## Chapter 6

# Sustainable Development and Use of Reservoirs

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by
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## 6.1 Introduction

The construction of reservoirs is one of the most important practices for the development and management of water resources. Reservoir construction serves agricultural, flood control, hydropower generation, water supply, navigational, recreational, and environmental purposes.

Many large reservoirs were built without a thorough or systematic evaluation of the long-term environmental, social, and economic interactions of different alternatives. The "dead storage" concept has been used in the planning and design of reservoirs to store sediment for a predetermined useful life, say 50 to 100 years. However, many existing reservoirs have reached, or may soon reach, their designed useful life. In addition, environmental, social, economic, and political considerations, and the fact that suitable damsites are scarce now, necessitate new and innovative approaches for water resources development and management.

To cope with population increases and the increasing demands of higher standards of living, more reservoirs will be built, especially in developing countries. How to plan, design, construct, and operate reservoirs for sustainable use for generations to come is a challenge to engineers and policymakers.

This chapter explains the concept of sustainable development and use of water resources and the dynamic adjustments of river systems. Methods for planning, designing, operating, and maintaining a reservoir; reducing sediment inflow; and removing sediment in a reservoir are described. Yang (1997) provides a comprehensive review of these methods. New technical tools are introduced to enhance our ability to sustain the development and use of reservoirs where erosion and sedimentation are concerns.

## 6.2 Sustainable Development and Use of Water Resources

The description of "sustainable development" given by the World Commission on Environment and Development (WCED, 1987) is:

> Humanity has the ability to make development sustainable to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs.

Concerning the "limits of development," the WCED (1987) states:

> The concept of sustainability implies limits: not absolute limits, but limitations imposed by the present state of technology and social organization on environmental resources and by the ability of the biosphere to absorb the effect of human activities.

Because the environment has an absorption limit, its overuse over a considerable time span can bring about irreversible changes. If this overuse continues, the irreversible changes can make the earth environmentally unsuitable for human habitation. It should be noted that the limitations are not fixed; they depend on the state of technology and the social organization which manages environmental resources (Takeuchi and Kundzewicz, 1998). In the use of "sustainable development,"

> Development does not necessarily mean growth in the quantitative sense. It is rather a qualitative process which does not have any limit. Development is a continuous process of changing state from one form to another seeking to meet ever changing objectives. Sustainable human existence, if ever possible, must be an endless process of change in social, cultural, and industrial states within a certain limit of the sustainable use of energy and resources. (Takeuchi and Kundzewicz, 1998)

The idea of sustainability was advanced in the Rio Declaration on Environment of Development issued at the United Nations Conference on Environment and Development (UNCED, 1992). Of the 27 principles declared, the following 5 principles address the concept of sustainable development:

> *Principle 1*: Human beings are at the centre of concerns for sustainable development. They are entitled to a healthy and productive life in harmony with nature.
>
> *Principle 3*: The right to development must be fulfilled so as to equitably meet developmental and environmental needs of present and future generations.
>
> *Principle 4*: In order to achieve sustainable development, environmental protection shall constitute an integral part of the development process and cannot be considered in isolation from it.
>
> *Principle 5*: All states and all people shall cooperate in the essential task of eradicating poverty as an indispensable requirement for sustainable development, in order to decrease the disparities in standards of living and better meet the needs of the majority of the people of the world.
>
> *Principle 8*: To achieve sustainable development and a higher quality of life for all people, states should reduce and eliminate unsustainable patterns of production and consumption and promote appropriate demographic policies.

The above five principles state that human beings have the right to develop a higher quality of life. In the process of developing a higher quality of life, environmental protection should be treated as an important and integrated part of development. Chapter 18 of the UNCED documentation, entitled "Protection of the quality and supply of freshwater resources: Application of integrated approaches to development, management and use of water resources," states that the following four principles should be pursued:

> (a) to promote a dynamic, interactive, iterative and multisectoral approach to water resources management, including the identification and protection of potential sources of freshwater supply, that integrates technological, socio-economic, environmental and human health considerations;
>
> (b) to plan for the sustainable and rational water utilization, protection, conservation and management of water resources based on community needs and priorities within the framework of national economic development policy;

> (c) to design, implement and evaluate projects and programmes that are both economically efficient and socially appropriate within clearly defined strategies, based on an approach of full public participation, including that of women, young people, indigenous people and local communities in water management policy-making and decision-making;
>
> (d) to identify and strengthen or develop, as required, in particular in developing countries, the appropriate institutional, legal and financial mechanisms to ensure that water policy and its implementation are a catalyst for sustainable social progress and economic growth.

The UNCED (1992) documentation also suggested the following three holistic approaches for sustainable water resource management:

> "(a) consideration of various alternative means and components of water resource management in every stage of planning, design, construction, and operation;
>
> (b) multidisciplinary approach to include engineering, biology, economics, sociology, health, laws, public administration, etc.;
>
> (c) multisectoral exercise to include all levels and sectors of legislative and governmental units, cultural and interested groups, indigenous people, women and young people, non-governmental organizations and similar groups."

The worst enemy of sustainable use of reservoirs is sedimentation. Reservoir sedimentation replaces and depletes useful reservoir volume for flood control, hydropower generation, irrigation, water supply, recreation, and environmental purposes. The conventional concept of allocating "dead storage" for a predetermined useful life of 50 to 100 years is no longer acceptable. In the planning and design of new reservoirs, engineers must incorporate the concept of sustainable use and operation. For existing reservoirs, engineers should take appropriate remedial measures to prolong their useful functions within economic, social, political, and environmental constraints. If a reservoir has stopped serving its useful purposes, decommissioning should be considered to restore a river's natural pre-dam condition to the extent possible.

The following sections will discuss the concept of dynamic adjustment of a river system, methods used to reduce sediment inflow to a reservoir, reservoir sediment removal, and technical tools available for engineers.

In summary, sustainable development and use of reservoirs means that:

- We should develop and use reservoirs for the benefits of present and future generations in a socially, environmentally, and economically acceptable manner.

- Development can be growth in a quantitative sense, a qualitative sense, or both.

- Sustainable development and use of reservoirs implies that there are limitations imposed by the present state of technology. These limitations can be changed due to changing social, environmental, and economic considerations.

Basic principles in sustainable development and use of reservoirs are:

- Human beings are at the center of concerns for sustainable development and use. Humans are entitled to a healthy and productive life in harmony with nature.

- Along with the right to develop and use reservoirs comes the responsibility to meet the needs of present and future generations.

- To achieve sustainable development and use of reservoirs and a higher quality of life for all people, we should gradually reduce and eliminate unsustainable patterns of development and use subject to social, environmental, and economic considerations.

- Reservoir sedimentation shortens the useful life of reservoirs. Systematic and thorough consideration of technical, social, environmental, and economic factors should be made to prolong the useful life of reservoirs.

