Proceedings of the International Seminar
Rain water harvesting and management of small reservoirs in arid and semiarid areas

an expert meeting within the EU-INCO collaboration HYDROMED (Program for research on hill reservoirs in the semiarid zone of the Mediterranean periphery).
Lund University, 29 June - 2 July, 1998

Editor Ronny Berndtsson

Sponsoring organizations: ORSTOM/HYDROMED, Swedish International Development Cooperation Agency (SAREC), Swedish Natural Science Research Council (NFR), and Lund University

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Preface

The increasing need for water in arid and semiarid countries is putting larger and larger stress on the management system for drinking water, irrigation water, sanitation, etc. In many of these countries, the management systems have traditionally relied on large-scale reservoirs for the collection and storage of fresh-water. Large-scale solutions can, however, not be applied everywhere and for climatic and physiographical conditions. Instead, there is now a tendency to try to find solutions which are based on local pre-requisites and traditional knowledge. In Tunisia, within the framework of the program "Planning of sloping lands, utilization of potential water resources, and maintenance and protection of existing resources" included in the 8th Tunisian governmental plan, the building of 1000 small hill reservoirs by the year 2000 is planned. Out of these, 250 small reservoirs have already been constructed. The objectives are further to reduce soil erosion for farming lands (estimated losses at present 10000 ha/year), to reduce sedimentation in dams (estimated at present 25 M m³), to increase the groundwater recharge in order to save about 500 M m³ of water which at present are lost to evaporation (source: Tunisian Ministry of Agriculture, Direction of Water and Soil Conservation). During 1996 an INCO-DC European Union program was started including Tunisia, Morocco, Syria, Lebanon, France, England, Spain, and Sweden. The objective of this program was to study sustainable management alternatives for small fresh-water reservoirs. The cooperation program, HYDROMED - Research on small reservoirs in the arid zone of the Mediterranean, lead also forward to a specialized seminar on rainwater harvesting and management of small reservoirs in arid and semiarid areas. The objective of the seminar was to exchange ideas and techniques for rainwater harvesting in dry countries as a way to safeguard limited water resources. The final outcome of the seminar is the present proceedings.
## Contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Observation techniques; GIS/remote sensing; climatic, soil, agronomic, and socioeconomic data storage and processing for small watersheds; (chairman: Dr. Jean Albergel, ORSTOM).</td>
<td>9</td>
</tr>
<tr>
<td>Hydrology of Sindyaneh Wadi Basin in Syria, Dr. Abdallah Droubi, ACSAD, Dr. Salah Kara Damour, MIDS, Dr. Jean Albergel, ORSTOM, and Yasser Ibrahim, ACSAD.</td>
<td>11</td>
</tr>
<tr>
<td>Small dams' water balance: experimental conditions, data processing and modeling, Dr. Jean'Albergel, ORSTOM, Mr. Slah Nasri, INRGREF, and Dr. Mohamed Boufaroua, MAT.</td>
<td>45</td>
</tr>
<tr>
<td>Integrating soil profile and soil hydraulic properties data bases to be used in simulation models and land evaluation expert systems, Prof. Felix Moreno, Dr. D. de la Rosa, and Dr. J. E. Fernandez, IRNAS.</td>
<td>59</td>
</tr>
<tr>
<td>Lebanese hydrology and needs for water storage, Dr. Bassam Jaber and Dr. Fuad Saad, MHER.</td>
<td>71</td>
</tr>
<tr>
<td>Remote sensing applications for the management of small catchments in arid and semi-arid areas, Dr. Chuqun Chen, CAS.</td>
<td>85</td>
</tr>
<tr>
<td>2. Water quality and quantity; hydrological and transport modeling; (chairman: Dr. Jean Khouri, ACSAD).</td>
<td>93</td>
</tr>
<tr>
<td>Water chemistry characteristics in small reservoirs of semiarid Tunisia, Dr. Nathalie Rahaingomanana, ORSTOM.</td>
<td>95</td>
</tr>
<tr>
<td>Water chemistry of a small reservoir catchment in central Tunisia, Dr. Jean-Pierre Montoroi, Dr. O. Grunberger, ORSTOM, and Mr. Slah Nasri, INRGREF.</td>
<td>107</td>
</tr>
<tr>
<td>Solute transport and soil water content measurements in arid soils using time domain reflectometry, Dr. Magnus Persson, I.U.</td>
<td>123</td>
</tr>
<tr>
<td>Decision support system in hydrological modeling, a case study in China, Dr. Linus Zhang, I.U.</td>
<td>135</td>
</tr>
</tbody>
</table>
3. Rainwater harvesting; infiltration techniques and modeling; infiltration and erosion (chairman: Dr. Nejib Rejeb, INRGREF).

Water harvesting techniques in the Mediterranean, Prof. Dr. Dieter Prinz, KU. 151

The use of TDR for wetness measurements in soil erosion and conservation practices in small watersheds, Mr. Slah Nasri, INRGREF, and Dr. Patrick Zante, ORSTOM. 165

Land use transformation impact on reservoir siltation in Morocco: the need for better assessment tools, Dr. Abdelaziz Merzouk, IAV. 191

Modeling small dams' siltation with MUSLE, Dr. Jean Albergel and Mr. Yannick Pepin, ORSTOM. 195

Small-scale cistern system for rainwater collection and storage in north-western China, Dr. Linus Zhang, LU and Prof. Kun Zhu, LRI, and Dr. Ronny Berndtsson, LU. 205

Disinfection and fresh-keeping of rainwater in small scale cisterns, Prof. Kun Zhu and Dr. Chen Hui, LRI, Dr. Linus Zhang and Dr. Ronny Berndtsson, LU. 215

Strategy of soil and water conservation in Tunisia, Dr. Habib Farhat and Dr. Mohamed Boufaroua, MAT. 231

4. Reservoir planning, operation and management; Rainfall-inflow relationships; Dam design and operation; Surface-groundwater interactions (chairman: Dr. Abdelaziz Merzouk, IAV).

Groundwater recharge and modeling in an experimental catchment, Mr. Slah Nasri, INRGREF. 257

Deterministic versus stochastic hydrological modeling; uncertainties and decisions, Mr. Jan Hoybye, LU. 275

Neural network methodology to simulate discharge, Dr. Cintia Uvo, LU. 295

Appendix

1. Program 307
2. List of participants 311
Abbreviations:

ACSAD: Arab Center for the Studies of Arid Zones and Dry Lands, Syria.
CAS: South China Sea Institute of Oceanography, Chinese Academy of Sciences, China
IAV: Institute for Agronomy and Veterinary Hassan II, Morocco.
IRNAS: Institute for Natural Resources and Agrobiology, Spain.
KU: Karlsruhe University, Germany.
LRI: Lanzhou Railway Institute, China.
LU: Lund University, Sweden.
MAT: Ministry of Agriculture, Tunisia.
MHER: Ministry of Hydraulic and Electric Resources, Beirut, Lebanon.
MIDS: Ministry of Irrigation, Damascus, Syria.
ORSTOM: French Institute for Scientific Research and Cooperative Development, France/Tunisia.
SLU: Swedish Agricultural University, Uppsala, Sweden.
Session 1.

Observation techniques; GIS/remote sensing; climatic, soil, agronomic, and socioeconomic data storage and processing for small watersheds; (chairman: Dr. Jean Albergel, ORSTOM).
Rain water harvesting and management of small reservoirs in arid and semiarid areas

Lund University, Sweden, 29 June – 2 July, 1998

Hydrology of Sindyaneh Wadi Basin in Syria

Dr. Abdallah Droubi¹, Dr. Salah Kara Damour², Dr. Jean Alberge³, and Mr. Yasser Ibrahim¹

¹ACSAD, Arab Center for the Studies of Arid Zones and Dry Lands
Division of Water Resources
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²Ministry of Irrigation
Damascus, Syria

³Mission ORSTOM B.P. 434
1004 Tunis, El Menzah, Tunisia
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A. Droubi¹, S. K. Damour², J. Alberge³, and Y. Ibrahim¹

¹ACSAD, Arab Center for the Studies of Arid Zones and Dry Lands, Division of Water Resources, B.P. 2440, Damascus, Syria.
²Ministry of Irrigation, Damascus, Syria.
³Mission ORSTOM B.P. 434, 1004 Tunis, El Menzah, Tunisia.

1. GENERAL PRESENTATION:

1.1 Physiography:

The territory of Syria can be divided into three main physiographic units:
1. The Western Mountain Ranges
2. The Southern Plateaux
3. The Eastern Plains.

In the northern part of the country, the western mountains stretch northwards along the Mediterranean coast. The southern part of the western mountain ranges includes the Anti-Lebanon mountains (2600 m) and Jebel Esh-Sheikh (2814 m).

The southern Plateaux include the Hauran volcanic plateau in the south-west and the Hamad plateau in the south-east.

The eastern plains include an arid steppe, and also a semi-arid region with the most fertile land in the country. The steppe includes Badiet-Esh-Sham and Badiet-Er-Rasafa, south of Euphrates river, and Badiet-EI-Jezireh, north of Euphrates river. The semi-arid region includes the Homs- Hama plains, the Idlib-Aleppo plain and the northern Jezireh plains.

1.2 Climate:

The climate of the Syrian Arab Republic is of the Mediterranean type, characterized by a cold rainy winter and a dry hot summer with two transitional periods in spring and autumn. The precipitation pattern is influenced mainly by two mountain belts: The western mountain ranges which run northward along coastline and the Taurus mountain ranges which extend along the northern boundary, mainly beyond the limits of the country.

The rainy season usually begins in September and ends in April with the possibility of heavy showers in May. High rainfall intensities are recorded in winter in the northern regions, and in spring or autumn in the southern and south-eastern regions. The rainfall distribution in the country is summarized in table (1,2).
Table (1)

Annual Rainfall and Evaporation

<table>
<thead>
<tr>
<th>Name of Basin</th>
<th>Area Km²</th>
<th>Average Annual Rainfall</th>
<th>Av. An. Pot. Evaporation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>mm</td>
<td>Billion m³</td>
</tr>
<tr>
<td>1. Barada &amp; Awaj</td>
<td>8630</td>
<td>308</td>
<td>2.658</td>
</tr>
<tr>
<td>2. Yarmouk</td>
<td>6724</td>
<td>287</td>
<td>1.930</td>
</tr>
<tr>
<td>3. Assi</td>
<td>26446</td>
<td>316</td>
<td>8.357</td>
</tr>
<tr>
<td>4. Coastal</td>
<td>5049</td>
<td>967</td>
<td>4.882</td>
</tr>
<tr>
<td>5. Tigris &amp; Khabour</td>
<td>21129</td>
<td>402</td>
<td>8.494</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td></td>
<td><strong>240</strong></td>
<td></td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td>185180</td>
<td></td>
<td><strong>44.537</strong></td>
</tr>
</tbody>
</table>
Average total Precipitation (mm) Yearly in Syria

Legend

 Isohyet

- 100
- 150
- 200
- 250
- 300
- 350
- 400
- 500
- 600
- 800
- 1000
- 1200
- 1400

• City

Figure (1)
Average Potential Evaporation (mm) Yearly In Syria

Legend
- City
- Evaporation line

- 1200
- 1600
- 1800
- 2000
- 2200
- 2400
- 2600
- 2800

Figure (2)
Climatic Zones of Syria

Legend
- City
- Humid
- Sub humid
- Semi arid
- Arid
- Very arid

Figure (3)
Figure (4)
Table (2)

Rainfall Distribution in Syria (mm)

<table>
<thead>
<tr>
<th>Region</th>
<th>Annual Rainfall</th>
<th>Maximum Rainfall within 24 Hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>South-Eastern Region</td>
<td>&lt; 200</td>
<td>20-40</td>
</tr>
<tr>
<td>Northern Region and Jebel El Arab</td>
<td>200-400</td>
<td>40-70</td>
</tr>
<tr>
<td>Jawlan and Extreme North-East</td>
<td>400-600</td>
<td>60-90</td>
</tr>
<tr>
<td>Coastal Plains</td>
<td>800-1000</td>
<td>90-120</td>
</tr>
<tr>
<td>Western Mountain Region along the Coast</td>
<td>1200-1600</td>
<td>235</td>
</tr>
</tbody>
</table>

Potential evaporation rates range from 1200 to 2800 mm per annum.

The absolute maximum temperature rises above 40°C in the interior region, starting from May. Between September and April, temperatures may drop below zero in most regions except in the coastal plains.

Figures (1) and (2) show the yearly averages of total precipitation, and potential evaporation in Syria respectively. Figure (3) shows the climatic zones of Syria.

1.3 Wadis:

Syria is endowed with mature clear hydrographic networks. The different shapes of these networks reflect the morphology, the precipitation regime, and the geologic formations.

Figure (4) shows the Syrian hydrographic basins which are in the mean time the principal hydrologic basins. Three main hydrographic groups can be distinguished in Syria:

1.3.1 Coastal Wadis:

Coastal wadis originate in the western foothills of the coastal mountains facing the Mediterranean sea, they cross the coastal plains forming parallel basins in general, then they empty in the Mediterranean sea. The totality of these basins is called the Coastal basin. In addition to the ephemeral wadis, there are perennial streams in the Coastal basin, namely Kabir Chamali, and Kabir Janoubi rivers.
1.3.2 **Open Interior Wadis:**

These wadis originate in the eastern coastal mountains, on the interior mountains, and on the hills. They cross the plains and hills and empty eventually in the sea. These wadis form the following three principal basins:

1.3.2.1 **Assi Basin:** consisting of Assi River and a group of ephemeral and perennial tributaries the most important of which is Afrin River. Assi river empties in the Mediterranean sea.

1.3.2.2 **Middle Euphrates Basin:** Euphrates Basin extends in Turkey (upper part), Syria (middle part), and Iraq (lower part). The Middle Euphrates Basin consists of the main river valley and a number of ephemeral and perennial tributaries, the most important of which are: Khabour river, Balikh river, and Saour river. Euphrates river empties in the Arabian Gulf. The Middle Euphrates Basin (Syrian Jezira) is subdivided into two hydrologic basins: Tigris and Khabour Basin, and Euphrates Basin.

1.3.2.3 **Yarmouk Basin:** this is the upper part of Jordan Basin consisting of ephemeral and perennial tributaries, the most important of which are Yarmouk river and Banias river. Jordan river empties in the Dead Sea.

1.3.3 **Closed Interior Wadis:**

These wadis originate on the interior mountains, on the southern part of the Anti Lebanon mountains, and on the interior hills. They then cross the plains and the hills and empty in the internal depressions. These wadis form the following three principal basins:

1.3.3.1 **Damascus Basin:** consisting of a number of seasonal and perennial wadis, the most important of which are Barada River and Awaj River.

1.3.3.2 **Aleppo Basin:** consisting of seasonal and perennial wadis, the most important of which are Quaik River and Dahab River. Aleppo Basin has been recently split into two sub-basins, the eastern sub-sub-basin is considered as a component of Euphrates Basin, and the sub-western basin is considered as a component of Assi Basin.

1.3.3.3 **Badia Basin:** consisting of eight closed basins, the most important of which is Dawa Basin having an important groundwater potential and an integrated hydrographic network. There are no perennial wadis in the Badia Basin. The southern part of Badia Basin called Hamad is characterized by scattered shallow un-integrated ephemeral wadis due to low precipitation and to the existing geologic and lithologic conditions.
1.4 Water Resources:

The water resources originating inside the boundaries of the Syria Arab Republic are estimated to be 9700 MCM per year on the average. Table (3) gives a breakdown of the annual water resources by basin.

**Table (3)**

<table>
<thead>
<tr>
<th>Name of Water Resources</th>
<th>Total Water Resources (MCM/Year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name of Basin</td>
<td>Springs</td>
</tr>
<tr>
<td>Barada &amp; Awaj</td>
<td>525</td>
</tr>
<tr>
<td>Yarmouk</td>
<td>250</td>
</tr>
<tr>
<td>Assi</td>
<td>1200</td>
</tr>
<tr>
<td>Coastal</td>
<td>500</td>
</tr>
<tr>
<td>Tigris &amp; Khabour</td>
<td>1300</td>
</tr>
<tr>
<td>Euphrates</td>
<td>50</td>
</tr>
<tr>
<td>Badia</td>
<td>15</td>
</tr>
<tr>
<td>Total</td>
<td>3840</td>
</tr>
</tbody>
</table>

2. GEOGRAPHIC DISTRIBUTION AND STORAGE CAPACITIES OF SMALL DAMS IN SYRIA:

According to the definition of small dams adopted by the International Committee of Large Dams (ICOLD), a small dam is that one having a height less than 15 meters, and a storage capacity less than 1 MCM ($H \leq 15 \text{ m, } W \leq 1 \text{ MCM}$), the Syrian Arab Republic has already 43 small dams. Table (4) presents a breakdown of the specifications of these small dams by basin. Figure (5) shows the locations of these 43 small dams.

2.1 It can be noticed that small dams in Syria are unevenly distributed over the basins; most of them exist in Assi, Yarmouk, and Badia basins. This is due to the fact that in Assi and Yarmouk basins, the mountainous areas do not provide suitable topographic conditions for building medium and large dams, while in Badia the annual water resources are insufficient for medium dams.
2.2 The storage capacity of the impoundment lake is determined according to the topographic conditions and to the annual water runoff in the wadi in a humid year (probability 10% to 25%), rather than the average annual runoff. This rule has enabled the exploitation of more water, and rendered the topographic conditions of the dam site the governing factor for choosing the storage capacity.

Table (4) gives a breakdown of the number of small dams in each basin by storage capacity:

<table>
<thead>
<tr>
<th>S Storage Capacity 1000 m$^3$</th>
<th>Basin</th>
<th>Barada &amp; Awaj</th>
<th>Badia</th>
<th>Yarmouk</th>
<th>Assi</th>
<th>Coastal</th>
<th>Euphr. &amp; Aleppo</th>
<th>Tigris &amp; Khabour</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S \leq 100$</td>
<td></td>
<td>1</td>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4</td>
</tr>
<tr>
<td>$250 \geq S \geq 100$</td>
<td></td>
<td>2</td>
<td>2</td>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>7</td>
</tr>
<tr>
<td>$500 \geq S \geq 250$</td>
<td></td>
<td>4</td>
<td>1</td>
<td>5</td>
<td>2</td>
<td></td>
<td></td>
<td>1</td>
<td>13</td>
</tr>
<tr>
<td>$750 \geq S \geq 500$</td>
<td></td>
<td>4</td>
<td>2</td>
<td>1</td>
<td></td>
<td>1</td>
<td></td>
<td></td>
<td>8</td>
</tr>
<tr>
<td>$1000 \geq S \geq 750$</td>
<td></td>
<td>1</td>
<td>7</td>
<td>2</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td>11</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>18</td>
<td>10</td>
<td>10</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td></td>
<td>43</td>
</tr>
</tbody>
</table>
Table (4). Characteristics of small dams in Syria.

**SMALL DAM IN SYRIA**

<table>
<thead>
<tr>
<th>No.</th>
<th>Name of Dam</th>
<th>Basin</th>
<th>Height (m)</th>
<th>Retention Volume M. m$^3$</th>
<th>Lake Surface Hect</th>
<th>Construction Year</th>
<th>Chashmewat Area (Km$^2$)</th>
<th>Average Annual Precipitation (mm)</th>
<th>Design Annual Runoff Volume M. M$^3$</th>
<th>Average Annual Stored Volume M. M$^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Azaafaranah</td>
<td>Assi</td>
<td>9</td>
<td>0.231</td>
<td>9</td>
<td>1966</td>
<td>3.6</td>
<td>350</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>2</td>
<td>Khurbet El-Hama</td>
<td>Assi</td>
<td>15</td>
<td>1.15</td>
<td>185</td>
<td>1967</td>
<td>10</td>
<td>600</td>
<td>1.15</td>
<td>1.1</td>
</tr>
<tr>
<td>3</td>
<td>Maaret Elhounman</td>
<td>Assi</td>
<td>11.2</td>
<td>0.229</td>
<td>8.6</td>
<td>1968</td>
<td>235</td>
<td>250</td>
<td>0.25</td>
<td>0.06</td>
</tr>
<tr>
<td>4</td>
<td>Al_Shundakieh</td>
<td>Assi</td>
<td>12</td>
<td>1.05</td>
<td>26.2</td>
<td>1968</td>
<td>8</td>
<td>600</td>
<td>1.44</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>Tili</td>
<td>Assi</td>
<td>14</td>
<td>0.818</td>
<td>20.7</td>
<td>1968</td>
<td>7.4</td>
<td>550</td>
<td>1.02</td>
<td>0.58</td>
</tr>
<tr>
<td>6</td>
<td>Um _Ejlad</td>
<td>Assi</td>
<td>14.1</td>
<td>1.86</td>
<td>46.2</td>
<td>1969</td>
<td>58</td>
<td>280</td>
<td>1.85</td>
<td>0.14</td>
</tr>
<tr>
<td>7</td>
<td>Telkaiah</td>
<td>Assi</td>
<td>10</td>
<td>0.29</td>
<td>9</td>
<td>1970</td>
<td>1.75</td>
<td>1000</td>
<td>0.435</td>
<td>0.24</td>
</tr>
<tr>
<td>8</td>
<td>Al_Baroudien</td>
<td>Assi</td>
<td>13.2</td>
<td>0.31</td>
<td>8.6</td>
<td>1972</td>
<td>6.5</td>
<td>850</td>
<td>0.31</td>
<td>0.31</td>
</tr>
<tr>
<td>9</td>
<td>Nuboul</td>
<td>Assi</td>
<td>12</td>
<td>0.358</td>
<td>0.935</td>
<td>1993</td>
<td>12</td>
<td>400</td>
<td>0.358</td>
<td>0.1</td>
</tr>
<tr>
<td>10</td>
<td>Sulaim</td>
<td>Badia</td>
<td>11</td>
<td>0.75</td>
<td>7.5</td>
<td>1967</td>
<td>75</td>
<td>100</td>
<td>0.75</td>
<td>0.1</td>
</tr>
<tr>
<td>No.</td>
<td>Name of Dam</td>
<td>Basin</td>
<td>Height (m)</td>
<td>Retention Volume Mm3</td>
<td>Lake Surface Hec</td>
<td>Construction Year</td>
<td>Catchment Area (Km²)</td>
<td>Average Annual Precipitation (mm)</td>
<td>Design Annual Runoff Volume Mm3</td>
<td>Average Annual Stored Volume Mm3</td>
</tr>
<tr>
<td>-----</td>
<td>-----------------</td>
<td>-------</td>
<td>------------</td>
<td>----------------------</td>
<td>------------------</td>
<td>-------------------</td>
<td>----------------------</td>
<td>----------------------------------</td>
<td>-------------------------------</td>
<td>-------------------------------</td>
</tr>
<tr>
<td>11</td>
<td>Jabat Shakra</td>
<td>Badia</td>
<td>14</td>
<td>0.975</td>
<td>24.8</td>
<td>1959</td>
<td>380</td>
<td>200</td>
<td>1.3</td>
<td>0.633</td>
</tr>
<tr>
<td>12</td>
<td>Wadi El_Kabir</td>
<td>Badia</td>
<td>10</td>
<td>0.515</td>
<td>20</td>
<td>1958</td>
<td>263</td>
<td>200</td>
<td>0.85</td>
<td>0.16</td>
</tr>
<tr>
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3. ENVIRONMENTAL, SOCIAL, AND ECONOMIC IMPACTS OF SMALL DAMS:

It is hard to evaluate the environmental and social impacts of the construction of small dams in Syria because of the lack of quantitative environmental and social data prior to dams construction, as well as the difficulties and complications inherent in preparing the studies necessary for that evaluation. The following discussion will merely mention the outstanding effects without using any analysis or statistics.

3.1 Environmental Impacts of Small Dams:

The majority of small dams were built in mountainous areas characterized by very high longitudinal slopes of wadis, or in Badia regions where the surface runoff is characterized by a high suspended and bed load content. After dam construction, it was noticed that the retention lakes have become a sediment trap due to the enlargement of the flow cross section upon entering the lake. This has naturally impeded the sediments from reaching the original areas at the end of the wadi course.

The formation of lakes and the subsequent rise up in the water levels in lakes have led to obvious changes in the morphology of the tributaries close to the main course. The erosion and sedimentation regime was substantially changed in the tributaries. The banks of the impoundment lakes were susceptible to scour due to wave formation during wind blowing. This effect could be attenuated by planting suitable plants around the lake or by stone revetment on the weak areas.

A lot of dam lakes were planted with fish, but the high turbidity of inflowing water especially in Badia dams has caused fish death. The sedimentation of suspended particles contained in the turbid water has resulted in the suffocation or death of fauna and flora originally existing in the bottom of the dam lakes and led to the formation of bacteria and pollutants.

Water stored in the lakes of some small dams is used as water supply for people and for livestock watering. Practice has proven that it is possible to get water of acceptable quality from these lakes if the following measures are taken:

1. Removal of trees and plants from the lake bottom, and sometimes the removal of the upper soil, prior to storing water and especially before the first filling up.

2. Prevention of any human, industrial, or agricultural waste from reaching the impoundment lake.

3. Control of eutrophication which may be accompanied by disgusting odour, and avoiding or deepening the shallow water areas.
4. The use of human, animal, and fish safe pesticides and insecticides to combat disease bearing organisms.

Besides the adverse environmental impacts of small dams, there are doubtless positive effects like:

1. Creating a local mild summer climate around the dam sites.
2. Increasing wind blowing over the lake surface and in the area which results in a mild atmosphere.
3. The green landscape (trees, plants, grass,...) in areas that were arid just before building the dams. Such areas were green only for short time after rainfall.
4. Migration of new kinds of birds and animals into the dam area. Such kinds are incomparable with the previously existing kinds prior to dam construction.
5. Reducing air pollution caused by the diesel engines that were used for pumping water from wells.

3.2 Social Impacts of Building Small Dams:

The Syrian climate, characterized by a short rainy winter and a long dry summer, implies providing water in summer either from groundwater or by storing water during winter for using it in summer. It is not always feasible to rely on groundwater which is in many times very deep or of inconvenient quality. Small dams represent the best alternative which has an advantage even over large dams. Small dams contribute in distributing the national water resources more evenly over the country, while large dams concentrate a huge quantity of water at the dam site and do not permit upstream areas to benefit from that quantity.

The distribution of water resources over numerous areas by small dams had many positive socio-economic impacts, the most important of which are:

1. The provision of domestic water for the inhabitants of Badia and mountainous regions has contributed in improving their hygienic conditions and resulted in a better urbanization level to people living around and downstream of the dam site.

2. The construction of small dams has created temporary jobs during the execution of the dam and its annexed structures, and created permanent work opportunities for the exploitation and maintenance of the dam.

3. The income increase resulting from the irrigation of previously rainfed arable lands has contributed in improving the living and cultural level of local inhabitants.
4. Most of the small dams implied the construction of new modern access roads. This has strengthened the mutual relations between urban and rural areas, and led to better level of civilization.

5. Many of the small dams became public tourist centers due to water and green areas. They became also points of contact for farmers from neighboring areas and contributed in developing mutual relations.

6. The amelioration of the conditions of rural areas due to the new water supplies has contributed in the contraction of migration into urban areas. Small dams have also encouraged many Bedouins to settle around their lakes.

The adverse social impacts of small dams are relatively few, they can be mentioned as follows:

1. The formation of impoundment lakes has led to the inundation of some arable lands and some houses already built in the area. The land owners were reimbursed, and house tenants were moved into other areas.

There were strong objections against dam construction from inhabitants living upstream the dam sites, a complaint atmosphere was created among beneficiaries and damaged people. These problems were settled in the case of dams used for irrigation, the government has deprived the property of both the damaged and beneficiary lands and reallocated the reclaimed land to all land owners. By this way the hurt farmer could obtain a new irrigated land.

2. The new created lakes became attractive swimming centers for local inhabitants. The unsupervised swimming causes the death of many people every year. In spite of warning, people still swim in the dam lakes; in the meantime, fencing the lakes is quite expensive.

3.3 Economic Impacts of Small Dams:

3.3.1 The money which was spent to transport water from remote water resources into thirsty areas has been saved. This applies for Swaida, Badia, and mountainous areas.

3.3.2 Economic studies have shown that the provision of water supply by small dams is much less expensive than by groundwater wells. The operation and maintenance costs of wells are higher than those of dams. Hard currency that was spent to equip, maintain, and operate wells has been saved.

3.3.3 Small dams have contributed in the attenuation of the overpumping of some irrigation wells.
3.3.4 Water stored in some of the small dams is used for supplementary irrigation of cereals in some rain irrigated areas. This has led to more and stable revenue.

The adverse economic impacts of small dams are very few, some arable lands were inundated and became no more productive, but this loss is incomparable with the gain of new irrigated lands.

4. HYDROMED PILOT RESERVOIRS:

Two hill reservoirs were selected to be as pilot sites for Hydromed project. The two sites are located west of Homs at about 200 Km from Damascus. The two reservoirs are Sindyaneh and Telkalakh hill reservoirs.

4-1 Sindyaneh Reservoir:

This reservoir was built in 1967, the catchment area is 4.2 Km2, the dam height is 12 m, and the impoundment volume is 360 000 m3. Several activities have been conducted on this site after it was selected as a pilot site.

1- The spillway threshold was restored and equipped with a staff for reading water levels.
2- The staffs for reading water levels in the lake were rehabilitated.
3- An automatic water level recorder and a rainfall recorder provided by Hydromed were installed.
4- Class A pan for evaporation measurement was installed.
5- Preparations for measuring sedimentation in the lake were made.

4-2 Telkalakh Reservoir:

This reservoir was built in 1970, the catchment area is 1.75 Km2, the dam height is 10 m, and the impoundment volume is 290 000 m3. The activities that have been taking place after it was selected as a pilot site are:

1- The spillway threshold was restored and equipped with a staff for reading water levels.
2- The staffs for reading water levels in the lake were rehabilitated.
3- The already existing weather station was equipped with class A evaporation pan. This station has the following equipment: Rainfall recorder and rainfall gauge, hygrometer, temperature recorder, and maximum and minimum temperature thermometers.
5. PROCESSING OF INITIAL DATA ACQUIRED FROM SINDYANEH RESERVOIR:

The Sindyaneh Lake was equipped with an automatic recorder of type PLUVIO-LIMNI 92 recommended by ORSTOM. This equipment can record continuously the variation of the water level in the lake. It is also attached to a rainfall recorder. The data recorded are stored on a memory.

Since we have one year of continuous hydrological observation (November 1997-November 1998) a tentative estimation of the hydrological budget of the Lake has been conducted.

Using the softwares developed by ORSTOM within the framework of HYDROMED activities which include;

HYDROM : A data bank dealing with data related to water level in the lack, volume stored, surface flooded and outflow on the spillway.

PLUVIOM : A database dealing with pluviometry, daily and monthly precipitation data.

ARES : Used to calculate the intensity of rain and capacity of erosion.

SURFER : Used to calculate curves of thickness/surface/volume based on sedimentation measurements (Bathymetry).

The outputs of this primary study are described below;

- Estimation of flood and volume of water stored are shown in table 5. Which was constructed using HYDROM software. On this table we have mentioned only days with precipitation, beginning from 31 December 1997 and up to 30 November 1998. It is clear from this table that reservoir has been completely filled on 28 January 1998, then all the water coming to the lake has not been stored.

From this table we can identify the storm event of 6-7 January 1998 where about 102 mm of precipitation was recorded and initiated a flood of 236600 m3. By the end of winter season we had about 434295 m3 of water stored.

- Figure (6-B) shows an analysis of different rainfall storms reflected as variation of water level in the lake (HCm to the left): we can see that by the end of January, the level of the water in the lake reached the level of the spillway. The reservoir stayed full of water until May, after that the water level and volume in the lake has decreased (Fig.6-A).

- An analysis of 2 floods arrived on 7th January 1998 and 28 to 31 January is also done on figures 7 and 8.
Table (5) Analysis of flood in Sindyaneh.

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33
Fig. 6-A - The relationship between precipitation (in mm) and variation of water level in the lake expressed as H in cm.

Fig. 6-B - Variation of volume of water stored in the lake from December 97 to 2 Dec. 98.
Fig. 7 – Flood analysis of rain storm event on 7 January 1998.
Fig. 8 – Flood analysis of rain storm event of 28-31 January 1998.
These Figures show the relationship between precipitation and quantity of runoff given as $Q$ for a given time.

We can see the variation of discharge related to each quantity of precipitation.

A tentative estimation of runoff coefficient has been done in figure 10 where we have as coordinates the precipitation in mm and runoff in mm expressed as thickness of water. The runoff coefficient could be estimated to vary between 30 to 40%, which is in good agreement with values known for such areas.

**Conclusion:**

It is the first time that a study on water budget of small catchment areas could be done in Syria. HYDROMED research programm has facilitated this work by providing the necessary equipment and the scientific support to conduct such study. The processing of initial data acquired from the pilot site of Sindyaneh has shown that the results obtained by using softwares produced by ORSTOM within the framework of HYDROMED programm, are in good agreement with observation. It was also possible for the first time in Syria to calculate the runoff coefficient for Sindyaneh basin.

Monitoring on the site will continue later, and a new campaign to measure the sediments in the lake will be done. Such measurement will help to estimate the rate of erosion on the watershed, which is a major question in Syria.
References


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PLUVIOM 2.1 (1994). Logiciel de gestion de données pluviométriques manuel d'utilisation, Laboratoire d'hydrologie, ORSTOM.

SAFARHY (1994). Logiciel de calculs statistiques et d'analyse fréquentielle adaptés à l'évaluation du risque en hydrology, Manuel de reference, ORSTOM.
SINDYANEH HILL RESERVOIR

Latitude : 34° 42 N
Y = 4843 Km
Mohafazat : Houns

Longitude : 36° 25 E
X = 377.8 Km
Basin : Assi

Characteristics of Catchment Area:

Surface Area : ................................................................. 4.2 ............ Km²
Annual Precipitation: ................................................... 767 ............ mm
Rainfall Stations : .......... Sadd K. Hammam .................
Years Covered : ............. 1972-1993 ......................
Annual Evaporation: ...................................................... 1370 ............ mm
Length of Wadi : ......................................................... 4.2 ............ Km
Maximum Altitude : ....................................................... 620 ............ m
Minimum Altitude : ......................................................... 500 ............ m
Slope : ................................................................. 29 ............ m/Km
Rocks : ................................................................. Basalt
Soils : ....... Clay
Sediments : ...... Low Suspended Load
Socio-Economic Conditions: .. Well educated, medium to poor people ....

Characteristics of Lake:

Year of Construction : ................................................... 1967 ........
Volume of Retention (V) .............................................. 360 000 ..... m³
Surface of Retention (S) .................................................. 90 000 ..... m²
Ratio (V/S) ................................................................. 4 ............ m
Dyke Height ................................................................. 12 ............ m
Dyke Length ................................................................. 512 ............ m
Nature of Spillway .................. Lateral
Height of Spillway ...................................................... m
Width of spillway ...................................................... 12 ............ m
Maximum discharge of Spillway .................. 20 ............ m³/Sec
Diameter of Outlet Pipe ................................................. 300 ............ mm
Water Use : .................. Irrigation
Water Quality : .................. Hydrocarbonate

N.B. : No Crest for spillway.
Characterestic curves for dam Al_sundlaneh

510.6 Max Storage level

Surface (m^2)

Level (m)

Storage (m3)

0 50000 100000 150000 200000 250000 300000 350000 400000

0 20000 40000 60000 80000 100000

Surface

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TELKALAKH HILL RESERVOIR

Latitude : 34° 41' N
Y = 3841.2 Km
Mohafazat : Homs

Longitude : 36° 16' E
X = 361.5 Km
Basin : Assi

Characteristics of Catchment Area:

Surface Area : ........................................... 1.75 .......... Km²
Annual Precipitation: ..................................... 789.......... mm
Rainfall Stations : .................. Sadd Telkalakh
Annual Evaporation: ................................. 1370......... m m
Length of Wadi : ........................................ 3.3 .......... Km
Maximum Altitude : .................................... 390.......... m
Minimum Altitude : ..................................... 210.......... m
Slope : ........................................... 54.5 .........m/Km
Rocks : ........................................ Basalt
Soils : ........................................ Very thin Clay
Sediments : ................................ Medium
Socio-Economic Conditions: .. Poor to average standard

Characteristics of Lake:

Year of Construction : ....................................... 1970
Volume of Retention (V) .................................. 290 000 .... m³
Surface of Retention (S) .................................. 90 000 .... m²
Ratio (V/S) ........................................... 3.22 .... m
Dyke Height ........................................... 10 ........ m
Dyke Length ........................................... 270 .... m
Nature of Spillway .................................. Lateral
Height of Spillway ..................................... 0.94 .... m
Width of spillway .................................... 20 .... m
Maximum discharge of Spillway .................. 7 .... m³/Sec
Diameter of Outlet Pipe .............................. 300 .... mm
Water Use : ................................ Irrigation
Water Quality : ................................ Hydrocarbonate with high turbidity
Characteristic curves for dam Telkalakh

- Storage
- Surface

Surface

269.3 Max. Storage level

Storage (M3)

Levels

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0 50000 100000 150000 200000 250000 300000 350000

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Rain water harvesting and management of small reservoirs in arid and semiarid areas

Lund University, Sweden, 29 June – 2 July, 1998

Small dams’ water balance: experimental conditions, data processing, and modeling

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Small dams' water balance: experimental conditions, data processing, and modeling

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Abstract

Within the HYDROMED program, to assess hydrological variables describing the water balance of small dams, each reservoir is equipped with a water level gauge, an evaporation pan, and two stations for automatic data collection. The first station is connected to a tipping bucket rain gauge (resolution of 0.5 mm rainfall), while the second is connected to a submerged probe that measures the water level, within 1 cm, and temperature each 5 minutes. The spillway is designed in such a way that the discharge can be estimated.

The bathymetry of each reservoir is recorded at least once every hydrological year, and is compared with a detailed ground survey, making it possible to determine the silting rate of each reservoir, and to create level-volume and level-surface relationships. The water abstraction for main users around the reservoirs is observed daily.

A software package allows to take the data directly and store it in a single hydrological data bank:
• rainfall and evaporation,
• level-volume and level-surface curves for the reservoir,
• water level - spillway discharge curves,
• water level, spillway discharge, volume and surface area of water in the reservoir,
• water abstraction.

The software allows editing tables of data and curves. Many different time steps can be chosen and various ways to present the data are possible.

For a certain time period t, the general water balance equation for a reservoir can be applied by using the principle of water volume conservation. The variation of the water volume stored in the reservoir is equal to the sum of water volumes entering minus water volumes exiting the system.

The instantaneous flow entering in the reservoir can be assessed at a time step of 5 min. Water balances can be computed at a daily time step.
Introduction

Management of surface water is inseparable from economic and social development (ICWE, 1992). In arid and semiarid regions, large rivers have been the object of numerous development projects to improve agriculture, produce energy, or favour navigation.

Micro improvements and on-site hydromechanical interventions are becoming important factors in rural development (Conac et al., 1984; Dumont, 1986; Rochette, 1989; World Bank, 1993). Predicting rainfall and flow and controlling the resulting water volumes are a constant concern here. Experimental watersheds have long been recognized to be the most suitable measurement device for analyzing the water resources of small hydrological systems (Toebes and Ourivaev, 1970; Dubreuil et al., 1972). These are also ideal places for research on mechanisms of the water cycle (Verel and Houi, 1994), and on the interactions between soil use, hydraulic engineering works, and water availability and quality. The difficulty and cost of managing systems of rainwater and water measurement in small watersheds are a serious handicap when attempting to understand the resource constituted by temporary rivers.

Many countries have carried or are now carrying out programmes to build small reservoirs, particularly in semiarid regions, to increase water resources, intensify agriculture in densely populated areas, and to mobilize that vital resource, water. Sri Lanka and southern India are among the world regions in which systems of small water tanks have been installed almost to a point of saturation, and indeed this has been the case for a very long time (since the 3rd or 4th century). The construction of these systems is also becoming intense in the north of the country, and is contributing to the green revolution on that continent (Grewal, Samra et al., 1995). In Brazil's Nordeste region, 70,000 açudes (the Portuguese word for small tanks) have been built (Molle and Cadier, 1992). Minor tanks have existed in the Mediterranean world since Roman times, but it was only recently that ambitious building projects were initiated in Tunisia (Talineau et al., 1994, Albergel and Claude, 1997).

A reservoir fed by a single tributary, or at least by one principal tributary, can provide as much information as a classical hydrometric station. To achieve this, certain conditions must be met, but these are often less difficult and burdensome than those required for the correct functioning of a hydrometric station (Nouvelot, 1993).

In central Tunisia, in the semiarid dorsal region that extends from the Cap Bon to the Algerian border, 30 artificial reservoirs were chosen to constitute a network of hydrological observations (Albergel and Rejeb, 1997). These lakes have highly diverse intake areas ranging from somewhat uninhabited semi-forests to areas that are devoted entirely to agriculture. Their watershed areas vary from a few hectares to several dozen square kilometers. They are also representative of the rainfall gradient of the semiarid region, which is 250 to 500 mm of rainfall annually.

This paper shows that it is possible, from a minimum survey of the reservoir, to assess major hydrological variables and to predict the reservoir behavior, especially concerning water management.
Experimental set-up and methods

Experimental observation set-up of a reservoir and data collection

The small reservoir is equipped with a water level gauge, an evaporation pan, and two stations for automatic data collection. The first of these is connected to a tipping bucket rain gauge (resolution of 0.5 mm rainfall), while the second is connected to a submerged pressure probe that measures the water level, within 1 cm, and temperature.

Figure 1 shows an example of recorded rainfall and water level at the Kamech reservoir in the Cap Bon province of Tunisia, during the hydrological year 1995-1996.

Bazin's formula (Nouvelot, 1993):

$$ Q_s = 0.385 \times 2g \times b \times h^{2/3} $$

(1)

where $Q_s$ is discharge in m³/sec, $b$ and $h$ respectively are the width and height, in meters, of the water depth at the weir.

The spillway is arranged in such a way that the discharge can be estimated. At the entrance to each flood channel there is a concrete weir. The slope downstream of the discharge channel is sufficient to prevent this weir from being flooded, except in cases of exceptional flow. The weir lies in the immediate vicinity of the reservoir, making it possible to assume that the initial speed is zero, allowing us to use the flow formula at the weir.

Manning-Strickler's formula (Nouvelot, 1993):

$$ Q_s = s \times n \times i \times 1/2 \times R_{f}^{2/3} $$

(2)

where $Q_s$ is the discharge in m³/sec, $s$ is the wet cross section in m², $n$ is Strickler's roughness
coefficient, \( i \) is the slope of the water line in m/m, \( R_h \) is the hydraulic radius in m, with \( R_h = s/p \) (\( p \) being the perimeter of the wet cross section \( s \)).

The bathymetry of each reservoir is measured at least once every hydrological year, and is compared with a fine resolution land survey, making it possible to determine the pond's rate of silting, and to establish level-volume and level-surface curves.

Figure 2 shows the change in level-volume curve from the dam construction to present at the Kamech dam.

