Please let me know if you want to be a co-author and whether you will be able to attend.

R. J.

The report is coming soon. I plan to complete it soon. Software is needed for field level use.

OPTIMIZING CONJUNCTIVE WATER USE FOR SUSTAINABLE PRODUCTION: TOOLS FOR THE MANAGEMENT SPECTRUM

Richard C. Peralta, Professor, Dept. of Biological and Irrigation Eng., Utah State Univ., Bldg. EC-216, Logan Utah, 84322-4105, USA ph (801) 797-2786, FAX (801) 797-1248, E-mail peralta@cc.usu.edu

Arumugam Kandiah, Senior Officer (Sustainable Water Development), Food and Agriculture Organization of the United Nations, Room B-727, Viale delle Terme di Caracalla - 00100 Rome, ITALY

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S/O models have long been used for managing reservoir releases and surface water resources. S/O model use for large-scale groundwater management and contaminant plume management is becoming more common. Advances in computer power and mathematical optimization procedures make it possible to address large problems previously impractical.

Likewise, increasing availability and power of PC computers and operating systems make it now practical for water district personnel and field engineers to develop optimal water management strategies. By exercising care appropriate for data and model accuracy, field-level S/O model users can develop better solutions for their management problems.

The use of S/O models at all water management levels makes it easier to negotiate compromise solutions when goals differ. S/O models are easily used to develop trade-off curves showing how much of one goal achievement must be forfeited to achieve more of another goal. Communication is enhanced when both negotiating parties have reliable trade-off information. Furthermore, S/O model and trade-off curve use highlights differences in data or understanding of data available to the parties—making it easier to resolve those differences.

This paper discusses robust S/O software available and useful for the spectrum of groundwater and surface water managers. This software promotes improved water management and goal achievement. Case studies illustrate benefits of S/O model use.
a looming crisis

International Conference
on
at the beginning of the 21st Century
UNESCO Paris, 3-6 June 1998

Participants are invited to submit papers or posters on the themes of the Conference, for presentation both at the plenary sessions and during the working group sessions.

Abstracts of no more than one page are to be sent to the Division of Water Sciences, UNESCO, Paris, before 15 September 1997. An International Organizing Committee will select the papers to be presented at the Conference and the related authors will be notified by the end of December 1997. The deadline for submission of the full papers is the end of April 1998.

Water: a looming crisis?

Water: a looming crisis?

World Water Resources

Title: Prof./Dr/Ms.
Name:
Institution/Organization/Company:
Postal Address:
Fax:
E-Mail:
Tel:
Fax:

Date: Signature:

All those interested in taking part in the Conference and/or presenting papers or posters are invited to complete this form and to return it at once, as possible, by post or by fax to:

Division of Water Sciences
1 Rue MiLe Can
75732 Paris Cedex 15 - France
Fax: 33 1 45 68 58 15

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At the end of the century, concern about the availability of water resources to meet the needs of future economic and social development is increasing. Awareness of the importance of this vital resource heightens daily. Countries situated in the arid and semi-arid regions will face a water crisis in the years to come; sharing of transboundary rivers or groundwater system may bring about conflict in others. What is the present situation with respect to the availability of water resources in the world and what are the problems to be encountered in the future?

The publication by UNESCO, in the framework of the International Hydrological Programme, of the monograph World Water Resources at the beginning of the 21st Century gives an opportunity to the international scientific community to review and discuss the knowledge gathered to date on the water resources of the world and to identify the problems to be faced in the next century.

**Objectives**

- To take stock of the present knowledge of water resources of the world, considering both the quantitative and qualitative aspects.

- To identify water problems to be faced in the next century due to the increasing demand for water for human water supply, irrigation and industry.

- To make recommendations to the international scientific community for dealing with future challenges.

The Conference takes the place of the 4th IAH5/IHP Kovacs Colloquium. The programme is as follows:

**Day 1: Plenary session**

Presentation and discussion of:

- the IHP monograph on World Water Resources at the beginning of the 21st Century;
- other monographs and synthesis of the regional and/or global assessment of water resources.

**Day 2 and 3: Working group activities**

The working groups will be established to consider the main themes of the conference and to work in parallel.

**Day 4: Plenary session**

Presentation, discussion and adoption of the main conclusions and recommendations submitted by the working groups.

**Languages**

Plenary sessions: English, French, Spanish and Russian with interpretation.

Working groups: English and French without interpretation.

Themes of the Conference:

- State of knowledge of the water resources of the world (both quantitative and qualitative aspects).
- Data and improvement of water resources assessment.
- Water quality and environmental impact.
- Impact of human activity on water resources.
- Scarcity of water resources.
- Resource management and balance of water resources.
With the compliments of

H. Zehidi

Division of Water Sciences

In reply to your fax of 5 September please find herewith a copy of the request for abstracts of our International conference on World Water Resources at the Beginning of the Twenty-First Century.

Water: a looming crisis?

Mr Richard Parsons
Utah State University
Biological and Irrigation Engineering
Logan, UT 84322-4108
USA

16 September 1997
Pre-Registration Form

Title: Prof./Dr/Mr/Ms (delete as appropriate)
Name:
Institute/Organization/Company:
Postal Address:
Fax:
E.Mail:
Tel:
Telex:

1. Plan to attend the Conference
2. I wish to present a paper/poster on the following topic:

Abstracts of no more than one page are to be sent to the Division of Water Sciences, UNESCO, Paris, before 15 September 1997.

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The Proceedings will be published after the Conference and will include the main overviews and recommendations.

Water: a looming crisis

UNESCO
Paris
3-6 June 1998

Convened
- The United Nations Education, Scientific and Cultural Organization (UNESCO)
- The International Hydrological Sciences
- The World Council of Water Sciences
- The International Association of Hydrological Sciences
- The Water Council (WAC)
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- To take stock of the present knowledge of water resources of the world considering both the quantitative and qualitative aspects;

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**Themes of the Conference**

- State of knowledge of the water resources of the world (both quantitative and qualitative aspects)

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- Impact of human activity on water resources

- Scarcity of water resources

- Economic and social aspects of water resources

**Organization**

The Conference takes the place of the 4th IAHS/IHP Kovacs Colloquium. The program as follows:

**Day 1: Plenary session**

Presentation and discussion of:

- the IHP monograph on World Water Resources at the beginning of the 21st Century;

- other monographs and synthesis of the regional assessment of water resources.

**Day 2 and 3: Working group activities**

Five working groups will be established to cover the main themes of the conference and to work on:

- Water quality and environmental impact
- Impact of human activity on water resources
- Scarcity of water resources
- Economic and social aspects of water resources

**Day 4: Plenary session**

Presentation, discussion and adoption of the conclusions and recommendations submitted by the working groups.

**Languages**

Plenary sessions: English, French, Spanish and with interpretation.

Working groups: English and French without interpretation.