## 6.3 Dynamic Adjustment of a River System

A river is a dynamic system. Its channel roughness, geometry, and longitudinal profile continuously adjust in response to natural and human caused changes. Lane (1955) pioneered the concept of dynamic adjustment with the following qualitative relationship:

$$Q_s d \propto QS \tag{6.1}$$

where $Q$, $Q_s$ = water and sediment discharges, respectively,
$d$ = sediment particle diameter, and
$S$ = channel slope.

Equation (6.1) states that $Q_s d$ is proportional to $QS$. "Because $Q_s$ released from a reservoir is less than the amount of sediment a river is capable of transporting without the reservoir, downstream channel slope will be reduced through degradation" (Yang, 1996). It should be noted that Equation (6.1) provides a qualitative relationship which cannot be used by engineers for quantitative computations of dynamic adjustments of a river caused by the construction and operation of a reservoir.

Yang (1986) introduced the following quantitative equation for the prediction of dynamic adjustments of a river based on his unit stream power equations (Yang, 1973, 1979):

$$C_t = I\left(\frac{VS}{w}\right)^J \tag{6.2}$$

or

$$\frac{Q_t}{Q} = I\left(\frac{QS}{WDw}\right)^J \tag{6.3}$$

where $V$ = average flow velocity,
$S$ = water surface or energy slope,
$w$ = channel width,
$D$ = channel depth,
$W$ = sediment fall velocity,
$C_t$ = total bed-material concentration,
$Q$ = water discharge,
$Q_t$ = total bed-material load, and
$I, J$ = coefficients.

Because sediment fall velocity is directly proportional to the square root of sediment diameter, Equation (6.3) can be rewritten as:

$$\frac{Q_t d^{J/2}}{K} = \frac{Q^{J+1} S^J}{W^J D^J} \tag{6.4}$$

where $K$ = a site-specific parameter.

Most natural rivers have a $J$ value between 0.8 and 1.5. If an average value of 1.0 is used, Equation (6.4) becomes:

$$\frac{Q_t d^{0.5}}{K} = \frac{Q^2 S}{WD} = \frac{Q^2 S}{A} \tag{6.5}$$

where $A$ = channel cross-sectional area, and
$d$ = median sediment particle diameter.

The following example illustrates how to use Equation (6.5) to predict river morphologic adjustments due to the proposed construction of Chi-Ban Hydropower Project in Taiwan. The example was based on the study done by Yang and Yeh (1992), which was later summarized by Yang (1996).

**Example 6.1** Li-Wu Creek in eastern Taiwan, as shown in Figure 6.1, has a total length of 58 kilometers. The combined effects of tectonic movement and erosion caused by rapid flow created the narrow Taroko Gorge, more than 1,000 meters deep, between Chiu-Chu-Tung and Taroko. The proposed Chi-Pan Hydropower Project has a capacity of 160,000 kW. The project consists of a main dam at Ku-Yuan and three diversion dams at Pai-Yang, Ho-Shou, and Hsiu-Te. A regulation dam is also proposed on Li-Wu Creek just upstream of Tien-Hsiang. The construction of diversion dams can increase inflow to the Chi-Pan Powerplant. The regulation dam can regulate and maintain a minimum daytime flow of 5.55 $m^3/s$ and nighttime flow of 4.5 $m^3/s$ through the Taroko Gorge to meet minimum flow requirements for environmental reasons.

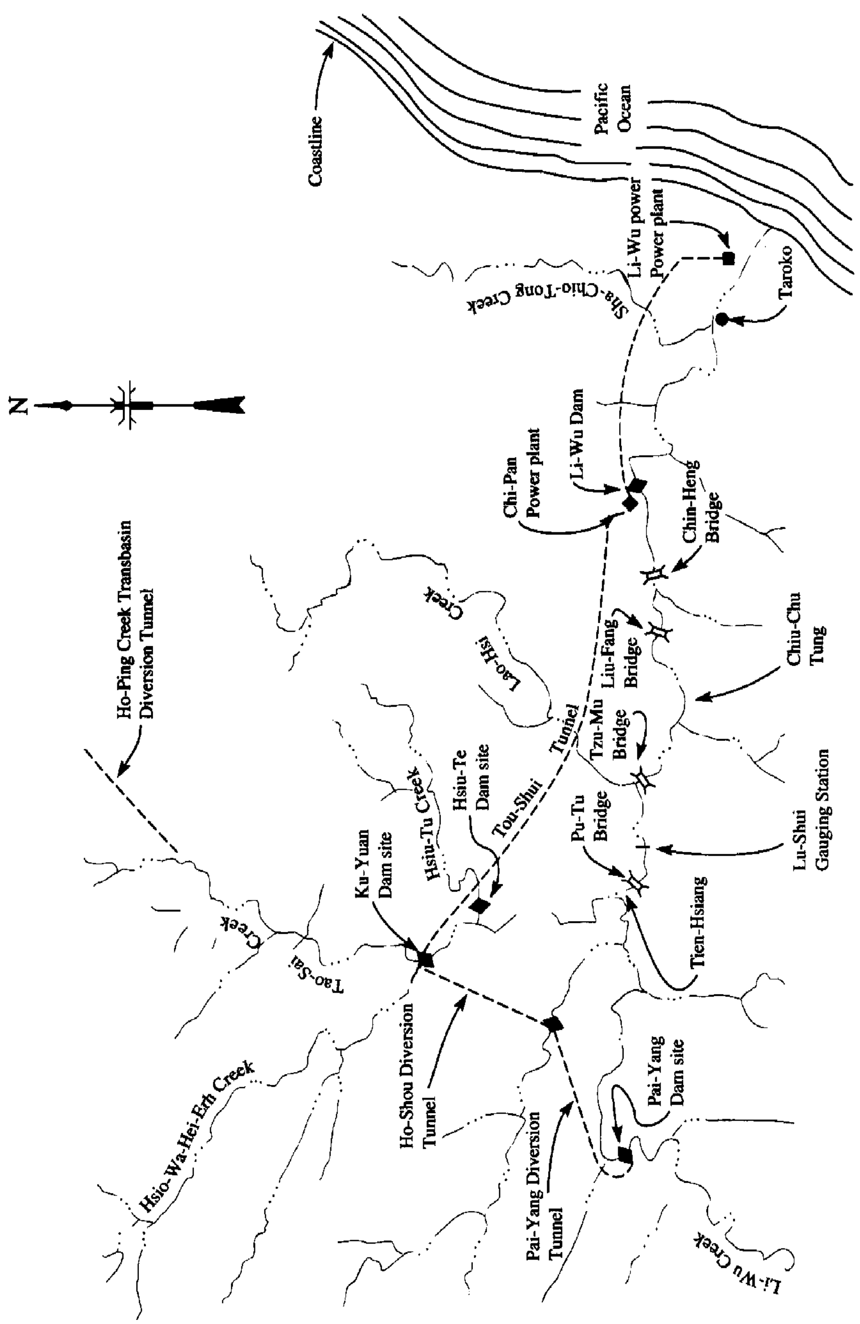

Figure 6.1. Chi-Pan Hydropower Project plan.