![Figure 2. Level-volume relationships at Kamech.](image)

The data characterizing the watershed, the reservoir, and the hydrological measurement station are recorded in a geographically classified data bank which is updated after every modification of the equipment, every new measurement of the bathymetry, and every change noted in land occupancy (Smaoui et al., 1996).

**Hydrological balance method**

For a specific time step \( t \), the general water balance equation for the reservoir can be found by applying the principle of the conservation of water volume according to:

\[
\Delta V = (V_r + V_{ecs} + V_p + V_f) - (V_{ev} + V_d + V_{vl} + V_l + V_u) \tag{3}
\]

where

\( \Delta V \): variation of the water volume stored in the lake. This is known very accurately from the gauge recording and from the level-volume curve of the lake (every 5 min for a variation of 1 cm water level);
$V_r$: water from catchment runoff;
$V_{ecs}$: contribution from groundwater;
$V_p$: rainfall directly on the pond. This is known accurately from the rain gauge recordings and from the reservoirs level-surface curve;
$V_f$: water from melting snow. This is nil for most of the reservoirs studied. There may be some in winter for high-altitude reservoirs, but on an annual level the quantity is generally negligible;
$V_{ev}$: volume of water evaporated. This is found by multiplying the daily evaporation by the average surface of the reservoir on the same day;
$V_d$: volume of water discharged from the reservoir. This can be determined with good accuracy when the spillway is gauged. For most reservoirs, it is sufficient to use a spillway formula appropriate to its geometry;
$V_{vi}$: the volume leaving through the draw-off weir. This is known from the levels noted by observers at the beginning and end of the draw-off, and from the length of time it lasts;
$V_i$: the losses through seepage (at the level of the dam, or in the bottom of the reservoir);
$V_u$: the volume of water removed for various purposes. This is estimated from simple observations: a volumetric meter on the arrival pipes, observation of pumping times, etc.

Figure 3 shows the hydrological balance of a reservoir.

![Diagram of reservoir hydrological balance]

$DV = (V_p + V_r + V_f + V_{ecs}) - (V_i + V_{ev} + V_d + V_{vi} + V_u)$

**Figure 3. Hydrological balance of a reservoir.**

**A few models derived from the hydrological balance**

*Reconstruction of instantaneous water arrival during rainfall*

For reconstruction of instantaneous water arrival during rainfall Eq. (3) is used to calculate the quantity $V_r + V_{ecs}$ representing the natural wadi flow entering the reservoir:
The largest inflow to the reservoirs results from direct runoff from the surface slopes. This results in water level rise that is associated with rainfall, and it is well defined in the reservoir level recording. The time span is usually several hours. During runoff, the water balance equation can be simplified in the following way: \( V_{ecs} \) is very small in comparison with \( V_r \); \( V_f \) is negligible, if not nil; \( V_{ev} + V_i + V_u \) is very small during the time of water level rise. Equation (2) then becomes:

\[
V_r = \Delta V - V_p + V_d + V_{vi}
\]  

(5)

Deriving Eq. (5) with respect to time, we obtain:

\[
Q_e = \frac{d\Delta V}{dt} - \frac{dV_p}{dt} + Q_s + \frac{dV_{vi}}{dt}
\]  

(6)

where \( Q_e \) = flow entering the reservoir, in liters/sec; \( \frac{d\Delta V}{dt} \) = the difference in stored volume during time \( t \) (here, 5 min), related to the middle of the time interval; \( \frac{dV_p}{dt} \) = the difference in the volume of rainfall during the time related to the middle of the time interval; \( Q_s \) = flow leaving through the spillway (Eq. (1) or (2)); \( \frac{dV_{vi}}{dt} \) = the difference in volume discharged over the weir during time \( t \) related to the middle of the time interval.

Figure 4 shows calculated discharge at the Kamech reservoir during the storm event of 1st February 1996. The figure shows the rainfall in mm/h; the discharge over the weir, and the calculated flow entering in the reservoir. This flood, with a volume of 114,000 cubic meters, and a peak reaching 14.7 m\(^3\)/s occurred when the reservoir was almost full. The overflow over the weir was 109,000 cubic meters and a peak reaching 6.54 m\(^3\)/s. A lot of small floods, from October to January filled the reservoir which capacity is 139,000 cubic meters.
Figure 4. Calculated discharge during the rainfall events of 1st February at the Kamech dam.

Calculation of filling up of a reservoir with a typical flood occurring for different water or silt levels

Generally, in designing a dam, the designer has defined the hydrograph of a natural characteristic flood, for example, the flood which occurs every 10 or 25 years. With the water balance model it is possible to calculate the overflow depending on the initial volume of the reservoir. For example, Fig. 5 shows a simulation of different overflows created by an observed large flood following different initial water levels between 5 and 9 m in the reservoir of Janet Dam in Central Tunisia.

The knowledge of the overflow allows one to simulate the filling up of the dam. Figure 5b shows that the same flood occurring for a reservoir with a water level exceeding 8 m causes an overflow of the dyke crest. For this situation the dam can be damaged.
Management plan of a reservoir

Small reservoirs often dry up every year during the summer period. The use of water for irrigation (garden crops, fruit trees, etc) starts in spring and continues until the end of July. The water balance model allows one to estimate an average daily decrease of water excluding pumping. For a reservoir we can calculate the natural decrease from the beginning of spring until fall when the probability of rain starts to increase.
Assuming no rain during the irrigation period, and knowing the water needs of different irrigated crops it is possible to study different scenarios for the coming year, to plan and manage the irrigation.

We will develop this model for the case of the Kamech dam. For each period without rain, we calculate the natural daily losses of water (evaporation + infiltration + reservoir leakage). We thus plot the water volume and depth decrease from April to November (average daily evaporation, infiltration, and leaks calculated according to the water depth). The manager reads the reservoir water level gauge before starting field preparation (April the 15th; Fig. 6). He reports this information and the volume decrease (Fig. 6b). By comparing the corresponding curves in Fig. 6a and 6b he will know exactly the available water quantity at the beginning of the irrigation season.

He can thus plan different scenarios for the irrigation schedule, cropping area, and type of crops, and thus reducing the risk by planning for no rain and finishing the water reserve within the cropping period. When a scenario is decided, the manager can survey the progress of the agricultural campaign. At any time it is possible to compare the calculated water consumption with the present situation by reading the water level gauge.

For the calculated natural level curves (Fig. 6), we added the observed water variations in the years 1994-97. The validation of our model was done by the data for 1994, before any use of water, and by the data during periods without irrigation (for example, in September 1997, between the two first rains). In Fig. 6 we can also see the intensive water use for the tomato crops from May to July and after this the decrease of water use in August and September (pepper crops, and few other vegetables).

Ongoing research on water needs for the main cropping systems and for different irrigation systems (traditional, sprinkler, or drop irrigation) will quantify the water needed to abstract from the reservoir. This method allows one to evaluate different scenarios to increase the efficiency between crop water use and water availability.
Conclusion

The above examples of using the water balance equation for a small artificial reservoir show that a relatively simple experimental setup can provide a lot of hydrological information for small watersheds. This information, which in developing countries is easier and cheaper to obtain compared to classical hydrometric stations, can be collected at the outlet of the watershed.
If available the above information is equally well suited for basic research as for water management and agricultural development for small watersheds. However, other applications are equally suited; the optimization of the reservoir size (Ragab and Albergel, 1997).

Since 1994, annual records of all observations made during the hydrological year on a network of 30 small dams in semiarid Tunisia have been published. A computerized bank of hydrological data has been set up. The parameters describing the watersheds have also been recorded in a similar data bank. Maps of the different watersheds have been stored using GIS. The main objective of this work is to find dependent indicators for the hydrological functioning of the watersheds. Modeling and hydrological simulation will provide us with an accurate understanding of this resource, and will make it possible to evaluate the impact of development works and to plan rules for its management.

References


Rain water harvesting and management of small reservoirs in arid and semiarid areas

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Integrating soil profile and soil hydraulic properties data bases to be used in simulation models and land evaluation expert systems

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Integrating soil profile and soil hydraulic properties data bases to be used in simulation models and land evaluation expert systems

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Introduction

The protection of land resources is of prime importance in many regions of the world. The effects of agricultural and climate changes on the degradation of land resources are characterized not only by long-term perspectives, but also by large geographic areas impacted. The protection of these resources, mainly soil and water, depends on the correct prediction of such effects.

Presently, there is no reliable framework in the Mediterranean region for the protection of soil and water resources from erosion processes and contamination by agrochemical compounds. In spatial and temporal terms, the modelling of erosion processes and water and solute movement in the soil are relatively well advanced at local scale, but extrapolation to a regional scale is still a major priority. This extrapolation can be made i) by scaling-up techniques, developing a linkage between the controlling variables included in the erosion and or contamination process models and information contained in spatial databases; or ii) by land evaluation techniques, combining expert knowledge on these processes and spatial database information.

At the same time, the increase of process modelling of soil erosion, water and solute transport in the soil, and the use of expert systems have imposed a demand of accurate measurements of hydraulic properties of soils. For given climatic conditions and soil type, tillage methods and irrigation practices are the main factors that can alter the soil structure of top layers and consequently the hydraulic properties (Messing and Jarvis, 1993; Somaratne and Smettem, 1993; Moreno et al., 1997). For cultivated soils, the transport properties of the soil surface can change during the growing season (Angulo-Jaramillo et al., 1997). However, in modelling the processes mentioned above, it is usually assumed that the characteristics of the soil remain temporally without changes.

Although increasing consideration is being given to agricultural diversification and to lower input agriculture, it is still important to identify optimum land use systems for resource sustainability and environmental quality. Land evaluation makes it possible to use according to its potential. During the last few years, increasing application of information technology to land evaluation procedures has led to the development of land evaluation information systems. The MicroLEIS system developed by De la Rosa et al. (1992) is a good example of such systems. MicroLEIS represents an interactive and user-friendly system for optimal allocation of land use and management systems under Mediterranean agroforestry conditions.

Land evaluation procedures, as defined by FAO (1976, 1983), have been applied to provide a rational basis for making landuse decisions based on relations between land use and land qualities
(Davidson et al., 1994). However, these production-oriented applications can also be focused on land degradation or vulnerability predictions (De la Rosa et al., 1995). In this sense, it is interesting to test the applicability of the land evaluation techniques for predicting land vulnerability risk. The fundamental purpose of land evaluation is to predict the positive or negative consequences of change. Hydrological changes in Mediterranean regions, produced by extensification/ intensification character of agricultural systems and by periods of drought, will have important effects on the behaviour of land degradation processes. Simulation models and land evaluation expert systems can be useful prediction techniques if we can improve the databases, particularly those referring to soil hydraulic properties, and the integration of different soil databases.

This paper tries to show an example of a prediction land evaluation approach and the use of an integrated soil properties database (soil profile and soil hydraulic properties).

The basic framework of MicroLEIS

The MicroLEIS framework is a microcomputer-based integrated package for rural resources data transfer and agro-ecological land evaluation. Table 1 gives the framework and shows the orderly arrangement of rural resources data through spatial databases and computerized land evaluation models (land production and degradation oriented assessments).

In this paper we present two examples of models included within the framework of MicroLEIS. These two models deal with the evaluation of land degradation (erosion and specific soil contamination) under different agricultural practices. The evaluation models are based on three kinds of information: monthly meteorological data, soil survey data, and agricultural management information.

One of these models, namely Raizal, was developed as a semi-quantitative evaluation approach for assessing the risk of soil erosion under different climatic conditions and land uses. The model was partly constructed in accordance with the criteria of the FAO-framework for Land Evaluation (1976). Land qualities (LQ) and their associated land characteristics (LC) were considered in a limitation sense as well as the management qualities (MQ) and their associated management characteristics (MC). The biophysical variables or land-related characteristics were used to calculate the attainable or potential erosion risk, and the agricultural practices or management-related characteristics to calculate the management erosion risk.

Table 2 shows the list of land and management characteristics selected as input variables to the Raizal model. The characteristic values, classes for the qualitative variables and ranges for the quantitative variables, were grouped into generalisation levels to continue the evaluation procedure. For each vulnerability type, the land evaluation procedure followed is based on decision trees rather than on matching tables. The decision trees, (as for example, shown in Figure 1) are hierarchical multiway keys in which 'leaves' are choice classes/ranges such as degrees of severity, and interior 'nodes' of the tree are decision criteria such as the characteristic generalisation level.
Table 1. Current framework of the microcomputer-based land data transfer and evaluation information system: MicroLEIS™ integrated package

<table>
<thead>
<tr>
<th>Inventory/evaluation modules</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>A. Rural resources inventory (Inf&amp;Kno).</strong></td>
</tr>
<tr>
<td><strong>Basic information data transfers</strong></td>
</tr>
<tr>
<td>SDBm: Multilingual Soil Database</td>
</tr>
<tr>
<td>CDB: Climate Database</td>
</tr>
<tr>
<td>MDB: Management/technology Database</td>
</tr>
<tr>
<td><strong>B. Agro-quality land evaluation (Pro&amp;Eco).</strong></td>
</tr>
<tr>
<td><strong>Land production oriented models</strong></td>
</tr>
<tr>
<td>Terraza: Agro-climatic classification</td>
</tr>
<tr>
<td>Cervatana: Ecological capability zoning</td>
</tr>
<tr>
<td>Marisma: Fertility capability classification</td>
</tr>
<tr>
<td>Almagra: agricultural soil suitability</td>
</tr>
<tr>
<td>Albero: Crop yield prediction</td>
</tr>
<tr>
<td>Sierra: Forestry land suitability</td>
</tr>
<tr>
<td><strong>C. Agro-vulnerability field evaluation (Ero&amp;Com).</strong></td>
</tr>
<tr>
<td><strong>Land degradation oriented models</strong></td>
</tr>
<tr>
<td>Raizal: Soil erosion</td>
</tr>
<tr>
<td>Arenal: General soil contamination</td>
</tr>
<tr>
<td>Pantanal: Specific soil contamination</td>
</tr>
<tr>
<td>Zapal: Soil salinisation</td>
</tr>
<tr>
<td>Pedregal: Desertification index (Total vulnerability)</td>
</tr>
</tbody>
</table>

The other example is the Pantanal model that focuses on diffuse ‘soil agrocontamination’ from agricultural substances namely: (1) phosphorus (P), (2) nitrogen (N), (3) heavy metals (H), and (4) pesticides (X).

This model was constructed in a similar way to that of the Raizal model. Table 3 shows the list of land and management characteristics selected as input variables to the Pantanal model. A branch of the decision trees used in this model is given in Table 4.

The models were initially formulated and calibrated using data from Andalusia region (8.7 M ha), southern Spain, and from 42 representative sites within the European Union. To store and analyse efficiently and systematically large amounts of rural resources data the following databases were used: i) SDBm (soil-related information), ii) CDB (climate-related information), and iii) MDB (management-related information).
These empirically based models include also a simple precipitation partitioning submodel to calculate surface runoff and leaching degree, by using the humidity index as the relation between yearly amounts of precipitation and potential evapotranspiration.

To increase the accuracy of the evaluation models described above, other databases or simulation procedures can be used. In the case of Raizal and Pantanal models, the use of accurate and detailed soil hydraulic properties within the module 'Soil-related land characteristics' can improve the accuracy of the evaluation of erosion and contamination risks.
Table 2. Input variable list of the Raizal model.

<table>
<thead>
<tr>
<th>Land/management characteristics, class or unit</th>
</tr>
</thead>
</table>

**Site-related land characteristics**
- LC Landform, classes
- LC Slope gradient, %
- LC Groundwater table depth, m

**Soil-related land characteristics**
- LC Drainage, classes
- LC Particle size distribution, classes
- LC Superficial stoniness, %
- LC Organic matter, %
- LC Sodium saturation, %

**Climate-related land characteristics**
- LC Mean monthly precipitation, mm
- LC Max monthly precipitation, mm
- LC Mean monthly temperature, °C
- LC Latitude, °

**Crop-related management characteristics**
- MC Land use type, classes
- MC Leaf duration, classes
- MC Growing season length, days
- MC Leaf situation, classes
- MC Specific leaf area (SLAmax), m² kg⁻¹
- MC Plant height, m
- MC Maximum rooting depth, m
- MC Structure of crop, classes

**Cultivation-related management characteristics**
- MC Sowing date, classes
- MC Tillage practices, classes
- MC Tillage depth, classes
- MC Tillage method, classes
- MC Row spacing, m
- MC Artificial drainage, classes
- MC Soil conservation techniques (water), classes
- MC Soil conservation techniques (wind), classes
- MC Residues treatment, classes
- MC Crop rotation, classes
Table 3. Input variable list of the Pantanal model.

<table>
<thead>
<tr>
<th>Land/management characteristics, class or unit</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Site-related land characteristics</strong></td>
</tr>
<tr>
<td>LC Landform, classes</td>
</tr>
<tr>
<td>LC Slope gradient, %</td>
</tr>
<tr>
<td>LC Groundwater table depth, m</td>
</tr>
<tr>
<td><strong>Soil-related land characteristics</strong></td>
</tr>
<tr>
<td>LC Drainage, classes</td>
</tr>
<tr>
<td>LC Particle size distribution, classes</td>
</tr>
<tr>
<td>LC Organic matter, %</td>
</tr>
<tr>
<td>LC pH(H₂O)</td>
</tr>
<tr>
<td>LC Cation exchange capacity, meq/100g</td>
</tr>
<tr>
<td><strong>Climate-related characteristics</strong></td>
</tr>
<tr>
<td>LC Mean monthly precipitation, mm</td>
</tr>
<tr>
<td>LC Mean monthly temperature, °C</td>
</tr>
<tr>
<td>LC Latitude, °</td>
</tr>
<tr>
<td><strong>Crop-related management characteristics</strong></td>
</tr>
<tr>
<td>MC Land use type, classes</td>
</tr>
<tr>
<td>MC Crop rotation, classes</td>
</tr>
<tr>
<td>MC Land use on slopes, classes</td>
</tr>
<tr>
<td><strong>Fertilizer-related management characteristics</strong></td>
</tr>
<tr>
<td>MC Use of P-fertilizer, classes</td>
</tr>
<tr>
<td>MC Use of N-fertilizer, classes</td>
</tr>
<tr>
<td>MC Use of animal manure, classes</td>
</tr>
<tr>
<td>MC Use of industrial /urban waste, classes</td>
</tr>
<tr>
<td>MC Time of fertilization, classes</td>
</tr>
<tr>
<td><strong>Pesticides-related management characteristics</strong></td>
</tr>
<tr>
<td>MC Use of pesticides, classes</td>
</tr>
<tr>
<td>MC Persistence of pesticides, classes</td>
</tr>
<tr>
<td>MC Toxicity (LD-50) of pesticides, classes</td>
</tr>
<tr>
<td>MC Application methods, classes</td>
</tr>
<tr>
<td><strong>Other cultivation-related management characteristics</strong></td>
</tr>
<tr>
<td>MC Artificial drainage, classes</td>
</tr>
<tr>
<td>MC Artificial groundwater level, classes</td>
</tr>
<tr>
<td>MC Tillage method, classes</td>
</tr>
<tr>
<td>MC Residues treatment, classes</td>
</tr>
<tr>
<td>MC Soil conservation techniques, classes</td>
</tr>
<tr>
<td>MC Tillage practices, classes</td>
</tr>
</tbody>
</table>
Integration of soil hydraulic properties databases in simulation models and land evaluation expert systems

Land evaluation expert systems, simulation models and evaluation models usually assume that properties of the soil remain temporally without changes. For this reason, they use, in most cases, values of soil physical and hydraulic properties that were determined for a specific soil condition without taking into account the spatial and temporal variability of these properties. To increase the accuracy of the evaluation produced by the models and expert systems more detailed soil hydraulic properties databases that take into account the spatial and temporal variability are needed.

Two kinds of databases can be used in the evaluation models and expert systems: one is referred to local or reduced areas and other for large areas.

Soil hydraulic property databases for local or reduced areas

These databases are mainly generated for reduced areas in which the soil unit is more homogeneous. Such is the case of the soil hydraulic properties data generated by the group of IRNAS in the province of Seville. These data were generated through several studies (Moreno et al., 1995; Moreno et al., 1996; Angulo-Jaramillo et al., 1997; Moreno et al., 1997) and correspond to different soil types, ranging from sandy to clay texture, and give quantitative information on the soil hydraulic properties for different conditions of the top soil layer. These data were obtained in situ taking into account the spatial variability, and the temporal variability according with the tillage works applied, crops and irrigation practices. The use of these results in the Raizal and Pantanal models allows to evaluate the risks of soil erosion and contamination of soil and water for the different situations of a reduced area under different agricultural practices.

Soil hydraulic property databases for large areas

A good example of a hydraulic soil properties database for large areas is HYPRES (Hydraulic Properties of European Soils). This database was developed recently in an study funded by the EU, in which 21 laboratory were involved. This database comprises six separate tables each of which uses a geo-reference as primary key. These tables include general soil properties, hydraulic properties and soil water retention properties. From these data were derived the pedotransfer functions.

References


Rain water harvesting and management of small reservoirs in arid and semiarid areas

Lund University, Sweden, 29 June – 2 July, 1998

Lebanese hydrology and needs for water storage

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Autostrade El Nahr
Beirut, Lebanon
Lebanese hydrology and needs for water storage

B. Jaber and F. Saad


Introduction

LEBANON is known to have plenty of water and to be the “Reservoir” of the Middle East.

In fact, if Lebanon is better provided in water than other countries around him in the Middle East, we have to admit that it is still facing major water problems, and solutions of these problems are neither easy nor rapid.

One of these problems is water storage, which is a must with the inequitable water resources distribution in time and place over Lebanon’s territories.

It is an expensive solution, we know it, nevertheless the implementation of a large program of dams and hill lakes construction will not exclude, in the near future, that we should look for new, non conventional resources, to satisfy our growing water needs, to cope with our socio-economic development.

Our paper on Lebanese Hydrology and needs for water storage, will include the following sections:

1- Hydrology of Lebanon
   Resources Needs – General balance- Principal problems and issues.

2- Needs for water storage
   Major Solutions - Planification and implementation - Technical and financial constraints.

3- Conclusion
I-Hydrology of Lebanon

A-General Situation
1-A-1 Lebanon Geography

- Rectangle South - North 210 km Long
  50 km width

- Regions
  Narrow Coastal Strip
  Lebanon Moutain chain
  Bekaa plateau, Bekaa Valley
  Antilebanon Mountain chain

1-A-2 Lebanon Geology

- Mainly composed of fissured karstic limestone
  60% of the surface of Lebanon
- Volcanic basaltic formations in the North

1-A-3 Climate of Lebanon

Climate of Lebanon is influenced by its situation

- Hot temperated zone
- Eastern Mediterranean
- Border of the Syrian desert

- Its climate is rather drought moderately hot
- Heavy rains in winter about 80 days of rainfall/year
- Dominating winds: South-West

1-A-4 Temperature

*Minima averages December-January 7°C Beirut
  5.5°C Ksara

*Maxima averages July-August 27°C Beirut
  24°C Ksara
1-A-5 Evaporation
- Depends upon temperature, humidity, solar ray, wind speed etc...
- Strongest in the Bekaa 1761 mm/year than in Beirut 1341 mm/year

1-A-6 Relative Humidity
- Relatively strong on the coast and west-slopes of the Lebanon Mountains
- Mean minimum 61% in November
- Maximum 73% in August
- Sunshine 3225 h/year which is relatively high

B- Resources
1-B-1 Hydrological metering
- Limigraphic network
  First installed since 1930–70 stations in 1974, only 20 stations had been rehabilitated and are working actually.
- Pluviometric network
- AUB since the end of 19th century
- 150 stations in 1974 = 1 station 73 km
- 10% rehabilitated
- Practically no metering of snows
- Rainfall map 1970 by R. Plassard
- Spring flow metering – all the known springs
  - Stopped since 1976

1-B-2 Precipitations
Mainly rainwater. In some regions snows and other precipitations constitute the main hydraulic resources of Lebanon
- However, these precipitations are not distributed uniformly in time and space
  - In time 80 to 90 days of rainfall/year
  - In space 2000 mm/year on the peaks of Mount Lebanon
  - 250 mm/year in North Bekaa
  - 700-800 mm/year on the Coast
  +/− 50% variation from year to year.

- Total precipitations reach about 8600 Mm3/years as an average
- Snow is estimated as 1 cm of snow = 1 mm of rain and in some places snow height reaches about 7 m at the level of 1800 m above sea level
1-B-3 Evapotranspiration
- Difficulty in metering, inaccurate metering
- Estimation or computing using experimental formulas
  ---- 50% of the total rainfall

1-B-4 Surface Water
- 15 perennial water courses
- 12 are coastal rivers (East to West)
- 3 are in the inland (interior)
- 3 international water courses
  - the Orontes
  - the Nahr El Kebir
  - the Hasbani

- Approximately 27% of the resources

1-B-5 Underground Water
- Alimentation of ground water due to infiltration and percolation of rainfall
- Regenerable Water Reservoirs. Easy to reach and to use.

1-B-6 Available Water
- Precipitation 8600 Mm³/year
- Evapotranspiration losses 4500 Mm³/year
- Tranboundary flow 670 Mm³/year

  Orontes 410
  Kebir 95
  Hasbani+Wazzani 160
  670

- Ground Water losses to the sea
  Houla lake and Syria 850 Mm³/year
  Total Potentially available water 2580 Mm³/year

Of this total, the available surface runoff

in the 7 months dry period 800 Mm³
thus assuming 600 Mm³ of ground water 600 Mm³
and 800 Mm³ to be stored behind dams 800 Mm³
--------- 2200 Mm³

However those quantities are reduced to 55% every 10 years and decrease to their third or less in case of three consecutive dry years, as in the years 1988-1991.
## C- Needs

### 1-C-1 Domestic Needs

<table>
<thead>
<tr>
<th>Year</th>
<th>Inhabitants (Mill)</th>
<th>Average Consumption Rate L/c/d</th>
<th>Total Daily Needs m³/d</th>
<th>Annual Needs Mm³</th>
</tr>
</thead>
<tbody>
<tr>
<td>1996</td>
<td>4.5</td>
<td>165</td>
<td>750000</td>
<td>271</td>
</tr>
<tr>
<td>2000</td>
<td>7.1</td>
<td>215</td>
<td>1500000</td>
<td>550</td>
</tr>
<tr>
<td>2015</td>
<td>9.1</td>
<td>260</td>
<td>2500000</td>
<td>90</td>
</tr>
</tbody>
</table>

### 1-C-2 Industrial Needs

There is no available data on the industrial needs as light industries are considered part of the domestic needs.

Industries requiring large volume of water do not exist in Lebanon.

Lebanese industries with the largest water needs are beverages and other food industries.

The source of the industrial water is mainly ground water and artesian wells.

The needs are actually estimated to be 70Mm³ in 1996 of which 50Mm³ are from groundwater and with the Infrastructure Development and National Recovery Programs, these needs are estimated to reach 240 Mm³/year by 2015.

### 1-C-3 Irrigation needs

Area of arable lands in Lebanon is about 430000 ha of which 75000 ha are irrigated in 1996 needs are estimated to be 900Mm³/year.

In 2015 according to UNDP and FAO reports the area will become 170,000 ha needing 1500Mm³/year.

Irrigation needs could be reduced to 1300Mm³/year if advanced techniques are used.

### D-general Balance

<table>
<thead>
<tr>
<th>Year</th>
<th>Water(Mm³/year)</th>
<th>Needs (Mm³/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Potentially Available</td>
<td>in fact available</td>
</tr>
<tr>
<td>1996</td>
<td>2580</td>
<td>2200</td>
</tr>
<tr>
<td>1320</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2015</td>
<td>2580</td>
<td>2200</td>
</tr>
<tr>
<td>2840</td>
<td>(1300)</td>
<td>(2440)</td>
</tr>
</tbody>
</table>
Finally it can be concluded that water resources in Lebanon are hardly sufficient to meet the actual and future needs and it will be compulsory to resort to non traditional Water Resources.

2-NEEDS FOR WATER STORAGE
2-A-ACTUAL SITUATION
As we have seen and in face of the inequitable distribution of water resources in time and space, there is a need for big efforts to reach an equilibrated water balance.

The first priority should be given to water storage, to face water deficit in the long dry season.

It is fact that storage of rainfall and surface water in rainy season is the optimal solution to use this water in the dry season.

Lebanon, since early fourties, started a large program of studies to construct dams all over the Country. The only relatively big dam was Qaraouin dam on the Litani river (capacity 220Mm³), some others were built on El Bared, Kadisha-Abou Ali and Ibrahim rivers to store daily needed water for hydro-electric production (12Mm³). There are 2 little dams almost Hill lakes at Kawashra in the North and Ballout in Central Lebanon (500,000 m³) and a multitude of small hill lakes in the region of Tannourin – Lklouk. These hill lakes are private.

In the fifties, preliminary studies were conducted to implement number of dams on the Nahr el kabir, Estouène, Arka and Bared in North Lebanon Nahr Ibrahim, Chabrouh, Nahr Beyrouth, Nahr El Damour, and Bisri on the Awali river in central Lebanon, Khardali and Meifedoun, Azzibeh in south Lebanon.

In 1975 an exhaustive study was conducted to identify adequate sites for hill lakes. From 156 sites only 38 were chosen to be studied more in details.

Lebanese events stopped this program since 1975, but it started again after 1993 and the studies of some of them are nearly completed and their implementation will begin soon, since financing is under negotiations: I will mention Bisri (120Mm³), Chabrouh (8Mm³), Dahr El Kaissa-manì (500000m³), Massa(8Mm³)
2-B Purpose of dams construction
- Water supply of actual population and to face needs resulting from demographic growth
- Irrigation of cultivated areas just to be independent of the rainfall fluctuation and to increase their production and consequently their revenues
- Soil Conservations
- Limitation of damages due to inondation
- Contribution to underground water recharge
- Helping in intensive pisciculture (fishery) and encouraging migratory birds to nest in Lebanon
- Encouraging Tourism
- Encouraging people to stay in their villages and not to migrate to the town (better revenues for the peasants).

2-C Potential sites of dams in Lebanon

The selected dam sites are the following.

2-C-1 NORTH LEBANON
- Nahr El Kabir (60Mm³) to be shared with syria (30Mm³)
- Nahr Estourene – Kfar Harra and Hidd dams (35Mm³)
- Nahr Arka – 1lat dam (40Mm³)
- Nahr Arka – Karkaf dam (15Mm³)
- Nahr El Bared (15Mm³)
- Nahr El Bared and Abou Ali – laal dam (15 Mm³)
- Nahr el Asfour – Dar Beechtar (40Mm³)

2-C-2 LEBANON Mountain Chain
- Nahr Ibrahim – Jenneh dam (30Mm³)
- Chabrouh (8Mm³)
- Nahr Essalib – Wadi Mairouba lake (20 Mm³)
- Bequaata dam (10Mm³)
- Nahr Beirut – Dachounieh dam (40Mm³)
- Nahr El Damour – Blata dam (5Mm³)
- Bisri dam (120Mm³)

2-C-3 SOUTH LEBANON
- Meifedoun dam (40Mm³)
- Khardaleh dam (120Mm³)
2-C-3 Bekaa Valley

- Kamed El Lawz dam (40Mm^3)
- Massa dam (8Mm^3)
- Chmestar dam (8Mm^3)

2-D- Financial and technical Constraints

Implementation of this big program of dams construction is facing big constraints in Lebanon.

2-D-1 Financial constraints

It is known that dams are the most expensive installations in civil works, and in the actual financial situation of LEBANON it is not easy to find financing.

2-D-2 Technical constraints

- Soil of Lebanon is a karstic limestone for more than 60% of its area and consequently highly permeable.
- Solutions to store water are very expensive but not impossible.
- Lack of information about rainfall and flood flow for more than 25 years, since the beginning of civil war, cut information series and does not help to finalize feasibility studies.
- No information about the solid flow and big erosion occurred because of torrents which could fill storage lakes very quickly.

3-CONCLUSION

It is obvious that the complete and optimal utilization of Lebanese water resources needs the construction of dams of different sizes to store the water in the wet season and use it in the dry one.

We know that it is not the only one, complementary dispositions and actions should be taken for water conservation: management of the resources and the demand, new techniques specially in irrigation, which is the biggest water consumer and motivation of consumer, to economize.

We hope that this presentation presented an idea of the real situation of water in Lebanon which is in fact very different from the one perceived abroad. And no doubt that in the coming twenty years we will be forced to seek non-conventional water resources. Water as a source of life needs to be preserved. It is priceless. I would rather say: it is beyond any price but its use has a cost if we want to have it in sufficient quantity and good quality.
Fig. 1. — Les climats du Liban, d'après C. Comber, s.j., 1945.
Climats méditerranéens: 1, maritime, humide,
2, d'altitude, tempéré
3, continental, sec.
Climat subéquatorial 2.
LEGEND

IRRIGATED AREA
IRRIGABLE AREA

SOURCE: TARIFICATION STUDY-CADRES
LITANI RIVER AUTHORITY
MINISTRY OF HYDRAULIC & ELECTRICAL RESOURCES.

IRRIGATION PROJECTS
Rain water harvesting and management of small reservoirs in arid and semiarid areas

Lund University, Sweden, 29 June – 2 July, 1998

Remote sensing applications for the management of small catchments in arid and semiarid areas

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Remote sensing applications for the management of small watersheds in arid and semiarid areas

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Abstract

This paper introduces the general methodology on the remote sensing applications for the environmental management of small watersheds in arid and semiarid areas. The main contents include: a) the available satellite remote sensing data and their characteristics; b) the methods on image interpretation and the classification for thematic mapping; and c) the method of soil erosion modelling for small watersheds, taking the typical small watersheds in the Loess Plateau as examples, from remote sensing data and ground measurement data, and the method of reservoir siltation prediction.

Introduction

The satellite remote sensing technology has played an important role in the investigation and management of the environment and the natural resources since early 1970s when the first satellite was launched for the Earth observation. All scientists related to geo-sciences can extract useful information from the remotely sensed data for many purposes, such as, geological mapping, mineral resources surveying, weather report, land use and land cover investigation, land evaluation, urban planning, water quality monitoring, environment assessment and management, crop yield estimation, natural disasters monitoring and their loss estimation, and so on. The remote sensing technology has become a useful and effective tool for geologists, geographers, oceanographers, meteorologists, hydrologists, and ecologists.

Comprehensive information is required for watershed management, and the remotely sensed data just right contain the comprehensive information. The main information for watershed management, such as land use, land cover, the topography, soil erosion, the river (water-net) system, gully density, water quality, etc., can be interpreted from the remotely sensed images. The dynamic variation of watershed environment can be monitored by using multi-temporal remotely sensed data. This paper will introduce the properties of related remotely sensed data, the methods on image interpretation, soil erosion modelling and reservoir siltation prediction for management of small watersheds.

The satellite remote sensing data

There are plenty of remote sensing data, such as the aerial photographs, the satellite visible and infrared images, and satellite radar images, which can be used for watershed management. The Landsat Thematic Mapper (TM) data and the Spot Earth Observation Satellite SPOT data are widely used for small watershed management.
The TM sensors was carried by Landsat 4, launched on 16 July 1982, and Landsat 5, launched on 1 March 1984, both of which are in Sun-synchronous orbits with equatorial crossing time approximately 9:45 a.m. The satellite orbits are at an altitude of 705 km and provide a 16-day, 233-orbit cycle with a swath overlap that varies from 7 percent at the Equator to nearly 84 percent at 81 degrees north or south latitude. These satellites were designed and operated to collect data over a 185-km swath. The TM sensor has seven spectral bands, which wavelength ranges are from the visible, through the mid-infrared (IR), into the thermal-IR portion of the electromagnetic spectrum (Tab. 1). The TM sensor has a spatial resolution of 30 meters for bands 1 through 5, and band 7, and a spatial resolution of 120 meters for band 6. The TM data provide the surface information of watersheds from the early 1980's to the present, can be employed to monitor the changes occurring on the surface of watersheds.

Table 1. Bands of Thematic Mapper (TM) and SPOT Data

<table>
<thead>
<tr>
<th>TM Bands</th>
<th>Wavelength (μm)</th>
<th>Resolution (meters)</th>
<th>SPOT Bands</th>
<th>Wavelength (μm)</th>
<th>Resolution (meters)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.45-0.52</td>
<td>30</td>
<td>1</td>
<td>0.5-0.59</td>
<td>20</td>
</tr>
<tr>
<td>2</td>
<td>0.52-0.60</td>
<td>30</td>
<td>2</td>
<td>0.61-0.68</td>
<td>20</td>
</tr>
<tr>
<td>3</td>
<td>0.63-0.69</td>
<td>30</td>
<td>3</td>
<td>0.79-0.89</td>
<td>20</td>
</tr>
<tr>
<td>4</td>
<td>0.76-0.90</td>
<td>30</td>
<td>Panchromatic</td>
<td>0.51-0.73</td>
<td>10</td>
</tr>
<tr>
<td>5</td>
<td>1.55-1.75</td>
<td>30</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>10.40-12.50</td>
<td>120</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>2.08-2.35</td>
<td>30</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The SPOT satellite series has been operational for more than ten years. SPOT 1 was launched on 22 February 1986, and withdrawn from active service on 31 December 1990. SPOT 2 was launched on 22 January 1990 and is still operational. SPOT 3 was launched on 26 September 1993. An incident occurred on SPOT 3 on November 14, 1997. After 3 years in orbit the satellite has stopped functioning. The SPOT 4 was launched on 24 March 1998. The SPOT 5 is scheduled to be launched late in 2002. The SPOT data have 3 multispectral bands, which wavelength ranges are from the visible, near-infrared (IR) portion of the electromagnetic spectrum, and 1 panchromatic band (Table 1). The SPOT data have a high spatial resolution, 20 meters for 3 multispectral bands and 10 meters for the panchromatic band.

SPOT’s oblique viewing capacity makes it possible to produce stereo image pairs by combining two images of the same area acquired on different dates and at different viewing angles. The Stereo image pairs are mainly used for stereo-plotting, topographic mapping, and automatic stereo-correlation, from which Digital Elevation Models (DEM) can be directly derived without the need of maps. SPOT’s oblique viewing capacity allows it to image any area within a 900 km swath. Oblique viewing can be used to increase the viewing frequency for a given area during a given cycle. The frequency varies with latitude: at the equator, a given area can be imaged 7 times during the same 26-day orbital cycle. At latitude 45 degree, a given area can be imaged 11 times during the orbital cycle, i.e. 157 times yearly and an average of 2.4 days, with an interval ranging from a maximum of 4 days to a minimum of 1
day. The high frequency viewing is very important for monitoring the variation in some case. On comparison with other satellite data, SPOT data have many advantages: high spatial resolution, high temporal resolution (high frequency viewing), stereo image pairs, which making the data ideal on environmental monitoring and management applications for small watersheds.

**Interpretation and classification of remotely sensed image**

Different ground covers have different characteristics in their size, shape, texture, spectral value and temporal appearance, and the classification from remotely sensed images is based on all these characteristics. For instance, the spectral grey values from water bodies are much lower than that from other kinds of ground covers, that makes it easy to distinguish water bodies from other kinds of ground covers. It is also not difficult to identify ponds from reservoirs or rivers according to their shape, texture and the positional relationship with other land covers.

The land covers are different from place to place. A classification system for land covers should in advance be set up on consulting experts. Here is an example of a classification system for land covers (Table 2), and the system can be adjusted from the actual situations of the research watersheds.

<table>
<thead>
<tr>
<th>Classes</th>
<th>sub-classes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 crop land</td>
<td>1.1 maize; 1.2 cereal; 1.3 bean.</td>
</tr>
<tr>
<td>2 forest land</td>
<td>2.1 timber forest; 2.2 mixed forest; 2.3 bush; 2.4 orchard.</td>
</tr>
<tr>
<td>3 grass land</td>
<td>3.1 sparsely covered; 3.2 dense covered.</td>
</tr>
<tr>
<td>4 water body</td>
<td>4.1 pond; 4.2 reservoir; 4.3 river.</td>
</tr>
<tr>
<td>5 barren land</td>
<td>5.1 rock; 5.2 soil.</td>
</tr>
<tr>
<td>6 others</td>
<td>6.1 village; 6.2 road.</td>
</tr>
</tbody>
</table>

The classification can be carried out by interpretation with barren eyes according to the characteristics, such as the colour, shape, texture, etc., or carried out by computers on the base of the grey value or grey combinations of the remotely sensed images. The supervised or non-supervised classification methods are generally used in computer classification. The accuracy of supervised classification is usually better than that of non-supervised classification for small-scale areas. The classification can provide much thematic information for watershed management.
Soil erosion modelling and reservoir siltation prediction

Soil erosion modelling

There are several methods to estimate the amounts of soil erosion in a watershed. One method is to draw a soil erosion map which can be interpreted from remotely sensed images on consideration of the erosive factors and their combinations. The topography, the ground slope, the plant coverage and the contents and structure of the soil are generally considered as the main erosive factors. For instance, in the Loess Plateau area within Northern Shaanxi province, three-level classification system was used for soil erosion mapping. The first level was classified, according to erosive forces, into water erosion, gravity erosion and wind erosion. In the second level classification, the water erosion, for example, was classified into 7 grades according to the erosive intensity: feeble erosion (<1000 t/km²·a), light erosion (1000-2500 t/km²·a), middle erosion (2500-5000 t/km²·a), intensive erosion (5000-8000 t/km²·a), extra intensive erosion (8000-15000 t/km²·a), strong erosion (15000-25000 t/km²·a), and extremely strong erosion (>25000 t/km²·a). Then the total amount of the soil erosion in a watershed can be estimated from the grade map of soil erosion.

Another method for estimation of the amount of soil erosion in a watershed is to calculate it from a soil erosion model, which could be developed from remotely sensed data and ground truth data, and can provide more accurate estimation of total amount of soil erosion for a small watershed.

Here is an example of a soil erosion model developed for small watersheds in the Loess Plateau of the North Shaanxi province, which is developed from the ground truth data and remotely sensed data of six typical small watersheds.

The selection of erosive factors for modelling: The erosive factors, including the motive force factors and the affecting factors, which affect the ways of erosive action and the evolution of the motive force factors, are selected for modelling according to the principle of soil erosion dynamics and their function in the process of soil erosion. The runoff-producing rainfall, \( R \), is selected as the motive force factor, and other six factors are selected as the affecting factors. They are the factor of loess contents, \( S \), shown by the coefficient of sand (diameter >0.05mm) to silt (diameter <0.0005mm) in the loess; the topography factor for surface erosion, \( F \), shown by the ratio of surface area of watershed to its projection area; the topography factor for gully erosion, \( L \), shown by the gully density; the topography factor for gravity erosion, \( C \), shown by the cliff density; the man-made erosion factor, \( P \), shown by population density; and the human anti-erosion factor, \( H \), shown by the ratio of harnessed area to the total area of a watershed. The data of \( R \), \( S \), and \( P \) are obtained from field investigation or from historical data collection, and the data of \( F \), \( L \), \( C \) and \( H \) are from the interpretation of aerial photographs on the scale of 1:10000. All data are listed in Table 3.