A transbasin diversion of 7 $m^3/s$ from Ho-Ping Creek was also considered in order to increase the flow and sediment transport capacity in Li-Wu Creek. Environmentalists raised the concern that the proposed project might reduce Li-Wu Creek's sediment transport capacity to the extent that sediment might be deposited in the gorge, and the spectacular gorge would eventually disappear. Figure 6.2 shows the flow duration curves at Lu-Shui gauging station under different alternatives.

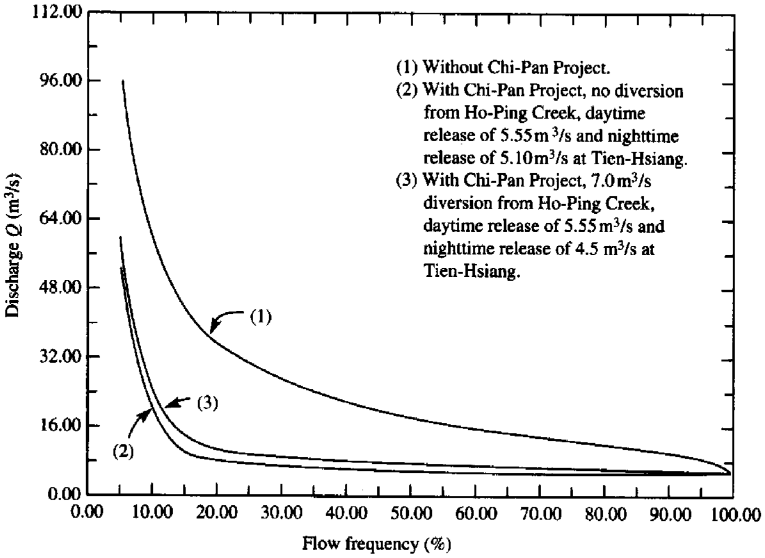

Figure 6.2. Flow duration curves at Lu-Shui gauging station.

Manning's roughness coefficient has a value of 0.035. Channel slopes at different stations can be obtained from 1:1000 topographic maps. Figure 6.3 shows bed-material size distributions at Lu-Shui station. Table 6.1 shows measured and computed sediment loads at Lu-Shui. Assess the sedimentation impact along the Taroko Gorge due to the proposed project.

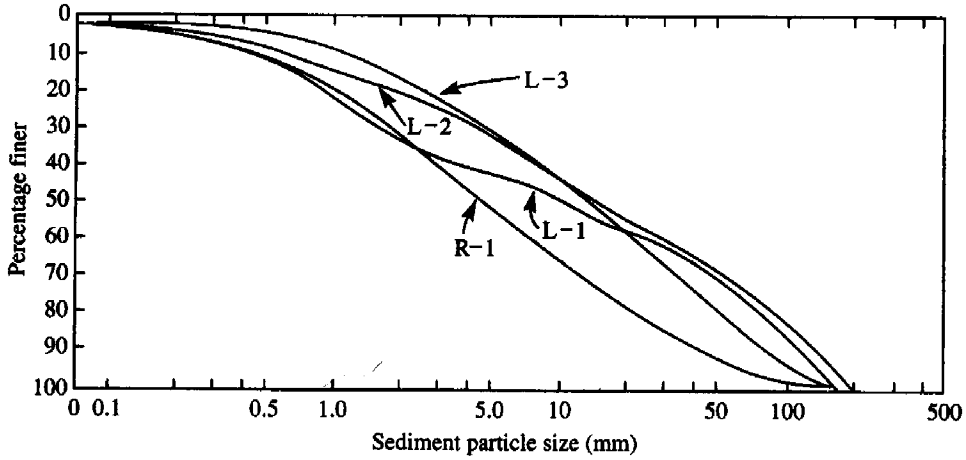

Figure 6.3. Bed-material size distribution at Lu-Shui gauging station.

Table 6.1. Computation of sediment transport rate at Lu-Shui gauging station

| Flow duration (%) | Time interval (%) | Median (%) | Water discharge ($m^3/s$) | Einstein method ($10^6$ t/yr) | | Schoklitsch method ($10^6$ t/yr) | | | Measured suspended load ($10^6$ t/yr) |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Bedload | Suspended load | $d_{40}$ | $d_{50}$ | $d_{60}$ | |
| 0-0.08 | 0.08 | 0.04 | 1,323.9 | 0.07* | 0.05 | 0.12 | 0.08 | 0.06 | 0.96 |
| 0.08-0.02 | 0.12 | 0.14 | 802.9 | 0.06 | 0.04 | 0.10 | 0.08 | 0.05 | 0.79 |
| 0.2-0.5 | 0.3 | 0.35 | 444.4 | 0.09 | 0.04 | 0.14 | 0.10 | 0.08 | 0.77 |
| 0.5-1.5 | 1.0 | 1.0 | 247.8 | 0.16 | 0.06 | 0.27 | 0.19 | 0.14 | 1.17 |
| 1.5-5.0 | 3.5 | 3.25 | 132.2 | 0.35 | 0.12 | 0.50 | 0.36 | 0.25 | 1.12 |
| 5.0-15 | 10 | 10 | 59.95 | 0.61 | 0.17 | 0.64 | 0.45 | 0.32 | 0.56 |
| 15-25 | 10 | 20 | 35.38 | 0.45 | 0.11 | 0.37 | 0.26 | 0.18 | 0.12 |
| 25-35 | 10 | 30 | 26.98 | 0.36 | 0.08 | 0.28 | 0.20 | 0.13 | 0.06 |
| 35-45 | 10 | 40 | 21.48 | 0.29 | 0.07 | 0.22 | 0.16 | 0.10 | 0.03 |
| 45-55 | 10 | 50 | 18.09 | 0.25 | 0.05 | 0.19 | 0.13 | 0.09 | 0.02 |
| 55-65 | 10 | 60 | 15.34 | 0.20 | 0.04 | 0.16 | 0.11 | 0.07 | 0.01 |
| 65-75 | 10 | 70 | 13.19 | 0.17 | 0.04 | 0.14 | 0.09 | 0.06 | 0.01 |
| 75-85 | 10 | 80 | 11.32 | 0.14 | 0.03 | 0.12 | 0.08 | 0.05 | 0.01 |
| 85-95 | 10 | 90 | 9.59 | 0.11 | 0.02 | 0.10 | 0.07 | 0.04 | — |
| 95-100 | 5 | 97.5 | 6.99 | 0.03 | 0.01 | 0.04 | 0.02 | 0.01 | — |
| Total | | | | 3.34 | 0.93 | 3.39 | 2.28 | 1.63 | 5.63 |

* For $Q = 1323.0\ m^3/s$, $Q_b = 2.643$ t/s or $Q_b = 2.643 \times 365 \times 86{,}400 \times 0.08\% = 0.07 \times 10^6$ t/yr.