The field investigation and experiments show that the gully erosion, gravity erosion, and surface erosion are separately the results of the factors of runoff-producing rainfall interacting separately with gully, cliff, and loess surface, under the effect of ground materials. So the products of runoff-producing rainfall, \( R \), multiplied by \( S \), the ratio of sand to silt in the loess, and then separately multiplied by \( L \), the gully density; by \( C \), and the cliff density; and by \( F \), the ratio of surface area to its projection area; i.e. the \( RSL \), \( RSC \), and \( RSF \), are separately taken
as factors for gully erosion, gravity erosion (gravity-and-water erosion) and surface erosion. Similarly, the product $RSH$ is taken as the comprehensive factor of anti-erosion.

Table 3. Basic data of erosive factors in typical watersheds

<table>
<thead>
<tr>
<th>Watersheds</th>
<th>Shang Bian Gou (1)</th>
<th>Shang Bian Gou (2)</th>
<th>Da Bian Gou</th>
<th>Xiao Bian Gou</th>
<th>Jiu Yuan Gou</th>
<th>Wang Mao Gou (1)</th>
<th>Peijia Mao (2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_s$ (t/km².a)</td>
<td>14009</td>
<td>8051.4</td>
<td>6294.5</td>
<td>7884.9</td>
<td>16906</td>
<td>16957</td>
<td>14921</td>
</tr>
<tr>
<td>$R$ (mm)</td>
<td>494.8</td>
<td>326.8</td>
<td>249.4</td>
<td>257.2</td>
<td>223.0</td>
<td>205.0</td>
<td>223.1</td>
</tr>
<tr>
<td>$F$</td>
<td>1.2195</td>
<td>1.2195</td>
<td>1.1445</td>
<td>1.2450</td>
<td>1.2725</td>
<td>1.3130</td>
<td>1.2680</td>
</tr>
<tr>
<td>$L$ (km/km²)</td>
<td>34.32</td>
<td>34.32</td>
<td>27.44</td>
<td>33.31</td>
<td>33.83</td>
<td>30.33</td>
<td>32.15</td>
</tr>
<tr>
<td>$C$ (km/km²)</td>
<td>10.0</td>
<td>10.0</td>
<td>10.27</td>
<td>13.47</td>
<td>12.58</td>
<td>15.02</td>
<td>13.53</td>
</tr>
<tr>
<td>$P$ (persons/km²)</td>
<td>29.3</td>
<td>37.0</td>
<td>120.9</td>
<td>62.7</td>
<td>124.2</td>
<td>106.0</td>
<td>114.6</td>
</tr>
<tr>
<td>$H$ (%)</td>
<td>8.5</td>
<td>27.19</td>
<td>23.6</td>
<td>0.05</td>
<td>32.4</td>
<td>25.0</td>
<td>5.0</td>
</tr>
<tr>
<td>$S$</td>
<td>1.008</td>
<td>1.008</td>
<td>1.008</td>
<td>1.008</td>
<td>2.6445</td>
<td>2.6445</td>
<td>2.6445</td>
</tr>
</tbody>
</table>

Note: $M_s$ is the erosive modulus from ground investigation data, t/km².a

The development of the soil erosion model: The Grey System Theory is used for factor-analysis. The erosive modulus ($M_s$) is taken as the mother-factor and the other factors are taken as sub-factors. The analysis results show that $RSF$, $RSL$ and $RSC$ are the main erosive factors, which have good relationship with erosive modulus ($M_s$), and $RSH$ is a secondary factor. The population density, $P$, has a very complicated relationship (which could be positive or negative) with erosive modulus, as the man could destroy the environment and make soil erosion stronger or protect the environment and make the soil erosion less. So it is not used for the development of the soil erosion model. On the base of factor analysis, a soil erosion model is developed as:

$$M_{es} = 10.1478 \times RSF + 0.29623 \times RSL + 0.40337 \times RSC - 0.2830 \times RSH - 151$$

Where $M_{es}$ is the estimated erosive modulus (t/km².a).

The model can be used for calculation of rain-related erosion of watersheds in the gully and hill regions of the Loess Plateau. Comparing the estimated erosive modulus with the measured erosive modulus, the relative errors of the model are calculated, and the maximum of relative error is 12.38%, the mean relative error is 7.48%. The model can be used for forecasting the erosion amounts and for estimating the percentage of the three erosive types (i.e. the surface erosion, the gully erosion and the gravity erosion) in the whole erosion amounts. The surface erosion is the strongest one, which takes 46.8%, the gully erosion is the second strongest one, which takes 35.1% and the gravity erosion is the third one, takes 18.1%, in the experimental watersheds in gully and hill area of Loess Plateau in the north Shaanxi province.
Prediction of reservoir siltation

The volume of reservoir can be calculated from the topography data or DEM (digital elevation model) data before and after the reservoir construction. The DEM can be made from SPOT images or aerial photos. The amounts of siltation can be estimated from the total erosion amounts of watersheds, which can be calculated from erosive model or erosive grade map as mentioned above. And then the life span of reservoir can be estimated and the siltation prediction can be made.

Discussion

The remote sensing technique is a useful tool for geo-sciences. The SPOT data or TM data are recommended for the management of resources and environment of small watersheds in arid and semiarid areas for their low cost and very high spatial resolution.

The accuracy of estimating the soil erosion amount from model is better than from erosive map, but most soil erosion models have limitation when applied for other regions as the erosive mechanism is different from place to place. It is better to develop a local erosive model for a watershed or a type of watersheds.

It is very important to combine the remotely sensed data with the ground truth data in the image interpretation and the model development.

References

Session 2.

Water quality and quantity; hydrological and transport modeling; (chairman: Dr. Jean Khouri, ACSAD).
Rain water harvesting and management of small reservoirs in arid and semi-arid areas

Lund University, Sweden, 29 June – 2 July, 1998

Water chemistry characteristics in small reservoirs of semi-arid Tunisia

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Water chemistry characteristics in small reservoirs of semiarid Tunisia

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Abstract

The variation of water quality in 24 small reservoirs of semiarid Tunisia was studied in relation to catchment and hydrological context during two successive and contrasting hydrological years. Measured salinities generally satisfied the various uses. Three geochemical groups were identified based on the water quality during the inflow period. Calcium sulphate water types characterize reservoirs located in Zeroud and Merguellil catchments. They have the greatest dissolved salt contents and an increase of salinity by evaporation may limit their suitability for irrigation. Calcium bicarbonate dominated waters, especially observed in the Medjerda sub-catchments, are far more diluted and present less constraints. Two reservoirs located in Cap Bon are made conspicuous by sodium chloride dominated waters with a low ionic content. The salinity of this kind of water increases more quickly with evaporation and can then impose constraints for irrigation use.

Introduction

As part of a decennial strategy (1990-2000) for water resources mobilization, Tunisia has undertaken the creation of a thousand hillside-reservoirs, half of which will be located in the semiarid zone of the country. Hillside reservoirs (from 10 000 to 500 000 m³) are used for surface water control, in order to support groundwater recharge and to combat erosion and silting of dams located downstream. Besides, this allows the creation of water resources in deprived remote areas (Talineau et al., 1994). The use and valorisation of this new resource through micro-irrigation are then encouraged (Selmi, 1996). However, the quantitative and qualitative characteristics of the water have to be known to ensure its optimal exploitation and management. Therefore, a survey of hillside-reservoirs is conducted by the Water and Soil Conservation Service and Orstom (Smaouï et al., 1996). In respect of water quality, salinisation concern may be significant since strong evaporation in the semiarid context favours salt concentration in water, that can limit the resource availability for irrigation. This paper presents the geochemical characteristics of 24 hillside-reservoirs of semiarid Tunisia and an analysis of the water quality evolution during evaporation.

Material and methods

The mentioned 24 hillside-reservoirs were studied. Their geographical distribution covers the entire semiarid Tunisia, from Cap Bon to the Algerian frontier. The topography of this area is structured by limestones and Cretaceous and Eocene marls.
Reservoirs were created between 1989 and 1993 with capacities between 15 000 and 235 000 m³. Maximum water surfaces vary from 1 to 10 ha. Catchments extend from 85 to 1800 ha, they mainly consist of cultivated areas and grazing grounds, and sometimes of forested areas when slopes are not degraded. The reservoir water is used for small irrigation, feeding livestock, and domestic needs but not for drinking water supply.

Water samples were collected seasonally during the hydrological year 1994-1995, and more frequently for some reservoirs during the hydrological year 1995-1996. Electric conductivity (E.c.) and pH were measured and major ions were analysed (Rahaingomanana, 1998). The PCwateq model (Plummer et al., 1976; Rollins, 1988) was used to determine solute activity. The EXPRESO model (Rieu et al., 1998) was used to carry out evaporation simulation of water, assuming that solutions are in equilibrium with:

- calcite \( \text{CaCO}_3 \) \( \text{pK}_s = 8.37 \) (Hegelson, 1969);
- gypsum \( \text{CaSO}_4 \) \( \text{pK}_s = 4.85 \) (Robie et al., 1968).

Results

*Identification and characterization of geochemical groups*

Identification of geochemical groups is based on the analysis of water observed during reservoir filling. Consequently, indications about runoff water composition is given by the Piper diagram (Fig. 1). Three geochemical groups are noticed: calcium sulphate (12 reservoirs), calcium bicarbonate (10), and sodium chloride (2) dominant water. Inflow (runoff) water composition is related to catchment characteristics. Bicarbonate dominant water comes from slopes where limestone prevail while sulphate water results from marl and groundwater drainage. Figure 2 indicates that hillside reservoirs located in Zeroud and Merguellil catchments present sulphate runoff water while hillside reservoirs in the southest part of Medjerda catchment present bicarbonate dominant runoff water. Chloride dominant runoff water is localised in Cap Bon.

We evaluate water quality for irrigation with E.C. and Sodium Adsorption Ratio1 (SAR). The E.C. indicates the salinity level of the water. In Tunisia, water salinity is considered suitable for all crops up to 1.5 g l⁻¹. The SAR is related to the sodium proportion in the water and indicates alkalization risks for irrigated soils. For a SAR value, this risk depends on the water salinity. The values for runoff water are shown in Table 1. Sulphate runoff water presents a higher level of salinity: E.C. ranging between 0.6 and 3.0 dS m⁻¹ is equivalent to salt concentrations of 0.4 to 2.0 g l⁻¹.

\[ \text{SAR} = \frac{\text{Na}^+}{(\text{Ca}^{2+} + \text{Mg}^{2+})^{1/2}} \text{ (mmol}^{1/2} \text{ l}^{1/2}) \]
Figure 1  Hill-side reservoir flood water in a Piper diagram.
The lowest level of salinities is observed in bicarbonate dominant runoff water which has an E.C. <0.5 dS m\(^{-1}\) (0.3 g l\(^{-1}\)). Runoff water with chloride dominant type has intermediate salinity levels, up to 0.8 dS m\(^{-1}\) (0.5 g l\(^{-1}\)). Since the water is dominated by calcium, the SAR is low. A slight risk related to SAR exists for water of bicarbonate and chloride type which has SAR>1 whereas E.C. is <0.7 dS m\(^{-1}\). Beside this and slightly saline sulphate water, runoff water displayed a good quality for irrigation.

Table 1. E.C. and SAR ranges of hillside reservoirs storing runoff water.

<table>
<thead>
<tr>
<th>Flood waters</th>
<th>E.C. (dS m(^{-1}))</th>
<th>SAR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sulphate type</td>
<td>0.62 - 3.10</td>
<td>0.3 - 2.9</td>
</tr>
<tr>
<td>Bicarbonate type</td>
<td>0.16 - 0.45</td>
<td>0.3 - 1.0</td>
</tr>
<tr>
<td>Chloride type</td>
<td>0.51 - 0.78</td>
<td>2.7 - 3.3</td>
</tr>
</tbody>
</table>
Water geochemical evolution

The salinity variation observed in the geochemical groups is indicated in Table 2. The salinity variation is small in water which is of sulphate type. Nevertheless, salinity reaches a maximum level in this group since runoff water contains the highest amounts of dissolved salts. An E.C. of 8.1 dS m⁻¹ observed at Fidh Ben Ali reservoir indicates a salinity around 5.5 g l⁻¹. Salinity variations are greatest in the group with bicarbonate dominant runoff water which is the most diluted. The maximum E.C. observed was 3.1 dS m⁻¹ at the El Hnach reservoir and corresponds to a salinity around 2 g l⁻¹. Salinity variations are moderate for the group with chloride dominant runoff water but the maximum E.C. observed is also 3 dS m⁻¹ at the Es Seghir reservoir.

Table 2. E.C. variations observed in hillside reservoirs.

<table>
<thead>
<tr>
<th>Geochemical group</th>
<th>E.C. variation factor</th>
<th>E.C. max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sulphate type</td>
<td>1.3 to 3.8</td>
<td>8.1 dS.m⁻¹</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Fidh Ben Ali</td>
</tr>
<tr>
<td>Bicarbonate type</td>
<td>1.5 to 11.7</td>
<td>3.1 dS.m⁻¹</td>
</tr>
<tr>
<td></td>
<td></td>
<td>El Hnach</td>
</tr>
<tr>
<td>Chloride type</td>
<td>3.0 to 4.1</td>
<td>3.1 dS.m⁻¹</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Es Seghir</td>
</tr>
</tbody>
</table>

The increase in salinity for reservoir water is mainly related to evaporation but the time evolution of the water composition also depends on inflow and outflow. The time evolution also depends on geochemical processes of salt precipitation and dissolution during water concentration or dilution. Ion exchange processes with sediment can occur too. The smallest salinity variation was observed at the El Mouidhi (Fig. 3a) reservoir which runoff water of a calcium sulphate type had an E.C. of approximately 1.2 dS m⁻¹ (0.8 g l⁻¹). Percolation is significant and induces a fast decrease of the water volume which limits salts accumulation in the reservoir by evaporation. On the other hand, the greatest salinity variation was observed at the M'Richet el Anze reservoir (Fig. 3b): during the hydrological year 1994-95, inflows are very limited and measured E.C. is approximately 1 dS m⁻¹ until the beginning of spring. The E.C. reached 2 dS m⁻¹ at the beginning of the summer, before end of the wet season. The reservoir filled up at the beginning of the hydrological year 1995-96 and then, E.C. fell to 0.2 dS m⁻¹. The high salinity during the first period was favoured by the low water volume that increased the evaporative effects. In addition, we observed a spring discharge near the reservoir, presenting a greater salinity than the runoff water. During the first period, this kind of contribution could have influenced the geochemical evolution of the stored waters.
Figure 3. The E.C. and mean daily volume (Vm.d.) variations at El Mouidhi (a) and M'Riehet el Anze (b) hillside reservoirs.

Figure 4. Most significant water type evolution in the hillside reservoirs.
The geochemical evolution related to the most important salinity variations are shown in Fig. 4. For the sulphate runoff group, we observed similar or increased sulphate proportions during the dry period. In the same way, chloride proportions increased in the case of the chloride dominant runoff group. On the other hand, we observed important changes for the bicarbonate dominant runoff group since the water observed during the dry period can present a sulphate or a chloride dominant type. For cations, a decrease in calcium generally occurs. This evolution can be related to calcite and gypsum precipitation when water is evaporated. Indeed, Fig. 5a shows that water in hillside reservoirs can be over-saturated compared to calcite equilibrium, so that calcite can precipitate and decrease the calcium and carbonate proportion in the water. The hillside reservoirs water are under-saturated compared to gypsum equilibrium but \((Ca^{2+})\) and \((SO_4^{2-})\) activities increase jointly until saturation (Fig. 5b).

\[
\begin{align*}
\text{Calcite} & : pK_s = 8.37 \\
\text{Gypsum} & : pK_s = 4.58
\end{align*}
\]

Figure 5. Calcite (a) and gypsum (b) equilibrium diagrams for the hillside reservoir water.

**Evaporation simulations**

Although the water chemical evolution is not only determined by evaporation processes, we compared the observed geochemical evolution with evaporation simulations for Fidh Ben Ali, M'Richet el Anze, and Es Seghir reservoirs which represent the three different geochemical groups. We considered periods where salinity increased. In Fig. 6, we can note differences between the observed and the simulated evolution regarding concentration for Fidh Ben Ali. These differences could be expected since, as mentioned before, the actual water evolution may be influenced by secondary inflow, coming from groundwater for example. Moreover, the simulations assume that thermodynamic equilibrium regarding calcite is realised as over-saturation was often observed. In spite of these differences, the measured and simulated E.C. evolutions are rather close (Fig. 7a). On the other hand, SAR tends to be over-estimated in the model compared to observations (Fig. 7b). This may result from the greater precipitation of calcium in the model, as a result of calcite and gypsum thermodynamic equilibrium. Differences are all the more significant since the water is over-saturated regarding these minerals. The M'Richet el Anze water is quite diluted and only slightly over-saturated regarding calcite, thus, no difference between observations and simulations appears.
Figure 6. Water composition evolution with increase of the concentration factor (FC): observations and Expreso evaporation simulation for Fidh Ben Ali hillside reservoir water.

Figure 7. E.C. (a) and SAR (b) evolutions with increase of the concentration factor (FC): observations (empty symbols) and Expreso evaporation simulation (full symbols) for Fidh Ben Ali, Es Seghir, and M'Richet el Anze hillside reservoirs water.

Evaporation simulations allow to determine the theoretical evolution of water quality during dry periods if we assume that no inflow occurs during this period. We carried out evaporation simulations for water with specific initial compositions that allow to delimit the risks related to E.C. and SAR increase. A concentration factor of 5 was considered, it can for example be reached at the end of the summer, in a reservoir having a water level below 2 m at the beginning of the dry season.
Results are shown in Table 3 where E.C. values are expressed as quality grades for crops and SAR is presented according to the risk for irrigated soils. As we noted before sulphate dominated runoff presents the greatest salinity and some constraints can exist for irrigation. During the concentration process, the increase in salinity can be limited by gypsum precipitation. Indeed, initial constraints can only be increased and salinity reaching a concentration factor of 5 may be unsuitable for irrigation. Salinity of bicarbonate and chloride dominant runoff is low and entirely satisfactory for irrigation. For a concentration factor of 5, E.C. remains very satisfactory for the bicarbonate dominant water. In the case of the chloride dominant water, E.C. at a concentration factor of 5 indicates that problems may occur for salt sensitive crops. In this group, E.C. is initially higher than for the bicarbonate dominant water and it increases more quickly since Cl and Na do not take part in the salt precipitation. The evolution of the SAR related risk depends on the relative evolution of the cationic proportions and salinity of water. For sulphate water, a high salinity prevents the SAR related risk. For bicarbonate and chloride dominant water, the lowest salinity favours a slight risk, especially in the case of sodium chloride dominant water.

Table 3. Hillside-reservoirs water quality evolution during evaporation simulation.

<table>
<thead>
<tr>
<th>Geochemical group</th>
<th>E.C. class*</th>
<th>SAR related risk</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>FC = 1</td>
<td>FC = 5</td>
</tr>
<tr>
<td>Sulphate type</td>
<td>A to B</td>
<td>B to D</td>
</tr>
<tr>
<td>Bicarbonate type</td>
<td>A⁺</td>
<td>A⁺ to A⁻</td>
</tr>
<tr>
<td>Chloride type</td>
<td>A⁻</td>
<td>A⁻ to B⁻</td>
</tr>
</tbody>
</table>

* Tunisian E.C. classes for irrigation:

A = all uses (< 1.5 g l⁻¹)  
B = not for sensitive crops (1.5 to 3 g l⁻¹)  
C = tolerant crops only (3 to 5 g l⁻¹)  
0 = unsuitable for crops (> 5 g l⁻¹)

Conclusion

The geochemical characterization of water in the hillside reservoirs of semiarid Tunisia put highlighted different major geochemical groups with indications about localization and quality of water during the reservoir filling period. The observations made during different hydrological periods helped us to understand the actual geochemical evolution of water and confirmed the importance of reservoir hydrology for this evolution. Expresso simulations were used to detail the risk of water quality deterioration under evaporation for each group. The geochemical and hydrological information acquired for Tunisian hillside reservoirs can now be integrated to bring around concrete actions necessary for the reservoir management. According to above, it would be useful to investigate the nature and volume of secondary inflows. Moreover, exchange phenomena between water and sediments needs to be studied to better understand the geochemical evolution of the stored water. This may be significant for hillside reservoirs where particle transport is important. It may also be interesting to analyse the impact of the reservoirs on the groundwater quality.
References


Rain water harvesting and management of small reservoirs in arid and semiarid areas

Lund University, Sweden, 29 June – 2 July, 1998

Water chemistry of small reservoir catchments in central Tunisia

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Water chemistry of a small reservoir catchment in central Tunisia, preliminary results of water-soil-rock interactions

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Abstract

Numerous small hill reservoirs have been constructed in Tunisia since the early 1990's. The water chemistry of a representative small reservoir catchment was investigated to elucidate water-soil-rock interactions. The groundwater and surface water of the calcareous and marly watershed were characterized by field chemical investigations and pedological observations. The reservoir water was alkaline, with a low concentration, highly oxygenated and weakly carbonated while the groundwater was neutral, displayed higher concentration, weakly oxygenated and highly carbonated. Field observations have shown that the reservoir water is infiltrating and supplying a downstream aquifer and that the groundwater is flowing downstream under and inside reservoir sediments. Reservoir water loss was estimated using a conservative tracer and daily water balances. With regard to the chemical composition and the volume of water reservoir, it can be concluded that (i) the reservoir has a minimum infiltration rate of 126 m\textsuperscript{3} d\textsuperscript{-1}, (ii) above a 4.5 m water level, the daily infiltration rate mostly ranges from 200 to 300 m\textsuperscript{3} d\textsuperscript{-1}, below a 4.5 m level infiltration approximately ranges from 50 to 150 m\textsuperscript{3} d\textsuperscript{-1}. Further chemical and isotopic analyses will allow to better understanding of the geochemical processes of the watershed and possibilities to model the water-soil-rock interactions.

Introduction

At present, approximately 450 hill reservoirs have been constructed in northern and central Tunisia since the early 1990's. The Direction of Water and Soil Conservation at the Ministry of Agriculture has assigned different aims for these reservoirs: decreasing of soil losses, reducing of dam sedimentation, and replenishing groundwater tables (Albergel and Rejeb, 1997). Water reservoirs should give an opportunity for nomadic families to settle and to find water supplies for agriculture and domestic uses (Talineau et al., 1994; Selmi, 1996).

The widespread use of agricultural practices, such as extraction of groundwater for irrigation and use of fertilizers, leads to a modified groundwater quality. This is particularly the case in Mediterranean climate, where high water demands during the growing season coincides with the dry period (Stigter et al., 1998).
At present, thirty reservoirs are monitored and allow the calculation of water budgets and modelling of catchment water flows (Fig. 1). Most reservoirs receive water from surface runoff. The subsurface component of the water balance is usually not a dominant term. From a chemical transport perspective, however, subsurface flows can be important as mechanism of transport for chemicals to and from reservoirs (Winter, 1995).

Although hydrochemical investigation combined or not with hydrogeological inventory is well established throughout the Mediterranean basin (Armengol et al., 1994; Marc et al., 1996; Ben Othman et al., 1997; Petelet et al., 1997; Stigter et al., 1998), little is known in Tunisia about the influence of hill reservoirs on groundwater. A chemical and regional typology of hill reservoir water, recently performed by Rahaingomanana (1998), gives a general framework to more detailed studies such as the present one included in the EU sponsored project Hydromed.

The main objectives of our work consisted in characterizing spatial water chemistry at a given time (flow and dry periods), in identifying geochemical tracers explaining the relationships between reservoir water and groundwater table and, in fine, in modelling the water-soil-rock interactions. In this paper, we report the preliminary results of a field study carried out during a dry period within and beyond a hill reservoir watershed.

Study site

The El Gouazine hill reservoir was chosen among five test sites of the Hydromed project because the water balance is highly negative suggesting an important water loss by infiltration (Fig. 1). The catchment is situated in the Ousseltia province, 50 km northwest of Kairouan and more precisely between the Ousseltia and Ksar Lamsa villages (Fig. 2). El Gouazine river is an affluent of Maarouf river and belongs to the endoreic basin of Nebhana river (central Tunisia). The basin outlet forms the Kelbia sebkha located few kilometers north of Kairouan.

![Figure 1. Localization of El Gouazine hill reservoir in central Tunisia.](image-url)
The watershed is approximately 18.1 km² in area and bordered by SW-NE orientated hills. Elevations decrease from 575 m above sea level for the highest hills to 375 m above sea level near the reservoir (Fig. 2). With a topographic variation of 200 m and a main river length of 11 km, the average slope is approximately 1.8% or 18 m km⁻¹. This value is higher than 5% in the upper parts of the valley cross-sections.

The El Gouazine region is characterized by a Mediterranean climate with a warm and dry summer, a cool and rainy winter, and highly variable rainfall in autumn and in spring. Mean annual precipitation was 395 mm at Ousseltia during the 1962-1989 period (Bocquet, 1993) and 355.8 mm at El Gouazine during the 1994-1997 period (Guiguen and Ben Younes, 1994; CES/ORSTOM, 1996a; 1996b; 1997). Mean annual air temperature is 19.1°C, with a minimum of 10.4°C in January and a maximum of 28.6°C in August (Bocquet, 1993). Potential evapotranspiration strongly exceeds precipitation and is approximately 1680 mm at Kairouan during the 1964-1982 period (Karray and Fakhfakh, 1998) and 1460 mm at Ousseltia during the 1993-1995 period (Riou, 1980; Pernin, 1998).

Vegetation originally consisted of Alep pines and Carob trees. Owing to increasing agricultural activities, a large part of the original vegetation has been replaced by rainfed cereals and by irrigated agriculture (mainly tomatoes, peppers, cucumbers, watermelons, almond trees, and olive trees). Alep trees are found only on poor calcareous soils at the top of the hills.

Figure 2. Study site of El Gouazine catchment with geological outcrops.
**Geology and hydrogeology**

El Gouazine watershed is located on the east edge of a SW-NE orientated syncline, known as Ousseltia syncline and characterized by marly calcareous and gritty deposits (Fournet, 1969). These deposits were raised by tectonic movements in the eastern part of the watershed with a southeastern and nearly vertical dip (Castany, 1951; Jauzein, 1967). The southeastern part of the basin is formed by Eocene sediments which include a mostly carbonated deposit composed of marl and nummulitic limestone from Ypresian or lower Lutetian, and a mostly clayey deposit composed of marl and shelly limestone from upper Lutetian. The northwestern part is formed by Oligocene sediments whose detrital facies is mostly gritty and known as Fortuna formation. Filled up at Quaternary, the syncline deposits have been cut by the rivers (locally known as oued). Gravelly and pebbly colluviums were extensively deposited and calcreted. Layers of shelly limestone (containing Oyster and/or Gastropod fossils), limy sandstone and marl outcrop in some catchment places (Fig. 2).

A regional aquifer is flowing towards the eastern endoreic lowlands (locally known as sebkhas) of the Kairouan plain and is discerned in El Gouazine catchment (Karray and Fakhfakh, 1998).

**Soils**

Most of the watershed soils are highly calcareous and clayey (Brunisso, 1967; Albouy et al., 1995; Bellier et al., 1997; Montoroi et al., 1997; Bellier et al., 1998). Calcreted horizons are observed on the summit of most hills. On the hillslope, colluvium is found with a high stone content.

According to the World Reference Base for Soil Resources (ISSS Working group RB, 1998), the main soils include calcrete calcisols and calcaric cambisols. Cambisols are mainly formed from marl deposits and locally from limy sandstone deposits.

**Dam characteristics**

The earth and embankment dam was built in 1990. The dyke is 232 m long, 56 m wide, and 10.6 m high, and the spillway overflows at a maximum water level of 8.28 m. The reservoir surface in overflow situation is of $9.597 \times 10^4$ km$^2$ for a 18.1 km$^2$ watershed surface defining a surface rate of 0.53% and a maximum capacity of 233 370 m$^3$ (Guiguen and Ben Younes, 1994).

In 1997, the reservoir capacity was lower owing to sedimentation, the value being 217 340 m$^3$. The reservoir capacity loss of 16 030 m$^3$ in 7 years corresponds to a mean annual loss of 2 290 m$^3$ and approximately to a maximum 3 m thick sediment deposit (CES/ORSTOM, 1996a; 1996b; 1997).
Methods

Water sampling

In May 1998, systematic water sampling was done within the catchment and beyond (Fig. 3). Surface water, groundwater, and reservoir water were sampled and filtered using a 0.2 μm mesh size. Electrical conductivity at 25°C (EC25°c), pH, and dissolved oxygen were measured in field before and after water filtration with WTW devices (LF 330 conductivimeter, pH 340 pHmeter, and OXY 330 oxymeter). Bicarbonate content was assessed in field by complete alcalimetry titration (CAT) with 0.1 N HCl. Filtered water was analyzed at laboratory for major and isotopic elements.

Soil and rock sampling

The reservoir was almost empty in May 1998 and bottom sediments were drying. Four pits were dug in the reservoir bottom and two others at the downstream side of the dam. Soil profiles were described and samples were collected for chemical analysis. Rocks were collected at different places of the catchment close to the wells where groundwater was sampled.

Other data

The water level of the reservoir was automatically recorded using an Elsyde device (Guiguen and Ben Younes, 1994). Data were stored in the Hydromed database using Hydrom software (CES/ORSTOM, 1996a; 1996b; 1997).

Chemical analyses, carried out by Job et al. (1995) and by Rahaingomanana (1998) for different periods during 1994 and 1995, were used for calculation.
Results

Water chemistry

Surface water and groundwater are highly contrasting in the catchment and the reservoir. The reservoir water is alkaline (pH > 10), weakly concentrated (EC < 1 dS m⁻¹), highly oxygenated (> 120 %; range from 9 to 12 mg L⁻¹), and weakly carbonated (CAT < 2 mmol L⁻¹) (Table 1). The chemical characteristics of El Gouazine reservoir water are consistent with those of other reservoirs belonging to the same geological environment.

In turn, groundwater is close to neutral, more concentrated (2 < EC < 8.5 dS m⁻¹), weakly oxygenated (< 80 %; range from 3 to 8 mg L⁻¹), and highly carbonated (4 < CAT < 11 mmol L⁻¹) (Table 2).

The groundwater is less concentrated in the downstream part of the dam suggesting that an upstream groundwater flow is diluted by reservoir water.
Table 1. Chemical data of surface waters in El Gouazine watershed (data are given for filtered (F) and nonfiltered (NF) samples).

<table>
<thead>
<tr>
<th>Date</th>
<th>Sample</th>
<th>Depth (m)</th>
<th>EC (µS cm⁻¹)</th>
<th>pH</th>
<th>T (°C)</th>
<th>Dissolved O₂ (mg L⁻¹)</th>
<th>CAT (mmolC L⁻¹)</th>
</tr>
</thead>
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<td>14/05/98</td>
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<td>0.1</td>
<td>0.859</td>
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<td>28.7</td>
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<td>9.76</td>
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<td>-</td>
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<td></td>
<td></td>
<td>lake 2</td>
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<td>9.93</td>
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<td>9.05</td>
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<td>43.8</td>
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<td>2.840</td>
<td>7.23</td>
<td>25.6</td>
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<td>1.90</td>
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<td>14/05/98</td>
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<td>7.665</td>
<td>7.03</td>
<td>22.5</td>
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<td>7.700</td>
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<td>9.20</td>
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ECₑₑₑₑ electrical conductivity measured at 25°C
CAT complete alcalimetry titration

Table 2. Chemical data of groundwater in El Gouazine watershed (data are given for nonfiltered samples).

<table>
<thead>
<tr>
<th>Date</th>
<th>Well (w) or pit (p)</th>
<th>Depth (m)</th>
<th>EC (µS cm⁻¹)</th>
<th>pH</th>
<th>T (°C)</th>
<th>Dissolved O₂ (mg L⁻¹)</th>
<th>CAT (mmolC L⁻¹)</th>
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</thead>
<tbody>
<tr>
<td>17/05/98</td>
<td>w1 River bed</td>
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<td>2.220</td>
<td>7.06</td>
<td>19.5</td>
<td>4.40</td>
<td>56.4</td>
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<td></td>
<td></td>
<td>-15.0</td>
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<td>7.15</td>
<td>18.1</td>
<td>7.15</td>
<td>80.3</td>
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<tr>
<td>21/05/98</td>
<td>w2 River bed</td>
<td>-1.0</td>
<td>2.130</td>
<td>7.04</td>
<td>17.8</td>
<td>2.94</td>
<td>33.3</td>
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<td></td>
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<td>-2.5</td>
<td>2.130</td>
<td>7.08</td>
<td>17.3</td>
<td>2.54</td>
<td>27.4</td>
</tr>
<tr>
<td>21/05/98</td>
<td>w3 River bed</td>
<td>-1.0</td>
<td>2.990</td>
<td>7.10</td>
<td>17.7</td>
<td>4.57</td>
<td>42.9</td>
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<tr>
<td></td>
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<td>-2.3</td>
<td>2.990</td>
<td>7.11</td>
<td>17.7</td>
<td>4.18</td>
<td>45.5</td>
</tr>
<tr>
<td>21/05/98</td>
<td>p1 Footdyke</td>
<td>-</td>
<td>1.888</td>
<td>7.38</td>
<td>18.7</td>
<td>3.87</td>
<td>43.4</td>
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<td>p2 River bed</td>
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<td>7.05</td>
<td>17.2</td>
<td>3.73</td>
<td>41.2</td>
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<td>16/05/98</td>
<td>w4 River bed</td>
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<td>8.300</td>
<td>7.02</td>
<td>17.0</td>
<td>6.45</td>
<td>66.5</td>
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<td></td>
<td></td>
<td>-4.0</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>16/05/98</td>
<td>w5 Calcareous outcrop</td>
<td>-1.0</td>
<td>2.240</td>
<td>6.98</td>
<td>20.0</td>
<td>3.80</td>
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<td></td>
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<td>-</td>
</tr>
<tr>
<td>16/05/98</td>
<td>w6 El Aafou</td>
<td>-1.0</td>
<td>1.212</td>
<td>7.34</td>
<td>16.1</td>
<td>2.60</td>
<td>26.7</td>
</tr>
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<td>-1.6</td>
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<td>-</td>
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<tr>
<td>23/05/98</td>
<td>w7 Souk</td>
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<td>3.240</td>
<td>7.13</td>
<td>19.5</td>
<td>7.48</td>
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<td>18.1</td>
<td>6.92</td>
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<td>w8 Fountain</td>
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<td>8.75</td>
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<tr>
<td>21/05/98</td>
<td>w9 Head</td>
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<td>3.230</td>
<td>7.26</td>
<td>17.1</td>
<td>5.56</td>
<td>62.1</td>
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<td></td>
<td></td>
<td>-8.3</td>
<td>3.230</td>
<td>7.30</td>
<td>17.2</td>
<td>7.54</td>
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<tr>
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<td>p4 Sediment</td>
<td>-</td>
<td>2.020</td>
<td>7.72</td>
<td>25.6</td>
<td>5.28</td>
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<tr>
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<td>p6 Sediment</td>
<td>-</td>
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<td>Beyond the watershed</td>
<td>w10 Bou Haleb</td>
<td>-1.0</td>
<td>4.180</td>
<td>7.23</td>
<td>18.4</td>
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<td></td>
<td>w11 Larbi</td>
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<td>7.25</td>
<td>16.8</td>
<td>3.74</td>
<td>39.8</td>
</tr>
</tbody>
</table>

ECₑₑₑₑ electrical conductivity measured at 25°C
CAT complete alcalimetry titration
(1) sampling depth below groundwater level
(2) groundwater level referencing to soil surface
Pedological observations

Reservoir sediments are composed of fine clayey layers alternating with coarse sandy layers. They are overlying the old river bed deposits composed mainly of coarse calcareous gravel and pebble. The sediment thickness is approximately 3 m at the p4 pit confirming the measurements carried out by sounding the reservoir water (CES/ORSTOM, 1996a; 1996b; 1997). Within the gravelly and pebbly layer, a groundwater table is observed at about 2.5 m depth (Fig. 4).

As shown at the two upstream reservoir cross-sections, a sandy layer is situated at the left side embankment of the reservoir and was overlying the gravelly and pebbly layer. Concerning the reservoir cross-section situated more upstream, the sandy layer is nearly 1.5 m thick, the base being at a 5 m level. In turn, concerning the wider reservoir cross-section, a sandy layer of 1 m thickness is present in the sediments. According to these facts, we can assume that the high permeability of the sandy layer explains partly the high water loss of the reservoir, especially when the water level amounts to more than 4 m.

Figure 4. Deposit structure of El Gouazine hill reservoir (May 1998).

The measurements of water level, carried out in the pits and the wells, define a hydraulic gradient from upstream to downstream (Fig. 5). It seems relevant to conclude that an upstream groundwater table is flowing downstream under and inside the sediments confirming the assumption suggested by the chemical data.
Infiltration rate estimation of reservoir water by chemical tracer method

During a dry period, we considered the temporal evolution of the reservoir volume \( V \) and the concentration of a conservative element (Cl\(^-\)). We compared the reducing volume factor \( F_v \) and the concentration factor \( F_c \) calculated from an initial given time \( i \) to a final given time \( f \) by the relationships \( F_v = V_f / V_i \) and \( F_c = C_{f \text{Cl}^-} / C_{i \text{Cl}^-} \). If both factors are equal, there is no infiltration or the groundwater inflow compensates the groundwater outflow. In turn, the reservoir loses water if \( F_c > F_v \) (outflow) and gains water if \( F_c < F_v \) (inflow).

If we assume, for the last two cases, that there is no infiltration during the considered period, we can calculate a theoretical concentration \( C_{i \text{Cl}^-} \) by the relationship \( C_{i \text{Cl}^-} = F_v C_{i \text{Cl}^-} \) and a theoretical volume by the relationship \( V_{i \text{th}} = V_i / F_c \). The deviation from the theoretical volume \( V_{i \text{th}} \) and the measured volume \( V_i \) gives an estimation of the groundwater balance. A negative value corresponds to a volume of water outflow while a positive one corresponds to a volume of water inflow.

This method was applied to 1994 and 1995 data for which 5 simultaneous measurements of reservoir volume and chloride concentration were available as shown in Fig. 6 (Rahaingomanana, 1998). The calculations showed that the hill reservoir had no infiltration or gained water from December 1994 to April 1995 while it lost 7068.7 m\(^3\) from April to June 1995 corresponding to an infiltration rate of 126.2 m\(^3\) per day (Table 3).

However, the calculated volumes did not exactly represent the groundwater flow because a non-negligible amount of rainfall occurred during the four considered periods. During the first three periods, the rainfall ranged from 9 to 14.5 mm while the amount was 57.3 mm for the last one. The water inflow led to a decrease in Cl\(^-\) concentration by dilution during the given period. Thus, the calculated concentration factor \( F_c \) was underestimated while the calculated theoretical volume \( V_{i \text{th}} \) and deviation \( V_{i \text{th}} - V_i \) were overestimated.
Taking into account this approximation, we can only assert that, from April to June 1995, the hill reservoir had a minimum infiltration rate of 126 m$^3$ per day.

![Figure 6. Daily reservoir volume versus time for El Gouazine hill reservoir.](image)

### Table 3. Infiltration rate of El Gouazine reservoir water during the 1994-1995 period.

<table>
<thead>
<tr>
<th>Period</th>
<th>$V_i$</th>
<th>$V_f$</th>
<th>$C_i$</th>
<th>$C_f$</th>
<th>$F_v$</th>
<th>$F_c$</th>
<th>$C_{F}^{i}$</th>
<th>$V_{sh}$</th>
<th>$V_{sh} - V_i$</th>
<th>$N$</th>
<th>Rate</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>m$^3$</td>
<td>(mmol$C$ L$^{-1}$)</td>
<td>(mmol$C$ L$^{-1}$)</td>
<td>m$^3$</td>
<td>d</td>
<td>m$^3$ d$^{-1}$</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>13/12/94</td>
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<td>114000</td>
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<td>1.28</td>
<td>1.21</td>
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<td>121047.3</td>
<td>7047.3</td>
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<td>81600</td>
<td>53900</td>
<td>1.32</td>
<td>2.30</td>
<td>1.51</td>
<td>1.74</td>
<td>2.00</td>
<td>46831.3</td>
<td>-7068.7</td>
<td>56</td>
<td>-126.2</td>
</tr>
</tbody>
</table>

**Water loss evolution**

Water level data were recorded when water level variation was higher than 1 cm and were converted into volume by a relationship calculated for El Gouazine reservoir. As data were too numerous, only those recorded at 8:00 am were selected for processing. They were smoothed by a six-day running average for a series of 130 days starting from 1/1/1997.
The observed volume variations between two given dates correspond either to a water inflow if the variation is positive or to a water outflow if the variation is negative. Taking into account the measured evaporation, rainfall, and runoff volumes, we can estimate the groundwater inflow and outflow volumes. The values are compared to the water level data in Fig. 7.

A change was observed in groundwater balance at the 4.5 m water level. Above this value, the infiltration rate of groundwater mostly ranged from 200 to 300 m$^3$ per day. Below the 4.5 m level, infiltration rate approximately ranged from 50 to 150 m$^3$ per day. For the lower water level, there is either no infiltration or a water supply. It is quite interesting to notice that the level change corresponds nearly to the sandy layer position previously described.

![Figure 7. Water loss by infiltration for El Gouazine hill reservoir (plotted data correspond to a series of 130 days starting from 1/1/1997).](image)

### Conclusion

The water chemistry and pedological observations confirm that the El Gouazine reservoir can infiltrate and supply a downstream aquifer. We need more information to assess the permeability of porous deposits. It seems that a general (maybe regional) aquifer flows in the watershed, temporarily supplying the hill reservoir and maintaining an alluvial aquifer.

The laboratory analyses will allow to distinguish the different chemical composition of waters defining different water types and to determine the interactions of subsurface water with surface water features such as reservoir and river. Geochemical modelling will lead to an evaluation, on the one hand, how the different geological and pedological parts of the watershed contribute to the chemistry of the reservoir water and, on the other hand, how reservoir water contributes to aquifer recharge.
Acknowledgments

The authors are grateful to Dr. Jean Albergel and Yannick Pépin who kindly provided access to the hydrological database of El Gouazine hill reservoir. We also thank Nathalie Rahaingomanana for the chemical analyses of surface water which were extracted from her thesis.

References

Rain water harvesting and management of small reservoirs in arid and semiarid areas
Lund University, Sweden, 29 June – 2 July, 1998

Solute transport and soil water content measurements in arid soils using time domain reflectometry

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Solute transport and water content measurements in arid soils using time domain reflectometry

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Abstract

Clayey and saline soils have been shown to be problematic for TDR measurements. However, if one is aware of the problems encountered, they can in most cases be solved. This study presents some of these problems and discusses solutions to them. The water content (θ) measurement in clayey soils is less accurate and precise than in sandy soils, soil specific calibration might be necessary. In very saline soils, coated probes or a remote shorting diode system should be used in order to make θ measurement. Another option is to use shorter probes. For solute transport experiments in heavy clay soils I recommend that the indirect calibration method is used. Both the σs and θ measurements are temperature dependent. The temperature dependency of σs can easily be accounted for. The temperature dependency on θ is, however, hard to take into account. Depending on soil texture and soil salinity, the θ measurement can increase or decrease with temperature. Using non-invasive TDR measurements, rapid non-destructive measurements of near surface θ and σs can be made. Thus, it can provide a useful tool in erosion and evaporation studies.