*Solution*: Based on measured relationships among $Q$, $A$, $d$, a slope of 0.001, and computed $Q_t$ from the Einstein method shown in Table 6.1; Table 6.2 shows the $K$ values in Equation (6.5) at different discharges. The following regression equation can express the $K$ values in Table 6.2:

$$\log K = 3.6063 - 0.3115 \log Q \qquad (6.6)$$

Table 6.2. Lu-Shui gauging station $K$ values at different discharges

| $Q$ ($m^3/s$) | 1,323.9 | 802.9 | 444.4 | 247.8 | 132.2 |
|---|---|---|---|---|---|
| $K$ | 461 | 512 | 561 | 642 | 816 |
| $Q$ ($m^3/s$) | 59.95 | 35.38 | 26.98 | 21.48 | 18.09 |
| $K$ | 1,171 | 1512 | 1647 | 1712 | 1744 |
| $Q$ ($m^3/s$) | 15.34 | 13.19 | 11.32 | 9.59 | 6.99 |
| $K$ | 1756 | 1753 | 1736 | 1697 | 1504 |

Equation (6.6) has a correlation coefficient of 0.98. From Equations (6.5) and (6.6) and curve (1) in Figure 6.2, the average annual total bed-material load at Lu-Shui station is 4.2 x $10^6$ metric tons, which is very close to the 4.27 x $10^6$ metric tons computed from the Einstein method, as shown in Table 6.1. Assume that sediment size distribution, $K$ values, and computed total bed-material loads at Lu-Shui station can be applied to other stations through the study reach. Channel cross-sectional areas under different discharges can be computed from Equation (6.5). Table 6.3 summarizes the mean annual discharge and bed-material transport capacity under different alternative plans obtained from Equations (6.5) and (6.6) and the $K$ values in Table 6.2.

Table 6.3. Water discharge and sediment transport capacity at different stations along Li-Wu Creek

| Station | Mean annual discharge ($m^3/s$) | | | Annual sediment transport capacity ($10^6$ t/yr) | | |
|---|---|---|---|---|---|---|
| | | Postproject | | | Postproject | |
| | Preproject | Without diversion | With diversion | Preproject | Without diversion | With diversion |
| Pu-Tu Bridge | 32.41 | 16.04 | 17.92 | 10.97 | 5.29 | 5.96 |
| Lu-Shui station | 32.71 | 16.35 | 18.23 | 4.20 | 2.02 | 2.29 |
| Tzu-Mu Bridge | 35.24 | 18.88 | 20.72 | 2.91 | 1.56 | 1.71 |
| Chiu-Chu-Tung | 36.74 | 20.37 | 22.25 | 15.34 | 8.40 | 9.22 |
| Liu-Fang Bridge | 36.88 | 20.52 | 22.40 | 14.82 | 8.10 | 8.86 |
| Chin-Heng Bridge | 37.48 | 21.12 | 23.00 | 17.48 | 9.55 | 10.46 |
| Li-Wu Dam | 38.39 | 22.03 | 23.91 | 7.49 | 4.21 | 4.57 |

Table 6.3 shows that the reach between Lu-Shui station and Tzu-Mu Bridge has the lowest sediment transport capacity, while the gorge reach between Chiu-Chu-Tung and Chin-Heng Bridge has the highest sediment transport capacity. Field surveys and observations confirmed bedrock exposure with no deposition between Lu-Shui station and Tzu-Mu Bridge. This indicates that the total bed-material entering the gorge reach should be less than 2.91 metric tons per year. The results in Table 6.3 indicate that the Li-Wu Creek sediment transport capacity through the gorge reach far exceeds the bed-material supply from upstream, with or without the transbasin diversion. Consequently, the current downcutting trend of the gorge reach should continue with the proposed project. Yang and Yeh (1992) have published a more detailed description of the project.

Yang (1971) introduced two basic laws in river morphology. They are the law of average stream fall and the law of least rate of energy dissipation. Yang derived these two laws from the concept of entropy and from thermodynamic laws. The law of average stream fall states that under the dynamic equilibrium condition, the ratio of the average fall between any two different order streams in the same river basin is unity. The law of least rate of energy dissipation states that during the evolution toward its equilibrium condition, a natural stream chooses its course of flow in such a manner that the rate of potential energy expenditure per unit mass of water along this course of flow is a minimum. This minimum value depends on the external constraints applied to the stream (Yang, 1971). The first law can be used to predict whether a river's longitudinal profile will aggrade or degrade in the future. The second law can be used to explain and predict a river's morphologic changes.

The theory of minimum energy dissipation rate and its simplified version of minimum unit stream power were first introduced by Yang (1976). This theory was later expanded (Yang and Song, 1979, 1986) as a basic theory for all closed and dissipative systems, including river systems. The theory states that for a closed and dissipative system at its dynamic equilibrium condition, its energy dissipation rate is at its minimum value. The minimum value depends on the constraints applied to the system. If the system is not at its dynamic equilibrium condition, its energy dissipation rate is not at its minimum value. However, the system will adjust itself in such a manner that the energy dissipation rate can be reduced and regain equilibrium. The theories of minimum unit stream power and minimum stream power are simplified and special versions of the general theory of minimum energy dissipation rate. This theory is consistent with, but more general than, the law of least rate of energy dissipation. This theory or its simplified theories of minimum stream power and minimum unit stream power can be applied to solve a wide range of fluid mechanics and river morphology problems. The theory of minimum stream power also provides the theoretical basis for the GSTARS 2.0 (Yang et al., 1998), GSTARS 2.1 (Yang and Simões, 2000), and GSTARS3 (Yang and Simões, 2002) computer models, which are discussed in Chapter 5.

## 6.4 Planning

### 6.4.1 Background Information and Field Investigation

Planning starts with collecting background information for field investigations. Typical background information is identified in Table 6.4. Table 6.5 provides a checklist of tasks to accomplish during a reconnaissance inspection, and Table 6.6 provides a list of related observations (Dorough and Yang, 1996).

### 6.4.2 Basic Consideration

It is important to minimize sediment inflow to a reservoir. This process starts with selection of a reservoir site. Areas with high rates of erosion should be avoided. If this is not possible, a reservoir can be located offstream, and water can be diverted to it from the main river. In most cases, out of necessity, reservoirs are built on streams, and sediment control measures must be implemented to reduce the capacity loss of the reservoir.

In locations where the reservoir traps large volumes of sediment, the accumulated sediment can impair the effectiveness of the reservoir. In those cases, whether to remove sediment from the reservoir becomes an important consideration.

### 6.4.3 Sediment Control Measures

Sediment control measures include soil conservation practices, control of distribution of deposits, construction of debris basins, control of turbidity, and design of a proper intake structure to reduce sediment inflow. The following is a brief description of some issues related to sediment control measures (Wu et al., 1996):

Table 6.4. Background information for field investigations (Dorough and Yang, 1996)

| | |
|---|---|
| Reservoir survey data | Provide point measurements of sediment yield. This serves as an indicator of sediment production from a localized contributing drainage area. |
| Topographic maps (suggest 1:24,000 scale) | Illustrate topographic relief and indications of land use and road and highway access. When combined with aerial photographs, this may help to identify non-sediment-contributing areas (i.e., lakes, ponds, and reservoirs). |
| Road maps | Provide road and highway access routes. Identify stream locations and locations of roads, highways, railroads, and other constraints to sediment movement within the basin. |
| Aerial photographs | Provide broad aerial view of the study area. Depict land usage and vegetation cover. May illustrate locations of gullying and channel head cutting and provide opportunity to assess changes with time. Show roads and other access routes. |
| Sediment sampling data | Additional indicator of sediment yield from the contributing drainage area. |
| Hand-held photographs | Provide historical view of field characteristics. Useful onsite for comparison against existing gully and channel head-cutting to assess time-related changes. |
| Soil conservation maps | Depict locations and types of soil conservation structures. May help in identifying locations of non-sediment-contributing areas or areas with significant reductions in sediment yield. Permit sedimentation specialist to conduct a site inspection of structure effectiveness. |
| Soil conservation practices | Provide information on soil conservation practices, locations, and projections on reductions in soil loss. May identify future plans. |
| Land-use maps | Delineate types and perimeters of different land usages. Permit field engineer to compare erosion potential from area to area. |
| Urbanization projections | Permit the sedimentation specialist to review areas that are undergoing, or may undergo, urbanization during the project life. |
| Regional sediment reports | Provide preliminary information on basin-wide sediment yield rates; may be especially useful if reports contain maps delineating isogram sediment yield lines. |
| Reservoirs, lakes, ponds, and strip mine sites | Reservoirs, lakes, ponds, and strip mines (other than spoil pile sites) serve as non-contributing sediment yield areas and should be noted on topographic maps and aerial photographs for inspection in the field. |

Table 6.5. Field reconnaissance tasks (USACE, 1989)

Verify topographic maps
Note boundary conditions
Note bed and bank material slope
Note slope of stream in general and any break points
Obtain representative samples of bed-material
Note condition of banks, whether stable or caving, and the type of material found in the streambed and banks
Record conditions by location
Record drift accumulations, debris
Estimate percent of bed-material that is naturally armored
Note problem areas and attempt to ascertain the cause
Note changes in bed gradation and take representative samples for sediment study

Table 6.6. Field reconnaissance observations (USACE, 1989)

| |
|---|
| Note channel mining observations |
| Note tributary entry points, amounts of flow, turbidity of flow, condition of the tributary |
| Note diversion points |
| Note natural grade controls such as rock outcrops |
| Note presence of protection measures, their size, why they were placed |
| Note gauge locations, type of gauge |
| Note structural feature locations and observe bank and bed conditions in the vicinity of the structures |
| Note existing similar projects on same or adjacent streams—how they are performing |
| Note overbank conditions—areas of scour or deposition; if deposition exists, obtain samples and measure depth, and note extent on map |
| Take velocity measurements at several locations using surface floats, pacing, and stop watch |
| Talk with locals to identify problem areas; get an estimate of time or problem. Also, inquire as to local land use history—when urbanized, cleared, etc. |

- *Soil conservation practices.*—Soil conservation practices greatly reduce erosion of the land surface, channel bank cutting, and head-cutting. Where a reservoir controls a small drainage of only 1 or 2 square miles, the sediment contribution to the reservoir can be reduced by as much as 95 percent by intensive conservation measures. For large reservoirs with large drainage areas, however, it should be recognized that it may not be economically feasible to control or greatly reduce the sediment inflow.

- *Control of distribution of deposits.*—When a stream enters a wide reservoir, the location of the deposits can be controlled to some extent by judicious breaching of the channel formed in the delta. In this manner, the major part of the sediment, including silts and clays, can be retained in the upstream portion of the pool.

- *Construction of debris basins.*—The U.S. Army Corps of Engineers, the U.S. Bureau of Reclamation, and the U.S. Natural Resources Conservation Service, among others, have designed and installed debris basins in mountainous areas. These are essentially reservoirs, generally located in canyons, designed to catch the coarse sediments and prevent their being carried downstream onto residential or other critical areas. In some cases where the topography permits adequate storage, the debris basins are designed to hold a 5-year or more sediment inflow, but the basins are more often designed to hold the sediment from a 100-year frequency storm plus the sediment yield of 2 or 3 average years. The basins are maintained by periodically removing the accumulated sediment by mechanical means. Where these structures are above reservoirs, they can be an effective means of reducing the amount of sediment transported to the reservoirs.

- *Trap efficiency.*—The actual accumulation of sediment in a reservoir depends on the proportion of the inflowing sediment that will be retained in the reservoir (i.e., trap efficiency). Two empirical relationships commonly used by engineers for estimating trap efficiency are those proposed by Brune (1953) and Churchill (1948).

- *Sediment storage planning.*—The major steps of reservoir sediment storage planning are determining:
  - watershed sediment yield
  - sediment inflow
  - amount of sediment trapped
  - location of reservoir sediments
  - distribution of reservoir sediments
  - sediment control measures needed
- *Estimation of reservoir life.*—Most of the prediction methods are based on measurements or computer model simulations. However, existing records can give us a general indication of sedimentation rate and useful life of reservoirs.

A study of several large reservoirs with large trap efficiencies (Table 6.7) indicates that the ratio of storage capacity to average annual water inflow is a good indicator of the reservoir's storage life. When the ratio of acre-feet of storage capacity to acre-feet per year of inflow is less than 1, the storage life of the reservoir is measured in tens of years. When the ratio is larger than 1.5, the storage life is measured in hundreds of years (Richardson, 1996).

Table 6.7. Statistics of listed reservoirs (Richardson, 1996)

| River | Lake or dam | Millions |  |  | Ratio capacity/ inflow | Trap efficiency estimated | Reservoir life years |
|---|---|---|---|---|---|---|---|
|  |  | Storage capacity (ac-ft) | Water inflow (ac-ft/yr) | Sediment inflow (t/yr) |  |  |  |
| Nile | Nasser | 133.1 | 68.1 | 140 | 1.95 | 99% | 1,000+ |
| Nile | Old Aswan | 5.0 | 67.8 |  | 0.07 | 0.01% | Forever |
| Indus | Tarbela | 11.1 | 63.0 | 397.4 | 0.18 | 99% | 50 to 100 |
| Colorado | Mead | 32.5 | 13.4 | 142.9 | 2.43 | 99% | 1,000+ |

## 6.5 Design of Intakes

### 6.5.1 Location of Intakes

Tan (1996) summarized the basic criteria for selection of intake structure locations as follows:

- An intake should be located on a stable reach without frequent wandering of a flow path.
- The concave bank of a bend is an ideal location for an intake because it can divert relatively clear water with low sediment concentration.
- An intake on a straight reach is usually not favorable for preventing sediment from entering it.