Introduction

During recent years, the time domain reflectometry (TDR) technique has been proven to make reliable water content (θ) and bulk electrical conductivity (σs) measurements (Topp et al., 1980; Dalton et al., 1984). The fact that TDR measure both θ and σs in the same soil volume over a very short time makes the method appealing for solute transport measurements. Furthermore, TDR has the ability of being automated for nearly continuous measurements.

The σs can been related to soil solution electrical conductivity (σsw) or solute concentration. Due to the complicated σs-σsw-θ relationship, most studies have been made under steady state conditions with constant water content (Kachanoski et al., 1992; Vanclooster et al., 1993). However, methods have also been developed for solute transport measurement under transient conditions with varying water content (Risler et al., 1996; Persson, 1997a, b; Hart and Lowery, 1998).

Clayey, saline, and dry soils have been shown to be problematic in the sense of measurement accuracy using TDR (e.g., Topp et al., 1980). These soil types are often found in arid and semi-arid regions. The purpose of the present study is to investigate these problems and present solutions to some of them. A non-invasive approach for water content and electrical conductivity measurements using TDR is also presented.
Theory

Water content measurements

In 1980, Topp and co-workers introduced TDR for the measurement of soil moisture (Topp et al., 1980). They based their method on the work of Fellner-Feldegg (1969) who used TDR for measuring the dielectric constant. Topp et al. (1980) introduced the apparent dielectric constant \( K_a \), which they related to volumetric water content \( \theta \) using an empirical third-order polynomial equation. In addition to the empirical relationship by Topp et al. (1980), various types of dielectric mixing models have been used. In these models, the wet soil is described as a multiple phase system. Typically three phases are used, solid, gaseous, and free water. The dielectric numbers of the different phases are known and if the volume fraction of each phase also is known, the water content can be calculated. A detailed description of these models can be found in Jacobsen and Schjønning (1995).

Electrical conductivity measurements

Dalton et al. (1984) were the first to show how the attenuation of the TDR trace can be used to calculate the soil bulk electrical conductivity. Following the thin sample approach by Giese and Tiemann (1975), the electrical conductivity \( \sigma \) can be described by (Giese and Tiemann, 1975; Topp et al., 1988; Nadler et al., 1991)

\[
\sigma = K_c f_T/Z_L
\]  

where \( Z_L \) is the impedance load of the transmission line (in \( \Omega \)) measured after a long time, \( f_T \) is a temperature correction coefficient, \( K_c \) is the cell constant of the TDR probe, a calibration constant that can be determined by immersing the probe in solutions with known conductivity. Himovaara et al. (1995) showed that the temperature dependency of the \( \sigma \) is identical to the temperature dependence of the soil extract. The temperature correction coefficient of a standard 0.01 M KCl solution can be described by

\[
f_T = \frac{1}{1 + 0.019(T - 25)}
\]  

where \( T \) is the temperature (\( ^\circ C \)) at which the electrical conductivity measurement was made (Franson, 1985).

Calibration approaches for solute concentration measurements

Two main calibration approaches have been developed for the relationship between the electrical conductivity and solute concentration, direct and indirect calibration. Using the indirect calibration approach, a separate calibration is not needed, the calibration is made simultaneously with the solute transport experiment. The soil is leached with water with a constant flux. When steady state conditions have been established, the solute free water is replaced by a salt solution with constant \( \sigma_w \). After some time, all water in the soil has been replaced with the salt solution and the reference impedance can be determined (Kachanoski et al., 1992; Mallants et al., 1996). Since there is a linear relationship between the impedance and solute concentration at constant
8, the impedance measured with the TDR can easily be related to solute concentration. This method has been used in several laboratory studies and in some field studies (Kachanoski et al., 1992; Ward et al., 1994).

Steady-state conditions are not likely to persist for prolonged periods in nature. If TDR should replace traditionally measuring techniques, methods must also be developed for transient conditions with variable water content. If the indirect calibration method is to be used under these conditions, several leaching experiments with different water fluxes have to be made in order to relate the TDR measurements to solute concentration over a range of water contents. If instead the $\sigma_s-\sigma_w-\theta$ relationship is determined, solute concentration measurements can be made under transient conditions with variable water content (Heimovaara et al., 1995; Risler et al., 1996; Persson, 1997a, b). This approach has been called direct calibration due to that a separate calibration experiment has to be conducted.

In the $\sigma_s-\sigma_w-\theta$ models, the electrical conductivity of the soil depends mainly on three variables, (i) the effective volumetric water content $\theta - \theta_0$, where $\theta_0$ is a correction factor accounting for water close to the solid particles which can be considered immobile, (ii) the electrical conductivity of the soil solution, and (iii) a geometry factor, accounting for the complex geometry of the soil matrix (Mualem and Friedman, 1991). The $\sigma_s$ is also affected by the surface conductivity of the soil matrix $\sigma_s$. For unsaturated soils the simplified conductivity model of Rhoades et al. (1976) is often used and is given as

$$\sigma_s = \sigma_w T(\theta) + \sigma_s$$  \hspace{1cm} (3)

where $T(\theta)$ is the transmission coefficient accounting for the tortuosity of the current flow. Rhoades et al. (1976) proposed a linear relationship between $T(\theta)$ and $\theta$, i.e. $T(\theta) = a\theta + b$, where $a$ and $b$ are soil specific parameters. Rhoades et al. (1989) re-interpreted $T(\theta)$ as simply the fraction of the total soil water that is mobile. Other $\sigma_s-\sigma_w-\theta$ relationships have also been developed (Mualem and Friedman, 1991; Heimovaara et al., 1995; Vogeler et al., 1996; Persson, 1997b; Kim et al., 1998). Risler et al. (1996) and Persson (1997a) showed how the TDR probes can be calibrated in situ using the direct calibration.

**Materials and methods**

**TDR system**

All TDR measurements in this study were made with a Tektronix 1502C metallic TDR cable tester (Beaverton, OR). The cable tester was built into a system designed by Campbell Scientific Ltd., Shapshed, UK. The system consisted of a CR10 data-logger with a TDR PROM controlling the cable tester via a communication interface. An eight to one coaxial multiplexer was also included in the system. Two types of three-rod probes were used, which were 0.2 m long and had a wire spacing of 0.05 m, (Soilmoisture Equipment Corp., Santa Barbara, CA). One of these was the standard type with stainless steel rods, the other was a coated three-rod probe. This probe has a hard dielectric polymer around the central rod which provides optimum energy retention for maximum TDR reflections, allowing moisture content measurement in saline soils. However, electrical conductivity measurements are not possible with this probe. All temperature
measurements were made with type K thermocouples (Pentronic AB, Gunnebo, Sweden) connected to the data-logger. Reference electrical conductivity measurements were made with a digital conductivity meter (Shott-Geräte, Germany).

The TDR probes were calibrated as described by Heimovaara (1993) for water content measurements. Furthermore, the probes were immersed in water with different electrical conductivities to establish the relationship between the impedance load $Z_L$ of the transmission line and the bulk electrical conductivity according to Heimovaara et al. (1995).

**Solute Transport Experiment**

A quasi steady state solute transport experiment was conducted in a column (0.23 m in diam and 0.30 m high) of undisturbed soil collected in the M'Richet el Anze catchment in Tunisia. The soil properties have been presented in Palmquist and Tullberg (1997). The soil column was placed over a sand column of 0.7 m height in order to establish unsaturated conditions at the bottom of the soil column. The column was then equipped with five TDR probes at depths of 0.05, 0.10, 0.15, 0.18, and 0.34 cm. Thus, four TDR probes were put in the soil and one in the sand. The outflow was collected and the electrical conductivity was measured once a day.

A constant flux was achieved by adding 0.012 m of tap water ($\sigma_w = 0.041$ dSm$^{-1}$) a day in a single dose. The dose was applied over a several minutes to avoid ponded conditions at the soil surface. After one week, steady-state flow conditions were obtained and a step pulse of KBr solution ($\sigma_w = 3.33$ dSm$^{-1}$) was added to the column. The KBr solution was added daily in the same way as the tap water until the $\sigma_w$ of the outflow reached the input level. Time series of relative concentrations were fitted to the convective dispersive equation model (CDE) using the CXTFIT program.

**Results and discussion**

This section shows the TDR performance in arid soils, based on experimental data presented in previous work (Persson, 1997a, b; Persson and Berntsson, 1998a, b, c, d) as well as unpublished data.

**Water Content Measurements**

Many researchers have reported problems with the water content measurement in clayey soils (e.g., Topp et al., 1980). The major reason for this is that bound water has different dielectric properties than free water. Since bound water has a $K_s$ close to the soil particles, it is difficult to measure with TDR. Hook and Livingston (1996) suggested a model that gives the free water content in clayey soils. The bound water content can then be determined as the difference between the gravimetric and TDR measured water content. They also presented a model in which the total water content can be calibrated using a soil specific calibration. The water content has also been shown to be over estimated when the $\sigma_w$ is larger than about 8 dSm$^{-1}$ (Dalton, 1992).
The accuracy of the water content measurement is also lower in clayey and saline soils. This was shown already by Topp et al. (1980). This can also be seen in Fig. 6 in Persson (1997a) and in Table 2 in Persson and Berndtsson (1998b). If the electrical conductivity is too high, the reflection of the end of the TDR probe disappears and no water content measurement can be made. This can be overcome, however, by using coated probes. The drawback is that electrical conductivity measurements cannot be made with this probe. Another option is to use shorter probes, since these are less influenced by electrical conductivity. Some TDR systems use remote shorting diodes to find the end reflection of the TDR probe (Hook et al., 1992). These probes are, thus, less sensitive to high electrical conductivity.

**Solute transport measurements**

Several studies have shown that TDR measurements of solute transport can be made during both steady-state and transient conditions. These studies have mostly been made in soil with relative low clay content. Risler et al. (1996) used the direct calibration method following an in situ calibration in different soils including a clay loam. However, in solute transport experiments in heavy clay soils I recommend that the indirect calibration method is used. This is based on (i) the water content is not changing as much or as rapid as in light textured soils, especially during solute transport experiments, (ii) the $\sigma_s-\sigma_e-0$ relationship is more complicated for clayey soils (see e.g., Nadler, 1982; Nadler et al., 1984), and (iii) the combination of clayey soils and high electrical conductivity in the tracer pulse often leads to that water content measurements not are possible due to the signal attenuation.

**Solute Transport Experiment**

In Fig. 1, the relative solute concentration profile over time during the experiment is presented. It can be seen that the solute pulse reaches some depths quicker than other. Especially in the sand layer the velocity $v$ was much higher than for the other locations. This is also reflected in the fitted CDE parameters presented in Table 1. This can be explained by that the solutes were transported in preferential flow paths that was not detected by the TDR probes, indicating that the solute transport was heterogeneous at a scale smaller than the TDR measurement volume. In the sand layer, the solute pulse was mixed horizontally which explains why the TDR probe in the sand detected the solute pulse. The dispersion $D$ is increasing linearly with depth indicating that the solute transport follows the stochastic-convective concept (see e.g., Jury and Roth, 1990; Persson and Berndtsson, 1998d). This was expected since the solute transport in clayey soils often follow this concept.

<table>
<thead>
<tr>
<th>Depth [cm]</th>
<th>$V$ [cm/day]</th>
<th>$D$ [cm$^2$/day]</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>2.13</td>
<td>5.06</td>
</tr>
<tr>
<td>10</td>
<td>1.46</td>
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<tr>
<td>14</td>
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<td>9.50</td>
</tr>
<tr>
<td>34</td>
<td>12.33</td>
<td>930</td>
</tr>
</tbody>
</table>

Table 1. The fitted CDE parameters in the undisturbed soil column.
It should be noted that as TDR is not ion selective, it is not clear what actually is being measured. Chemical reactions, ion exchange, and adsorption might change the electrical conductivity. Risler et al. (1996), however, did not find large differences in solute concentrations based on electrical conductivity or ion chromatograph measurements in the outflow from a column with clay loam. However, it is recommended that the solute concentration of the tracer also is measured with an independent method in water collected from e.g., solution samplers.

Figure 1. Solute concentration profile during the solute transport experiment.

**Temperature dependency of TDR measurements**

Both the $\sigma_s$ and $\theta$ measurements are temperature dependent. The temperature dependency of $\sigma_s$ measured in soil is similar to that of the soil solution (Heimovaara et al., 1995; Persson and Berndtsson, 1998b) and it can be accounted for by using Eq. (2). The temperature dependency on $\theta$ is however hard to take into account. Depending on soil texture and soil salinity, the $\theta$ measurement can increase or decrease with temperature (Persson and Berndtsson, 1998b). In sandy soils a temperature correction factor of $-0.028 \, ^\circC^{-1}$ should be used (Pepin et al., 1995; Halbertsma et al., 1995; Persson and Berndtsson, 1998b). In soils with high clay or organic matter content the temperature effects on $\theta$ are not consistent and need to be examined in detail for a particular soil in order to achieve accurate measurements. It should be noted that the temperature effects on $\theta$ are small compared to other calibration errors. However, when the relative changes in soil moisture are measured with a single probe, the temperature effects might impose an apparent change in soil moisture, e.g., between day and night.
Non-invasive TDR measurements

One problem in arid climates is that the soil surface becomes very hard when it dries out. This makes insertion of a measurement instrument almost impossible without great soil disturbances. One way to overcome this problem is to use non-invasive measurement techniques. In Persson and Berndtsson (1998c) it was shown how an ordinary three-rod TDR probe could be used together with a PVC block for non-invasive measurements of \( \theta \) and \( \sigma_s \). The method gave good results in the laboratory, but a field evaluation has not yet been done.

Conclusions

Clayey and saline soils have been shown to be problematic for TDR measurements. Thus, few studies have been made in these soil types. However, if one is aware of the problems encountered, they can in most cases be solved. This study presents some of these problems and discusses solutions to them.

The \( \theta \) measurement in clayey soils is less accurate and precise than in sandy soils. The variability can be overcome by taking several \( \theta \) measurements and calculate the average. The accuracy can be improved by using specific \( K_r-\theta \) models such as the one presented by Hook and Livingston (1996). Water content measurement in saline soils can be impossible due to signal attenuation. The solution to this problem is to use coated probes or a remote shorting diode system. Another option is to use shorter probes. A guide for determine maximum probe length with respect to \( \sigma_s \) can be found in Dalton (1992).

Several studies have shown that TDR measurements of solute transport can be made during both steady-state and transient conditions. These studies have mostly been made in soil with relative low clay content. However, my results from an undisturbed soil column with a heavy clay soil from Tunisia (Typic Xerorthent) suggest that solute transport can be estimated by TDR even in soils containing as much as 60% clay. For solute transport experiments in heavy clay soils I recommend that the indirect calibration method is used. This is based on (i) the water content is not changing as much or as rapid as in light textured soils, (ii) the \( \sigma_s-\sigma_r-\theta \) relationship is more complicated for clayey soils (see e.g., Nadler, 1982; Nadler et al., 1984), and (iii) the combination of clayey soils and high electrical conductivity in the tracer pulse lead to that water content measurements not are possible due to the signal attenuation.

Both the \( \sigma_s \) and \( \theta \) measurements are temperature dependent. The temperature dependency of \( \sigma_s \) can be accounted for by using Eq. (2). The temperature dependency on \( \theta \) is, however, hard to take into account. Depending on soil texture and soil salinity, the \( \theta \) measurement can increase or decrease with. In sandy soils a temperature correction factor of \(-0.028 \, ^\circ\text{C}^{-1}\) should be used. In soils with high clay or organic matter content the temperature effects on \( \theta \) are not consistent and need to be examined in detail for a particular soil in order to achieve accurate measurements.

Using non-invasive TDR measurements, rapid non-destructive measurements of near surface \( \theta \) and \( \sigma_s \) can be made. Thus, it can provide a useful tool in erosion and evaporation studies.
Acknowledgments

This study was funded by the Swedish Natural Science Research Council. Experimental equipment was purchased partly through grants from the Crafoord and Lundberg Foundations and partly through the EU funded HYDROMED research program on hill reservoirs in the semiarid Mediterranean zone. Their support is gratefully acknowledged.

References


Rain water harvesting and management of small reservoirs in arid and semiarid areas

Lund University, Sweden, 29 June – 2 July, 1998

Decision Support System in Hydrological Modeling,
A case study in China

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Background and problem

Generally speaking, computer based numerical hydrological models have been playing a central role during the last decades in dealing with water resources related problems. Various kinds of conceptual, physical, and stochastic models have been developed. Perhaps the most important contribution of these models is the ability of simplifying and schematizing a complex problem in nature and solve it mathematically against the predefined conditions. Another indispensable contribution of the numerical models is the ability to carry out tedious, time consuming calculations to test different assumptions and scenarios. However, practical applications of the models indicate severe limitations. Most existing models of hydrological systems are facing the following problems: models require tremendous effort in calibrating and parameter identification and thus, it is difficult to generalize their usage; trial-and-error approach must be used due to lack of data; even when the model structure and algorithms are perfect the modeling results are limited by the spatial and temporal resolutions of the models.

Like any other numerical models, hydrological models require that underlying physical mechanisms of the problem are well defined and that a mathematical algorithm is established. This is the case for most existing models. However, the obstacles preventing improved modeling results are mostly due to the inability by handling the hydrological processes and properties in both spatial and temporal domains with satisfactory resolution. By joined efforts of GIS (Geographical Information System) and RS (Remote Sensing) techniques, not only the results of the existing models can be largely improved, but also new concepts and functions can be incorporated in new era hydrological modeling.

The present study concerns development of an integrated model to combine and incorporate GIS and RS into an existing hydrological modeling system. The aim is to provide an integrated hydrological modeling system (or a Decision Support System, DSS) for water resources management at basin-wide, regional scale, capable to solve complex problems in four dimensions (spatial and temporal). The existing hydrological model system may consist of basin-wide rainfall-runoff model with user interface and data treatment unit.

Current research trend

Water management in both rural and urban areas is based on a detailed knowledge about spatial and temporal properties of its dynamic system. Parallel to the development of hydrological models, which traditionally focus on processes in time domain (time series), a relatively new technique has emerged. The Geographical Information System (GIS) is a digital model for treatment, storage, analysis, and representation of map-related data (Dodson, 1993). A GIS emphasizes the strong connection between data and relationships to the spatial position, allowing
advanced analyses of properties of the defined entities (objects) and attributes. Although initiated by geographical and cartographical applications, the potential of GIS tools are recognized by more and more hydrologists (Maidment, 1993; Leipnik et al., 1993).

Simple applications of GIS in hydrological fields can be found in e.g., Pentland and Cuthbert (1971), who used a grid data representation derived from remotely sensed data to map ungauged fields. A summary of GIS applications in various hydrological modeling procedures is given by DeVantier and Feldman, (1993). Djokic and Maidment (1993) used a TIN based GIS approach to river flow routing. Successful results were reported by Meyer et al. (1993) in applying GIS to manage urban storm water with SWMM model.

New concepts were introduced by e.g., Muzik (1992), who used GIS to obtain unit hydrographs. Flügel (1996) used a GIS approach to identify the catchment properties by using the Hydrological Response Unit concept, which is well suited to GIS functionalities to derive assembled, spatially distributed physiographical properties of a basin. Walsh (1993) developed a combined approach of GIS and DSS (Decision Support System) to demonstrate the potential of these systems in advanced decision making tools, including water resources decision making. Similar efforts in using GIS to develop expert systems were reported by McKinney and Maidment (1993), Fedra and Jamieson (1996) and Lam and Swayne (1996).

Case study in China

In the framework of a joint research program between China and Sweden, a methodology for flood analysis for evaluation of protection and operation of river systems is developed. (Bengtsson et al., 1995; Dept. of Water Resources Eng., 1996). Such a method includes approaches for assessment of design rainfall, calculating river flows from precipitation, statistical analysis of river discharge, estimating probabilities of different events, transfer of observation data from one basin to another, and evaluation of consequences of flooding and of droughts. The primary purpose of the joint program is to establish a graphical computer information system that can be used by non-experts for easy input of data and for easily understandable output and develop and adapt a rainfall-runoff model for Chinese conditions. A DSS is also to be incorporated into this planning and designing tool. The general scheme and components used in this case study is displayed in Fig. 1.

A pilot study was conducted at a selected river basin (Hongru river basin) in China. The basin is a tributary to the Huai River which is situated between the Yellow River and the Yangtze River basins. The Huai River basin has a comparatively small drainage area (270 000 km$^2$) but a large national economic importance. The basin occupies 1/37 of the national territory but 1/8 of the total population. The Hongru River basin has one of the most comprehensive hydrological and climatological observation networks in China. Starting from early 50's, an extensive, continuous database has been established for this area. The data set includes: precipitation, runoff, potential evapotranspiration, discharge, and water level as well as temperature, wind velocity and direction, data on irrigation, land use, vegetation, human activity, soil moisture, and groundwater.
Figure 1. Flow chart and components used in the Chinese DSS case study
The Framework of Decision Support System used in the case study

A Decision Support System (DSS) may consist of three collections of system components: databases, models, and user-interfaces. The framework design of each of these components is described in the following sections.

In a flood-protection planning DSS, the established databases are in charge of large amounts of information in various format. The basic function of the databases are storage, indexing, and processing. The basic operations of the databases are retrieval, reorganizing, maintaining as well as regenerating databases, based on SQL queries by the flood-protection planning DSS. The assembly of databases consists of a database management system, the databases and an application software. The structure of a such system is illustrated in Fig. 2.

![Concept of the Database Management System in a DSS](image)

Figure 2. Concept of the Database Management System in a DSS

The design strategy of databases

A flood-protection planning DSS is multi-disciplinary system including not only hydrological, engineering sub-system but also social, economical, and environmental aspects. This information has also a complex combination in space and time scales. It can be summarized as follows:

- Wide range of data series
- Complex inter-relationships
- Incomplete observations
The assembly of databases needs to satisfy the following criteria in a flood-protection planning DSS:

- Capable for random storage and retrieval.
- Easy to be expanded.
- Besides the original, basic data, it should be capable to store intermediate data series as well as multiple simulation results.
- Capable for data augmentation.
- Capability for easy external data importing.
- Easy SQL query for retrieval and output display, especially graphical and multi-media.
- Capability of reorganizing, reprocessing, recalculation of original database in order to generate new set of database.

**Database management system**

Database Management System (DBMS) is a system software which resides directly in the computer operation system. Its basic functions are:

- Definition of databases
- Management of databases
- Maintenance of databases
- Communication between databases

Various database types include stratum, mesh, and relational options. The relational databases are getting more and more popular in recent years. The current study also used relational databases. The rapid development in commercial DBMS has provided a number of choices when implementing such a system. In Fig. 3, all the components of the DBMS used in the case study are presented together with their inter-relationships.
Figure 3. Components and their inter-relationships of the DBMS used in the Chinese case study.
Framework of flood-protection planning DSS

The definition and connection between the physical system and the database in a flood-protection planning DSS are based on two basic components: Node and Line. A node is usually an intersection of two elements in the system, such as hydraulic intersection of river reaches. An areal element, such as a reservoir or lake, may be included in node by assigning an areal attribute to the node. In this case a new element for a reservoir may be defined. A line describes the relationship between two nodes, such as river reach, canal, etc. The inter-connections of a number of these components are capable to define the framework of a catchment area, with its drainage network.

In order to show this method, the framework design for Hongru river basin is taken as an example. The hydraulic structure of the river basin is schematized in Fig. 4 and the text following the figure. It can be noted that some of the elements for different components are the same. For instance Code Name can appear in several components, linking them together to build up the inter-relationships in the databases. Figure 4 presents a such scheme for the pilot study area in China.
Sample screen shots

In the following section, some sample screen shots are displayed to show the user interface and built-in functionality of GIS in the DSS. In Fig. 5, a sample for user interface of FLAPS modeling system built-in in the DSS for Chinese pilot study is shown. In Figs. 6 and 7, the functionality of GIS is displayed.

Figure 5. User interface of FLAPS modeling system built in the DSS for the Chinese pilot study.
Concluding remarks

From the case study the following general concluding remarks may be drawn for a DSS in flood protection and planning tool:

- Integrated model with GIS and RS
- Scalable and distributed in space and time domain
- Advanced DBMS for data analyses and manipulation
- Decision support based on modeling scenarios
- User friendly

Figure 6. GIS capability used in the FLAPS system for China.
GIS capability used in FLAPS system where urban area, reservoir, raingauge and drainage are displayed.

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Session 3.

Rainwater harvesting; infiltration techniques and modeling; infiltration and erosion (chairman: Dr. Nejib Rejeb, INRGREF).
Rain water harvesting and management of small reservoirs in arid and semi-arid areas

Lund University, Sweden, 29 June – 2 July, 1998

Water harvesting techniques in the Mediterranean region

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Water harvesting techniques in the Mediterranean region

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Abstract: In the Mediterranean region, pumped ground water and water taken from (permanent) rivers and reservoirs becomes scarcer and scarcer. Therefore new interest came up in recent decades to evaluate traditional water management techniques, especially those techniques which are not based on river or pumped ground water.

Water harvesting techniques have been practised in the Mediterranean region since millennia. Some prominent examples mentioned in this paper are rainwater harvesting, floodwater harvesting and groundwater harvesting by qanats and underground dams etc. The revival and improvement of these methods could provide excellent opportunities to ease the water scarcity for small-scale irrigation in the Mediterranean Basin.

Keywords: Traditional irrigation, water harvesting, qanats, underground dams

INTRODUCTION

Water scarcity is already a fact in most parts of the Mediterranean and will be one of the major threats to human development in this region in the next century (Hamdy & Lacirignola 1994). Low and erratic rainfall always posed problems to the farming community, but in modern times four more problems must be faced by the farmers of this region:

1. The tremendous population growth with its unpredictable impact on the natural resources.
2. An increase in competition for water resources between agriculture and the urban centres.
3. The consequences of global warming and
4. Sea water intrusion into coastal groundwater aquifers.

To ease future water scarcity, we have to find means to deal with this problem in a sustainable manner. This includes a reassessment of certain traditional irrigation methods to find out their value. Traditional methods are covered in this paper, which were developed in areas without permanent rivers, where people had to rely on rainfall or subsurface flow of water. In future, these methods, coupled with water conservation techniques, may supplement the other sources of irrigation water and help to secure future water supply.

Since ancient times, farmers and herders in the Mediterranean have, under widely varying ecological conditions, attempted to ‘harvest’ water to secure or increase agricultural production. A wide range of indigenous techniques can be found in areas between 100 and 1000 mm annual precipitation and with population densities varying from 10-300 persons / km². These traditional methods played a much greater role in the past and were the backbone of ancient civilisations in the Mediterranean (Prinz 1995).
The technical means of the 20th century in lifting groundwater or establishing large canal systems even with inter-basin water transfer, coupled with a distinct government policy favouring ‘modern’ water supply and distribution techniques, brought about a decline in traditional systems.

GENERAL OVERVIEW

To ease water scarcity in the Mediterranean without using irrigation water from permanent rivers, from reservoirs or lifted groundwater, three groups of water harvesting techniques can be applied (Tab. 1):
1. Rainwater Harvesting,
2. Floodwater Harvesting and

<table>
<thead>
<tr>
<th>WH Group</th>
<th>RAINWATER HARVESTING</th>
<th>FLOODWATER HARVESTING</th>
<th>GROUNDWATER HARVESTING</th>
</tr>
</thead>
<tbody>
<tr>
<td>WH Type</td>
<td>Micro-Catchment WH</td>
<td>Macro-Catchment WH</td>
<td>Flood Water Diversion</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Qanat Systems</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Groundwater Wells</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Special Wells</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Techniques</td>
<td>Treated Surfaces e.g. Sealed Paved, Compacted, Smoothened Surfaces</td>
<td>Interrow-WH</td>
<td>Hillside Conduit Systems</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Hillside Conduit Systems</td>
<td>Jessour Type</td>
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<td></td>
<td>Hillside Conduit Systems</td>
<td>Wild Flooding</td>
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<tr>
<td></td>
<td></td>
<td>Hillside Conduit Systems</td>
<td>Short Qanats</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Hillside Conduit Systems</td>
<td>Sand Storage Dams</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Hillside Conduit Systems</td>
<td>Horizontal Wells</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cultivated Reservoirs/Tanks</td>
<td>With Percolation Dams</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cultivated Reservoirs/Tanks</td>
<td>Water Distribution</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cultivated Reservoirs/Tanks</td>
<td>Long Distance Qanats</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Eyebrow Terraces</td>
<td>Stone Dams</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Vallerani Type WH</td>
<td>Liman Terraces</td>
</tr>
<tr>
<td>Kind of Storage</td>
<td>Cisterns, Ponds, Jars, Tanks</td>
<td>Soil Profile</td>
<td>Soil Profile</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Soil Profile, Cisterns, Ponds</td>
<td>Soil Profile</td>
</tr>
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<td></td>
<td></td>
<td>Soil Profile, Cisterns, Ponds</td>
<td>Reservoirs</td>
</tr>
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<td></td>
<td></td>
<td>Soil Profile, Cisterns, Ponds</td>
<td>Ponds</td>
</tr>
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<td></td>
<td>Soil Profile, Cisterns, Ponds</td>
<td>Substrate Profile</td>
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<td>Soil Profile, Ponds</td>
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<tr>
<td>Aquifer Recharge</td>
<td>None</td>
<td>Very Limited</td>
<td>Limited</td>
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<td>Very Limited</td>
<td>Limited</td>
<td>Strong</td>
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</tbody>
</table>

Tab. 1: Groups, types and subtypes of ‘Water Harvesting’ for agriculture
Conventional irrigation methods use the rainfall after it has infiltrated into the ground, using underground water or the water of permanent streams and rivers. Rainwater harvesting techniques collect the rainfall before it enters the soil, i.e. as surface runoff. The collection and concentration of rainfall and its use for the irrigation of crops, pastures, trees, for livestock consumption and household purposes is called rainwater harvesting (Siegert 1994).

Each rainwater harvesting system requires a:
- "runoff area" (catchment) with a sufficiently high run-off yield, and a
- "run-on" area for utilisation and / or storage of the accumulated water. These methods can be subdivided according to their way of water collection and the kind of storage.

Three types of WH for agricultural purposes are covered by ‘Rainwater Harvesting’:

- **Water collected from roofs and courtyards** and similar paved, bituminized, compacted or otherwise treated surfaces. The collected water is used for domestic purposes, for animal water consumption or for garden crops.
- **Microcatchment water harvesting** is a method of collecting surface runoff (sheet or rill flow) from a small catchment area and storing it in the root zone of an adjacent infiltration basin. The basin is planted with a single tree or bush or with annual crops.
- **Macrocatchment water harvesting** is also called "water harvesting from long slopes" or "harvesting from external catchment systems" (Pacey & Cullis 1988). In this case, the runoff from hillslope catchments is conveyed to the cropping area located below the hill foot on flat terrain.

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**Fig. 1:** A: Microcatchment ‘Negarin’ Type, B: Macrocatchment ‘Hillside Conduit’ system, C: Floodwater Harvesting: Floodwater diversion system

Sources: A: Rocheleau et al. 1988, B and C: Prinz 1996
The higher the aridity of an area, the larger is the required catchment area in relation to the cropping area for the same water yield, and paved courtyards.

Fig. 2: The Tunisian "Meskat" microcatchment system.

Source: Adapted from El Amami 1983

FLOODWATER HARVESTING

Floodwater harvesting is also called 'Large catchment water harvesting' or 'Spate irrigation', and comprises two forms:

- In case of "floodwater harvesting within the stream bed" the water flow is dammed and, as a result, inundates the valley bottom of the flood plain. The water is forced to infiltrate and the wetted area can be used for agriculture or pasture improvement.
- In case of "floodwater diversion", the wadi water is forced to leave its natural course and conveyed to nearby cropping areas. These two systems - the catchments being many square kilometers in size - require more complex structures of dams and distribution networks and a higher technical input than the other two water harvesting methods (Fig. 1B).

It is difficult to give exact figures on the present total area under the various forms of 'Rain and Floodwater Harvesting'. Fig.3 shows the irrigated area under flood water harvesting in North Africa and the Middle East, according to FAO (1997), totalling about 2 million hectares.

Fig. 3: Area under floodwater harvesting ('spate irrigation') in selected countries of North Africa and the Middle East

Source: FAO 1997

* 1000 hectares
Storage

The methods mentioned above have the drawback of uneven water supply during the year. In the case of rain water harvesting, the agricultural production is even limited to the rainy season, if no storage (outside the soil matrix) is available. Therefore a number of storage media are employed, ranging from ferrocement tanks of a few m$^2$ content to large reservoirs, storing millions of m$^3$.

Further means of above-ground storage aside of large reservoirs are ‘lacs collinaires’ in North Africa, and small reservoirs behind barrages, small weirs and check dams.

There are several disadvantages connected with surface storage of water - large evaporation losses, loss of storage caused by siltation, pollution problems, health problems and loss of agricultural land. These problems can be avoided by underground storage of water, e.g. in cisterns.

Cisterns are man-made caves or underground constructions to store water. Often the walls of these cistern are plastered; their water losses by deep percolation or by evaporation can be minimal. The construction of cisterns was already practised several thousand years ago; chalky rocks were preferred. Traditionally, in Mediterranean houses, one cellar room was specifically designed to store rainwater. Nowadays cisterns are often constructed using concrete.

GROUNDWATER HARVESTING

The term ‘Groundwater Harvesting’ is a rather new one and is employed to cover traditional and unconventional ways of groundwater extraction, e.g. by ‘Qanat’ systems, ‘Underground Dams’ and special types of wells.

Qanat systems

A Qanat is a horizontal tunnel that taps underground water in an alluvial fan without pumps or other equipment, brings it to surface so that the water can be used. Quanat tunnels have an inclination of 1-2 % and a length of up to 30 km (Fig. 4).

Groundwater Dams

To store water in sand-filled reservoirs has a number of advantages: (1) evaporation losses are reduced or even completely avoided, (2) the water stored is less susceptible to pollution, (3) health hazards such as mosquito breeding and spreading of snail fever are avoided, (4) no reduction in storage volume due to siltation. The main disadvantage is the general reduction in water storage volume per total volume (Nilsson 1988).

The higher the aridity of an area, the larger is the required catchment area in relation to the cropping area for the same water yield.
In a few locations the natural geohydrological conditions allow the use of sand-filled reservoirs without any dam construction. But in most cases the advantages can only be gained when building a groundwater dam. Groundwater dams obstruct the flow of groundwater or the subterranean flow of ephemeral streams and rivers in a river bed. The water is stored in the sediment below the ground surface. The stored water can be used to recharge an aquifer or to raise the level of an aquifer thus making it better accessible for lifting.

There are basically two types of groundwater dams: subsurface dams and sand storage dams. A sub-surface dam is constructed below ground level and arrests the flow in a natural aquifer. A trench is dug across the valley, reaching down to the bedrock, and a dam is constructed in the trench. Water is extracted at the upstream side of the dam by shallow wells. A sand-storage dam (Fig. 5) impounds the water in the sediments which accumulate because of dam itself. Often these dams are constructed in stages. The lengths of the dams is between 30 and 160 m (Nilsson, 1988).
TRADITIONAL USE

"Rainwater and Floodwater Harvesting" have been practised in many dry regions of the Mediterranean since millennia (Prinz 1995, 1996).
In the Middle East archaeological evidence of water harvesting structures appears in Jordan, Israel, Palestine, Syria, Iraq, the Negev (Evenari et al. 1971) and the Arabian Peninsula (mainly the Yemen); the oldest being believed to have been constructed over 9,000 years ago. In North Africa, rainwater and floodwater harvesting have a long tradition, too; they were the basis for the 'granary of the Roman Empire', and are still used extensively in Morocco (Kutsch 1982), Tunisia (El-Amami 1983) and to a lesser extent in Algeria.

Qanats: The origin of the "qanat" technique is Persia, where it was developed about 3,000 years ago. The knowledge spread to the neighbouring countries and later to whole North Africa and even to Spain.

Groundwater Dams: Groundwater dams were already constructed during Roman times in North Africa and on Sardinia.

RECENT DEVELOPMENT (SINCE ABOUT 1950)

Rainwater and Floodwater Harvesting: After 1950, water harvesting has again received renewed interest in research and implementation partly due to the successful reconstruction of ancient water harvesting farms in the Negev by Evenari and his colleagues (Evenari et al. 1971), partly due to intensive research in Arab countries. Excellent overviews offer Khouri et al. (1995) and other UNESCO/ROSTAS publications.
The development of 'Water Harvesting' in recent decades differs from country to country:

Syria: In the Dei-Atiye community of Syria, rainwater harvesting was established in 1987 on an area of 130 ha. The project site was sub-divided into four parts for tree crops, range plants, cereals and runoff research (Ibrahim 1994). The International Centre for Agricultural Research in the Dry Areas (ICARDA) in Syria, is currently working on the identification of water-harvesting areas and techniques suitable for different West Asian and North African (WANA) environments (Prinz et al. 1998). In the Mehasse Area of Syria, there is a project on a 500 ha arable land currently being carried out with IDRC and aimed at implementing research findings of rainwater harvesting for crop production in this region.

Jordan: In Jordan, earth dams have been constructed since 1964 in order for runoff to infiltrate for pasture improvement. At the final stage the total area flooded shall be about 2,500 ha (Al-Labadi 1994). In 1972, a project known as "Jordan Highland Development Project" was initiated. Rock dams, contour stone bunds, trapezoidal bunds and earth contour bunds are used to increase soil moisture around the trees planted on steep lands (Shatanawi 1994). The total area utilized since its inception is estimated to be 6,000 hectares. Between 1985 and 1988, Jordan's Ministry of Agriculture, in collaboration with ACSAD, used contour terraces and ridges for pasture and range improvement in the Balama district. (Shatanawi 1994). In 1987 the Faculty of Agriculture of the University of Jordan initiated the construction of earth and stone dams to impound and store flood waves for irrigation purposes (Fig. 6).
Palestine: Rooftop Water Harvesting from individual homes as well from greenhouses, with subsequent storage in cisterns, has been successfully implemented in the West Bank. Spate irrigation is practiced at a low level. Some hillside conduit systems exist (Khouri et al. 1995).

Israel: The Israeli water harvesting research work focused on
- testing of specific WH techniques, (Negarin-Type, Limans, Hillside Conduit Systems)
- studying soil surface characteristics, especially crust formation
- studying and modelling runoff behaviour (Boers, 1994)
- analyzing the economics of water harvesting techniques.

Egypt: In Wadi El-Arish region of Egypt, stone dykes are used to direct the runoff water flow for irrigation purposes. Also cisterns, which store water meant for animal and human consumption as well as for supplemental irrigation, are common in Egypt. The number of cisterns has increased from less than 3,000 in 1960 to about 15,000 in 1993 with a capacity of about 4 million m³ (Shata & Attia 1994). In the North-West region there was a GTZ/FAO sponsored project on land use planning including water harvesting activities (see Fig. 4).

Libya: In different part of Libya, experimental sites of contour-ridge terracing covering more than 53,000 ha have recently been established (Al-Ghariani 1994).

Tunisia: In Southern Tunisia, some 10 million olive trees are said to be cultivated today by means of water harvesting techniques. In 1990, the Government of Tunisia started the implementation of the ‘National Strategy of Surface Runoff Mobilization’ which aims, among other things, at building 21 dams, 203 small earth dams, 1,000 ponds, 2,000 works to recharge water tables and 2,000 works for irrigation through water spreading by the year 2,000. Up to 1984, "Meskats" covered 300,000 ha where 100,000 olive trees were planted (see Fig. 2), "Jesso-urs" covered 400,000 ha (see Fig. 7; Tobbi 1994). Modern spate irrigation techniques have been applied in Central Tunisia since 1980, covering an area of 4,250 ha and harvesting about 20 Mm³ of water annually.

Morocco: "Matfia" is an old technique of storing water for human and animal consumption in Morocco, which still continues (Tayaa 1994). Since 1984, Morocco has started constructing small dams ("Barrages Collinaires") to harvest flood water. The upstream catchment area under these dams ranges from 500 to 10,000 hectares. The dams provide irrigation water for about 160,000 animals and 3,000 ha of cultivated plots. Several large spate irrigation project are under construction e.g. in the Tafilalet region.

Qanats: Though new qanats are seldom built today, many old ones are still maintained and deliver steadily water to fields and villages. In Morocco, many of the large oases of the South
receive a considerable amount of their irrigation water from qanats; the rest is harvested floodwater.

![Diagram of Qanats, Jessours, and Tabla]

**Fig. 7**: A row of "Jessour" in the South of Tunisia. Source: Adapted from El Amami 1983

**BENEFITS AND LIMITATIONS**

**Rainwater and Floodwater Harvesting**: Rainwater and Floodwater Harvesting have the potential to increase the productivity of arable and grazing land by increasing the yields and by reducing the risk of crop failure. They also facilitate re- or afforestation, fruit tree planting or agroforestry. With regard to tree establishment, rainwater and floodwater harvesting can contribute to the fight against desertification. These techniques are relatively cheap and can therefore be a viable alternative where irrigation water from other sources is not readily available or too costly. Unlike pumping water, water harvesting saves energy and maintenance costs. Using harvested rainwater helps in decreasing the use of other valuable water sources like groundwater. Remote sensing and Geographical Information Systems can help in the determination of areas suitable for water harvesting (Prinz et al. 1998).

Although water harvesting can increase the water availability, the climatic risks still exists. and in years with extremely low rainfall, it can not compensate for the shortage. Successful water harvesting projects are often based on farmers’ experience and trial and error rather than on scientifically well established techniques, and can therefore not be reproduced easily. Agricultural extension services have often limited experience with it. Further disadvantages are the possible conflicts between upstream and downstream users, and a possible harm to fauna and flora adapted to running waters and wetlands.

**Qanats**: Since qanats can yield substantial quantities of water (5-60 l/s, in extreme cases up to 270 l/s; (Achtnich 1980) and being a traditional method, the local people are aware of the value of this technique and more ready to maintain or restore it. On the other hand, qanats require relatively high labour input. Often they bear the maximum flow during the rainy season and the minimum flow during the dry season, as opposed to the demand for the
irrigation water. Tubewells, extracting water from near-mountain aquifers, may cause sharp reductions in qanat water yields.

**Groundwater Dams:** Only very few dams are still maintained, but the value of this technique will increase in future, as they offer the possibility to extract water from near-surface aquifers (e.g. wadi beds) over a longer period of time after the end of the rainy season.

**OUTLOOK**

All the above mentioned techniques have the advantage to increase the amount of water available for agricultural and other purposes, and to ease water scarcity in the Mediterranean region. Most of them require relatively low input and, if planned and managed properly, can contribute to the sustainable use of the precious resource water.

The results of traditional water management methods are encouraging and should be promoted.

During recent years some methodological and technological developments took place in regard to the combination of two or more irrigation / water conservation techniques. Surplus water from macrocatchment systems, for example, can be used as supplemental water source for rainfed agriculture, when the runoff is stored for application after the rainy season. Water harvesting has been used in combination with underground dams that recharge the groundwater.

Water management problems can only be tackled in an **holistic way.** Production increases by improved irrigation have to be paralleled by promoting adequate employment and balanced regional development. "A new approach to watershed management must be evolved to integrate land, water and labour management" (Agarwal & Narain 1997).

In some cases the available knowledge is sufficient to solve a specific problem, but the application or the promotion by state / local authorities is lacking. In other cases, further research and experimentation is still required before a certain method can be recommended. The potential is there, and hopefully, sustainable traditional water supply / irrigation methods will also receive the required backing of politicians and planners, who become aware of the potential of these ‘old’ and most probably also ‘modern’ techniques to reduce future water related problems in the Mediterranean Basin.

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162


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The use of TDR for wetness measurements in soil erosion and conservation practices in small watersheds

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The use of TDR for soil moisture measurements in soil erosion and conservation practices in small watersheds

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Introduction

Among all actions regarding water in a watershed, two are especially important within the HYDROMED project for Tunisia. They concern soil erosion and soil conservation, respectively.

The Kamech watershed in the Cap Bon area, represents watersheds with layers of marls and clayey soils, between sandstone. Marl areas supply the most silt to reservoirs. Compared to calcareous soils, it can reach 7 to 1 (Meddi, 1992). In this kind of landscape, linear erosion is more important than interrill erosion. Rills and gullies are an important source of silting and badlands are the ultimate term of soil degradation (Kouri, 1993; GTZ, 1996). In the watershed of Kamech, some creeps appear along the slopes, most of them on the right side of the main drainage net. An important question to answer is what is the effect of water on the erosion along the slopes and especially is there a particular location in the soil where water contributes to creeping and slumping.

The watershed of El Gouazine is situated in the centre of the dorsal mountains. This area is shaped by geological calcareous formations that produced hills and cliffs and by glaciers resulting in silty-clayey deposits covering calcareous crusts. The valleys are are formed from alluvial silts and clays. Mountains and hills are covered with forests and bushes and the slopes are cultivated for cereal cropping and well protected by levelling. These anti-runoff practices have already limited sedimentation and the silting up of the lake. Another important question to answer is what the impact of these anti-runoff practices has on the water circulation. The TDR technique was applied to try to contribute in answering these questions.

Principles of the time domain reflectometry

Theory

Originally the time domain reflectometry (TDR) was used to detect defaults in transmission lines and cables. A voltage pulse is introduced into the cables. The pulse propagates along the cables as an electromagnetic signal in the frequency range of 1 MHz to 1 GHz. In coaxial lines the electromagnetic field is inside the cable. In parallel lines, the field is both between and around the cables. The pulse shape and the transit time depend on the cable properties, length, and the termination of the cable where the signal is reflected. The TDR equipment typically consists of a 2 or 3 rod transmission line, a coaxial connecting cable, and a TDR instrument to generate fast-increase time pulses and to measure the time. A probe is considered to consist of the transmission line and any structure or component between the transmission line and the connecting cable.
In 1969 Fellner-Feldegg used TDR for measuring the dielectric constant. In 1980, Topp et al. introduced TDR for the measurement of soil moisture. They measured the apparent dielectric constant of a large number of soils and related it to volumetric water content using a third-order polynomial equation (Fundinger et al., 1995):

$$\varepsilon_r = 3.03 + 9.3 \theta + 146 \theta^2 - 76.7 \theta^3$$

Most researchers found this relationship appropriate for their soils, but it is possible to fit a better relationship by a specific calibration. TDR probes with 2 or 3 rods are now also used to measure soil solution electrical conductivity for transient conditions with varying water content. This application allows also non-destructive measurements of solute transport in the unsaturated zone (Persson, 1997; Persson and Berndtsson, 1997).

The TDR technique is based on a measure of the velocity $c$ of an electromagnetic wave in the soil. This velocity depends on the dielectric constant of the soil and the dielectric constant in turn mainly depends on the water content for this specific soil (Fig. 1).

![Figure 1. The velocity $c$ must be measured in order to determine the dielectric constant.](image)

**Velocity measurement**

The wave travels along the 2 or 3 rods of the probe with the length $l$ and is reflected at the end, then returns. Consequently, the velocity $c$ is known by the measurement of the transit time $t$ (Fig. 2).

![Figure 2. Calculation of velocity by use of the transit time and probe length.](image)

For large-scale measurements, the length of the transmission lines is dependent on the soil type.
In high clay content soils the signal attenuation limits the maximum length to <1 m, while longer lines can be used in sandy soils (Amato and Ritchie, 1995).

The use of short transmission lines for small-scale measurements is limited by the instrument accuracy. For a 15-cm long TDR probe the difference between the transit time in air $t_a$ and in water $t_w$ is only 8 ns.

$$t = \frac{2l}{c} \sqrt{\varepsilon r}$$

with

$$t_a = \frac{0.3m}{3.10^8 \text{ms}^{-1}} \cdot \sqrt{1} = 1 \text{ ns}$$

and

$$t_w = \frac{0.3m}{3.10^8 \text{ms}^{-1}} \cdot \sqrt{81} = 9 \text{ ns}$$

**Technical realisations**

**Traditional methods**

The reflected TDR pulse is scanned by the sampler. Each point of the pulse signal is measured as a voltage value for a distinct time. The transit time is graphically derived from the voltage signal (Fig. 3). For this expensive high frequency electronic components are needed and the evaluation of the probe transit time part of the curve is difficult for low water contents or short TDR-probe rods.
TRIME method (IMKO Gmbh)

Using this method, the points of the TDR pulse are determined by direct time measurements at distinct voltage levels. This requires another pulse shape with a high amplitude of the reflected pulse and a reduction of the attenuation (Fig. 4).

The shape of the TDR-pulse is formed by a suitable impedance matching the pulse generation output, the connecting cable, and the probe. The coating of the rods with PVC is the second important measure to get this kind of signal:

- low frequencies are blocked
- only high frequencies (>> 300MHz) travel through the soil and can be attenuated.
Thus, the total attenuation is reduced and the amplitude of the reflected pulse is high. A special algorithm derives the amplitude of the reflected pulse from measurements at particular points of the curve. When the amplitude, which depends on the electrical conductivity of the soil, has been determined, the transit time is measured at the corresponding voltage. This gives short measurement times and low power consumption. Because of averaging of many measurements, transit time can be determined with a resolution of 3 ps. This allows one also to work with short rods and with low water contents.

Moisture calculation

Two or three steps are necessary to calibrate the probes according to Fig. 5 and below:

1) Basic calibration

\[ t_p = t + \frac{A}{D} \]

2) Probe calibration

\[ \theta_v = \sum_{i=0}^{5} c_i \cdot t_p^i \rightarrow \theta_v \]

3) Specific calibration

\[ \theta_{vs} = \sum_{i=0}^{5} c_i \cdot \theta_v^i \rightarrow \theta_{vs} \]

Figure 5. Procedure for the calibration.

1) Basic calibration: to compensate cable length, geometry of the rods...each TRIME probe is individually precalibrated,
2) Standard soil moisture: calculated for each probe type by a universal calibration function (Topp et al., 1980) for mineral soils.

This calibration procedure is stored in the EEPROM inside the probe connector.
3) **Specific calibration**: the user can calibrate the probe for his specific material.

A measurement table with reference values and TRIME values are designed and used by a calculation program to calculate new $C_0$ to $C_4$ coefficients. These new coefficients are stored in the EEPROM.

**The TDR station at Kamech**

*The lake and the watershed*

Kamech is situated in the north of the Cap Bon area. The climate here is classified as sub-humid with cool winters (Gounot and Le Houerou, 1968) where annual rainfall can vary from 300 to 1000 mm. The median rainfall is 385 mm (Nabeul, 47 years). The rainfall at Kamech during 1996-97 was 405.5 mm.

The reservoir at Kamech was built in 1993. The dike is 125 m long and 10 m high. The initial volume of the lake was 142,560 m$^3$ with a surface at overflow of 4.466 ha. On 31/7/97, silting reached 14,850 m$^3$ which decreased the initial volume to 127,710 m$^3$.

The area of the watershed is 245.5 ha with a difference in altitude of 108 m and a slope index of 40 m/km. The morphology of the watershed is formations from Miocene rocks. The watershed is constituted of mainly marl, which was deposited between sandstone banks. The drainage net is formed in the primary area of marl with a main axle parallel to sandstone banks and a secondary network perpendicular to the first. The secondary drainage network is more developed on the right bank and is within secondary valleys with creeps, rills, and gullies. The agriculture for wheat is the main land occupation with range lands for sheep breeding. There is no forest. The water of the lake is used for orchard and industrial tomato irrigation.

The original area, with slopes from 0 to 20%, is planted with annual crops. The secondary valleys, with slopes from 20 to 40%, are range lands.

*The soils*

The most important area of the watershed is covered with clays and marls. In the upper parts of the valleys, lye calcimagnesic soils with silt and some pieces of an old calcareous crust. The slopes of the valleys are eroded clay soils on geological marls such as the one described below. These soils are swelling clays so that, in the dry season, they produce very large and deep cracks. At the bottom of the slopes, we find alluvium with also swelling clays and some hydromorphic characteristics with depth.
Surface horizon, wet, clayey, plenty of roots.

Transitional horizon, with fine marl pieces (1 to 3 mm) included in the silty clay matrix, some roots.

Beginning of geological marls, having more numerous pieces of marl from 3 to 10 mm, very few roots.

Figure 6. Soil profile along the sloping side and TDR location.

The creeping occurs between the second and the third horizon, generally at the beginning of the geological layer (Fig. 6). In winter, it is believed that differences in soil moisture capacity between the two main layers can contribute to creeping and slumping. In summer, cracks up to 5 cm wide at surface can reach more than one meter depth.

The TDR station

Location of the TDR station

The site is located on the slope of a secondary valley, on the right side of the main river, next to the reservoir. The downstream area of this valley displays a creep line at the third bottom of the slope. The slope is 34 m long and the TDR are installed at 12, 14, and 16 m from the ridge. Totally 6 TDR probes have been placed along the valley side, upstream the creep. They are arranged in three groups, each group includes 2 probes, one between 15-30 cm and the other between 50-65 cm depth (Fig. 6). The central group is close to a slope change, the upper one, is 2 m upstream and the lower one is 2 m downstream. This is due to the limited length of the cables.
Equipment of the TDR station

The probes

We have chosen P2Z type probes with a large distance between the rods because they can be fitted into the clayey soil with 20-30 mm peds (Fig. 7).

![Diagram of a P2Z probe]

Figure 7. Design of a P2Z probe.

The multiplexer

The six probes are connected to a TRIME MUX 6 for multiplexing (Fig. 8). The probes must be connected to individual plugs because of the individual calibration. In operating mode the measurement control (sample rate, start time etc...) is started by a software installed in the datalogger.
Figure 8. Design of the TRIME MUX6.

The datalogger

The datalogger is connected to the TRIME MUX6 with an IMP 232 micronet wire (Fig. 9). The datalogger is within a waterproof rugged aluminium case including a HP laptop-PC with a PCMCIA Sram chip-card and a software (INMEWA) for the management of the measuring circuit and storage of the data. The complete system is powered by a 12V battery.

Figure 9. The datalogger.
Technical data

Power-supply: 7-15V DC
Supply current: 8 mA standby, 350 mA while 10-15 seconds measuring time per channel.
Measurement range: 0-70% volumetric water content
Conductivity range: 0-6 mS/cm for P2, P2Z, P2G probes
Accuracy: depends on the calibration for the soil type. Standard calibration for P2Z probes:
moisture range 0-40%: +-1%,
moisture range 40-70%: +-2%.
Repeated accuracy: +-0.3%.
Temperature range: -10 to 45°C

Preliminary results

All the soil moisture data are given according to standard calibration of the probes. Measurements began on 18 of February 1998, each day, at 0h 6h 12h and 18h. We have selected the 12h data to illustrate our purpose, we will later look at the variability between the hours.

The data will be analysed first for each group of 2 TDR probes, according to depth and in a second time, for each depth along the slope. Rainfalls are also on the graphics to illustrate the response of the soil.

Soil moisture according with depth

Figure 10 shows soil moisture according to depth for the upper observation group (AM). Until 10 of May, the bulk soil moisture mainly remained between 30 to 35%. But there was a large variation for the entire period, 18 to 40%. There was a significant response to rainfall for the two soil layers. From 18/2 to 30/3 there was a dry period. The moisture decreased for the first layer and increased for the second layer. It is probable that evaporative forces acted on the first layer and water transfer, not necessarily from the upper layer, but more certainly by lateral flow appeared along the slope for the second layer.
From 25/4 to 25/5, two periods can be distinguished: a first one, with a length of about 15 days, where there was a decrease of moisture for the two layers because of efficient capillarity links. During the second one, there is a disruption of the capillarity links because of an increase in cracks and the soil matrix divides into smaller aggregates that act as mulch. The first layer becomes increasingly dry because of no supply of water from the bottom layer. The moisture of the second layer can increase because rainfall bypasses the first layer directly into the cracks.

Figure 11 shows soil moisture with depth for the central observation group (M). The moisture is lower than for the upper observation group, most of data are between 25-28%. There is also a significant response to the main rainfall during the period, particularly for the first layer. During the measurement period, the variation remains small (25-35%) with a slow decrease for the two layers at the end of the rainy season. Here the capillarity links remain for a longer time than at the upper location. These links appear to stop functioning around 25/5.
Figure 12 shows the soil moisture with depth for the lower group (AV). Compared to the upper group there is a quite constant moisture level during the measurement period. As for the central site, moisture does not decrease very much at the end of the rainy season. Soil water remains around 30% but there is a significant response to the main rainfall for the two layers and particularly for the second layer. Average soil moisture is greater than for the central station. Capillarity links remain functioning until 25/5.

Soil moisture variation along the slope

Figure 13 shows soil moisture variation along the slope for the upper soil layer. During the entire rainy season, the upstream site is wetter than the downstream but here the soil moisture decreases faster after the rains. The central site is the driest (1). The central site remains the driest until start of the dry season (2). At the beginning of the dry season, soil moisture increases along the slope from the upper to the lower site because the upstream site dries faster (3).
Figure 14 shows the soil moisture variation along the slope for the bottom layer. In the first part of the measurements, there was no significant difference between upstream and downstream locations (i). The central site was also the most dry but for these depths it remained the dryer even in May and its response to rainfall was small.

In the beginning of the dry season (2), soil moisture slowly decreased for the central and the downstream site while the upper site firstly displayed an increase. This is difficult to explain except by lateral flow from the upper part of the hillside. For bottom layers, at the beginning of the dry season, the upper site was the wettest.

These results confirmed the behaviour shown in Figs. 10 and 11. There are two drying processes. For upslope areas, an early break of the capillarity link between the upper and lower soil layers and for downslope areas the supply rate of water from the bottom to the upper soil layer.

**Variability of data**

To increase the information and effects on rainfall variation, measurements were taken four times a day, at 0, 6, 12, and 18 h.
Figure 15 and 16. Watershed of Kamech, variability of data for the central site.

For an example, data variability was investigated for the period from 21/02 to 21/03, with several rainfalls. Figures 15-17 show the four measurements per day during this period. It appears that there is a daily cycle and perhaps some erroneous measurements.

Points 1 and 2 in Fig. 15 can be considered as errors, because the rainfall is too small to give rise to such an increase in soil moisture between 15 and 35 cm depth. However, the same phenomenon is seen for the downstream site (Fig. 17). The reason was a general disturbance of the measuring circuit.
Figure 17. Watershed of Kamech, variability of data for the lower site.

If we compare Figs. 15-17, we notice a significant daily cycle in soil moisture for two to four observations per day. Temperature dependence can be the reason for this but for the upstream site (Fig. 15) most of the elevated values were observed at 18 h and the lower values at 12 h while for the downstream site, these observations were reversed.

Individual calibration

Figure 18 shows the outcome of the first trial to obtain individual calibration curves. Standard calibration is certainly sufficient for most soils. However, in the case of swelling soils, we suspected that absolute values of soil moisture would be different between TDR and gravimetric (105°C) samples. Between February and May samples of soil were taken with an auger at 0.5 m distance from the TDR probes and at the same depth. One hole per site was sampled. These preliminary results showed that it is not possible to get good individual calibration curves except perhaps for the S1 and S2 probes.

Table 1. Bulk soil densities.

<table>
<thead>
<tr>
<th>date</th>
<th>5-10 cm</th>
<th>15-20 cm</th>
<th>35-40 cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>13/02/98</td>
<td>1.35</td>
<td>1.43</td>
<td>1.45</td>
</tr>
<tr>
<td>14/02/98</td>
<td>1.38</td>
<td>1.38</td>
<td>1.52</td>
</tr>
<tr>
<td>27/03/98</td>
<td>1.48</td>
<td>1.36</td>
<td>1.45</td>
</tr>
<tr>
<td>average</td>
<td>1.41</td>
<td>1.37</td>
<td>1.46</td>
</tr>
<tr>
<td>standard dev</td>
<td>0.053</td>
<td>0.054</td>
<td>0.049</td>
</tr>
</tbody>
</table>
A small range in soil moisture variation and the presence of swelling clays may explain these results. In swelling clay soils, moisture can vary greatly for short distances and bulk density changes with soil moisture. This is shown in Table 1. Samples taken at 13/2 are representing a dry period and samples taken at 27/3 are representing a wet situation (just after a rainfall). There was no effect on the 35-40 cm bulk density but a big change for the 5-10 cm bulk density. The rainfall increased the bulk density where there were no cracks. Samples need to be taken to obtain shrinkage curves and a laboratory calibration based on undisturbed soil is needed.
The TDR station at El Gouazine

The reservoir and the watershed

El Gouazine is situated in the centre of the Tunisian Dorsal mountains, at 50 km northeast of Kairouan. The climate is semiarid with cool winters (Gounot and Le Houerou, 1967). Annual rainfall is very erratic and varies from 200 to 800 mm with a median rainfall of 358 mm (Ousseltia, 47 years). The rainfall during 1996-97 at El Gouazine was 252.5 mm.

The reservoir of El Gouazine was built in 1990. The dike is 232 m and 10.6 m high. The initial volume of the lake was 233 370 m$^3$ with a surface at overflow of 9 597 ha. On 10/06/97, silting reached 16 030 m$^3$ and the reservoir thus had an effective volume of 217 340 m$^3$.

The area of the watershed is large, 1 694 ha, but the difference in altitude is not important, 199 m, for a slope index of 18 m/km. The watershed is long (11.3 km) and narrow (1.6 km). Most of the soils are developed on quaternary deposits (silt and clay), often with calcareous crust. The elevated parts are on geological calcareous outcrops from the end of the cretaceous era (Campanien and Maestrichien).

Soil occupation is divided between forest (35%) and agriculture (55%). Forest with pine trees and xerophytic shrubs occupies the hilly parts. Annual crops (wheat and fallow) grow on lower parts with some olive trees. Pasture areas are on calcareous crusts. Nearly all the cultivated areas are protected by large soil terracing. Figure 19 shows a typical soil profile of the area.

Figure 19. Soil structure and texture with depth.
The TDR station

The observation site is established on a slope (6 to 11%), protected by large new soil terraces. Soil occupation is production of cereals and fallow.

Two kinds of data are collected:
- spatial soil moisture with a surface probe, in the area between two soil terraces, and
- linear variations along the slope with three groups of 2 probes. One group is upstream a soil terrace (U1), the two others downstream (D1 and D2) a soil terrace.

Table 2. El Gouazine, position of the TDR probes.

<table>
<thead>
<tr>
<th>U1</th>
<th>D1</th>
<th>D2</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>P2</td>
<td>P3</td>
</tr>
<tr>
<td>45-60 cm</td>
<td>75-90 cm</td>
<td>45-60 cm</td>
</tr>
</tbody>
</table>

Figure 20. The hand measurement device: TRIME-FM.
For this kind of study on a large area and in ploughed fields it is impossible to use a datalogger with a network of connected cables. The TRIME-FM (Fig. 20) is a portable instrument developed for mobile field use. The four lines of the LC-display are used for soil moisture (%), TDR level, status and error messages, and battery level. The TRIME-FM for 3-rod probes does not accept 2-rod probes. Three kinds of probes are used: one for surface measurements, one for upper layer of the soil (0-15 cm) (Fig. 21), and one for deeper measurements (P3Z probes, Fig. 22).

The probe for surface measurements is only available with 3 rods. This means that if the surface probe is needed, all the other probes must be of 3 rod type unless two TRIME-FM are used. The device has no inner memory but datalogging is possible with a portable computer.

Figure 21. Surface layer probe.  Figure 22. Surface and bottom layer probe.
Preliminary results

Variability along the slope

The results showed that variations of soil moisture were very small during the observation period. However, only a few measurements are still at hand. This is because of the manual procedure and complicated measurements. Consequently, it is difficult to have measurements just before and after rainfall to obtain the response of the soil. In any case, there were a few rainfalls during the period. The most important rainfalls were: 13.1 mm on 25/1, 10 mm on 26/2, 16.2 mm on 30/3, and 8.3 mm on 27/4.

The observations also showed that the upslope site is the wettest and that soil moisture is almost constant with depth. At the D1 position, next to the downslope part of the soil terrace, the upper soil layer is always wetter than the deeper one. This may be an effect of the terracing.
For the D2 position, data are possibly erroneous (level 10) because of not parallel rods. This was restored on 3/6/98.

Spatial variability

This kind of measurements was coupled with the use of a Leica "laser tacheometer TC 805" to have the spatial position of each point of the TDR measurement in the field. The TDR data were obtained by the TRIME-FM connected to the surface probe. This use of the TDR probe was very efficient for a quick control of spatial soil moisture variation. Figure 25 shows an example of this for an area between two soil terraces, one part is a fallow area and the other one has been ploughed.

Figure 25. Surface soil moisture variation between two soil terraces.

Conclusion

Two main conclusions can be made regarding the above preliminary results on the use of TDR for soil moisture measurements for soil erosion and conservation practices in small watersheds. One concerns the results and the other the equipment. The results showed that:
- There are heterogeneity effects on the soil water transport in the hilly landscape of Kamech. This heterogeneity works along the slope and between the two soil layers. A first explanation of the dynamics of soil water along the slope can be done. Firstly, structural changes, due to the type of clay, create cracks which are connected. This creates an underground network for water flow and a drainage from upslope to downslope, so that the downslope part is wetter and even may retain more rain water as compared to the upper part. The observed wetness shows that the capillary pump can act from the bottom to the upper part of soil layers for downslope areas. On the other hand, for upslope areas, there is a lack of water, the upper soil layers become dry and the capillarity links with the bottom layer are interrupted.

- It should be possible to show the spatial effects of soil terracing on water infiltration. However, it needs a good coordination between rainfall occurrence and the manual data observations.

Regarding the TDR equipments:

- They permit to follow changes in soil moisture in the two instrumented watersheds.
- The different observation systems fit well together.

However,

- The datalogger needs probes with coaxial connecting cables: it is impossible to use such a network on large areas in the field (because of cattle, cultural practices, etc). An independent TDR system with a small memory card for each probe and an electrical supply by solar cell panels and battery for two or three probes will allow to assess soil moisture at different depths for each location.

- The TRIME-FM permits, on the other hand, installment of probes on large areas, but has no internal memory and high frequency measurements require long time.

- The individual calibration of the probes seems not so easy, particularly in swelling soils. This is mainly due to the heterogeneity on soil water transport (Yasuda et al., 1996a; 1996b). A specific laboratory calibration experiment seems necessary for these particular soils.

References


Rain water harvesting and management of small reservoirs in arid and semiarid areas

Lund University, Sweden, 29 June – 2 July, 1998

Land use transformation impact on reservoir siltation in Morocco: the need for better assessment tools

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Extended summary

Northern Morocco is comprised of a fragile mountainous environment with major changes occurring in term of land utilization, agricultural practices, water management and urbanization. These influential land use modifications, unless supervised and managed, will cause rapid environmental degradation. Soil erosion is by far the most damaging land degradation and urgent environmental problem in this region. This extension of this processes was enhanced by the rapid denudation and cultivation of forest and range lands, which lead to watershed degradation and soil loss far above sustainable levels in northern Morocco. The Rif mountains, representing less than 6% of the country, produce more than 60% of the total national sediment load (Merzouk, 1988). The extent and nature of soil erosion and its causing factors have been poorly documented, thus slowing down the watershed planning and assessment effort. Out of 80 major existing dams, less than 20 have a study and management plan, while their silting-up is progressing at the alarming rate of 60 Mm³ per year (Boutaieb, 1988). This makes the effective management of the nation’s watershed resources a priority of vital economic importance as it was confirmed lately in by the National Watershed Management Plan (NWMP, 1995).

A systematic, cost-effective, multi-disciplinary approach to watershed management is urgently required to reduce upstream land degradation and the threat to Morocco’s hydraulic infrastructures. This approach requires more advanced watershed planning and assessment technologies adapted to the Mediterranean mountains. In recent years, the Moroccan government has engaged a national applied research program with the technical assistance of FAO aimed at the development of simple and adapted watershed modeling tools. The program started with the adaptation of the Revised Universal Soil Loss Equation (RUSLE). The geographic information systems (GIS) and remotely sensed data have became a useful spatial data sources and handling tools for the application and the maintenance of the RUSLE model.

The primary objective of the present contribution to this research effort has been to apply the RUSLE for the evaluation of the effect of land use changes on soil erosion and sediment production rates within a representative watershed in the Rif mountains (Morocco). At these spatial and modeling scales, the objectives were to provide precise information on the extend of the problems and the causes of land degradation and on the watershed priorities for a sustainable development. A secondary objective was the setting up of a methodology integrating remote sensing and GIS techniques, and a spatially distributed erosion model for monitoring the dynamics of watershed replenishments and assessing the sediment sources in catchments.
For the first objective, spatial and temporal changes in land cover and use were analyzed for the 18,000 ha Tleta watershed using aerial photography (1976), SPOT-HRV (1990) and Landsat-TM (1996) imagery. The land use maps produced were integrated in a watershed resources geographic information system (GIS). C-factor of the well known RUSLE model were derived and used to estimate the gross soil erosion. The change analysis showed that land use shifting through cultivation of forest and brush land has increased the area of cultivated land by 30% in twenty years. This expanded slope cultivation caused the C factor of the Tleta watershed to increase from 0.49 to 0.62. Gross soil loss and sediment yields were estimated using RUSLE and delivery ratio for the 1976 and 1996 land use patterns. The predicted sediment yields agreed with the measured values in the Ibn Battouta reservoir downstream of the watershed. The results indicate that the integration of RUSLE, GIS and remote sensing technology provides a powerful simulator for conducting a global management of soil and water potentialities at watershed level.

The second phase in watershed management planning, following the global diagnosis, is informing the community and negotiating a participatory program with the most efficient portfolio of project activities. This calls for a more precise diagnosis and simulators at the farm and the local scale. Research efforts in Morocco to develop such tools for the farm and the small watershed levels did not mature yet. This is then one of the major objectives of Hydromed in Morocco. The program is working for the adaptation of a watershed simulator for global diagnosis and impact studies and integrating it to one or more precise simulators for the sub-watershed and farm levels that will be more useful for implementing and managing the proposed project activities. An adaptation and comparative study is presently conducted on the 7.2 Km² watershed upstream of the SABOUN small Dam (Tangier) starting with three simulators (EPIC, IMPEL and GOMMER). It is this system of adapted macro and micro watershed simulators, connected selected field monitoring sites, that can provide a more comprehensive management program and help customize the solutions and inform better the community.

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2 **EPI**C: Erosion Productivity Impact Calculator, USDA/ARS Tech.Bul.Nº 1768, Sept. 1990; **IMPEL**: Integrated Model to Predict European Land use is a decision trees/neural network hybrid model developed to predict the water erosion vulnerability, productivity reduction and optimal management strategies for an agricultural parcel (field-unit), IRNASE, 1997, Spain; **GOMMER**: Ecoulement et érosion dans des petits bassins versants à sols marneux sous climat semi-aride méditerranéen, Projet oued Mina, GTZ, Karlsruhe, Allemagne.
Modeling small dams' siltation with MUSLE

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Modeling small dams' siltation with MUSLE

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Abstract

Williams proposed in 1975 an equation derived from the Universal Soil Loss Equation (USLE) and adapted it to runoff models. This equation, called the Modified Universal Soil Loss Equation (MUSLE) requires flood parameters: peak of discharge, flow volume, and four parameters describing soil loss ability. These parameters are defined for standard runoff plots and may be extrapolated to small watersheds according to topography, soil, and land use and vegetation maps. Several methods are proposed in the literature to estimate these parameters with better or less precision. Using a water balance model, it is possible to estimate the instantaneous discharge entering into a reservoir and to obtain the flood parameters required by MUSLE. Other parameters necessary for using USLE are:

- K measures the resistance of the soil to erosion, it depends on the soil composition, percentage of organic matter, structure, permeability, and of different ratios: fine sand, loam, clay, and stones.
- LS comprehends land erodibility linked to relief, it depends of the length and the inclination of the slopes.
- C is defined as the ratio between the soil losses observed in two standard plots for the same soil, the first plot is cultivated, the second is bare; C varies between 0 and 1 during the year.
- P is a coefficient between 0 and 1 expressing erosion reduction to soil conservation practices.

In a first stage, these parameters were considered constant for the watershed and the MUSLE is computed by an optimization method. The total amount of soil losses during the floods are added and the result is compared to observed dam siltation. In a second stage, the parameters were estimated with fuzzy logic.

Introduction

Large reservoir sedimentation has been noticed in several places in the south and east Mediterranean countries. The top soils here consist of decomposed limestone, sandstone and marl that are eroded. Due to agricultural activities in unforested areas, high intensity rainfall causes soil erosion and consequently reservoir sedimentation. Globally, the dam volume lost is estimated as between 3 and 10% (Gazzalo et al., 1977). Less than ten years after their construction several dams, in the semiarid area, were filled with sediments up to the level of inlet so that it was impossible to use the outlet pipe. Some of these were filled with sediments up to the level of the spillway.

When the dykes have been filled with sediments, there exists no economical solution to recover the lost reservoir volume. Usually, new dykes will be built in the vicinity. An ancient Syrian dam, in Badia of Horns called the Bardeh dam that was built in the roman period was recently used in
a rehabilitation experiment (Kara Damour and Miski, 1997). The reservoir volume as recovered by opening a hole of 1.6 m diameter in the dam wall and forming a sloping tunnel towards the filled reservoir. The water reaching the lake and leaving through the hole could dredge about 800 000 m$^3$ of sediments by the mid-sixties. The hole was then closed with concrete and the dam became ready to store water again. However, again it has been filled up with sediments up to the crest of the dyke.

When small reservoir constructions are initiated, empirical formulas are often used to estimate the amount of bed load and suspended load at dam site (Fournier's or Tixeront's formula in Chérif et al., 1995). In central Tunisia, in the semiarid dorsal region that extends from Cap Bon to the Algerian border, 30 artificial reservoirs were chosen to constitute a network of hydrological observations (Albergel and Rejeb, 1997). These lakes have highly diverse intake areas ranging from somewhat uninhabited semi-forests to areas that are devoted entirely to agriculture. Their watershed areas vary from a few hectares to several dozen square kilometers. They are also representative of the rainfall gradient of the semiarid region, which is 250 to 500 mm of rainfall annually. The data obtained in this network are used to calibrate models for simulation of sediment transport and dam siltation.

Williams (1977) proposed an equation derived from the Universal Soil Loss Equation (USLE) and adapted to runoff models. This equation, named the Modified Universal Soil Loss Equation (MUSLE) requires various flood parameters, e.g., peak discharge, flow volume, and four parameters describing soil loss ability. These parameters are based on standardized runoff plots and then extrapolated to small watersheds according to topography, soil, land use, and vegetation. Several methods are proposed in the literature to estimate these parameters with better or worse precision.

In this paper we try to calibrate MUSLE with the data observed in the 18 watersheds of the small reservoirs in the semiarid mountains of Tunisia. Peak discharge and flow volume were measured for each event (Albergel et al., 1998). An estimation of the total annual soil loss was obtained through bathymetry measurements taking into account the sediment transport evacuated by the spillway. The model is validated by a comparison between the calculated soil losses and the observed silting up of the lakes. A method to estimate the MUSLE parameters is shortly presented.

**Annual soil loss estimation**

The bathymetry of each reservoir was done at least once every hydrological year, and was compared with a detailed ground survey, making it possible to determine the reservoir's rate of silting, and to estimate depth-volume and depth-surface relationships.
The bathymetry of the reservoir was assessed with spot probing of the lake bottom following transverse lines held by a cable stretched between two shores of the reservoir. The end of each transverse line was adjusted to level and positioned on the lake's plane. Each estimated point (approximately 500 per reservoir) was defined by three Cartesian coordinates (horizontal position and depth). A geostatistical approach using kriging (Matheron, 1965) made it possible to establish the reservoir's depth-volume ratio. The volume of silt was determined from the difference in effective reservoir volume from one year to the next. The reservoir acts as a sediment trap, and when the sediment is not discharged, the sediment volume corresponds to total sediment transport of the watershed. The density of the sediment is measured for samples taken when the lake is empty.

In the case of discharge, the volumes discharged were assigned an average concentration of solid matter. This concentration was calculated for samples taken during the floods. Figure 1 shows the initial bathymetry of the reservoir Fidh Ali in central Tunisia, built in 1991. Figure 2 shows the results of the bathymetry for 1991, 1993, 1996, and 1997.

![Fidh Ali Bathymetry](image1.png)

Figure 1. Bathymetry of Fidh Ali in 1991 (initial volume was 135 000 m³).

The total erosion was measured for each observed watershed. In table 1, we give an example of data for five Hydromed pilot sites, El Gouazine, Fidh Ali, Es Senega, Kamech, and M'Richet El Anze.
Table 1. Siltation of reservoirs and watershed erosion of five areas in Tunisia.

<table>
<thead>
<tr>
<th>Lake</th>
<th>Date of dyke</th>
<th>Date of last bathymetry</th>
<th>Initial volume $\text{m}^3$</th>
<th>Silt volume $\text{m}^3$</th>
<th>Watershed erosion (t)</th>
</tr>
</thead>
<tbody>
<tr>
<td>El Gouazine</td>
<td>1990</td>
<td>1998</td>
<td>237,000</td>
<td>16,000</td>
<td>20,600</td>
</tr>
<tr>
<td>Fidh Ali</td>
<td>1991</td>
<td>1998</td>
<td>135,000</td>
<td>46,000</td>
<td>55,200</td>
</tr>
<tr>
<td>Es Senega</td>
<td>1991</td>
<td>1998</td>
<td>80,400</td>
<td>12,100</td>
<td>17,200</td>
</tr>
<tr>
<td>Kamech</td>
<td>1993</td>
<td>1998</td>
<td>142,000</td>
<td>15,000</td>
<td>28,300</td>
</tr>
<tr>
<td>M’Richet</td>
<td>1991</td>
<td>1998</td>
<td>42,400</td>
<td>8,700</td>
<td>10,600</td>
</tr>
</tbody>
</table>

Figure 2. Time evolution of sediment build-up for Fidh Ali reservoir.

In Fig. 2 the dike crest height represents a y-axis value of 0. From 0 to 250 m we have a first type of sedimentation appearing in calm water and constituted by fine particles. More upslope, the lake bed presents holes and bumps, the flood deposits the sediments by waves. A deposit measured one year can be eroded next year, as the deposit measured at 300 m in 1996 was eroded in 1997.

Modified Universal Soil Loss Equation (MUSLE)

During a storm event causing a flood in a small watershed, the total amount of soil losses can be calculated by the Williams equation (Hadley, 1985):

$$ A = \alpha \times (Q_{\text{max}} \times V_{\text{flood}})^p \times K \times (LS) \times C \times P $$

(1) MUSLE

where $A = \text{total amount of soil loss during the flood (t)}$, $Q_{\text{max}} = \text{peak of discharge (m}^3\text{s}^{-1})$, $V_{\text{flood}} = \text{volume of the flood (m}^3\text{)}$. The $K$ is resistance of the soil to erosion, it depends on soil
composition, percentage of organic matter, structure, permeability, and on different ratios of fine sand, loam, clay, and stones. The LS includes land erodibility linked to the relief, it depends on lengths and the inclination of the slopes. The C is defined as the ratio between observed soil losses in two standard plots for the same soil, where the first plot is cultivated and the second is bare; (C varies between 0 and 1 during the year). The P is a coefficient between 0 and 1 expressing erosion reduction due to soil conservation practices. The α and β are two constants. Williams (1977) found the values α=11.8 and β=0.56 in S.I. units.

**Applying MUSLE to dam siltation**

*Statistical method*

In a first stage, the product $\alpha \times K \times LS \times C \times P$ and $\beta$ are considered constant and having the same value for one watershed. Values of these parameters are computed by an optimization method. The total amount of sediment transported by the flow considered as the total erosion is calculated using the following equation:

$$T = V_s \times d + \sum S_i \times C_i$$

where $T =$ total amount of sediment transported between two bathymetric measurements (t), $V_s =$ total measured volume of sediment (m$^3$), $d =$ average density of the sediments, $i =$ number of floods occurring between two measurements of bathymetry, $S_i =$ volume of water discharged over the spillway during the flood $i$ (m$^3$), $C_i =$ the average concentration of solid matter measured in the samples during the flood $i$ (t m$^{-3}$).

This total amount is compared with a total amount calculated with MUSLE as

$$T'_i = \sum a (V/Q)^{\beta}$$

The two first measurements of bathymetry are used to calibrate the model and to calculate $\alpha$ and $\beta$, the others are used for validation. Table 2 gives the values of the observed and calculated solid transport at Kamech reservoir.

<table>
<thead>
<tr>
<th>Date</th>
<th>Observed transport (t)</th>
<th>Calculated transport (t)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1991</td>
<td>0</td>
<td>0</td>
<td>Dyke building</td>
</tr>
<tr>
<td>01/10/94</td>
<td>1666</td>
<td>1666</td>
<td>Beginning of the observations</td>
</tr>
<tr>
<td>05/07/95</td>
<td>993</td>
<td>993</td>
<td>Calibration</td>
</tr>
<tr>
<td>31/07/96</td>
<td>8725</td>
<td>8014</td>
<td>Calibration</td>
</tr>
<tr>
<td>30/04/98</td>
<td>3468</td>
<td>3026</td>
<td>Validation</td>
</tr>
</tbody>
</table>
This model allows one to compute the solid transport for each flood since the beginning of the measurements. Figure 3 shows the sediment transport at the Kamech reservoir since the 1st October 1994. The solid transport is not a linear function of time. The hydrological year 1995-1996 caused about 60% of the sedimentation.

Analytic method

For dams where there are few or no bathymetry observations it may be useful to use the MUSLE by determining the coefficients K, LS, C, and P. In practical terms, these parameters are defined for standard erosion plots and very difficult to estimate for a field catchment.

In a recent study, the Modified Universal Soil Loss Equation (MUSLE) was successfully applied using the USLE parameters as fuzzy numbers in 18 Tunisian watersheds (Albergel et al., 1998). The validation of the model was done by a comparison between the calculated soil losses and the observed silting up of the lakes for which the sediments evacuated by the spillway were added.

![Figure 3. Sediment transport at Kamech reservoir.](image)

Conclusion

Since 1994, measurements of sediment rates in 30 reservoirs have been executed. This kind of observations is very expensive and cumbersome. In order to simplify this procedure we need to find an easy methodology based on readily observed variables such as daily rainfall and characteristics of the watersheds. These experiments are believed to lead forward to such a methodology. Studies like this may also lead to the revealing of which areas siltation is the most serious and to indicators that may be used as early warning signs of siltation.
References


Rain water harvesting and management of small reservoirs in arid and semiarid areas

Lund University, Sweden, 29 June – 2 July, 1998

Small-scale cistern system for rainwater collection and storage in north-western China

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Small-scale cistern system for rainwater collection and storage in northwestern China

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Background and problem

Despite the overall rapid economical development during the last decade in China, a number of regions in remote areas is still striving to alleviate poverty. These regions are commonly characterized by low level of industrialization and poorly developed agriculture, which almost entirely relies on climate situations. Water has often been a bottle-neck in the development of the agricultural, industrial, and social-economical sectors of the region. Among 30 provinces and autonomous regions of China, Gansu has the lowest per-capita income being ranked as the second from the bottom. Dingxi County, located in the central part of Gansu Province is the poorest area in the province, thus even in the whole China. According to 1997 economical statistics, the annual income per-capita in Dingxi County was only some 75 US$ which is much lower than the national average level.

The poverty of Dingxi County can be traced to the adverse natural conditions and harsh climate, especially severe water shortage. Drought, low temperature and hail are considered as the disastrous threats to agriculture. The worst fact is that the scarce rainfall is most often concentrated during the period of July to September, often in the form of storms, but the irrigation period for crops is from April to June. Thus, drought becomes a non-avoidable natural calamity almost every year. Moreover, heavy storms occurring in summer not only worsen the water shortage in spring, but also cause severe soil erosion of cultivated farming land and ecological imbalance due to the scarce vegetation and fertile soil loss (Wu, 1991). The mean corn production could be as low as 1 000 kg per hectare due to water shortage. Consequently, the severe water shortage worsens the poverty situations of the area. The farmers constituting about 86% of the 440 000 total population in Dingxi are still living under very harsh basic living conditions without guarantee for drinking water in drought years.

In drought years, which often means no rainfall at all for almost 3 months, the only water resources are deeply-buried groundwater and stored rainwater collected in the previous rainy season. However, groundwater resources have also showed a depleting tendency with large decreasing of groundwater tables. With depth of hundreds of meters below the land surface, it is too difficult to be effectively utilized by farmers. Under such inauspicious situations, the critical issue for the local people is how to get drinking water for survival and keep animals alive rather than agricultural activities. When the serious drought took place in 1995, for instance, 40% of the farmer families had to rely on the national emergency food aid for living meanwhile drinking water supply for the population in Dingxi County was distributed through transportation of water tanks. The provincial government has to make a special budget every year with drinking water transportation for Dingxi and other counties (see Government document, 1995).

Definitely, water shortage is the major obstacle for the local economic development and a crucial
factor for the cause of poverty, which, in turn, obviously contributes to the fact that the region is the most underdeveloped area in China not only in terms of agriculture and industry, but also the social, educational as well as health conditions.

In recent year, the practice of small-scale rainwater cistern system in the area has showed very promising results (e.g., Huang, 1997). With a simple and cost effective technique, a cistern can store around 70% of the rainfall water collected by a corresponding paved mini-catchment. The successful example of such family based water cistern showed that a simple, small cistern, by collecting the rainfall in the rainy days, can provide enough fresh water supply for the whole year for a normal family including animal feeding and necessary backyard irrigation. A lot of problems remain concerning water cistern systems. Such as water quality related problems (water purification, fresh-keeping), water seepage and infiltration, soil erosion, etc (Wang, 1996).

**Objectives**

There is a strong need on optimalization of the methods in extended use of small-scale rainwater harvesting cistern system in arid and semiarid areas throughout China. Following aspects are identified as most important in the near future:

1. The design and implementation of rainwater collecting ground and storage cistern.
2. Water quality assurance and storage water fresh-keeping.
3. Estimation and assessment of environmental impacts of water cisterns system, both positive and negative, including soil erosion, vegetation, and solute and particle transport.
4. Investigation of possibilities for larger, village scale cistern system.