- An intake should be as far as possible from the confluence of a tributary to avoid disturbing and complicating the flow pattern in front of the intake.

### 6.5.2 Types of Intakes for Sediment Control

Five types of intakes can be used for sediment control. They are intakes with sluice gates, lateral intakes, tiered intakes, bend-type intakes, bottom-grate-type intakes, and combined intakes (Tan, 1996). Each type of intake is adapted to certain conditions.

*Intakes with sluice gates.*—This type of intake is widely used. The diversion works are generally composed of flood sluice gates, desilting sluice gates, intakes, and other structures. The intake is usually located near desilting sluices and flood sluices to keep the main flow close to the intake. The axis of intake may be parallel, oblique, or perpendicular to the riverflow. Generally, a smaller angle is favorable for decreasing sediment entering an intake.

*Lateral intakes.*—This type of intake is still widely used in various diversion works because of the simplicity in the layout. An effective measure to improve the efficiency of lateral intakes for sediment control is to enhance the sediment-carrying capacity of flow in front of intakes by means of facilities such as circulation sluicing flumes, sediment intercepting devices, and releasing galleries. The approaching flow may also be regulated and directed toward the intakes by river training works such as guide walls, spurs, and vanes.

*Tiered intakes.*—The tiered intake has a double set of stairs of gate openings separated by a horizontal diaphragm. The upper opening is for a water diversion, and the lower opening is for sediment sluicing. This type of intake has been used in some mountain rivers in Middle Asia which are characterized by steep slopes (1/60 to 1/120), coarse sediment, and large seasonal variation of discharge. Tiered intakes also were constructed at Milburn Diversion Dam and Arcadia Diversion Dam on the Middle Loup River in Nebraska in the United States, where they were called short undersluice tunnels.

Generally, the tiered intake is appropriate for the conditions of a small watershed and a large river discharge (much more than diversion discharge). However, tiered intake structures are relatively complicated, water consumption for releasing sediment is large, and preventing floaters (timber, ice, garbage, etc.) from entering the intake is difficult. In practice, these factors limit, to a certain extent, the wide application of tiered intakes.

*Bend-type intakes.*—Bend-type intake refers to a combination of intake, sluice, and a natural, trained, or artificial bend in which the bend plays a key role for sediment control. The intake is commonly built on the concave bank at the end of a bend to divert water by meeting the main current and to release sediment toward the side under the effect of secondary flow in the bend.

A typical, artificial, bend-type intake consists of an upper flood escape, a diversion bend, and a water intake and sediment sluice at the end of the diversion bend. In fact, the effect of secondary flow in a bend, and the relevant principle of diverting water by meeting the main current and releasing sediment toward the side, are applied here twice. First, in inlet flood escape, most of the incoming sediment is flushed downstream through the flood escape. Second, in the combination of the intake and the sediment sluice, most of the sediment that enters the bend is released through the sediment sluice. Consequently, little sediment can enter the intake.

The bend-type intake is commonly suitable for mountain rivers carrying bedloads of gravel, cobbles, and coarse sand. Bend-type intakes have been widely built in Middle Asia and Western China.

*Bottom grate-type intakes.*—A bottom grate-type intake is usually built on medium and small mountain creeks with steep slopes and torrential currents carrying a great amount of large-sized bedload, such as gravels, pebbles, and cobbles.

This type of intake consists mainly of a weir with a bottom grate intake, diversion gallery, or canal, sluice, and spillway. When the current carrying sediment overflows the bottom grate on top of the weir, sediment coarser than the spacing between grate bars is excluded by the bars and carried downstream by the flow; the water passes through the grate and into a diversion gallery. A bottom grate intake commonly has a small diversion discharge and is characterized by a simple structure, easy construction, low cost, convenience of management, and high efficiency of coarse sand prevention. Therefore, the bottom grate intake is widely used in some rivers to keep the upstream channel straight. Some blocks or guide vanes can be provided for improving the flow condition.

*Combined intakes.*—A combination intake composed of a vortex tube, curved desilting channel, and settling basin can be used to control the amount of sediment inflow (Tan, 1996).

The vortex tube is a tube with a top slot that is set in the bottom of a diversion canal for releasing bedload. Water entering the tube forms a strong spiral flow that can raise coarse particles and cause them to be suspended and carried downstream. A major problem of the vortex tube is the inlet dimension and possible blockage by small trash. In a stream with floating and submerged trash and twigs, some provisions for clearing are necessary.

A curved desilting channel is a section of a diversion channel that has a broadened cross-section and curved route. This type of channel is used mainly to allow coarse sand and gravel to settle out and keep from entering the diversion canal. Because velocity decreases in the broadened section, the coarse particles descend to the channel bed and move toward a convex bank under the effect of circulation flow developed at the curved channel. Then, the coarse particles are flushed out through sediment sluicing galleries placed at the bottom of the convex bank.

A settling basin is a wider and deeper section of a diversion canal. It is mainly used to precipitate suspended load by providing a greater cross-section with less velocity and to exclude the suspended load through sediment-releasing facilities. A settling basin commonly consists of a diffuser, settling chamber, contractor, and sediment-releasing works.

## 6.6 Sediment Management for Large Reservoirs

The basic sediment management principle for large reservoirs is to alleviate reservoir sedimentation by sluicing density current and hyperconcentrated density current, and storing clear and flushing turbid water (Wan, 1996). Density current is a sediment-laden flow of greater density than that of clear water entering a reservoir.

A density current may carry a large amount of sediment and pass a long distance along a reservoir bed without mixing with surrounding clear water. Whether a density current can keep moving depends on two conditions. First, the incoming sediment-laden flow must be maintained. Once the incoming flow recedes and a turbid water supply is no longer available at the inlet of the reservoir, the density current will stop moving. Second, the density current must be strong enough to overcome the resistance along the path through the reservoir.

A density current reaching the damsite can be released only if some bottom sluices at a low enough elevation are open. Depending on the transition of its kinetic energy into potential energy, a density current can climb a certain height, but the height is not great.

The continuous motion of a density current depends on the sediment concentration of the incoming flow and the content of fine particles in it; the duration of the incoming flow; the magnitude of flow discharge; and the topography along its course, such as bends, abrupt expansions, and the slope of the reservoir bottom.

In reservoir sediment management, proper timing of the operation of sluices is important once a density current is formed at the inlet. If bottom sluices are opened much before the density current reaches the damsite, clear water will be released and wasted. If bottom sluices are closed when a density current reaches the damsite, sediment particles in the density current will deposit and cause siltation.