**Small rainwater cistern system**

Small rainwater cistern system is a family based, small-scale rainfall collecting system. The idea of rainwater cistern for drinking purpose is not very new. The local inhabitants used to build very simple cisterns by digging a hole on the ground for gathering of rainwater. Clay was often used as sealing material. Many families used to rely on these kinds of simple cisterns for drinking water supply during dry months. A small rainwater cistern system often consists of the following parts: rainfall collecting ground, either paved or unpaved; one or several storage cisterns constructed underground; pipe system for water transport and distribution. The practice in Gansu Province so far are focused on cost effective solutions with limited pavements for collecting ground and simple construction of the cistern and pipe systems. One example of a collecting ground is displayed in Fig. 1, where both house roof as well as family yard are used as collecting areas.

In recent years, local population facing severe water shortage was encouraged to further develop the cistern system to lessen the water resources crisis. This has proven to be very successful in providing water supply for farmers living in the area by building up rainwater collecting cisterns for essential living needs and backyard irrigation. With financial help and aid from governmental,
local organizations and individuals, some 40,000 cisterns have been constructed. This has greatly improved the living conditions for the poorest farmers. Up to now, crop production in backyard irrigated lands by collected rainwater has been doubled compared to the past in addition to the swift development of fruit trees and vegetable growing in backyard. The multi-economic agriculture has brought the benefits to a part of farmers who used to be very poor, and their income increased to 625 US$ per year compared to around 70 US$ in 1980's. Currently, rainwater collecting implementation in Dingxi County turns to the development of the sufficient agricultural economics, such as effective irrigation approaches, rainwater management, design of economical cisterns and large scale collecting systems, rainwater purification and fresh-keeping etc.

A normal construction of an underground cistern system includes: 1) An available (paved) ground of some 100 m² (plus house roof area) for gathering rainwater; 2) An underground cistern adjacent to the paved ground for water storage; 3) A pipe system for water distribution. The size of the cistern may be up to 30 m³ for family based usage, which may gather adequate water during the rainy season (with annual rainfall of 350-400 mm) for a 5-member family's routine consumption. The construction cost of a cistern system of this scale is estimated to be around 130 US$. Some of the poorest farmers have received local and national aid for construction of family based cisterns. Figure 2 shows two examples of commonly used constructions of cisterns in China. In (a) the figure, a layer of red-clay is used on the bottom of the cistern as natural purification medium. The seepage rate of the red-clay is neglectable whereas the effect of purification needs to be further studied.
The study area and work content

The study area is located at Dingxi County, Gansu Province of China. With an area of 3650 km², Dingxi lies in the inland arid loess plateau of Northwest China. The elevation of the area varies from 1800 to 2300 meters above sea level. The long term annual average precipitation is around 400 mm, but with a potential evapotranspiration more than 1500 mm. The precipitation occurs mostly in form of storms during summer months and causes severe temporary overland flooding with serious erosion and land loss. A number of cisterns has been constructed in this area. However, there is a lack of detailed investigation and analysis of problems related to such systems. The contents of the current study consisted of the following:

- Collection and analyses of local meteorological, hydrological, geographical data as well as soil and water quality samples.
- Issued related to water purification and fresh-keeping.

Figure 9. Commonly used underground water cistern types: (a) Cubic type with concrete wall and bottom layer of red clay; (b) Spherical type with concrete construction.
Achieved results

The research program is a cooperation project between Department of Water Resources Engineering (DWRE), University of Lund, Lund, Sweden and the Science and Technology Commission, Gansu Province, P. R. of China. Field investigations and more detailed studies are planned in the near future.

The results achieved so far have been concentrated on data compilation and analyses. One special concern is purification and fresh keeping for the collected water. In the storage process of rainwater in cistern, worrying issues of water quality deterioration have been widely found, which usually are caused by various pollutants and bacteria growth. Therefore, purification and fresh keeping is an important procedure for rainwater storage and utilization. As used in drinking water treatment, disinfectants, such as chlorine, chloroform, sodium hypochlorite, chlorine dioxide and ozone etc, were primarily considered. The oxidation capacities of these agents may be ranked as follows in order of decreased efficiency:

\[
\text{O}_3 > \text{ClO}_2 > \text{HOCl} > \text{OCl}^- > \text{NHCl}_2 > \text{NH}_2\text{Cl}
\]

A series of experiments simulating the oxidation processes of chlorine dioxide in contaminated rainwater samples was conducted in the laboratory. The oxidants ozone, chlorine dioxide, potassium permanganate and the mixing gas (mainly contained ClO_2 and a certain amount of Cl_2, O_3 and H_2O_2) were tested for removal of petroleum compounds. The study indicated that chlorine is an excellent oxidant to prevent waterborne diseases. Detailed results of this laboratory experiment are presented in a separate report (Zhu et al., 1998). It is concluded that chlorine dioxide can be utilized with strong disinfection effects and low cost, and it especially has high capacity to restrict formation of THMs and mutagens (Katz, 1980; Schalekamp, 1986). In fact, the technique of chlorine dioxide oxidation is a technique for drinking water disinfection and purification (Gordon, 1995). The research will be carried out in Dingxi project including the production of chlorine dioxide liquid and available utilization methods.

Future steps

The proposed project is expected to provide answers and guidelines to a number of unresolved questions for rainwater cistern systems in arid and semiarid China. The following results are expected from the project:

- Optimal design of collecting areas and structure of cistern, this includes formation and choice of collecting areas; optimal material combination and formation of cistern.
- Environmental impact of rainwater cistern system, this including reducing the risk for soil erosion and land loss; diminishing of solute and other contamination in the stored water.
Suggestions for if/when extra purification are needed in order to maintain portable quality water besides the natural purification.

Feasibility and guidelines for larger, village scale rainwater cisterns.

Scientifically validated, well designed rainwater cistern systems will play a central role in the future development of this areas in Gansu province. The potential for use and extension of rainwater harvesting system are far beyond the aspects of drinking water supply and backyard irrigation, it will act as catalyst in the overall social, economical and educational development of these areas. This is especially true for women and children because they would be released from the daily heavy duty of water supply workload. The improved living condition will also surely facilitate the effort of preventing the children from quitting school too early.

(1) Seepage and infiltration of cistern:

It is generally known that the infiltration capacity of local loess can be tremendous and orientation dependent compared to other soils. This is due to the special characteristics of the loess material. On one hand special care must be taken to diminish the soil erosion (as described above) and water seepage loss through the soils, on the other hand water stored in the cistern need to have direct contact to the soil materials, because the this contact has unique capability of natural purification. This natural purification has been proven by earlier studies to be effective and should be used prior to other methods (Zhu, 1997). Usually a layer of red clay is built into the bottom part of the cistern to minimize the water seepage and at same time maintain the natural purification process. Problems remain on how to optimally combine different materials used to construct the cisterns for the above purpose. A number of in situ soil/water interaction measurements and experiments are planned to solve these problems.

(2) Overall environmental impact assessment:

The extensive development of rainwater collecting system will influence the surrounding environment and ecosystem in Dingxi County. For the predictive purpose, environmental impact assessment will consider to the following aspects:

- Prediction of soil erosion and of suspended solids concentration in collected rainwater
- Impacts of surface soil structure and nutrients (N, P) losses
- Irrigation strategies to minimize land salinization
- Alternatives to periodic river flow affected by rainwater collection.
- Extent of stored rainwater quality guarantee and relevant chemical properties
- Impact on vegetation in the ecosystem

Dingxi County stands on the Northwest Loess Plateau where soil erosion is a predominant problem. Therefore, the impact assessment should pay a particular attention to soil erosion in rainwater collecting catchment field and the related SS value in the collected rainwater. Special care of these issues would be taken for construction of precipitation pond (field). This also will affect the final decision making in designing.
Under the arid natural conditions and loess land topography, salinity is likely to increase substantially during irrigation in the vadose zone. Consequently, based on past investigations TDS close to the soil surface has been shown to increase to around 6000 mg/L and even higher close to the root (Zhang and Zhu, 1998).

(3) Technical design of cistern systems for different scales:

The basic criteria in technical design is cost effectiveness and local condition suitability. Optimum design in cistern system involves site selection, shape, volume, as well as ratio of concrete and clay materials. The constructions done so far are all very small family based cisterns. The pilot village scale cistern is very important in resolving these problems and provide information for larger scale extended use of the system.

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Disinfection and fresh-keeping of rainwater in small scale cisterns

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Disinfection and fresh-keeping of rainwater in small scale cisterns

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Abstract

Various disinfectants were examined in a study for disinfection and fresh-keeping of collected rainwater in cisterns in arid areas of China. Among the tested disinfectants (chlorine, ozone, chlorine dioxide, potassium permanganate, chloramine and hydrogen peroxide etc.), chlorine dioxide proved to be the most feasible and effective oxidant for drinking water storage and disinfection of rainwater in collecting cisterns due to its low cost and simple way of utilization. A series of experiments indicate that chlorine dioxide can significantly restrain production of trihalomethane (THMs) and bacteria growth. The paper discusses oxidation capacity of chlorine dioxide, especially for removing petroleum compounds, which is affected by reaction time, gas injection method, and pH of rainwater.

Introduction

Facing the severe water resources scarcity in the arid areas in northwestern provinces in China, the local governments have called for family based cistern systems for collecting rainwater for basic living and agricultural usage. In recent years, the implementation of small-scale rainwater cistern systems in the area has showed very promising results. Successful examples of such family based water cisterns have proved that rainwater cistern systems could provide enough fresh water supply for a family's normal annual consumption including drinking, animal feeding, and necessary backyard irrigation. On the other hand, several problems remain concerning the use of these cistern systems regarding water quality. Collected rainwater gradually deteriorates with growth of bacteria, protozoan, and algae due to high contents of nutrients and pollutants often associated with annoying odors. Therefore, purification, and fresh-keeping of collected rainwater in cistern systems are urgent issues to be resolved in order to find effective measures for water quality protection.

Chemical and filtration treatments are two main methods used in China for treating drinking water. However, also UV irradiation has been used successfully for relatively low flow rate. On the individual farmer family level, though, only chemical treatment is a feasible alternative. The following guidelines exist for the selection of suitable disinfectants: the reaction must be strong enough to kill bacteria and control growth of micro-organisms, removal of contaminants should be done by decomposition, evaporation or precipitation etc, to eliminate or decrease the toxicity; oxidants or reaction by-products should not be harmful to human health, and the purification
process should be practical and economical. The objective of this paper is to evaluate and discuss available disinfectants for rainwater fresh-keeping. The different disinfectants are discussed regarding applied approach and purification efficiency.

Comparison of disinfectants

Disinfectants, used in drinking water treatment, such as chlorine, chloroform, sodium hypochlorous, chlorine dioxide, and ozone etc., were primarily considered. The oxidation capacities of these agents may be ranked as follows in order of decreased efficiency (Katz, 1980):

\[ O_3 > ClO_2 > HOCl > OC1^- > NHCl_2 > NH_2Cl \]

Referring to Fiessinger's (1985) suggestion the properties of these disinfectants are compared in Table 1.

Chlorine is shown to be an excellent disinfectant to prevent waterborne diseases such as typhoid fever over long periods. Chlorine reacts not only within oxidation, but also by electrophilic substitution to produce a variety of chlorinated organic by-products, particularly trihalomethanes (THMs) and other mutagens. Here THMs mainly refer to bromoform, dibromochloromethane, bromodichloromethane and chloroform etc. Since the 1970's, the usage of Cl₂ in drinking water disinfection has been questioned and substituted with ozone as the preferred disinfectant in the water supply plants. But, ozone could not be introduced to the rural farmer community due to its high costs and short half life (15-20 min.). As with other disinfectants, ozonation also leads to formation of organic by-products such as aldehyde, ketones, and carboxylic acids, and also mutagenicity may be induced if bromic anion exists.

<table>
<thead>
<tr>
<th>Table 1. Comparison of various oxidants.</th>
</tr>
</thead>
<tbody>
<tr>
<td>THM formation</td>
</tr>
<tr>
<td>---</td>
</tr>
<tr>
<td>+++</td>
</tr>
<tr>
<td>THM precursors removal</td>
</tr>
<tr>
<td>Formation of mutagens or toxic substances</td>
</tr>
<tr>
<td>Enhanced biodegradability</td>
</tr>
<tr>
<td>Taste removal</td>
</tr>
<tr>
<td>Iron and manganese</td>
</tr>
<tr>
<td>Ammonia</td>
</tr>
<tr>
<td>Disinfection</td>
</tr>
</tbody>
</table>

- no effect, + little effect, ++ effect, +++ largest effect
It is therefore suggested that chlorine dioxide should be used as preferred disinfectant for rainwater fresh-keeping considering to the following advantages over chlorine and chloramines.

- Its high oxidation capacity without formation of THMs, efficient increase (threefold in the pH range from 6 to 9).
- It does not disproportionate over the pH range normally encountered in water treatment as chlorine does.
- It is less active with demand substances than free or combined chlorine.

There are, however, some disadvantages with ClO₂, such as easy loss from solution due to volatilization, and may disproportionate above pH 10 into chlorate and chlorite ions, which are of certain oxidation capacity, but reported to be harmful if the concentration is higher than 0.5 mg/L according to US-EPA drinking water standard.

**Comparison of disinfection efficiency between chlorine dioxide, chlorine, and ozone**

Watson’s Law to study protozoan disinfection, reads as follows:

\[ K = C^\eta t \]

where

- \( K \) = constant for a given micro-organism exposed to a disinfectant under a fixed set of pH and temperature conditions,
- \( C \) = disinfectant concentration (mg/L),
- \( \eta \) = empirical coefficient of dilution,
- \( t \) = time required to achieve the fixed percentage inactivation.

The relation between disinfectant concentration and contact time can be established by using Ct products based on the experimental data. From this the effectiveness of disinfectants can be evaluated based on temperature, pH value, and contact time. Below are given some experimental results based on the above Ct product.

The mean Ct value for ClO₂ at pH 7 and 5°C was 11.9 mg min/L. This value dropped to 5.2 at pH 7 and 25°C. High temperature normally enhances the efficiency of disinfectants while lower temperature has opposite effect requiring additional contact time or extra quantity of disinfectants. The best performance for ClO₂ is at pH 9 and 25 °C, which yields a Ct product of 2.8 mg min/L (Rubin, 1989). Chlorine dioxide appears to be more efficient for Cryptosporidium oocysts than either chlorine or monochloramine. Exposure of oocysts to 1.3mg min/L at pH 7 reduces excystation from 87% to 5% in one hour at 25°C. Based on this result, Ct product of 78 mg min/L was calculated. However, the Ct product for ozone to do this work was examined as 5-10 mg min/L from observation that excystation decreased from 84% to 0% after 5 minutes with the ozone concentration of 1 mg/L (Korich et al., 1990). A comparison of the efficiency of ClO₂ to chlorine against N. gruberi shows that at pH 7 and 25°C, the Ct products are 12.1 and 5.51 mg
min/L, respectively. As with other disinfectants, increasing temperature decreased the Ct values and improved the cysticidal action. Increasing temperature unexpectedly decreased the Ct values from a high of 6.35 mg min/L at pH 5 to a low of 2.91 mg min/L at pH 9 (Rubin, 1989). It is generally the rule, that for protozoans ozone is the best cysticide, chlorine dioxide is superior to chlorine and iodine, but chlorine, in overall, is much superior to chloramines (Russell, 1992).

Although disinfection efficiency of ozone is higher than chlorine dioxide, this difference can be compensated by the contact time. The experiment indicated that chlorine dioxide could reach the same results for disinfection of coliform bacteria as ozone did if contact was long enough, which can be seen in Fig. 1. The added concentrations of both of ozone and chlorine dioxide were 2 mg/L.

**Purification of organic pollutants by chlorine dioxide**

Collected rainwater usually contains organic micropollutants through runoff on top soil, particularly, it often contains high concentrations of fertilizers and pesticides. It may even contain petroleum compounds when the catchment is located close to roads. According to WHO guideline for drinking water quality, much consideration should be paid to benzene homologous compounds, therefore, the study on purification effects of chlorine dioxide is focused on petrochemical pollutants.
Preparation of laboratory experiments

A series of experiments were carried out to simulate the oxidation processes of contaminated rainwater for restoration in a cistern system. The polluted solutions were prepared in a dark barrel (10 L) of seven kinds of benzene homologous compounds; Benzene, toluene, ethyl benzene, p-phenylmethane, o-phenylmethane, m-phenylmethane, and styrene. Samples were taken to determine the initial concentration of the compounds prior to the tests.

Standard chlorine dioxide solution was produced from sodium chlorite reacted with HCl 10% (APHA, 1989). A solution of 600 mg/L chlorine dioxide was prepared and diluted using doubly distilled water. The solutions were stored in light-proof bottles in a refrigerator at 5°C and the concentration of chlorine dioxide in each bottle was analyzed by iodimetric titration prior to use.

Chlorine dioxide (gas) was added into each solution using a molar ratio of the organic compounds to chlorine dioxide (equal to available chlorine) of 1 to 1-5. Samples of 10 ml each were collected at 2, 4, 6, 8, 10, and 15 min with CS₂ for later measurement by a gas-chromatograph, and calibrated with standard curves.

A GR-16A Gas-chromatograph with FID detector Shenyang LZ-2000 was used for measurement of Cl₂, ClO₂ ClO₃⁻ and ClO₄⁻ (Dietrich, 1992). Oil concentrations were determined with an UV-120-20 spectrophotometer (Shimadzu) following the procedure described by APHA (1989). Organic compounds in the water samples were measured with a GC-MS(QP-1000A). The ClO₂ and O₃ were standardized by iodimetric titration at pH 7.

Results and discussion

In the laboratory study, the oxidant ozone, chlorine dioxide, potassium permanganate, and the mixing gas (mainly contained ClO₂ and a certain amount of Cl₂, O₃ and H₂O₂) were tested for removal of the petroleum compounds, and results are shown in Table 2.

Table 2. Comparison of oxidation capacity for the various oxidants.

<table>
<thead>
<tr>
<th>Organic Compounds</th>
<th>Initial conc. (mg/l)</th>
<th>O₃</th>
<th>ClO₂</th>
<th>H₂O₂</th>
<th>Mixing Gas</th>
<th>KMnO₄</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oil</td>
<td>11.34</td>
<td>67.2</td>
<td>45.8</td>
<td>0</td>
<td>61.8</td>
<td>0</td>
</tr>
<tr>
<td>Benzene</td>
<td>3.61</td>
<td>78.3</td>
<td>71.4</td>
<td>0</td>
<td>82.3</td>
<td>0</td>
</tr>
<tr>
<td>Toluene</td>
<td>5.23</td>
<td>91.8</td>
<td>83.0</td>
<td>0</td>
<td>95.2</td>
<td>0</td>
</tr>
<tr>
<td>Ethyl benzene</td>
<td>8.37</td>
<td>95.1</td>
<td>91.1</td>
<td>0</td>
<td>94.5</td>
<td>0</td>
</tr>
<tr>
<td>P-phenylmethane</td>
<td>7.86</td>
<td>95.8</td>
<td>90.5</td>
<td>0</td>
<td>100</td>
<td>0</td>
</tr>
<tr>
<td>O-phenylmethane</td>
<td>8.36</td>
<td>95.9</td>
<td>90.3</td>
<td>0</td>
<td>100</td>
<td>0</td>
</tr>
<tr>
<td>M-phenylmethane</td>
<td>9.29</td>
<td>95.4</td>
<td>87.3</td>
<td>0</td>
<td>100</td>
<td>0</td>
</tr>
<tr>
<td>Styrene</td>
<td>9.36</td>
<td>96.2</td>
<td>84.7</td>
<td>5.7</td>
<td>100</td>
<td>46.1</td>
</tr>
</tbody>
</table>
For the purpose of chemical disinfection for drinking water, chlorine was ignored due to the formation of THMs and its mutagenic substances. The results indicated that potassium permanganate and hydrogen peroxide did not have enough oxidation capability to decompose petroleum contaminants achieving only 46% and 5.7% decomposition of styrene, respectively. Ozone was not selected due to its high cost, complex operation, and short half-life although it is an excellent oxidant for water treatment. Chlorine dioxide was the next most successful alternative for disinfection. The benefits include effective oxidation capacity, algicidal effect, and negligible formation of halogenated by-products. Based on economic and operational requirement, the mixing gases method is easily used. For drinking water treatment, it has been suggested that the mixture of chlorine 0.8 mg/l and chlorine dioxide 0.5 mg/l will achieve disinfection and control THMs formation in preference to use of pure chlorine dioxide (Schalekamp, 1986).

When the mixing gases react with water molecules and organic micro-pollutants, hypochlorous acid is formed by chlorine, chlorite and chlorate ions are produced from chlorine dioxide in a series of redox reactions. The principal reactions are summarized as follows:

\[ \text{ClO}_2 + \text{organic} \rightarrow \text{ClO}_2^- + \text{oxidized organic} \]  
\[ 2\text{ClO}_2^- + \text{Cl}_2 \rightarrow 2\text{ClO}_2 + 2\text{Cl}^- \]  
\[ 2\text{ClO}_2^- + \text{HOCl} = 2\text{ClO}_2 + 2\text{Cl}^- + \text{OH}^- \]  

If a high level chlorine has been contained in the solution, a side reaction with chlorine dioxide occurs:

\[ 2\text{ClO}_2 + \text{HOCl} + \text{H}_2\text{O} = 2\text{ClO}_2^- + \text{HCl} + 2\text{H}^+ \]  

The rate of chlorate yield can be described by Eqn. (5):

\[ \frac{d[\text{ClO}_3^-]}{dt} = 2k[\text{ClO}_2][\text{HOCl}] \]  

in which \( k = 1.28/\text{M/min} \) at 25°C (Aieta, 1986).

The stoichiometry of the undesirable reactions which forms chlorate in low concentration of chlorite or presents excess chlorine is given as:

\[ \text{ClO}_2^- + \text{Cl}_2 + \text{H}_2\text{O} = \text{ClO}_3^- + 2\text{Cl}^- + 2\text{H}^+ \]  
\[ \text{ClO}_2^- + \text{HOCl} = \text{ClO}_3^- + \text{Cl}^- + \text{H}^+ \]  

At alkaline conditions:

\[ \text{ClO}_2^- + \text{HOCl} + \text{OH}^- = \text{ClO}_3^- + \text{Cl}^- + \text{H}_2\text{O} \]  

At pH values in the range from 5 to 6, the equation is

\[ \text{ClO}_2^- + \text{O}_3 + \text{H}_2\text{O} = \text{ClO}_2^- + \text{O}_2 + 2\text{OH}^- \]
Typically, chlorine dioxide is used in drinking water treatment and the concentrations are ranging from 0.1 to 2.0 mg/l (Gordon, 1990). However, the relevant by-products of chlorine dioxide treatment, chlorite and chlorate have been found to induce methemoglobinemia in the human body when concentrations are more than 100 mg/l (Kmorita and Snoeyink, 1985).

A series of the experiments simulating the oxidation processes of chlorine dioxide in contaminated rainwater samples was conducted in the laboratory. Seven benzene homologous compounds; benzene, toluene, ethyl benzene, p-phenylmethane, o-phenylmethane, m-phenylmethane, and styrene were selected for the laboratory experiments when chlorine dioxide gas was directly pumped into the solutions for the reactions. The results of oxidation of the organic contaminants were affected by reaction time. The initial concentrations and removal rate at different times are listed in Table 3. It is shown that chlorine dioxide has a very strong oxidation capability, including the break down of the benzene ring. There are no other commonly used oxidants except for ozone.

Table 3. Removal rate of tested organic compounds at different operating time (at pH 7).

<table>
<thead>
<tr>
<th>Compound</th>
<th>Initial concen. (mg/L)</th>
<th>2 min</th>
<th>10 min</th>
<th>15 min</th>
</tr>
</thead>
<tbody>
<tr>
<td>Benzene</td>
<td>41.25</td>
<td>14.1</td>
<td>41.2</td>
<td>60.7</td>
</tr>
<tr>
<td>Toluene</td>
<td>31.75</td>
<td>17.5</td>
<td>54.9</td>
<td>86.8</td>
</tr>
<tr>
<td>Ethyl benzene</td>
<td>16.15</td>
<td>24.7</td>
<td>63.5</td>
<td>89.8</td>
</tr>
<tr>
<td>P-phenylmethane</td>
<td>10.75</td>
<td>25.9</td>
<td>84.9</td>
<td>100</td>
</tr>
<tr>
<td>O-phenylmethane</td>
<td>30.25</td>
<td>20.9</td>
<td>79.1</td>
<td>100</td>
</tr>
<tr>
<td>M-phenylmethane</td>
<td>33.20</td>
<td>28.6</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Styrene</td>
<td>62.40</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
</tbody>
</table>

By increasing the applied ClO₂ dose, for example, the molar ratio of 1:1-5 for the organic compounds and chlorine dioxide were reached. However, the removal rates were not obviously changed, which suggests that the molar ratio of 1:1.5, i.e. the concentration ratio of about 1:2, for the organic compounds and chlorine dioxide was optimal input for the purification. To accommodate this requirement, a portion of chlorine dioxide needs to be consumed by reaction with other substances attached on the wall of the rainwater cistern.

The injecting method for chlorine dioxide gas into the solution also has an apparent influence on the removal rate. With the indirect method, the gas firstly was dissolved in a certain amount of distilled water, and then added to the tested organic solutions. The removal rates of the 7 compounds after 5 min stirring are shown in Table 4.
Table 4. Removal rate of benzene homologous compounds by indirect contact (after 5 min).

<table>
<thead>
<tr>
<th>Compound</th>
<th>Initial conc.(mg/l)</th>
<th>Removal rate (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Benzene</td>
<td>41.25</td>
<td>9.5</td>
</tr>
<tr>
<td>Toluene</td>
<td>31.75</td>
<td>8.3</td>
</tr>
<tr>
<td>Ethyl benzene</td>
<td>16.15</td>
<td>7.9</td>
</tr>
<tr>
<td>P-phenylmethane</td>
<td>10.75</td>
<td>8.2</td>
</tr>
<tr>
<td>O-phenylmethane</td>
<td>30.25</td>
<td>7.4</td>
</tr>
<tr>
<td>M-phenylmethane</td>
<td>33.20</td>
<td>7.9</td>
</tr>
<tr>
<td>Styrene</td>
<td>62.40</td>
<td>21.4</td>
</tr>
</tbody>
</table>

Compared with the data listed in Table 3 and Table 4, the removal rates with indirect method after 5 min operation are much lower than for the direct blowing method. The main reason for the difference is due to the conversion and decomposition of chlorine dioxide in the indirect method before the reaction with the benzene homologous compounds. Thus, the indirect method contains a great quantity of chlorite and chlorate ion.

It is confirmed from Table 3 that the removal rate was proportional to operating time. Since chlorine dioxide showed very strong oxidation capability for organic chemicals but was reduced to chlorite anion according to Equation (1), the removal rate appeared quite high initially. Then, chlorite keeps the oxidation capacity at a level which allows decomposition of the organic compounds to continue even though the oxidation reaction gradually became weaker with reaction time.

The experiment indicated that pH values significantly influenced the removal rate of the organic compounds. Through the adjustment of pH values in the tested solutions, the degradation percentage of the compounds was measured after chlorine dioxide was injected into the test solutions at molar ratio of 1:1.5 relative to the benzene homologous compounds in the indirect method. The differences of degradation rates are shown in Table 5.

Table 5. Degradation rate of benzene homologous compounds with indirect method at different pH values (after 15 min).

<table>
<thead>
<tr>
<th>Compound</th>
<th>Initial conc. (mg/l)</th>
<th>Removal rate (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>pH 5</td>
<td>pH 7</td>
</tr>
<tr>
<td>Benzene</td>
<td>5</td>
<td>54.0</td>
</tr>
<tr>
<td>Toluene</td>
<td>5</td>
<td>71.7</td>
</tr>
<tr>
<td>Ethyl benzene</td>
<td>5</td>
<td>84.2</td>
</tr>
<tr>
<td>P-phenylmethane</td>
<td>5</td>
<td>84.4</td>
</tr>
<tr>
<td>O-phenylmethane</td>
<td>5</td>
<td>84.1</td>
</tr>
<tr>
<td>M-phenylmethane</td>
<td>5</td>
<td>84.0</td>
</tr>
<tr>
<td>Styrene</td>
<td>5</td>
<td>100.0</td>
</tr>
</tbody>
</table>
Chlorine dioxide was unstable in the solution even though it has a stronger oxidation capability than chlorite and chlorate resulting in the latter two anions being dominant in the oxidation processes. The actual concentration of chlorine dioxide depended on the existence of chlorine, chlorite and chlorate whose concentrations were determined by pH values of the solution according to Eqns (4), (6), (7), (8), and (9), respectively. Therefore, the pH is the critical controlling factor in the concentrations of chlorine dioxide, chlorite and chlorate.

The latter two harmful ions can be removed quite quickly by treatment with a reducing agent such as sulfur dioxide-sulfite ion at pH values of 5-7 (Gordon, 1990; 1995). The Fe(II) can be used to eliminate chlorite from the water, and the redox reaction is kinetically more rapid at pH 5-7 as well (Iatrou, 1992). It was evident that the decomposition in acidic conditions was much better than that in alkaline conditions because a disproportional amount of chlorine dioxide was consumed by the reactions under alkaline conditions. The relevant reaction is described in Eqn (8). The concentration in acidic conditions would remain stable as explained by Eqn (9). The details of the influence of pH on removal rates of benzene and styrene are displayed in Fig. 2. To apply this degradation method, alkaline rainwater should be excluded.

The contaminated water samples were taken from a confined aquifer in which 80 organic pollutants were found and 14 were considered toxic or carcinogenic substances. Treated by chlorine dioxide and analyzed 24 hours late, some organic compounds changed and results are shown in Table 6.
Table 6. Oxidation results of contaminated water samples with chlorine dioxide
(Analyzed with GC-MS).

<table>
<thead>
<tr>
<th>Organic chemicals</th>
<th>Contaminated water</th>
<th>Treated water</th>
<th>Mutagen toxic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Benzene</td>
<td>+</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>Toluene</td>
<td>+</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>Ethyl benzene</td>
<td>+</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>p-Phenylethane</td>
<td>+</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>o-Phenylethane</td>
<td>+</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>m-Phenylethane</td>
<td>+</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Styrene</td>
<td>+</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>1,4-Dimethyl-benzene</td>
<td>+</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Azidomethyl benzene</td>
<td>+</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>1,3-Benzodioxole-5-methanol</td>
<td>+</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Tricarbonyl iron</td>
<td>+</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>2,4-Imidazolidinedione</td>
<td>+</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Heptenoic acid</td>
<td>+</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Nanadecane</td>
<td>+</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>Docosane</td>
<td>+</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>Hexadecane</td>
<td>+</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>1-Iodio-ethanone</td>
<td>+</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>1,2-Benzenedicarboxylic acid</td>
<td>+</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>1-Iodo-hexadecane</td>
<td>+</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>6-Methyl-octadecane</td>
<td>+</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>1-Chloro-2-methylbenzene</td>
<td>+</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>1-Bromo-3-methylbenzene</td>
<td>+</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>2-Chloro-1,3-dimethylbenzene</td>
<td>+</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>2-Chloro-1,4-dimethylbenzene</td>
<td>+</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Bromo-dimethylbenzene</td>
<td>+</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>1,2-Diethyloxyethane</td>
<td>+</td>
<td>- *</td>
<td></td>
</tr>
<tr>
<td>2,4-Dimethylhexane</td>
<td>+</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>3,4-Dimethylheptane</td>
<td>+</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>1-Hexyloxy-3-methylhexane</td>
<td>+</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>2-Ethyloxypropane</td>
<td>+</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Chlorobenzene</td>
<td>+</td>
<td>-</td>
<td>*</td>
</tr>
<tr>
<td>1,3-Dimethylbenzene</td>
<td>+</td>
<td>-</td>
<td>*</td>
</tr>
<tr>
<td>1,2-Dimethylbenzene</td>
<td>+</td>
<td>-</td>
<td>*</td>
</tr>
<tr>
<td>1,2,3-Trichloropropane</td>
<td>+</td>
<td>-</td>
<td>*</td>
</tr>
<tr>
<td>1,2,3-Trimethylbenzene</td>
<td>+</td>
<td>-</td>
<td>*</td>
</tr>
<tr>
<td>1,2-Diethylbenzene</td>
<td>+</td>
<td>-</td>
<td>*</td>
</tr>
</tbody>
</table>
Table 6. cont. Oxidation results of contaminated water samples with chlorine dioxide (Analyzed with GC-MS).

<table>
<thead>
<tr>
<th>Organic chemicals</th>
<th>Contaminated water</th>
<th>Treated water</th>
<th>Mutagen toxic</th>
</tr>
</thead>
<tbody>
<tr>
<td>1,4-Diethylbenzene</td>
<td>+</td>
<td>-</td>
<td>*</td>
</tr>
<tr>
<td>1,3-Diethylbenzene</td>
<td>+</td>
<td>-</td>
<td>*</td>
</tr>
<tr>
<td>1,2,3,4-Tetrahydroxynaphthalene</td>
<td>+</td>
<td>-</td>
<td>*</td>
</tr>
<tr>
<td>Naphthalene</td>
<td>+</td>
<td>-</td>
<td>*</td>
</tr>
<tr>
<td>Lauric acid</td>
<td>+</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Myristic acid</td>
<td>+</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>di(2-methloxy-ethyl)-1,2-phthalate</td>
<td>+</td>
<td>-</td>
<td>*</td>
</tr>
<tr>
<td>1,2-Phthalate butyldecylate</td>
<td>+</td>
<td>-</td>
<td>*</td>
</tr>
<tr>
<td>1,2-Phthalate-di-sec-octyl</td>
<td>+</td>
<td>-</td>
<td>*</td>
</tr>
<tr>
<td>2-Methyloxy-butane</td>
<td>+</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>1,1,2-Trichloroethane</td>
<td>+</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>1-Ethyl-3-methylbenzene</td>
<td>+</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>1-Methyl-2(2-propenyl)-benzene</td>
<td>+</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>1-Ethenylbenzene-4-methylbenzene</td>
<td>+</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>1-(4-Ethylpropyl)ethanone</td>
<td>+</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>2,3-Dihydroxy-1H-indenone-1</td>
<td>+</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>[(2-Chloro-2-propenyl)-oxo]benzene</td>
<td>+</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Bromo-indanthrone</td>
<td>+</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>3-Methylpentane</td>
<td>-</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>5-(1-Isopropenyl)-1,3-cyclopentadiene</td>
<td>-</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>Cyclopropylbenzene</td>
<td>-</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>Propylbenzene</td>
<td>-</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>1-Methyl-3-methylbenzene</td>
<td>-</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>1-Propylenebenzene</td>
<td>-</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>1H-indene</td>
<td>-</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>4-Ethyl-1,2-dimethylbenzene</td>
<td>-</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>1,2,3,4-Tetramethylbenzene</td>
<td>-</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>1-Methylbenzene</td>
<td>-</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>2-Methylbenzene</td>
<td>-</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>2,3-Dimethylbenzene</td>
<td>-</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>1,1-Diethylbenzene</td>
<td>-</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>2,2-Diethylbenzofuran</td>
<td>-</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>1-Ethenyl-4-methylbenzene</td>
<td>-</td>
<td>+</td>
<td></td>
</tr>
</tbody>
</table>

Note: + detectable; - undetectable; * toxic or mutagenic
It can be seen that the unsaturated hydrocarbons were easily removed, but some of the saturated alkane and alkene, alkyl benzene, polycyclic aromatic hydrocarbons and heterocyclic compounds were not oxidized. Five of the 14 most toxic and mutagenic chemicals were undetectable with the disappearance or apparent decrease of another 42 organic chemicals after in situ treatment. However, 16 new by-products were produced in the reaction process, though none of them were considered to be mutagenic carcinogens. It proves that the chlorine dioxide method has obvious advantages in controlling the formation of mutagenic compounds making utilization of chlorine dioxide in the purification of the petroleum contaminated rainwater an effective option.

Conclusions

To purify and keeping rainwater stored in cistern systems fresh, chemical treatment is possible and feasible. Chlorine dioxide can be chosen instead of chlorine, ozone and other disinfectants because of its advantages of low cost and simple use. The utilization of chlorine dioxide has been found to efficiently restrict protozoa growth, to disinfect from bacteria and oxidize and remove oil and benzene homologous compounds in rainwater meanwhile the formation of mutagenic and toxic substances is limited. The degradation rate was proportional to input amount of oxidants and increase of operating time. The optimal molar ratio for the organic compounds and mixing gases was tested to be 1:1.5, i.e. concentration ratio of some 1:2 for this chemical treatment. The effective pH at which reactions occur is in the slightly acid range of 5 to 7 at which formation of chlorite and chlorate is minimized. The mixing gases should be injected directly into the treated water body, so that high concentrations of chlorine dioxide can be kept in the solution. Under these conditions, the elimination rate for organic pollutants will be much higher. For the cistern system, input dosage of chlorine dioxide concentration should be higher than that in laboratory studies due to complex pollutants in rainwater and adsorption of cistern walls.

The experiments indicated that oil, benzene group of organic compounds and other unsaturated hydrocarbons significantly decomposed or degradated by chlorine dioxide. However, compounds of saturated alkane and alkene were not oxidizable. A large proportion of the 80 organic pollutants mixed in the mixing water sample containing some more toxic and mutagenic chemicals were decomposed by adding chlorine dioxide solution. Some new by-products were produced in the reaction process, but no mutagenic carcinogens were found.

References


Rain water harvesting and management of small reservoirs in arid and semiarid areas

Lund University, Sweden, 29 June – 2 July, 1998

Strategy of soil and water conservation in Tunisia

Dr. Habib Farhat and Dr. Mohamed Boufaroua

Soil Conservation Directorate
Ministry of Agriculture
Tunis, Tunisia
Strategy of soil and water conservation in Tunisia

H. Farhat and M. Boufaroua

Soil Conservation Directorate, Ministry of Agriculture, Tunis, Tunisia.

INTRODUCTION

A major critical problem of agriculture in much of Tunisia is the recurring deficiency of soil moisture for crops and range production. The central farming regions (200-400 mm) and the intermontain plains (400-550 mm) in the north-western part of country are particularly affected. Because of non uniformity of precipitation patterns. Many sub-humid region areas (400-550 mm) are also influenced by moisture shortage during certain periods in the growing season.

The enormity of the problem is particularly evident in the annual variation of cereal yields. The total national production fluctuates commonly in a ratio of 1 to 5 depending on the amount and timing of rainfall. The soil moisture during the planting season affects also the hectarage used for cereals.

1- LAND DEGRADATION PROBLEM:

Intensive cultivation, poor farming practices, overgrazing and increased occurrences of drought, have all played a role in the decline of land productivity. Soil degradation causes an important reduction of arable and grazing land, accelerates sedimentation of reservoirs, reduces forestry and livestock production. Therefore, it represents a crucial danger for the sustained production of food.

Recent survey shows that 3 million hectares of arable land in Tunisia, which represent 18.3 % of its total territory, are suffering heavy or moderate erosion. Land degradation on such massive scale, becomes a serious problem which is beyond the farmer's capacity to solve. Since the Roman occupation, this danger has been given considerable concern. In fact
terraces were constructed 2000 years ago by the romans, with the aim of controlling drainage on the hillsides. Thus, they could transform this region into a granary for the Empire.

There is an estimate that about 29 billion m$^3$ of the rainfall is lost by evaporation and transpiration and 0.5 billion of m$^3$ last to the sea and to salty lakes. This water could be retained to improve the over-exploited water table. Furthermore, some 10,000 hectares of arable land are sterilized annually because of excessive erosion. This not only reduces the agricultural land and adversity affects soil fertility, but also provokes numerous sediment damages to dam reservoirs. An average of 25.8 million cubic meter of sediment are deposited annually in these reservoirs. Consequently, the dams lose this same volume of their storage capacity.

2- STRATEGY OF SOIL AND WATER CONSERVATION

Since independence, water and soil conservation represents an essential component of all rural development projects. It is recognized as a necessity to protect hydraulic infrastructures and to expand their life time. It is also admitted that for rural development projects, soil conservation practices are the major rural employment creating activities. Erosion control efforts have already covered about one million hectares.

A long term strategy stressing the necessity to conserve the national soil resources and to protect the existing infrastructure was set up. A national programme to invest in soil conservation was established, and an estimated budget of 567 million dinars was proposed to cover the cost of all needed interventions from 1991 to the year 2000. The introduction of new farming policies based on the use of technology and adequate farming
practices are adopted in order to conserve the soil and improve its productivity.

This national wide project concerns the management of one million hectares:

- 600,000 hectares in watersheds.
- 400,000 hectares in cereal production regions.

The construction of:

- 1000 mountain lakes (lac collinaire)
- 2000 small check dams to trap sediments
- 2000 diversion digues for water harvesting

The objectives of soil and water conservation plan is:

1- To reduce the loss of arable land estimated to 10,000 ha/year.

2- To maintain soil fertility in order to avoid the decrease in soil productivity.

3- To retain the 500 million cubic meters of run-off water (which are actually lost in the sea and sebkhas), by carrying out water and soil conservation works.

4- To recover arable land by establishing structures (jessours) in the south of Tunisia.

5- To improve the life span of dams which are threatened by sedimentation at the rate of 25.8 million cubic meter/year.

6- To reduce damages caused in valleys and plains by floods.
7- To implement a new farming policy which aims at utilizing anti erosion techniques in order to increase production.

8- To create job opportunities and to improve revenues of rural population in the marginal areas.

The anti-erosion interventions, as planned for in the VII th plan (1987-91), have covered 400,000 ha spread out through different regions. This corresponds to an annual average of 80,000 ha to be treated, which makes an ambitious objective to reach, particularly due to the fact that the anti-erosive interventions call not only for mechanical and physical measures such as (bank construction, waterway lying, drop structures, farm ponds…) but also for agricultural developing interventions (fruit tree planting, forage crop, range management, change in crop production) with an effective farmer's participation. The investments for the implementation of the 5 year plan (1987-91) are estimated to 80 million Tunisian dinars (90 million US dollars) at a rate of 16 million dinars a year. This creates 5 million work-days a year corresponding to the employment of 20,000 workers in rural areas.

Water and soil conservation division in collaboration with other technical institutions depending of the Ministry of agricultural objectives aiming at increasing production to reach food self sufficiency, improving revenues and standards of living of the rural population, creating job opportunities and reducing the rural urban migration.
3- An integrated water and conservation approach:

In order to reach the objectives of an adequate land management, an integrated approach, based on a methodological study; and a planning, which permit to find practical and rational solutions to the problems encountered in the struggle against erosion, will be adopted.

The approach is to protect the downstream of watersheds from sedimentation and floods, and to improve revenues of farmers and livestock herders established in the upper parts of the watersheds. The integrated conservation management will be considered at three levels:

- Technical: It is fundamental to define guidelines to help prevent and fight against soil erosion, and to consider the watershed management techniques which aim at maintaining the fertility of the soil in the watershed and reducing the transport of sediment to the dam reservoirs.

- Economical: In order to make the best micro and macro economical return of the conservation work, it is crucially important to count on the participation of the land-user. It is not expected that this one will change his usual practices unless he perceives that the change is directed towards his interests, that it will minimise his risks and increase his income.

At the macro level, the aim consists of meeting the government objectives of controlling the critical soil erosion situation, moving towards food self sufficiency, and ensuring the best global ratio cost-benefit of the government's investments.
- Social level: concern must be given to the support of the local population, as the objective is not only to fight against soil erosion and promote economic growth but is also related to the improvement of the public's conditions especially in the most seriously affected areas where misery, unemployment and under-development are present.

Successful land resource management involves the introduction of changes in farmers' behavioural patterns. Therefore the principal benefit of this approach is to give small and medium scale farmers the opportunity to break out of the vicious circle of abusive cereal cultivations which decline production yields and accelerate soil erosion by adopting an improved farming system based on animal production.

It is by taking into account these different factors that one conducts studies and plans interventions in the field. The integrated watershed management practices are carried out in order to contribute effectively to the socio-economical development of the country. It is however recommended to harmonize the socio-administrative aspect of the interventions through the following measures:

- Extend land resource management based on soil conservation techniques to cover all state-owned farms in order to increase production and also to use them as pilote areas for the surrounding farmers
- Organize and achieve people's decision and enthusiasm to participate in the process of struggle against erosion and turn in to the best account.
- Promulgate the appropriate legislative texts in order to ensure a legal status for the conservation structure. In Tunisia in order to reach the main objectives of the agricultural policy, the water and soil conservation division has established a master plan which states the practical methods of
interventions, and a legislative and institutional organization which best guarantees the coherence of its actions with the socio-economical context of the country.

4- WATER AND SOIL CONSERVATION MEASURES:

The conservation measures applied are of different types and tend to be site specific and tailored to fit in with the local farming systems, customs and environmental conditions. They are classified as follows:

4-1- Directly productive measures:

- **Tree plantation**: Undoubtedly the most effective way of controlling and preventing erosion is to ensure that the land is densely covered with vegetation. In this objective existing trees are maintained, dead or low producing trees are replaced with new ones. Empty areas are also planted and cultivated on the contour.

- **Pastures and range land improvement**: livestock must never be allowed to graze the orchards; therefore a strategy to increase the area of leguminous forage is to be followed in order to carry more livestock and to improve soil fertility. Proper range use will assure top production of the range land. The plants will be managed for optimum growth and allowed to make and store food reserves in its roots systems.

  Range land rehabilitation often requires a combination of banks, stone cordons, and planting with acacia, atriplex, cactus and other perennial forage plants, mainly completed by hand labour.

- **Crop rotation**: The practice of a cereal medic rotation in the cereal production regions permits to reduce the cost of land preparation for
cereal growing and the cost of applying nitrogen fertiliser, and to increase yields.

- **Mulching**: It is an important practice in maintaining good physical soil condition, as the land is protected from the direct impact of the rain.

- **Crop residue use**: To improve the organic matter content, residue from crops should be incorporated into the soil or left on the surface. The decaying plant material will furnish food for plants and provide vegetative cover to reduce soil and water losses.

- **Contour farming**: All farming operations are supposed to be performed on the contour of the land. In Tunisia, legislation requires plowing to be on the contour, but this practice is generally ignored and needs to be highly enforced.

  Contour ploughing and contour planting reduce erosion 40 to 50%. They limit runoff and increase production. Contour planting of spineless cactus at the usual spacing of 4 to 8 meters serves greatly to reduce erosion.

4-2-**Indirectly productive measures**:

Priority is given to the maintenance of the existing conservation structures and to traditional protective measures by ensuring an adequate budget for the areas where erosion control activities have taken place. Both traditional and modern techniques are considered:

- **Jessours**: It is a hydraulic traditional system, typical for mountain areas. They are made of stone and soil along the wadi and perpendicular to its flow. The main role of this measure in arid areas is to collect the silt and form further alluvial terraces to be planted by some
vegetables and fruit trees. Even with a low annual rainfall, this measure allows a favourable condition for crop production.

- **Contour banks** : Most of the arable land, between 2% and 10% slope, can be protected with normal size banks. These banks make a permanent guide for contour cultivation. They are spaced according to the slope.

- **Elements of banks** : These consist of a series of mini absorption banks-10 meter long and 1.2 meter high-with ends which allow the bank to discharge when it contains 30 cm of water. Trees are often planted above the elements and cereals are grown between the rows of elements.

- **Terraces** : Level broad terraces are constructed on sloping land to reduce soil erosion and retain runoff water. Constructing terraces mechanically with a bulldozer or a tractor provides the most satisfactory terraces. In orchards and olive plantations, it is preferred to use hand labour to build terraces and prevent damage to trees.

- **Stone Cordon** : Which consists of small stone walls built on contour and planted with grass or cactus.

**4-3 Water Management**

Water management is one of the keys to soil conservation. Therefore special attention is to be paid to save the run-off water. This can be achieved through the following interventions:

- **Check dams for aquifer recharge** : Small rock or concrete dam are built across the wadis to slow down the velocity of flow and enable a large amount of water to infiltrate into the alluvium under the river bed. This added infiltration.
- **Small farm dams**: Some small farm dams are built in selected areas to provide additional water points for livestock and eventually for irrigation. This structure is commonly established in areas where rainfall is higher than 350 mm.

- **Sequia and Mgoud**: It is a traditional practice used for water harvesting. It consists of a kind of canal often made from compacted soil or cement material. It is built perpendicular to the wadi flow, close to the cultivated area.

  This technique allows the use of water flow for irrigation and also to prevent the inundation of the downstream zone. These measures are frequently encountered in semi arid regions.

### 4.4- Protective measures:

Particular care is given to those soils which are subject to mass movement and gully erosion. To limit this form of soil degradation, gully control erosion is commonly practiced. It is used to reduce, as much as possible, the amount of water through water ways and gullies. The stabilization of these gullies is ensured by drop structures, plags and silty traps made with rocks, gabions or dead wood materials. The purpose of these drop structures is to reduce the slope, the water runoff velocity and the concentration of the amount of runoff. These structures are well keyed into the banks of the waterways. Such techniques is commonly seen in bad land seriously eroded areas in the central part of Tunisia.
CONCLUSION

The concept of a moral obligation to care for and preserve the land for future generations, incited the Tunisian government to invest more for the conservation of the soil. In fact, if the VII th plan (1987-1991) allocated 80 million dinars for water and soil conservation works, the VIII th plan (1992-1996) provided at least twice this budget for the same sector.

If some significant success has been achieved in the field of soil conservation, there is still a number of constraints to overcome. It is admitted that there is still a need for more long term programmes, for more flexibility in project designs and for better involvement and participation of farmers in all stages of planning, implementation and maintenance.

It is also recognize that, for more success and in order to get closer to the national aim, water and soil conservation works must be planned on individual farmer basis. They must also offer short term benefits to the farmer by providing a combination of biological measures and mechanical works, as well as putting more emphasis on water-harvesting.

More attention is also to be given for more effective forms of communication and better extension services to reach a larger public and call for their enthusiastic participation. Field training and applied research need to be more developed.

Concerning the water and soil conservation legislation there is a need to place more emphasis on the regulation of rangeland management and grazing by adopting a rotational grazing system, and to give more attention to the problem of land tenure and land use rights which is one of the keys for better land resource management.
## ANNEXE

**FIGURES, GRAPHS AND PHOTOS (in reference to Tunisia)**

<table>
<thead>
<tr>
<th>FIGURES</th>
<th>TITLE</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Map</strong></td>
<td>1 Traditional water and soil Conservation practices in Tunisia</td>
<td>1</td>
</tr>
<tr>
<td><strong>Figures</strong></td>
<td>Water Harvesting techniques jessours</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Profile of stony check dam</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Level broad terraces in crop land</td>
<td>3</td>
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<tr>
<td></td>
<td>Terraces in range-land</td>
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<tr>
<td></td>
<td>Rocky-drop structure</td>
<td>3</td>
</tr>
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<td></td>
<td>Terraces-made-by-stones</td>
<td>4</td>
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<td></td>
<td>Mgouds (Traditional water-harvestingsystem)</td>
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<td>Banks and elements of banks</td>
<td>5</td>
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<td></td>
<td>Individual basin</td>
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<tr>
<td></td>
<td>Zone cordons</td>
<td>6</td>
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<tr>
<td></td>
<td>Small farm dam</td>
<td>6</td>
</tr>
<tr>
<td><strong>Graphs</strong></td>
<td>Economic rate of return (oued sbiba -Kasserine)</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>Agricultural production improvement due to soil conservation works</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>Effect of soil conservation works on cereal production</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>Water and soil conservation works improve the life span of dams</td>
<td>10</td>
</tr>
<tr>
<td><strong>Photos</strong></td>
<td>Range land rehabilitation (kairouan)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Consolidation of banks cereal land (Mahdia)</td>
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<td>Contour farming in cereal production soil (Beja)</td>
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<td>Small farm dam (zaghouan)</td>
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<td>Combinaison of banks, planting of acacia and cactus (Zaghouan)</td>
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<td>Traditional water harvesting in arid zones-jessours (Mednine)</td>
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<td>Vegetation for gullies control (Siliana)</td>
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<td>Olive tree planting on contour terraces (Nabeul)</td>
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<td>Cereal production soil management</td>
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<td>Check dam for aquifer recharge</td>
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</tbody>
</table>
Traditional water and soil conservation practices in Tunisia

- Farm pond
- Terraces
- Water harvesting structures
- Jessour
- Water spreading measures Mgouds
- Well
- Oasis
- Under-ground cistern

I Subhumid
II Semi arid
III Superior arid
IV Inferior arid
V Saharian

Scale: 1/3000,000
Fig: 1

JESSOURS

Water ways

Natural depressions

Drop structure

Silted area

Bank

Fig: 2

PROFILE OF STONY CHECK DAM
Fig. 3  LEVEL BROAD TERRACES IN CROP LAND

Fig. 4  TERRACES IN RANGELAND

Fig. 5  Rocky drop structure to reduce runoff velocity

FRONT OF VIEW

Stony Check Dam

vegetation cover
Fig : 6

**TERRACES**

![Diagram of terraces with labels: Stone cordon, Sediment deposits, Sloping land]

Fig : 7

**MOUDS**: Traditional water harvesting system

![Diagram of Mouds with labels: Area to be cultivated, Main wadi canal]
Fig: 8

ELEMENTS OF BANKS

Fig: 9

Individual basin

Water collector

Terrace

Cultivated basin
STONE CORDONS

Fig : 10

Fig : 11  SMALL FARM DAM
Grapll

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Graph 1

ECONOMIC RATE OF RETURN
QUED SBIBA WATERSHED-GOVERNORATE OF KASSERINE

Added value in Dinars

1250,000

500,000

146,000

With anti-erosion management

Without anti-erosion management
EFFECTIVE OF SOIL CONSERVATION WORKS ON CEREAL PRODUCTION

Graph: 3

Production (100 kg/ha)

Improvement of production after intervention

years


253
Session 4.

Reservoir planning, operation and management; Rainfall-inflow relationships; Dam design and operation; Surface-groundwater interactions (chairman: Dr. Abdelaziz Merzouk, IAV).
Groundwater recharge and modeling in an experimental catchment

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B. P. No. 10 Ariana
Tunis, Tunisia
Groundwater recharge and modeling in an experimental catchment

S. Nasri

INRGRGF, Route de la Soukra, B. P. No. 10 Ariana, Tunis, Tunisia.

Introduction

Three million hectares of soil in Tunisia are currently threatened by erosion; 1.5 million ha of these are seriously affected, with annual losses of approximately 10 000 ha of farming land.

The main goals of the national strategy for water and soil conservation (1990-2000) are the following:

- improving of farm production by maintaining soil fertility;
- reducing soil losses;
- replenishing groundwater tables;
- use water and soil conservation structures to mobilize some of the 500 million cubic meters of runoff water lost annually into the ocean and the sebkhas (salt lakes).

The program for erosion prevention adopted under this strategy provides for:

- The development of one million hectares of land:
  * 672 500 ha in drainage areas and sloping land;
  * 305 000 ha in cereal-growing areas.
- The construction of 1 000 hill reservoirs.

The work to be done on sloping grounds consists primarily of mechanical earthworks or contour ridges, dry-stone walls, reforestation, rangeland improvement, planting of grass strips, etc.

Contour ridges can be created on slopes with less than 25% with non-marly soil, where land division into small plots is not a problem. They consist of a channel ending in a mound or fold of earth. The function of this arrangement is to hold back runoff water so as to improve the water balance in the area of the ridge. Where the contour ridge system discharges into the outlet, the channel cross-section must be wide and flat, and it must be protected by perennial plants or by stones.

This study shows the impact of the establishment of contour ridges in the El Gouazine drainage area, located 15 km from the delegation of Ousseltia in the governorate of Kairouan, in central Tunisia. We studied the impact of these contour ridges on the water balance of the hillside reservoir and on slowing down runoff and replenishing the groundwater downstream from a constructed reservoir.
Experimental area

The El Gouazine drainage area is divided into two main sub-areas. One of these includes an Aleppo pine forest and garrigue of juniper and lentiscus; it occupies approximately 45% of the total drainage area. The second (55% of the total area) is occupied by farmland, planted chiefly with cereals and olive trees.

We may assume that most of the runoff water stored in the reservoir comes from the farmland, where the runoff coefficient is much higher than for the forest and rangeland. Table 1 shows characteristics of the El Gouazine drainage area, Table 2 characteristics of the reservoir, and Table 3 observed rainfall.

Between July 1996 and July 1997, contour ridges for total water retention was set up in the El Gouazine drainage area. It is of considerable size, with an average ridge length of 100 m, an average height of 1.5 m, and an average distance of 25 m between ridges. The system was set up primarily in farmland, and also partly in degraded range land, with a view to recover the soil for future farmland use.

With the construction of this system, rainfall on the drainage area is almost caught between these ridges, and the runoff water does not reach the main oued until ridges have been filled. As a result, the volume of water stored in the lake tended to decrease after construction of the contour ridges (Table 4).

Table 1. Characteristics of the El Gouazine drainage area.

<table>
<thead>
<tr>
<th>Area (A) in ha</th>
<th>1,810</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum altitude in m</td>
<td>575</td>
</tr>
<tr>
<td>Minimum altitude in m</td>
<td>376</td>
</tr>
<tr>
<td>Land occupancy</td>
<td></td>
</tr>
<tr>
<td>Farmland</td>
<td>55%</td>
</tr>
<tr>
<td>Forest and rangeland</td>
<td>45%</td>
</tr>
</tbody>
</table>

Table 2. Characteristics of the reservoir.

<table>
<thead>
<tr>
<th>Year of construction</th>
<th>1990</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume of the reservoir at discharge (Vi) in cubic meters</td>
<td>233,370</td>
</tr>
<tr>
<td>Surface area of the reservoir at discharge (Si) in ha</td>
<td>9.597</td>
</tr>
<tr>
<td>Vi/Si in m</td>
<td>2.43</td>
</tr>
<tr>
<td>Volume of silting (Ve) in m3</td>
<td>June 10, 97</td>
</tr>
<tr>
<td>Useful capacity (Vu) in m3</td>
<td>June 10, 97</td>
</tr>
<tr>
<td>Vu/Si in m</td>
<td>2.26</td>
</tr>
<tr>
<td>Ridge height in m</td>
<td>10.63</td>
</tr>
<tr>
<td>Spillway height in m</td>
<td>8.28</td>
</tr>
<tr>
<td>Water use</td>
<td>irrigation</td>
</tr>
</tbody>
</table>
Table 3. Observed rainfall in mm.

<table>
<thead>
<tr>
<th>Year</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>94/95</td>
<td>88.5</td>
<td>61.0</td>
<td>23.5</td>
<td>2.5</td>
<td>8.0</td>
<td>0.0</td>
<td>9.0</td>
<td>21.5</td>
<td>3.0</td>
<td>50.0</td>
<td>2.0</td>
<td>29.5</td>
<td>298.5</td>
</tr>
<tr>
<td>95/96</td>
<td>98.0</td>
<td>30.7</td>
<td>65.4</td>
<td>73.1</td>
<td>57.5</td>
<td>83.0</td>
<td>42.5</td>
<td>15.0</td>
<td>48.5</td>
<td>41.5</td>
<td>0.0</td>
<td>20.5</td>
<td>575.7</td>
</tr>
<tr>
<td>96/97</td>
<td>60.0</td>
<td>13.8</td>
<td>0.5</td>
<td>11.7</td>
<td>39.9</td>
<td>11.4</td>
<td>7.0</td>
<td>46.9</td>
<td>4.0</td>
<td>6.5</td>
<td>0.0</td>
<td>43.3</td>
<td>245.0</td>
</tr>
<tr>
<td>97/98</td>
<td>136.5</td>
<td>72.0</td>
<td>37.5</td>
<td>12.5</td>
<td>24.5</td>
<td>20.5</td>
<td>5.0</td>
<td>18.0</td>
<td>7.5</td>
<td>5.0</td>
<td>0.0</td>
<td>0.0</td>
<td>339.0</td>
</tr>
</tbody>
</table>

Table 4. Water balance of the El Gouazine hillside reservoir.

<table>
<thead>
<tr>
<th>Year</th>
<th>Initial Capacity (m³)</th>
<th>Rainfall (mm)</th>
<th>Mean Volume (m³)</th>
<th>Volume ΔV (m³)</th>
<th>Runoff (Vr m³)</th>
<th>Rainfall (Vp m³)</th>
<th>Evaporation (Ve) (m³)</th>
<th>Discharge (Vd) (m³)</th>
<th>Empyting (Vv) (m³)</th>
<th>Vecs+Vi-Vu (m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>94-95</td>
<td>233 370</td>
<td>298.5</td>
<td>96 800</td>
<td>50 900</td>
<td>236 310</td>
<td>16 637</td>
<td>93 145</td>
<td>92 660</td>
<td>38 000</td>
<td>-102 902</td>
</tr>
<tr>
<td>95-96</td>
<td>227 950</td>
<td>575.7</td>
<td>155 000</td>
<td>40 400</td>
<td>482 153</td>
<td>42 055</td>
<td>96 513</td>
<td>37 160</td>
<td>0</td>
<td>-273 435</td>
</tr>
<tr>
<td>96-97</td>
<td>217 340</td>
<td>245</td>
<td>30 700</td>
<td>71 300</td>
<td>35 439</td>
<td>7 020</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-76 599</td>
</tr>
</tbody>
</table>

Effects of contour ridges on hillside reservoir water balance

Mechanized earthworks for contour ridge construction in the El Gouazine drainage area covered a total area of 536.5 ha, and were carried out in three periods.

- The first period, from June 17 to July 27, 1996, concerned an area of 103 ha.
- The second, between August 23 and December 7, 1996, concerned an area of 202 ha.
- The third, between June 6 and July 29, 1997, concerned an area of 231.5 ha.

Figure 1 shows the variations in water level in the reservoir from June 1993 until October 1998. This figure also shows the status of construction of the drainage area contour ridge system, in linear meters. It may be noted that the maximum water level in the lake at the end of the 1994-95 hydrological year was 7.5 m. In September 1995 a single 66-mm rainfall occurring before ridge construction caused large-scale runoff that brought the water level from 5.0 m to the discharge level (> 8.28 m). After construction of the contour ridges, the lake was dry in July 1997 and mid-April 1998, and the water level in the reservoir was not higher than 5.5 m, with 3 m of sediment. Only the 79.4 mm rainfall on September 24, 1998 brought the level up to 7 m, representing a height of 4 m of water in the reservoir.
Figure 1. Variation in water level for the El Gouazine reservoir before and after construction of contour ridges in the drainage area.

Figures 2 and 3 compare the water balance for a year before the establishment of the ridges and one year after. Before that, the year 1994-95, in which average annual rainfall was 298.5 mm, generated a total annual water volume of 236,310 m³, which fell during four rainfall events. Following the contour works, during 1996-97, when average annual rainfall was 245 mm, only one contribution of 35,439 m³ was recorded. Similarly, for 1997-98, with annual average rainfall of 339 mm, only a limited volume of water reached the reservoir, as can be seen in Fig. 1 showing the variation of the water level in the lake between June 1993 and July 1998.
Figure 2. Change in hydrological balance depending on contour ridging.

Effects of contour ridges on reducing runoff

To get a better picture of the effect of these ridges on the water balance, we compared certain characteristics of flooding; height of rainfall, maximum intensity, maximum flow, etc, before and after their construction.
Figure 3. Flooding on September 20-25, 1995, before contour ridging.

Figure 4. Flooding on September 5-7, 1997, after contour ridging.
Figure 3 shows the flood that occurred on September 20-24, 1995, before development of the system, and Fig. 4 shows the flood of September 5-6, 1997, after the contour ridging. The rain of September 20-24, 1995 measured 66 mm, and very quickly caused runoff after a very short lag time of 35 minutes with a very high maximum runoff rate of 35 m³/s. This flood carried an extremely large quantity of water, 278,580 m³, which was sufficient to fill the lake and lead to discharge with a maximum flow of 5 m³/s.

The rain of September 5-6, 1997, measuring 66.5 mm, led to runoff after a very long 8-hour lag time, with a maximum runoff rate of 1.36 m³/s, much lower than in the preceding case. The volume of water generated by this flood, collected in the reservoir, was only 13,250 m³, 20 times less than that generated by the flood of September 20-24, 1995. It was also noted that during this flood the first two rain episodes were intercepted by the contours, despite the relatively great intensity of rainfall. It was the third rain, occurring after that the contours were filled up, that caused runoff. It can also be noted that the rain on September 7, 1997 caused runoff immediately, a fact which is explained by that the contour ridges were full of water.

Figure 5 shows the flood on October 3, 1994, before development of the system, and Fig. 6 shows the flood on October 2, 1997, after contour ridges. The rain of October 3, 1994, which lasted 30 min, very quickly caused runoff after a very short lag time of 20 minutes and a very high maximum runoff rate of 28.66 m³/s. This flood brought a very large quantity of water, totally 48,600 m³.

The rain of October 2, 1997, measuring 24.5 mm, very quickly caused runoff after a very short lag time of 25 min, and a relatively low maximum runoff rate of 5.16 m³/s. The quantity of water carried by this flood was only 22,800 m³, or 47% of the volume of the October 3, 1994 flood.

The hydrograph of the October 3, 1994 flood shows a gradual increase in the runoff rate and an equally gradual decrease in water recession. The hydrograph of the October 2, 1997, flood begins with a sudden increase, or peak, in runoff rate, which could be due to the fact that the first rainfall was trapped by the ridges and that once they were full, the soil was already nearly saturated, favoring runoff at the expense of infiltration. The hydrographs of the recessions shows the same characteristics in both cases.
Figure 5. Flooding on October 3, 1994, before contour ridging.

Figure 6. Flooding on October 2, 1997, after contour ridging.
Figure 7 shows the flood on September 13, 1995, before development of the contour ridges, and Fig. 8 shows that of September 21, 1997, after contour ridges. The rain of September 13, 1995, totally 13.5 mm, caused runoff after a very short lag time of 47 min, with a high maximum runoff rate of 10.66 m$^3$/s. This flood brought a very large quantity of water, totally 36,900 m$^3$.

The rain of September 21, 1997, measuring 13 mm, caused runoff after a relatively long lag time of 2 hrs 53 min, with a very low maximum runoff rate of 1.50 m$^3$/s. The quantity of water carried by this flood was only 6,200 m$^3$, or 17% of the volume of the September 13, 1995 flood.

It was also noted that the first rain on September 20, 1997 (7 mm) did not lead to runoff, despite its considerable intensity of 60 mm/hr. The rain of September 21, 1997 (6 mm), with a very low intensity of less than 10 mm/hr, caused a maximum runoff flow of 1.50 m$^3$/s. The first rain served to fill the ridges, which are positioned perpendicular to the direction of runoff. The hydrograph of this latter flood confirms the role played by the ridges, as runoff shows a sudden increase, taking the form of a peak in the flow curve as a function of time. On the other hand, the curve $Q = f(t)$ for the September 13, 1995 flood shows only a gradual increase.

All the floods recorded following installation of the contour ridges show this sudden peak at the beginning of runoff. The form of the curves of water recession is normal, and is similar to the curves of floods recorded before the intervention.
Total rainfall: 13,5 mm
Maximum intensity: 60 mm/h
Q max: 10,66
Volume: 36 900 m³
Lag time: 47 min

Figure 7. Flooding on September 13, 1995, before contour ridging.

Figure 8. Flooding on September 21, 1997, after contour ridging.
Effects of ridges on runoff

The contour ridges set up in the drainage area were intended for a total runoff retention, meaning that their longitudinal slope was nil. They are interrupted by 3- to 4-meter openings every 100 linear meters. Each ridge segment is 100 m long and has a channel cross-section of 2.28 m², giving a maximum retention of 228 m³. The total length involved in development of the contour ridges in this drainage area is 117,540 linear meters, corresponding to a maximum retention capacity of 257,640 m³.

If we adopt an average runoff coefficient of 30% for this land and an intake area of 1000 ha (55% of the drainage basin area), then it would require a rainfall of over 86 mm to fill these ridges and result in runoff. Occasionally, however, we have recorded the arrival of water in the reservoir several hours after the rain has ceased. This is undoubtedly due to underground flow of water trapped by the ridges. Table 3 gives an indication of the volume and the runoff coefficient for every rainfall recorded before and after mechanical contour ridge development in the drainage basin.

Before establishment of the contour ridges, the average runoff coefficient for the entire drainage area was less than 10% for rainfall heights of less than 20 mm, and between 20 and 30% for heights over 20 mm. We note that the runoff coefficients are highest for the autumn rains (September-October). During this period, rainfall is characterized by very high intensity and the ground, not yet covered, has a crust in places. Similarly, between the months of December and May rainfall heights of over 20 mm were recorded, with very low runoff coefficients of less than 8%. These are very fine rains lasting a number of hours.

Following the construction of ridges, the rains recorded caused no runoff and the drainage area showed a runoff coefficient of zero. Only the rains of September 9, 1996, measuring 50.5 mm, and August 18, 1997, 32 mm, caused runoff, but it was insignificant, with a runoff coefficient of less than 3%. The water represented by these weak runoffs might be due to underground flow.

The rainfall recorded between September 20 and 24, 1998 had a total volume of 90.4 mm, 79.4 mm of which fell in a period of only 3 hours and 45 minutes during the night of September 24, with a maximum intensity of 120 mm/hr and an average intensity of over 60 mm/hr for approximately 2 hours. This rain generated a total contribution of some 127,000 m³, with a maximum runoff rate of approximately 23.39 m³/sec, but runoff did not start until after a relatively long lag time of around 1 hr 40 min. This flood would seem to confirm the hypothesis we formulated above, that runoff will not be substantial until rainfall exceeds 86 mm. Awaiting new recordings to confirm this hypothesis, we can deduce that the ridges reduced the water flowing into the El Gouazine reservoir to a remarkable degree. Figure 9 gives a comparison of the flood of September 20-21, 1995, before creation of the contour ridges in the drainage area, and that of September 24, 1998, following it.
Table 5. Flood characteristics.

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Effects of contour ridges on groundwater recharge

Downstream the El Gouazine reservoir are two groundwater wells located approximately 400 m and 700 m from the lake, respectively, that are used to irrigate plots devoted to orchard culture and truck farming. Following construction of the lake in 1990, the farmers in the region noted that the water level in the first well, had risen more than 10 m. This encouraged a neighbor to dig the second well, which reached the groundwater table only a few (3 to 4) meters from the ground surface. As a result, orchard, vegetable, and fruit cultivation developed around the wells very quickly, and there are now over 10 ha of irrigated plots there.

However, following the development of a very dense network of ridges in the drainage area, less and less water began flowing into the reservoir, and it dried out very early, in April or May, at the time of preparation for summer vegetable and fruit crops. The farmers therefore became anxious when they noted that the replenishment of their wells was decreasing daily, after every pumping.

Figure 10 gives an accurate picture of their observations. It is quite clear that the water in the wells remains nearly constant, returning to its initial level following every pumping, so long as there is water in the lake. But starting in March there is a distinct decrease in the piezometric level in both wells. In October 1997 the water level in the first well lay at a depth of 3.38 m, and that in the second well was at a depth of 2.29 m. In July 1998, the water levels were at 5.18 m and at 4 m, respectively, having decreased by some 2 m for the first well and 1.7 m for the second.

Adopting a pessimistic approach supposing that runoff water no longer reaches the lake and that direct groundwater replenishment by rain is negligible, then the rate of piezometric drop in the two wells means that the second, which is 6 m deep, will go dry in November 1998, and the first, with a depth of 20 m, will go dry in August 2005, after a 1-meter drop in the water level every six months. However, farmers will no longer be able to pump from it as of November 2000, as can be seen in table 7, since the pump strum is situated at a depth of only 8.5 m.
Figure 9. Flood on September 20-24, 1995, before contour ridges.

Figure 10. Flood on September 24, 1998, after contour ridges.
Figure 11. El Gouazine reservoir water level and groundwater level in two wells.

Conclusion

To summarize, the contour ridges constructed in the El Gouazine drainage area play a very important role, intercepting runoff and favoring infiltration. In addition, contour ridges help reducing the amount of sediment accumulating in the lake. They can, on the other hand, have undesirable consequences for the farmers downstream from the hillside reservoir, when the reservoir is used for irrigation and replenishment of groundwater.

Thus a solution should be identified which protects agricultural land upstream on the slopes and which at the same time ensures a minimum volume of reservoir filling to safeguard irrigated crops downstream. Such a solution might be to reduce either the area involved in the contour ridge system or the size of the ridges (their height and the distance between them). Clearly, the contour ridges in the El Gouazine drainage area will not be destroyed or rebuilt, but this area can serve as an example to use in planning other development programs under similar conditions.
Rain water harvesting and management of small reservoirs in arid and semiarid areas

Lund University, Sweden, 29 June – 2 July, 1998

Deterministic versus stochastic hydrological modeling; uncertainties and decisions

Mr. Jan Høybye

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Deterministic versus stochastic hydrological modelling, uncertainties and decisions

J. Høybye

Department of Water Resources Engineering, Lund University, S-221 00 Lund, Sweden.

Abstract

Research on stochastic analysis in hydrology has developed rapidly in the last decades, but applications of this approach have been limited. The purpose of this presentation/paper is to illustrate how currently available techniques and results can be used to answer important questions about uncertainties in hydrological modelling and water management. Examples from both water quality models and rainfall-runoff modelling/flood estimation are used to discuss predictive reliability and adequacy of system analysis prior to data collection. The stochastic modelling approach, mainly based on the theory of stochastic linear systems, can be evaluated through comparisons with different methods of analysis (analytical, first-order, Monte Carlo simulations, random variables and random processes). Simple models for estimation of predictive uncertainty and the influence from data and parameter uncertainties are presented.

Introduction

Integrated water management has developed into a complex task as a result of the contrasting demands made by competing groups of water users, especially in arid and semiarid areas, where the water scarcity is prominent. To obtain realistic and economically feasible solutions for the increasing problems, water-planning organisations need to include and synthesise information from many fields such as water resources, water quality/ecology, agriculture, water supply, flood protection, urban planning, and health. Due to the conflicting interests of these fields, the feasibility of an increasingly large set of scenarios has to be examined and the differences in their effects have to be quantified, for example, in intra-basin agreements or with environmental impact assessment (EIA) procedures. This is mostly achieved by using various models which simulate the phenomena implied by the scenarios.

Consequently, the pure numerical results of one or more hydrologic model simulations are no longer the final products delivered by water resources planners. Instead, results have to be translated systematically into hydrological causes and effects and subsequently into socially and economic relevant quantities. Due to the growing complexity of hydrological issues, additional data from different fields of expertise and different sources must be taken into consideration. Furthermore, new data acquisition methods (e.g., remote sensing, continuous water quality measurements) enter common usage in hydrology and raise the demand for data (e.g., for pesticides, water quality parameters and indicators in lakes and groundwater). These factors all result in a considerable increase in the data volumes involved in the modelling process.
In hydrological models for water resources management and planning, the model output or design quantities are functions of the input data and a number of parameters that are essentially stochastic processes or random variables. The task of uncertainty analysis is to estimate the uncertainty characteristics of the model output in terms of the uncertainties in the input, model parameters and initial conditions. Uncertainty analysis provides a formal and systematic framework to quantify those uncertainties. Furthermore, it offers the hydrologist a valuable insight regarding the contribution of each random component to the overall uncertainty of the model output. Such knowledge is essential to identify the parameters and input variables that most need attention in order to better assess their values and, accordingly, to increase the overall model reliability (Hoybye, 1998).

**Background**

The development and application of simulation models in hydrology and water resources have expanded greatly over the last decades. Such models are used in, for example, flood and drought analyses, groundwater simulation, design of irrigation systems and water quality assessments. In the future, models will be applied to a greater and greater extent for assessments, planning and decision-makings.

As an illustrative example of how uncertainties influence decisions, take a commonly used simple water quality model. This is a standard model used to predict the steady-state phosphorus concentration in lakes, and subsequently, to evaluate different catchment restoration plans and load reduction activities (Sas, 1989; Danish Environmental Protection Agency, 1978). The lake phosphorus model is a two-compartment model, one for water and one for sediment (Figure 1).

\[ L_i = Q_i C_i \quad \quad L_o = Q_o C_w \]

Figure 1. Simple water quality model diagram showing the input variables and model parameters.
The sedimentation and release mechanisms are modelled as first-order processes related to the surface area, $A$, and to the phosphorus concentrations in the water phase and sediment phase respectively. The two coupled differential equations describing the mass continuity of the system are

$$\frac{dM_w}{dt} = \sum L_i - L_o - S + R \quad \text{and} \quad \frac{dM_s}{dt} = S - R - F$$

where $M_w$ is mass of phosphorus in the water phase ($= V_w C_w$), $M_s$ is mass of phosphorus in the sediment phase ($= V_s C_s$), $\sum L_i$ is the total transport of phosphorus into the lake ($= \sum Q_i C_i$), $L_o$ is the advective transport out of the system ($= Q_o C_w$), $S$ is sedimentation ($= k_s A C_w$), $R$ is sediment release ($= k_r A C_s$), and $F$ is permanent confinement in the sediment ($= k_p S$).

The example is of a lake which has been subject to eutrophication caused by pollution from agriculture and urban development over the past thirty years. It was decided by the regional water authority to make a plan for the recovery of the lake, identify the key sources of pollution and evaluate different restoration techniques. Some chemical analysis and discharge measurements in the major tributary to the lake were available, however, the data are scarce with only 14 observations during a period of two years. From these data the average external phosphorus load into the lake was calculated to be 1230 kg phosphorus per year using a simple and highly uncertain but standard transport load model (trapeze integration of transport), see Fig. 2.

Based on the available data, the water quality model described above was calibrated, but not validated due to the short measurement period. The water quality model was run on a daily basis simulating the phosphorus concentration in the lake and sediment according to different scenarios. Finally, predictions projected 20 years into the future were compared to expected limits of maximum acceptable concentrations in the lake and sediment. The results of the analysis suggested that a combination of external load reduction and biological manipulation would give the greatest effect. The total investment would be around 2 million US$. Most of the funds would be allocated to the construction of sedimentation basins, improvement of an existing waste water treatment plant and the construction of sewer systems for farm houses in certain parts of the catchment. This represents a major investment for a relatively small community - an investment based entirely on the output of non-validated model with highly uncertain input data and virtually unknown initial concentrations in the sediment.

In fact there was no change at all in the lake after restoration. A re-examination of the chemical analysis of the river inflow and a re-calculation of the transport load using a better transport load model (linear interpolation of concentration) resulted in an alternative and more reliable estimate of the external phosphorus load of 500 kg/year. This load was less than half of the amount previously computed, and equal to the acceptable level expected after successful restoration of the lake. The eutrophication persisted due to the internal phosphorus storage of the lake. The water authority concluded that the net sedimentation rate was positive and substantial on the basis of the initially (wrong) high input load estimate. This belief influenced the
Figure 2. Illustration of two different methods for computing transport load in rivers from discrete water quality analyses. The simplest and most uncertain method (trapeze integration of transport) calculates transport from isolated chemical analyses and discharge measurements and interpolates the transport load between measurements. The better and more reliable method (linear interpolation of concentration) interpolates the concentration linearly between measurements and multiplies it with daily discharge values to obtain the daily transport load.

calibration of the model parameters, which in turn did not reflect the actual mechanisms of transport and exchange between water and sediment. Running the model, therefore, yielded results substantially different to the natural situation, so the entire project failed its main objective. One could argue that mistakes are of minor importance if the investment is low or the impacts from poorly made decisions are insignificant - provided that the conclusions not are used in other projects. However, when investments or societal impacts are great, it is of vital importance to understand the significance of the errors inherent in data and models. The central water authorities have claimed that any activity which decreases environmental pollution is a step towards the right direction. However, this viewpoint has increased the risk of mis-allocating resources on the basis of mechanisms distorted by uncertainties to (often politically motivated) projects which have limited effects on major pollution sources.
Another example is flood frequency analysis and rainfall-runoff modelling, these are treated in the last three appended papers. Rainfall-runoff models have historically been refined through better representation of physical processes occurring in watersheds. Hydrological quantities computed from mathematical expressions of physical laws tend to convey preciseness. Many users overlook the fact that unrepresentative sampling and imperfect measurements are inherent in any data collection process, particularly processes such as precipitation which are highly variable in time and space. Indeed, one is forced to take precipitation over a few square decimetres as representative of many square kilometres. Furthermore, modelling economy requires approximating simplifications which omit high order interactions over time and space and express spatially varying watershed characteristics as lumped parameters. Even the most recent developments in distributed physically-based models are extreme simplifications of reality. Calibration is still hampered by interdependence of parameters, criteria issues and short data series.

The data in Table 2 illustrates the problems inherent in prediction of, say, the flood peak flow with a return period of 500 years. The table compares the project design value based on approximately 15 years of data, to five different methods for peak flow frequency estimation having data from 1951 to 1987.

Table 1. Example from reservoir design in the Hongru River Basin, China. The design runoff measured in mm represents the 500 year return period. After Lund University (1997).

<table>
<thead>
<tr>
<th>Method of analysis</th>
<th>Design runoff</th>
</tr>
</thead>
<tbody>
<tr>
<td>Project design</td>
<td>270</td>
</tr>
<tr>
<td>EVD (1951-87 including the 1975 event)</td>
<td></td>
</tr>
<tr>
<td>General Extreme Value distribution</td>
<td>933</td>
</tr>
<tr>
<td>Pearson type III distribution</td>
<td>311</td>
</tr>
<tr>
<td>EVD (1951-52 and 1976-87)</td>
<td></td>
</tr>
<tr>
<td>General Extreme Value distribution</td>
<td>465</td>
</tr>
<tr>
<td>Pearson type III distribution</td>
<td>331</td>
</tr>
<tr>
<td>Partial Duration Series method</td>
<td>244</td>
</tr>
<tr>
<td>Regional estimation</td>
<td></td>
</tr>
<tr>
<td>GEV</td>
<td>207</td>
</tr>
<tr>
<td>Direct</td>
<td>706</td>
</tr>
<tr>
<td>Design rainfall/Rainfall-Runoff model</td>
<td>259</td>
</tr>
<tr>
<td>Observed extreme peak flow in 1975</td>
<td>455</td>
</tr>
</tbody>
</table>
It is clear that it is difficult to talk about a single value for the 500-year event. The five methods give estimates between 207 mm and 933 mm. The original design value was 270 mm which lies in the low end of the range. In August 1975, an extraordinary rainstorm hit the catchment and the peak runoff was recorded to 455 mm. The average of the seven 500 year estimates equals the observed peak flow during the storm which, however, is significantly above the original design peak flow. As a result, the dam was overtopped and totally destroyed, and the basin experienced a severe flood.

The considerable uncertainty in the extreme flow estimates suggests an extended analysis using physically-based models as well as proper methods for uncertainty and estimate reliability assessments, especially when the consequences of an erroneous design are so devastating as in the case presented here.

Sources of uncertainty

Uncertainty is the term applied to the condition of having incomplete knowledge about an effect or situation. All assessments or decisions, therefore, are made with varying degrees of uncertainty. In hydrology, the sources of uncertainty are traditionally regarded as threefold (O'Connell, 1986):

1. **Model uncertainty.** As the true state of nature is unknown, a model is an imperfect representation of reality. With a purely stochastic modelling approach, the governing probability law is unknown, and only inferences can be made about its form based on the limited sample information available. In the case of the physically descriptive approach, model uncertainty arises due to the fact that the governing laws, while known at the microscale, are not known precisely at the model grid scale. The model, itself, is a simplified representation of the system of interest, and there is uncertainty associated with both process formulations and interactions and whether all the important processes are incorporated into the model structure. In a mathematical model, for example, a decay relationship can be zero, first or second order, inverse or exponential. If the specific nature of the functional relationship is not known, incorrect assumptions about the nature of the decay relationship could be made when constructing the model.

2. **Parameter uncertainty.** Parameter uncertainty is attributable to the limited sample information available in space, time or both, depending on the sample space over which the model parameters are defined. For a stochastic approach, even if the form of the true model were known, sampling error in the parameter estimates will result. For the physically descriptive approach, parameter uncertainty will result from the interpolation of the model parameters on to the model grid square based on the limited sample information.

3. **Measurement error.** Arises from an inability to measure, without error, model inputs, outputs, or the variables from which the model parameters have to be estimated. For example, during extreme floods, river flows can only be measured approximately, while rainfall cannot be measured accurately over space.
A broader classification of sources of uncertainty includes the entire process of decision-making and comprises six stages ERL (1984). First, the scoping process involves deciding how to describe an effect and, therefore, on what to predict. The second stage, baseline studies, requires the collection of data about the activity in question and the environment in an ample sense. Thirdly, a method for obtaining the prediction, for example, with hydrological models, must be selected or developed. Fourthly, the method or model must be prepared for use, typically, by calibration and validation. The fifth stage involves the application of the model to produce the required prediction. Finally, the results of the analysis must be presented to the decision-maker. Uncertainty can be introduced at each of these stages.

Methods of uncertainty analysis

Once it is conceded that uncertainty is an unavoidable and inherent ingredient of every prediction, the question naturally arises as to whether management of the uncertainty is possible. In other words, can uncertainty be reduced to a level which is acceptable from the decision maker’s standpoint? Clearly, defining the limit of acceptability is part of any water resources assessment involving significant impacts or investments, and it is a natural part of identification and verification of processes in hydrological science. Research on stochastic analysis in hydrology has developed rapidly in the last decades, but applications of this approach have been limited.

Two methods in particular have been developed to find the most cost-effective way of improving accuracy in data collection and analysing error structures in hydrological models. These are sensitivity analysis and Monte Carlo simulations. Sensitivity analysis is a technique for identifying the parameter or variables within a model, which are most sensitive to change. Some limitations, however, restrict the use of this approach. Only small changes in an input value can be handled, with the exception of linear models. Yen (1986) and Ditlevsen (1981) are useful references on the use of sensitivity analysis or second-moment representations in hydraulic and civil engineering.