Due to the large density difference between the current and the clear water, a hyperconcentrated density current moves at a much higher velocity than a common density current. Because hyperconcentrated fluid possesses a higher yield stress and high viscosity, the interfacial mixing between the upper clear water and the lower hyperconcentrated density current is weak, and sediment particles in the hyperconcentrated water either do not settle or settle very slowly. Consequently, little deposition occurs, no obvious sorting phenomenon happens, and high concentration can be maintained while a hyperconcentrated density current passes through a reservoir.

For most rivers, runoff and sediment load are unevenly distributed among seasons. Most incoming flow and sediment are concentrated in flood season, with sediment load being the most uneven. For instance, at Sanmenxia on the Yellow River, 60 percent of the runoff and 85 percent of the sediment come in the flood season. The reservoir pool is lowered in the flood season so that the slope and velocities are high, increasing the sediment-carrying capacity of the flow. All of the incoming sediment in the flood season, and sometimes even the deposition in the preceding non-flood season, can be flushed out of the reservoir. In this way, sedimentation in the reservoir can be avoided or mitigated, and the storage capacity of the reservoir can be preserved for long-term usage. Chinese engineers refer to such a strategy as "storing clear water in the non-flood season and flushing turbid water in the flood season."

The uneven distribution of incoming runoff and sediment load and some amounts of available incoming runoff in non-flood season are the necessary hydrological conditions for adopting such a strategy. To lower the pool during floods, the dam must be equipped with bottom sluices of large enough sizes. Even if the pool is lowered, only the sediment in the channel within a certain width can be flushed. Flood plain deposits cannot be eroded. Therefore, a gorge-shaped reservoir (i.e., a reservoir with narrow cross-section) favors the adoption of such a strategy (Wan, 1996).

Associated with the storage of water in a reservoir, flow velocity decreases in backwater regions and sediment carried by the flow is deposited and creates a delta. The water level over the delta region rises simultaneously with the downstream development of the delta. This rise further decreases the flow velocity in this region and causes more deposition. Such a feedback phenomenon is called retrogressive deposition (Wan, 1996).

Retrogressive deposition may slow down incoming flow and attract more sediment more rapidly. This could create favorable conditions for dense aquatic growth and marsh weeds in the backwater reach, and the conditions would then spread upstream gradually. As a result, the delta can develop rapidly. The impact of retrogressive deposition on the environment should be studied.

## 6.7 Sediment Management for Small Reservoirs

Although the general strategies for reservoir sediment management are the same for large reservoirs and small reservoirs, sediment management practices for those two categories of reservoirs are often as different as their magnitudes. Some of the measures commonly used to reduce reservoir sedimentation, mainly for small reservoirs, are summarized in the following sections.

### 6.7.1 Soil Conservation

In the upstream watershed of a reservoir, three basic patterns of soil conservation measures are commonly taken to reduce sediment load entering the reservoir: structural measures, vegetative measures, and tillage practice. Structural measures include terraced farmlands, flood interception and diversion works, gully head protection works, bank protection works, check dams, and silt-trapping dams. Vegetative measures include growing soil and water conservation forests, closing off hillsides, and reforestation. Tillage practice includes contour farming, ridge and furrow farming, pit planting, rotation cropping of grain and grass, deep ploughing, intercropping and interplanting, and no-tillage farming.

The effectiveness of soil conservation measures in reducing sediment inflow to a reservoir is different for different watershed sizes. For a large watershed with poor natural conditions, soil conservation can hardly be effective in the short term. Nevertheless, if the watershed is not large, the effect of soil conservation can be felt in a short period.

### 6.7.2 Bypass of Incoming Sediment

Rivers, especially sediment-laden rivers, carry most of the annual sediment load during the flood season. Bypassing heavily sediment-laden flows through a channel or tunnel may avoid serious reservoir sedimentation. The bypassed flows may be used for warping, where possible. Such a combination may bring about high efficiency in sediment management.

When heavily sediment-laden flows are bypassed through a tunnel or channel, reservoir sedimentation may be alleviated to some extent. In most cases, however, the construction cost of such a facility is high. Where a unique topography is available, the cost of construction may be reduced and bypassing facilities may be practical.

### 6.7.3 Warping

Warping has been used around the world. It has a history of more than 1,000 years in North and Northwest China as a means of filling low land and improving the quality of salinized land. Now, this practice may have a dual role, not only improving the land but also reducing sediment load entering reservoirs. Warping is commonly carried out in flood seasons, when the sediment load is mainly concentrated, especially in sediment-laden rivers. Warping can also be used downstream from dams when hyperconcentrated flow is flushed out of reservoirs.

### 6.7.4 Joint Operation of Reservoirs

Joint operation of reservoirs is a rational scheme to fully use the water resources of a river with cascade development. For sedimentation management of reservoirs built on sediment-laden rivers, such an operation may also be beneficial to mitigate reservoir sedimentation and to fully use the water and sediment resources, provided a reasonable sequence of cascade development is made. There are various patterns of joint operation of reservoirs built in semi-arid and arid areas. The idea is to use the upper reservoir to impound floods and trap sediment and to use the lower reservoir to impound clear water for water supply.

Another idea is to use the upper reservoir for flood detention and the lower reservoir for flood impoundment. Irrigation water in the lower reservoir is used first; when it is exhausted, the water in the upper reservoir is used. The released water from the upper reservoir may not only erode the deposits in the lower reservoir, but also cause warping by the sediment-saturated water.

### 6.7.5 Drawdown Flushing

Drawdown flushing is a commonly used method of recovering lost storage of reservoirs. It may be adopted in both large and small reservoirs. The efficiency of drawdown flushing depends on the configuration of the reservoir, the characteristics of the outlet, the incoming and outgoing discharges, sediment concentrations, and other factors.

### 6.7.6 Reservoir Emptying

Reservoir emptying operations may be used for small or medium-size reservoirs to recover a part of the storage capacity if temporary loss of water supply is acceptable. In the process of reservoir emptying, three types of sediment flushing occur: retrogressive erosion and longitudinal erosion, sediment flushing during detention by the base flow, and density current venting. Data on the three types of sediment flushing are shown for Dongxia Reservoir in Table 6.8.

Table 6.8. Sediment flushing from 1978 to 1981, Dongxia Reservoir (Zhou, 1996)

| Types of sediment flushing | Retrogressive erosion | Detention | Density current |
|---|---|---|---|
| Duration (hr) | 93 | 3,552 | 814 |
| Average sediment concentration (kg/m$^3$) | 172 | 125 | |
| Average discharge (m$^3$/s) | 14.5 | 2.8 | |
| Water used (million tons) | 4.87 | 35.1 | 24.7 |
| Sediment flushed (million tons) | 0.83 | 4.4 | 2.44 |
| Unit water consumption (m$^3$/t) | 5.9 | 8 | 10 |

### 6.7.7 Lateral Erosion

The technique of lateral erosion is to break the flood plain deposits and flush them out by the combined actions of scouring and gravitational erosion caused by the great transverse gradient of the flood plains. In so doing, it is necessary to build a low dam at the upstream end of a reservoir to divert water into diversion canals along the perimeter of the reservoir. The flow is collected in trenches on the flood plains.