Monte Carlo error analysis is another way of treating the problem of uncertainty, especially for models based on (partial) differential equations, whereby the deterministic model is run several times using different realisations of the parameter field (e.g., Burges and Lettenmaier 1975; Beven 1993). Finally, statistical analyses are made of the results from all the deterministic simulation runs. The advantage of this approach is that the deterministic model can be preserved, whereas the main disadvantage is the very large CPU requirement. The Monte Carlo method in stochastic (partial) differential equations (SDE) corresponds to the deterministic approach of numerical solutions for the fundamental equations for a set of initial and boundary conditions. Classical examples of this approach are provided by Smith and Freeze (1979a,b) and Freeze (1980) for groundwater flow and rainfall-runoff processes, respectively. Another approach is to simplify the partial SDE and solve it analytically. This is usually much more difficult than solving ordinary SDE’s, but the analytical approach has proven very useful for obtaining general insight into fundamental research problems.
It is obvious that each of the methods involves approximations that may limit the applicability of the method to a given situation. The selection of methods will also depend on the type of problem and the kind of results that are sought. For example, analytical procedures often have the advantage that they produce generic analytical expressions that illustrate the dependence on several variables; however, analytical approaches can usually be applied only to relatively simple configurations, and may not easily be adapted to site-specific conditions. The numerically based techniques have the advantage that they can incorporate complicated boundary configurations and the influence of boundary conditions for site-specific situations. A drawback is that they often provide little general insight, because each condition involves a separate simulation and, therefore, a very large number of simulations may be required to understand and identify dependence on various input parameters.

Analytical models also have the advantage that they permit a general theoretical development without specifying an explicit form of the input covariance function. In most numerical analyses, the explicit form of the input covariance function must be specified. An important advantage of analytical solutions is that the assumptions and approximations are clearly evident from the precise mathematical statement of the problem. Analytical solutions also have the advantage that the results are readily accessible to all users. In contrast, numerical results are often quite inaccessible because of the personalised nature of much of the coding, the problems of adapting codes to other computer systems, and the proprietary nature of many codes; also, though in principle, numerical techniques apply to very general situations, in reality, a very substantial amount of time-consuming effort may be required to treat situations other than those for which the code was originally developed. It is seldom possible to find exact solutions to the stochastic differential equations involved in hydrological problems, so it is usually necessary to develop intercomparisons between several different methods in order to understand their capabilities.

It should be recognised that a number of different modelling approaches might be appropriate, depending on the purpose and ultimate use of the anticipated results. Some investigations focus on general scientific understanding of a phenomenon, whereas others emphasise the need to make practical decisions about a specific site. The selection of an approach depends on the kind of data that is either available or can be reasonably expected to be collected, and on the kind of applied problem that is being addressed. Clearly, no single approach will be suited to all the questions or problems that may arise.

A number of available approaches for reducing uncertainty in prediction are summarised in ERL (1985). Tables 2 and 3 give an overview of the different approaches and indicate the way models can be developed with the aim of reducing uncertainty. The hydrological phenomena usually applied in water resources planning make use of a number of different approaches, however, analytical approaches should be preferred because they provide a general basic understanding of the error propagation structures of different models.
Table 2. Objectives and description of techniques for handling uncertainty in input data.

<table>
<thead>
<tr>
<th>Technique</th>
<th>Objective</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Handling uncertainty in measurement and analysis</td>
<td>To select measurements and analytical methods to achieve a required level of accuracy in terms of bias and imprecision of data. These data may subsequently be used for prediction or other purposes.</td>
<td>All methods of measurement and analysis are subject to bias and imprecision which together contribute to total error. The selection of a method must reflect the need for accuracy; it is important for the data user to have some knowledge and understanding of the bias and imprecision in data.</td>
</tr>
<tr>
<td>Sampling programme design</td>
<td>To obtain information describing a system, with a required level of detail and accuracy by designing an appropriate sampling programme in terms of size, frequency, location and randomness of sampling.</td>
<td>The results from sampling are used to make inferences about the whole system; these are subject to uncertainty. Detail and accuracy are related to sample size and the frequency, location and randomness of sampling in relationship to the system characteristics and the measurement objectives. Various statistical techniques can be used to assist in sampling design.</td>
</tr>
<tr>
<td>Sensitivity analysis</td>
<td>To identify those inputs that contribute most to uncertainty in prediction and so allocate priorities for further effort to improve the accuracy of predictions. Inputs can be ranked according to their priority for further research to improve the accuracy of predictions.</td>
<td>Inputs are ranked according to the partial derivatives of the model equation or model system. Inputs with the highest sensitivity coefficient have the greatest influence of uncertainty in predictions. The sensitivity coefficient of each input and the cost of improving the accuracy of each, are considered in assigning priorities for decisions or research effort. Sensitivity analysis is, however, subject to certain key assumptions which, if violated, may lead to ambiguous results.</td>
</tr>
<tr>
<td>Monte Carlo error analysis</td>
<td>Same as sensitivity analysis</td>
<td>Inputs are ranked according to their correlation coefficient from the mean of the model output/input ratio over many repeated probabilistic simulations (Monte Carlo simulation). Inputs with the highest correlation coefficient have the greatest influence on uncertainty in predictions. Monte Carlo simulation is not subject to some of the constraining assumptions of sensitivity analysis but the mathematics/statistics are more complex.</td>
</tr>
</tbody>
</table>
Table 3. Objectives and description of techniques for handling uncertainty in prediction.

<table>
<thead>
<tr>
<th>Technique</th>
<th>Objective</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario approach</td>
<td>To predict a range of possible outcomes (maximum, minimum, typical) taking into account input uncertainty (variables and parameters).</td>
<td>Values of uncertain inputs (e.g., worst and best cases) are selected, which give rise to the specified outcomes. These are modelled deterministically to indicate the range of outcomes.</td>
</tr>
<tr>
<td>Monte Carlo simulation</td>
<td>To predict the probability distribution of possible outcomes taking into account input uncertainty.</td>
<td>Probability density functions ( (pdf's) ) are specified for uncertain input and parameters (and correlation between inputs if appropriate); a large number of input sets are randomly selected and each is used to make a deterministic prediction. The results can then be plotted to give a ( pdf ) of model predictions. Computation becomes very complex with correlated input.</td>
</tr>
<tr>
<td>First-order analysis - propagation of errors</td>
<td>To predict the uncertainty, i.e. the mean and variance of the outcome taking into account the mean and variance of uncertain inputs and parameters.</td>
<td>The means and variances of inputs are propagated through the model to give the mean and variance of the prediction. The method is analytical (or numerical in derivation of derivatives) in contrast to the entirely probabilistic approach of Monte Carlo simulation. The applicability of the approach is constrained by certain key assumptions, notably approximate linearity often not met in hydrological and environmental models.</td>
</tr>
<tr>
<td>Analytical approach (distribution convolution)</td>
<td>To obtain an analytical derivation of output ( pdf ) or moments based on ( pdf's ) or moments of inputs and parameters.</td>
<td>Transformation of distribution functions for deterministic relations. For general functional relationships (differential and integral equations) analytical solutions in the form of ( pdf's ) or moments can be found only for simple problems and boundary conditions.</td>
</tr>
<tr>
<td>'Delphic monkeys'</td>
<td>To elicit expert opinion on the system context and the uncertainty associated with data and model simulations in the form of ( pdf's ).</td>
<td>Interactive interview techniques are available to extract probability estimates and evaluate the impact on predictions. Methods for dealing with conflicting expert opinions have also been developed.</td>
</tr>
</tbody>
</table>
Methods for performing uncertainty analysis vary in different levels of sophistication and dependent on the actual problem. They are also dictated by the information available regarding the stochastic model parameters and input data. In principle, it would be most ideal to derive the exact probability distribution of the model output as function of those of the random model parameters and input processes. However, most of the models or design procedures used in hydrologic and environmental projects/analyses are highly complex and often non-linear. This basically prohibits any attempt to derive the probability distribution of model output analytically. Therefore, one has to resolve to approximations in most practical cases. These approximations can either reduce the model complexity or change the problem to a linear one or both at the same time.

Stochastic differential equations – an example of uncertainty modelling

The random dynamic systems often met in natural and geophysical sciences are described by random or stochastic differential equations. Ordinary differential equations are fundamental components in most hydrological models, either as a model in itself (e.g., water balance models) or as an element in more complex models (e.g., finite difference models based on mass, momentum and/or energy conservation). For this reason, the study of the error propagation characteristics of stochastic differential equations is of vital importance, including analysis of the influence of uncertain initial conditions, input and parameters.

To illustrate the error propagation characteristics of dynamic models, consider the simple stochastic first-order differential equation, which is a very common model or model component in hydrological and environmental models

\[
\frac{dX}{dt} = -\beta X(t) + Y(t) \tag{1}
\]

Assume first that the model coefficient \(\beta\) is a deterministic constant. In this case, the steady-state solution process covariance is governed entirely by the covariance function of the input function \(Y(t)\). In fact, although the problem of random differential equations at first sight appears to be complex, the solutions are nice and simple. Table 4 and Figure 3 illustrate the solution processes for three common input covariance functions for the simplest case where the model parameter is regarded as deterministic.
Table 4. Variance of the solution process $X$ of the first-order differential equation with deterministic parameter $\beta$ as a function of the input function covariance structure.

<table>
<thead>
<tr>
<th>Process</th>
<th>Input process autocovariance</th>
<th>Variance of solution process</th>
</tr>
</thead>
<tbody>
<tr>
<td>White noise</td>
<td>$c_w(k) = q_x \delta(k)$</td>
<td>$\sigma_x^2 = c_w(0) = q_x / 2\beta$</td>
</tr>
<tr>
<td>Markov</td>
<td>$c_M(k) = q_x \exp(-\alpha k)$</td>
<td>$\sigma_x^2 = c_M(0) = q_x / (\alpha + \beta)$</td>
</tr>
<tr>
<td>Random bias</td>
<td>$c_R(k) = q_x \delta(k)$</td>
<td>$\sigma_x^2 = c_R(0) = q_x / \beta^2$</td>
</tr>
</tbody>
</table>

The variance of the solution process depends on the input variance and the model coefficient and in the Markov case also on the input process autocorrelation coefficient. When the input process is a white-noise process, the variance of the solution process takes its minimum value, whereas the random bias covariance function makes the solution process variance its maximum.

![Solution process variance of a first-order random differential equation as a function of the model coefficient. The coefficient is assumed to be deterministic. The input covariance function used in the figure has the parameters: $q_y = 1$ and $\alpha = 0.5$.](image)

Figure 3. Solution process variance of a first-order random differential equation as a function of the model coefficient. The coefficient is assumed to be deterministic. The input covariance function used in the figure has the parameters: $q_y = 1$ and $\alpha = 0.5$.

If the input process is autocorrelated, then the magnitude of the solution variance will lie somewhere in the interval between that of the white noise process and the random bias process, depending on the correlation scale of the input process, $\alpha$. This is illustrated in Fig. 4 where the solution process variance is shown for three different input correlation scales. For small $\alpha$ (input correlation scale), the solution variance approaches that of the Markov input covariance, and for large $\alpha$-values it approaches the random bias case.
The error propagation property of the linear first-order differential equation is determined from
the model parameter \( \beta \) and the correlation scale \( \alpha \). For small values of \( \alpha \), that is, approximate
white-noise input processes, the input variance will be reduced for \( \beta \) values larger than 0.5,
whereas lower \( \beta \)-values imply an amplification of the input error. Thus, the solution process
variance is larger than that of the input process. The neutral limit is \( \beta = 1 \) for random bias
processes. In conclusion, the uncertainty in correlated input processes is expected to be amplified
for \( \beta \)-values less than 0.5 and reduced for \( \beta \)-values larger than 1.

Figure 4. Solution process variance for three different input correlation scales. The input variance
\( q_r = 1 \), which implies that the curves represent the error amplification ratio.

If the model coefficient, however, is random, either a random process or a random variable, then
the solution process variance naturally is increased, see Fig. 5. The two curves ('random variable'
and 'stochastic process') shown in the figure describe the effect of added variance due to the
uncertain parameter compared to the deterministic parameter white noise curve which is the same
as in Figs. 3 and 4. The importance of the choice of how to model the system parameter \( \beta \) is only
significant for parameter values less than 0.5. In other cases, the effect is only of minor
importance.

In general, the variance equation for the solution process of a linear stochastic differential
equation can be expressed as:

\[
\sigma_x^2 = \frac{1}{2\beta} \left( q_y + g(X)q_\beta \right)
\]  

\( (2) \)
where it is assumed that the input process $Y$ is a white-noise process ($q_y = 2\sigma_{\lambda y}^2$). The function $g(X)$ depends on how the parameter $\beta$ is modelled and is shown in Table 5. If $\beta$ can be considered to be deterministic, the parameter variance contribution, naturally, is zero and only the uncertain input process influences the output variance.

Table 5. Effect of added variance due to parameter uncertainty in first-order differential equations. The input process is taken to be a white-noise process.

<table>
<thead>
<tr>
<th>Equation parameter model</th>
<th>Effective model parameter</th>
<th>Function $g(X)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deterministic</td>
<td>$\beta$</td>
<td>0</td>
</tr>
<tr>
<td>Random variable</td>
<td>$\beta - q_\beta / \beta = \beta(1 - CV^2_\beta)$</td>
<td>$2X^2 / \beta$</td>
</tr>
<tr>
<td>Random process</td>
<td>$\beta - q_\beta / 2$</td>
<td>$X^2$</td>
</tr>
</tbody>
</table>

The effective model parameter in Table 5 reflects the inherent bias in the determination of random parameters in models based on ordinary differential equations. In other words, the randomness in the estimate of the parameter is manifest by a reduction below its mean value. Consequently, the random differential equation can be regarded as an equation with only random input if the effective parameter is substituted for the originally random parameter.

Figure 5. Steady-state solution process variance for the random parameter case. Data used in the graph is: $X_{\alpha} = Y / \beta$ where $Y = 0.25$, $Var\{\beta\} = 0.09$, and $Var\{Y\} = 1$. The curve for the deterministic parameter situation corresponds to the white-noise curve in Fig. 3.

The error propagation is illustrated by the following analysis of the steady-state component of a stochastic differential equation. Based on the results in Table 5, the solution process variance
for the steady-state case can be normalised by dividing the variance by the steady-state level $X_{ss}$, hence obtaining the coefficient of variation

$$CV_x = \frac{\sigma_x^2}{X_{ss}^2} = \frac{Y}{\beta} \frac{CV_y^2}{2 \beta X_{ss}^2} = \frac{\beta}{2} \left( CV_y^2 + CV_{\beta}^2 \right)$$

(3)

where $X_{ss} = Y/\beta$, $q_y = CV_y^2 Y^2$ and $q_{\beta} = CV_{\beta}^2 \beta^2$.

Figure 6. Error propagation factor $\phi$ for the first-order stochastic differential equation.

The parameter $\beta$ is in the above case modelled as a random process. Dividing by the squared coefficient of variation of the input process and taking the square root, the error propagation factor $\phi$ is defined as

$$\phi = \frac{CV_x}{CV_y} = \frac{\beta}{2} \left( 1 + \frac{CV_{\beta}^2}{CV_y^2} \right) = \frac{\beta}{2} \left( 1 + c^2 \right); \quad CV_y > 0$$

(4)

where $c$ is the ratio between parameter and input $CV$'s squared. This important, yet very simple result, relating relative input and output uncertainties of linear systems, is shown graphically in Fig. 6 for different parameter-input process uncertainty ratio's. This simple relationship is fundamental in linear random systems, and can be used as an indicator of how much input errors will be amplified or reduced in a general linear system.
General conclusion

At first sight, stochastic modelling and especially stochastic differential equations describing dynamic systems present a complex problem, and it is true that the development of solution processes is intricate. The solutions to simplified but relevant situations and assumptions, however, are on surprisingly simple forms. Thus the principal conclusion of the paper is that the stochastic approach in hydrological modelling adds complexity to the analysis and application of model simulations, but simple and useful results can be obtained to estimate the variance of functional relationships and stochastic differential equations.

Even though the problems presented in this paper can be complex, there appears to be three areas of potential benefits. These are the following:

Decision problems. As was explained earlier, current procedures that use the model with expected values do not yield the correct output values on the basis of the expectation of the model. Furthermore, since neither input data nor model parameters are deterministic properties, errors will be a propagated into the model output. The bias and inaccuracy implied by uncertain input and parameters will affect the decisions and account for misinterpretations.

Building simulation models. As hydrological models become larger and more complex, the information surrounding parameter values often decreases. The increased uncertainty in the model output should be analysed. Conceptually, there is a trade-off between a complex model with many hard to measure parameters and simple hydrologic models. Uncertain data in turn complicates the identification or refinement of model processes, and introduces a risk for the inclusion of minor processes or exclusion of important processes.

Data collection and value of information. An analysis of the type to be proposed here can indicate how input uncertainty and different parameter values affects the uncertainty in model outputs. Consequently, when collecting data, more effort can be put into those input variables and parameters that reduce uncertainty in the model output the most.

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Rain water harvesting and management of small reservoirs in arid and semiarid areas

Lund University, Sweden, 29 June – 2 July, 1998

Neural network methodology to simulate discharge

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Neural network methodology to simulate discharge

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Abstract

The observed annual variability in precipitation and water availability in the Amazonia, located in northeastern South America, has been shown to be influenced by sea surface temperature (SST). However, the links between the large-scale SST patterns and local and regional runoff patterns are essentially complex and still not fully understood. The processes involved are believed to be highly nonlinear, spatially and temporally variable and not easily described by simple deterministic models. Artificial Neural Networks were used to develop models to forecast discharge one or two seasons in advance at 10 sites in Northeastern South America from Pacific and Atlantic sea surface temperature (SST) anomalies. Results were very encouraging. The correlation coefficient between observed and estimated discharges reached values as high as 0.96.

Introduction

During recent decades the study of coupling processes between atmospheric and hydrological scales has become increasingly important (e.g., Eagleson, 1986). This has lead to great advances in the understanding and modeling of regional and global scale hydrology (e.g., Brubaker et al., 1993; 1994). The links between large-scale atmospheric motion and local and regional runoff patterns are, however, extremely complex and still not fully understood. The processes involved are believed to be highly nonlinear, spatially and temporally variable and not easily described by simple deterministic models (e.g., Hsu et al., 1995). The Amazon Basin is the largest river on Earth and it holds about one sixth of the global river water (Dickinson, 1987). About half of the 2-3 m annual rainfall is recycled by evapotranspiration while the rest discharges into the Atlantic Ocean (Molion, 1975; Salati and Marques, 1984; Junk and Furch, 1985; Salati, 1986). Interannual rainfall and discharge in the Basin have been shown to vary considerably from year to year under the influence of sea surface temperature (SST) over the Pacific and Atlantic oceans and climatic phenomena such as El Niño-Southern Oscillation (ENSO). Rao and Hada (1990), Ropelewski and Halpert (1987), Ropelewski and Halpert (1989), Marengo (1992) and Marengo et al. (1993) examined the response of the region's precipitation to El Niño-Southern Oscillation (ENSO) events and pointed out that warm/cold El Niño-Southern Oscillation events are related to below/above normal precipitation. Authors such as Moura and Shukla (1981), Hastenrath and Greischar (1993) and Uvo et al. (1997), showed by observational and/or modeling studies that the Atlantic anomalous SST meridional gradient play an important role on the precipitation falling in northeastern South America. Marengo (1992) pointed out that high Rio Negro levels are related to anomalously cold surface waters in the tropical North Atlantic and high SST anomalies south of the equator. Additionally, he showed that abundant rain during the wet season...
in northern Amazonia is associated with cold surface waters in most of the tropical North Atlantic and eastern Pacific. Molion and Moraes (1987) studied the correlation between the Southern Oscillation Index (SOI) and the discharge for rivers in different parts of the Amazon Basin and found that the SOI and discharge show a good correlation in the eastern part of the basin given a lag of three months.

In spite of comprehensive research efforts mentioned above, quantitative models to forecast long-term discharge in the Amazon Basin are still lacking. A main reason for this is that the complex physical connections between the general regional climate and the basin's local hydrology are still not well understood. Uvo and Graham (1998) developed a linear statistical model to forecast discharge from SST for different sites in the Amazon, Tocantins and Orinoco Basins. The results obtained by that work lead to the conclusion that it should be possible to forecast discharge for those sites from SST, but further efforts should be made to improve the results.

Some extensive long-term climatic and hydrological databases exist, however, for the area (e.g., Uvo and Graham, 1998). This work presents the development of nonlinear models using artificial neural networks (ANN) to forecast discharge at some site in Northeastern South America from Pacific and Atlantic oceans SST.

### Methodology

The ANN is a nonlinear mathematical structure which is capable of representing arbitrarily complex nonlinear processes that relate the inputs and outputs of any system (Hsu et al., 1995). The ANN provides better solutions than traditional statistical methods when applied to poorly defined and poorly understood complex systems that involve pattern recognition (Poff et al., 1996). It is a viable technique to develop input-output simulations and forecast models for situations when the objective is an accurate forecast (Hsu et al., 1995).

Hill et al. (1996) compared neural network models with traditional statistical models for different time series, and concluded that neural network model forecasts are more accurate when the data sets have less than 50 historical data points, which is the case of the data available for this work.

Steps necessary to develop and train an ANN involve: a) choosing a pair of data sets that are representative of the phenomenon to be described and forecasted; b) defining a suitable network (number of layers and number of neurons in each layer); c) training the network to relate the inputs to the corresponding outputs estimating the ANN's weights; and d) validating the identified ANN. If compared to a conceptual model, step (b) is equivalent to the development of the model and step (c) is the calibration of the parameters of the designed model.
In this study, a two-layer ANN was used with TANSIG neurons in the hidden (recurrent) layer and PURELIN neurons in the output layer. The TANSIG is a hyperbolic tangent sigmoid function given by: 
\[ a = \frac{e^n - e^-}{e^n + e^-} \] 
and PURELIN is a linear function given by: 
\[ a = n \] (Hagan et al., 1995). This configuration allows the network to approximate any function with a finite number of discontinuities (Demuth and Beale, 1994).

The choice of the number of neurons in the hidden layer was made through test runs that started from a small number of neurons and gradually increased the network size. An optimal relationship between the accuracy achieved and the time spent during the training was found with 40 neurons in the hidden layer.

We used back-propagation as training method. This is an iterative technique that involves computing the error between the known desired output and the computed neural network output. Based on the magnitude of the error, it adjusts the interconnection weights in a backward sweep through the network (French et al., 1992). As it employs a gradient search strategy, its performance is quite sensitive to the starting weights (Hsu et al., 1995). To train the network, the routine "trainelm" available in the Matlab Neural Network Toolbox was used. Training continued until either the sum squared error (SSE) goal was obtained or a maximum number of iterations was completed. In general, about 150 iterations were enough to reach the chosen SSE of 0.01.

The trained ANN should be able to estimate the March-April-May (MAM) average discharge at 10 sites in Northeastern South America from seasonal averaged SST anomalies. Trainings were made separately for each river station providing to the ANN different training sets composed by a pair of data sets that included the discharge series (target values or output) and different SST periods (input) described as follows:

Seasonal average SST anomalies for the four seasons prior to the MAM discharge season, i.e.,

a) March-May, June-August, September-November and December-February, hereafter referred to as MAM-JJA-SON-DJF. In this case, the information about the SST during the entire year prior to the main discharge season is provided to the network.

b) Seasonal average SST anomalies for the three seasons not immediately before the MAM discharge season, i.e., March-May, June-August, September-November, hereafter referred to as MAM-JJA-SON. In this case the estimation of the discharge could be made 3 month before the start of the main runoff season.

c) Seasonal average SST anomalies for December-February (DJF).

d) Seasonal average SST anomalies for September-November (SON).

The validation of the training was made using the "leave-one-out" cross-validation technique. This technique consists of removing one row at a time from the input pair of data sets, re-training the ANN and estimating the missing data. The cross-validation followed the methodology proposed by Derks et al. (1996). They base their approach on the assumption that local error minimum can be avoided by choosing various random starting weights for the training. In our case, the cross-validation was made using 10 different re-initializations for the training at each removed pair from the input.
The correlation coefficient between normalized observed discharge and normalized discharge estimated by the cross-validation and the sum squared error (SSE) of the estimated series when compared to the observed series were used to analyze the results from the cross-validation.

As pointed out above, the cross-validation used repetitions of the same training following Derks et al. (1996), starting from different starting positions on the error hyperplane chosen randomly. To better understand this process, we analyzed the distribution of the outputs generated from the different starting weights for a same training set.

One row of the training set was removed and the ANN was trained 50 times using this new input data, starting from different starting weights. The removed row was estimated for each of the 50 times. The difference between observed and estimated discharge was calculated for each of the 50 estimations and the distribution of these differences was analyzed.

Data

The pair of data sets used to train the ANN (training set) contained seasonal averaged SST anomalies and seasonal average discharge. The SST anomalies were chosen to represent climate variability inherent in phenomena such as ENSO and the meridional SST gradient in the Atlantic Ocean. The SST anomalies were used as input and the discharges as output.

SST

The SST anomalies were extracted from the UWM/COADS SST anomalies (da Silva et al., 1994) for the period 1945 to 1991 on a 5° longitude by 2° latitude grid from 30°S to 30°N for the Pacific and Atlantic Oceans. Two subsets of these data were utilized. They consisted of the Equatorial Pacific subset (10°S to 10°N) and the Tropical Atlantic subset (30°S to 30°N). In both cases, the SST data were seasonally averaged for March-May, June-August, September-November and December-February.

Discharge

The discharge data consisted of monthly average anomalies from 1946 to 1992 for six stations in the Amazon Basin, one station in the Araguari Basin, two in the Tocantins Basin and one in the Parnaiba Basin (Figure 1). These time series were provided by ELETROBRAS (Centrais Elétricas Brasileiras), ELETRONORTE (Centrais Elétricas do Norte do Brasil S.A.) and DNAEE (Departamento Nacional de Águas e Energia Elétrica). All data series were homogenized by the respective institutions using different methodologies depending on the data source. Average seasonal discharges for MAM were calculated and used as target values in the training set of the ANN.
Figure 1. Map showing the Amazon, Tocantins and Paraíba basin and sub-basins. The basins of the Negro, Araguari, Uatumã, Curua-Una, Xingu, Jamari, Paraíba, Trombetas and Tocantins Rivers are delineated by thinner lines, country borders are indicated by dashed lines. Numbered circles indicate river discharge stations: 1- Balbina/Uatumã River; 2- Belo Monte/Xingu River; 3- Boa Esperança/Paraíba River; 4- Coaracy Nunes/Araguari River; 5- Curua-Una/Curua-Una River; 6- Manaus/Negro River; 7- Porteira/Trombetas River; 8- Samuel/Jamari River; 9- Serra Quebrada; 10- Tucuruí (9 and 10 at Tocantins River). Modified from Uvo and Graham, (1998).

Table 1. Summary of the results obtained from The Equatorial Pacific models for all sites available. COR Are the correlations between the series of normalized observed and estimated discharges obtained from the hindcast and the cross-validation of the Artificial Neural Network. All correlations are significant at 95% or more. SSE is the sum squared error for the whole series and SSEp, the SSE only for the years with anomalous normalized discharge ±1 standard deviation, divided by the number of years used in this summation.

| SITE          | Equatorial Pacific SST |  |  | Tropical Atlantic SST |  |  |
|---------------|------------------------|  |  |------------------------|  |  |
|               | MAM JJA    | MAM JJA | DJF | SON | MAM JJA | MAM JJA | DJF | SON |
|               | COR | SSE  | COR | SSE  | COR | SSE  | COR | SSE  | COR | SSE  | COR | SSE  | COR | SSE  | COR | SSE  | COR | SSE  |
| Balbina       | 0.94 | 5.41 | 0.91 | 7.93 | 0.96 | 3.25 | 0.88 | 10.13 | 0.86 | 12.50 | 0.88 | 13.51 | 0.92 | 7.23 | 0.84 | 14.08 |
| Belo Monte    | 0.90 | 10.11 | 0.88 | 10.46 | 0.93 | 6.80 | 0.82 | 15.67 | 0.90 | 9.73 | 0.91 | 9.25 | 0.97 | 11.02 | 0.96 | 3.47 |
| Boa Esperança| 0.94 | 5.22 | 0.95 | 4.45 | 0.94 | 5.22 | 0.79 | 17.39 | 0.92 | 7.50 | 0.93 | 6.74 | 0.97 | 2.66 | 0.95 | 4.85 |
| Coaracy Nunes | 0.96 | 5.24 | 0.95 | 5.11 | 0.96 | 4.31 | 0.89 | 9.49 | 0.94 | 8.45 | 0.86 | 17.02 | 0.94 | 5.00 | 0.94 | 5.76 |
| Curua-Una     | 0.94 | 6.28 | 0.91 | 7.62 | 0.96 | 3.23 | 0.81 | 16.25 | 0.90 | 8.71 | 0.91 | 13.67 | 0.97 | 11.04 | 0.97 | 2.54 |
| Manaus        | 0.95 | 4.42 | 0.94 | 5.00 | 0.93 | 6.63 | 0.89 | 9.72 | 0.95 | 4.92 | 0.91 | 10.02 | 0.96 | 3.92 | 0.90 | 9.54 |
| Porteira      | 0.95 | 4.92 | 0.94 | 6.61 | 0.92 | 7.35 | 0.94 | 4.96 | 0.90 | 9.71 | 0.91 | 11.83 | 0.96 | 3.30 | 0.88 | 9.74 |
| Samuel        | 0.90 | 8.73 | 0.67 | 11.62 | 0.86 | 10.25 | 0.67 | 11.51 | 0.95 | 4.66 | 0.91 | 11.86 | 0.90 | 9.88 | 0.92 | 6.77 |
| Serra Quebrada| 0.94 | 5.79 | 0.94 | 5.30 | 0.87 | 11.76 | 0.87 | 11.24 | 0.94 | 5.88 | 0.89 | 9.33 | 0.89 | 9.29 | 0.85 | 12.71 |
| Tucuruí       | 0.94 | 5.59 | 0.92 | 7.18 | 0.89 | 10.80 | 0.78 | 18.40 | 0.95 | 5.31 | 0.78 | 18.81 | 0.95 | 4.15 | 0.67 | 11.98 |
Results

Training and validation

The ANN described in the methodology was trained by different training sets composed by a series of SST and one of discharge. The SST series tested consisted of different seasons or groups of seasons for the SST anomalies as described before. The discharge data and the ANN training results are presented for each station.

The results are summarized in Table 1. For each of the four SST inputs it is given a) correlation coefficients between the observed normalized discharges and the normalized discharges obtained from cross-validation of the trained ANN (COR) and b) SSE for the estimated series. All values of SSE and COR in the Table may be compared as the number of time steps in all the series is the same and both the SST anomalies and the discharges are normalized.

Results show that ANN is a convenient method for forecasting discharge at all studied sites, but the accuracy of the trained ANN depends on the ocean and the SST seasons used in the training set. The highest correlations between observed and estimated series (≥ 0.95 and statistically significant at 99") and lowest SSEs (< 5.5) were found when using either the Pacific or the Atlantic Ocean SST separately.

When the MAM-JJA-SON-DJF period for the Pacific Ocean SST was used in the training set, the correlation between observed and estimated discharge for Coaracy Nunes was of 0.96 and the SSE was 5.24 and for Manaus and Porteira correlation of 0.95 and a SSE of 4.42 and 4.92, respectively. For the MAM-JJA-SON period, Coaracy Nunes and Boa Esperança both had correlation of 0.95 and a SSE of 4.45 and 5.11, respectively. For DJF, the cross-validation for Coaracy Nunes (Figure 2a), Balbina (Figure 2b) and Curua-Una resulted in correlation of 0.96 each and SSE of 4.31, 3.25 and 3.23, respectively. For the last SST period tested (SON), Porteira, despite a correlation of 0.94, had a SSE of 4.96, which also indicated that the validation was accurate. Coaracy Nunes had correlation above 0.95 for most of the SST periods tested in the Pacific Ocean and consistently had the best correlations among all tested stations, even though its SSE were not the lowest when compared to other stations with similar correlation for the same SST period.

When Atlantic Ocean SST was used in the training set, the cross-validation using the MAM-JJA-SON-DJF SST period resulted in correlation of 0.95 between observed and estimated discharge at Manaus, Samuel and Tucuruí with SSE of 4.92, 4.89 and 5.31, respectively. When the DJF period was used, Boa Esperança had correlation of 0.97 and SSE of 2.66 (Figure 3a). Manaus and Porteira had a correlation of 0.96 each with SSE of 3.92 and 3.30, respectively, and Tucuruí had 0.95 correlation and SSE of 4.15. For SON, Curua-Una had correlation of 0.97 and SSE 2.54 (Figure 3b), for Belo Monte the correlation was 0.96 and SSE 3.47 and Boa Esperança had correlation of 0.95 and SSE 2.54. No correlations equal to or greater than 0.95 were found when MAM-JJA-SON Atlantic SST period was part of the training set.
Figure 2. Time series of normalized observed (dots) and estimated discharge (solid line) from the cross-validation using Pacific Ocean SST anomalies for a) Coaracy Nunes and b) Balbina, using DJF SST season. The correlation coefficient between the two time series is shown at the top right of each figure and are all statistically significant at >99%. The SSE is shown at the top left of each figure.

Figure 3. Time series of normalized observed (dots) and estimated discharge (solid line) from the cross-validation using Atlantic Ocean SST anomalies for a) Boa Esperança at DJF season and for b) Curua-Una at SON season. The correlation coefficient between the two time series is shown at the top right of each figure and is statistically significant at >99%. The SSE is shown at the top left of each figure.

Figure 4. a) Series of 50-estimation and b) histogram of the difference observed value - estimated values for Balbina discharge in 1992 estimated from Pacific Ocean SST anomalies. c) series of 50-estimation and d) histogram of the difference observed value - estimated values for Coaracy Nunes discharge in 1992 estimated from the Pacific Ocean SST anomalies during DJF. For a) and c) the dashed line is the normalized observed discharge, solid straight line is the average of the estimated values (solid broken line) and dotted line is a zero line.
The results obtained showed that the discharge at Boa Esperança, which is located in the Parnaíba Basin – Northeast Brazil, has high response to both the Atlantic and Pacific Ocean. These results corroborate those obtained by Uvo et al. (1997) who found high dependence on the precipitation at Northeast Brazil from both oceans SST.

Within Amazonia, generally the stations localized in northern sub-basins had high correlations and low SSE when the Pacific Ocean SST anomalies were part of the training set. Conversely when the Atlantic Ocean SST anomalies were used, the stations located in the southern sub-basins had high correlations and low SSEs. For all stations, the best results were obtained when using only one SST season as part of the training set.

**Forecasting**

The dependence of the designed ANN to the starting positions on the error hyperplane (starting weights) is a critical consideration when using the ANN for real time forecasting. We tested different forecasting possibilities in order to better understand the potentials of the ANN.

The ANN was used in a verification process to forecast discharge. The ANN was trained with the same training set starting from 50 different random positions on the error hyperplane (weights). In each case, the discharge of a year not included in the training set was forecasted. Our main concern was to observe how the estimation of discharge varies with the starting weights.

Different results were obtained depending on the pair of sets used as input. Two examples of the verification are shown in Figure 4. The figure shows a series of 50 verifications of discharge at Balbina in 1992 estimated from DJF Pacific Ocean SST anomalies. The cross-validation for the ANN trained with the same training set is shown in Figure 2b. Figure 4c shows the 50 estimations for Coaracy Nunes discharge in 1992, also from DJF Pacific Ocean SST anomalies. The cross-validation for this case is shown in Figure 2a.

From the first example it can be seen that the verified discharge does not vary greatly (solid broken line) and most of its values are below zero (dotted line) as it is the observed discharge (dashed line). The solid straight line shows the average of the 50 verified values and is not very far from the observed values. The error distribution related to these test series (Figure 4b) shows that the expected error is approximately zero.

The second example displays a situation where the estimated values (solid line) had the correct sign but oscillated around a value (solid straight line) considerably lower than the observed value (dashed line). The error distribution for this case (Figure 4d) shows that the expectation is about 1.5.
Conclusions

We used ANN to validate and forecast discharge from ocean SST sites in the northeastern South America. The ANN was a suitable technique for the estimation of discharge at the studied sites. The accuracy of the model depended on the site, on the ocean considered and on the SST period used in the training set. Within the Amazon Basin, the discharge at the sites situated in northern sub-basins was better forecasted when the Pacific Ocean SST anomalies were used as input. On the other hand, sites located in southern sub-basins were better forecasted when the input was Atlantic Ocean SST anomalies.

The validation of the trained nets gave correlations between observed and estimated series that ranged from 0.77 in the worst case to 0.97 in the best case. The SSE for estimated series from validation were, in general, small.

However, the dependence of the ANN model on starting weights prevents the ANN from providing a precise forecast, but even so, it proved to be useful as an indicator for the seasonal discharge anomaly one or two seasons in advance. More development and further experiments with different kinds of ANNs could, in the future, result in an ANN design and training technique less dependent on the starting weights.

References


Program

Appendix 1

Sunday 28 June,
Arrival, small get-together at Hotel Concordia 18:00-19:00.

Monday 29 June;

09:00-  - Gathering at Hotel Concordia for walking to Grand Hotel.
09:20-09:30 - Introduction (Dr. Ronny Berndtsson, LU, and Dr. Jean Albergel, ORSTOM).

Observation techniques; GIS/remote sensing; climatic, soil, agronomic, and socioeconomic data storage and processing for small watersheds; (chairman: Dr. Jean Albergel, ORSTOM).

09:30-10:00 - New developments in the Wadi Hydrology Network, Dr. Jean Khouri, ACSAD.
10:00-10:30 - The Sindyaneh Wadi Basin in Syria, Dr. Abdallah Droubi, Mr. Yasser Ibrahim, ACSAD and Dr. Jean Albergel, ORSTOM.
10:30-11:00 - Small dams' water balance: experimental conditions, data processing and modeling, Dr. Jean Albergel, ORSTOM, Mr. Slah Nasri, INRGREF, and Dr. Mohamed Boufaroua, MAT.
11:00-11:30 - Coffee and tea break.
11:30-12:00 - Integrating soil profile and soil hydraulic properties data bases to be used in simulation models and land evaluation expert systems, Prof. Felix Moreno, Dr. D. de la Rosa, and Dr. J. E. Fernandez, IRNASE.
12:00-12:30 - Lebanese hydrology and needs for water storage, Dr. Bassam Jaber and Dr. Fuad Saad, MHER.
12:30-13:00 - Remote sensing applications for the management of small catchments in arid and semiarid area, Dr. Chuqun Chen, CAS.
13:00-14:00 - Lunch

Water quality and quantity; hydrological and transport modeling; (chairman: Dr. Jean Khouri, ACSAD).

14:00-14:30 - Water chemistry characteristics in small reservoirs of the semiarid Tunisia, Dr. Nathalie Rahaingomanana, ORSTOM.
14:30-15:00 - Water chemistry of small reservoir catchments in central Tunisia, Dr. O. Grunberger, Dr. Jean-Pierre Montoroi, ORSTOM, Mr. Slah Nasri, INRGREF, Dr. Jean Albergel, Mr. Yannick Pepin, and Dr. Nathalie Rahaingomanana, ORSTOM.
15:00-15:30 - Modelling effects of preferential flow and transport on non-point source pollution, Prof. Nicholas Jarvis, SLU.
15:30-16:00 - Coffee and tea break.
16:00-16:30 - Solute transport and soil water content measurements in arid soils using time domain reflectometry, Dr. Magnus Persson, LU.
16:30-17:00 - The FLAPS system for data management and hydrological modeling, Dr. Linus Zhang, LU.
19:00-  - Dinner
21:00-  - Optional software demonstration (Hotel Concordia).
Tuesday 30 June;

**Rainwater harvesting; infiltration techniques and modeling; infiltration and erosion (chairman: Dr. Nejib Rejeb, INRGREF).**

09:00-09:30 - Microcatchment, macrocatchment, and flood water harvesting techniques applied in the Mediterranean, Prof. Dr. Dieter Prinz, KU.

09:30-10:00 - The use of TDR for wetness measurements in soil erosion and conservation practices in small watersheds, Dr. Patrick Zante, ORSTOM, and Mr. Slah Nasri, INRGREF.

10:00-10:30 - Coffee and tea break.

10:30-11:00 - Land use transformation impact on reservoir siltation in Morocco: the need for better assessment tools, Dr. Abdelaziz Merzouk, IAV.

11:00-11:30 - Modeling small dams’ siltation with MUSLE, Dr. Jean Albergel and Mr. Yannick Pepin, ORSTOM.

11:30-12:00 - Small-scale cistern system for rainwater collection and storage in north-western China, Dr. Linus Zhang, LU and Prof. Kun Zhu, LRI.

12:00-12:30 - Disinfection and fresh-keeping of rainwater in small scale cisterns, Prof. Kun Zhu and Dr. Chen Hui, LRI, Dr. Linus Zhang and Dr. Ronny Berndtsson, LU.

12:30-13:00 - Strategy of soil and water conservation in Tunisia, Dr. Habib Farhat and Dr. Mohamed Boufaroua, MAT.

13:00-13:30 - Lunch

14:00-16:00 - Guided round trip in Lund on foot, meeting place: Cathedral entrance.

18:00- - Optional software demonstration (Hotel Concordia)

Wednesday 1 July;

**Reservoir planning, operation and management; Rainfall-inflow relationships; Dam design and operation; Surface-groundwater interactions (chairman: Dr. Abdelaziz Merzouk, IAV).**

09:30-10:00 - Hydrodynamics and related water quality in small reservoirs, Prof. Lars Bengtsson, LU.

10:00-10:30 - Coffee and tea break.

10:30-11:00 - Groundwater recharge and modeling in an experimental catchment, Mr. Slah Nasri, INRGREF.

11:00-11:30 - Deterministic versus stochastic hydrological modeling; uncertainties and decisions, Mr. Jan Hoybye, LU.

11:30-12:00 - Neural network methodology to simulate discharge, Dr. Cintia Uvo, LU.

12:00-12:30 - Water reservoir management in practice, Dr. Laszlo Iritz, LU.

12:30-13:30 - Lunch

14:00-17:00 - Study visit to the Vomb water works and the Scania region.

18:00- - Optional software demonstration (Hotel Concordia)
Thursday 2 July;

**Study tour to Denmark and Copenhagen.**

08:00- Departure Hotel Concordia
09:00- Short stop in Helsingborg and the Kärnan castle
09:30- Ferry to Denmark.
10:15- The Cronborg Castle (the Hamlet and Shakespeare story)
12:45- Danish typical lunch
14:30- Free time in Copenhagen
16:00 - Departure for Malmoe and Sweden

Abbreviations:

ACSAD: Arab Center for the Studies of Arid Zones and Dry Lands, Syria.
CAS: South China Sea Institute of Oceanography, Chinese Academy of Sciences, China
IAV: Institute for Agronomy and Veterinary Hassan II, Morocco.
IRNAS: Institute for Natural Resources and Agrobiology, Spain.
KU: Karlsruhe University, Germany.
LRI: Lanzhou Railway Institute, China.
LU: Lund University, Sweden.
MAT: Ministry of Agriculture, Tunisia.
MHER: Ministry of Hydraulic and Electric Resources, Beirut, Lebanon.
MIDS: Ministry of Irrigation, Damascus, Syria.
ORSTOM: French Institute for Scientific Research and Cooperative Development, France/Tunisia.
SLU: Swedish Agricultural University, Uppsala, Sweden.
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