During lateral erosion, because the surface slope of the flood plain is steep and the flow has a high undercutting capability, intensive caving-in occurs at both sides of the collecting trench. The sediment concentration of the flow may be as high as 250 kg/m$^3$. This technique has the advantage of high efficiency and low cost, and no machines or power are required.

### 6.7.8 Siphoning Dredging

Siphoning dredging makes use of the head difference between the upstream and downstream levels of the dam as the source of power for the suction of deposits from the reservoir to the downstream side of the dam.

Siphoning dredging has a wide range of applications in small and medium-size reservoirs. In China, it has been applied in semi-arid areas where the flushed water and sediment mixture has been diverted into farmland for warping. Such an application is valuable to solve reservoir sedimentation and to fulfill the demand of irrigation if the head difference is adequate and the distance between upstream and downstream ends of the siphon is not too great.

### 6.7.9 Dredging by Dredgers

Dredging is used to remove reservoir deposits when other measures are not suitable for various reasons. In general, dredging is an expensive measure. However, when the dredged material may be used as construction material, it may be cost effective.

### 6.7.10 Venting Density Current

Density currents have been observed in many reservoirs around the world. The conditions necessary to form a density current, and allow it to reach the dam and be vented out if the outlet is opened in time, have been studied extensively, both from the data of field measurements and laboratory tests. Venting of density currents is one of the key measures for discharging sediment from several reservoirs in China, especially from impounding reservoirs. Density current venting may be carried out under the condition of impoundment, thus maintaining the high benefit of the reservoirs.

### 6.7.11 Evaluation of Different Sediment Management Measures

An in-depth evaluation of different sediment management measures by Zhou (1996) lead to the following conclusions:

- Sediment management strategies for large reservoirs may be applied to small reservoirs, but not vice versa.

- Soil conservation measures are the most commonly adopted measures of reducing sediment inflow to reservoirs. They are effective in a relatively short period in small watersheds. They are also effective for a mid-ranged period in large watersheds.

- Bypassing the inflow of heavily sediment-laden floods to reservoirs, warping, or joint operation of reservoirs must be done under specific conditions before they can be adopted for reducing sediment inflow to reservoirs.

- Lost storage capacity can be partially recovered by drawdown flushing, reservoir emptying, lateral erosion, siphoning dredging, dredging, venting of density currents, and other methods. The method most suitable for a specific reservoir depends on many factors. In the planning and design stage, this issue should be carefully studied and an optimum choice made. Due to the complexity of sediment problems, however, the issue of recovering lost storage capacity should be re-examined during the operation of the project.

## 6.8 Effective Management of Reservoir Sedimentation

Effective management of reservoir sedimentation should consider the following factors (Tomasi, 1996):

- *Legislation.*—In most countries, laws and regulations prescribe quality standards for the material removed from a reservoir and regulate the performance of the maintenance operations should be established. Examples include the maximum values of sediment concentrations in a flushing operation and the maximum sediment and water quality parameters downstream.

- *Territorial constraints.*—Reservoir topographic features, riverbed characteristics prior to dam construction, and local morphology and land use may drastically limit the methodology to be adopted. For example, the absence of a place to store material removed from the reservoir, difficulties in accessing the reservoir, and other factors may preclude excavation or dredging.

- *Human activities.*—Socioeconomic development of the area may strongly influence the quality of the deposited material. In industrialized, overcrowded areas, water and sediment pollution problems will certainly be more frequent than in less populated areas. Environmental protection is often a high-priority constraint in several countries.

- *Economic aspects.*—Besides the economic value of the recovered storage, sediment may also be valuable for industrial purposes, such as construction activities and landscape improvement. The overall economic (cost-benefit) balance must also be carefully evaluated. In particular cases, such as drinking and irrigation water reservoirs in semi-arid areas, preserving reservoir capacity could be the dominant objective.

- *Safety.*—Human lives must be protected by performing periodic maintenance on the submerged structures and testing the operation of such systems. This implies the removal of sediments from the reservoirs by any means.

- *Type, size, and elevation of outlet structures.*—Many dams do not have bottom outlets or structures located low enough to enable drawdown flushing. The installation of bottom outlets after dam construction, solely for the purpose of sluicing and flushing, is believed to be uneconomical and, in many cases, from a technical point of view, infeasible.

- *Incoming flow and sediment.*—Inflow of water, sediment yield, and sediment aggradation are the basic factors to be considered in effective reservoir management. Fine sediment load may be generally reduced by soil conservation work in the watershed. Coarse sediment transported by the river can be temporarily intercepted (and subsequently removed) by trenches, check dams, debris basins, or other hydraulic structures upstream from the dam.

The selection of one or more sediment control strategies must be made by a multidisciplinary team with a multicriterion approach that should be flexible. Indeed, certain water uses, such as environmental purposes, tourism, and recreation, and certain constraints have acquired a higher priority in the last decades. The selected methodology or combination of methodologies should represent a compromise among the parties that use the water. In this compromise, the environment, social needs, and other concerns must be evaluated carefully.

## 6.9 Operational Rules

The operational rules of reservoirs have significant influence on reservoir sedimentation. Three basic types of operating rules have been adopted around the world: impoundment, impounding the clear and discharging the muddy, and flood detention. The first two types are more often adopted in China. In Table 6.9, some basic characteristics of reservoir operating rules are listed.

Table 6.9. Operating rules of reservoirs (Zhou, 1996)

| Operating rule | Regulation of sediment | Method of sediment sluicing | Period of sediment sluicing |
|---|---|---|---|
| Sediment totally impoundment trapped | None | None or dredging | None |
| Sediment partly trapped | None | Density current venting, sluicing | Beginning of flood seasons |
| Impounding clear and discharging turbid | Yearly or seasonally | Discharging sediment during detention, density current, venting, etc. | Flood seasons |
| Detention | None | Discharging sediment during detention, reservoir emptying | Flood seasons |

Unfortunately, in the United States, the basic operating rules for reservoirs have been neglected for almost half a century. The above rules have been seriously considered as measures to alleviate reservoir sedimentation only after sedimentation problems in reservoirs built on heavily sediment-laden rivers have become acute.

If the operating rule of impoundment is adopted for a reservoir suitable for impoundment and detention, the benefit provided by the reservoir may be high in the short term, but reduced in the long term by the loss of reservoir storage. For a reservoir adopting the impoundment and detention operating rule, there are some conflicts between various function of the reservoir, as follows:

- *Conflicts with power generation.*—To fulfill the demands of sediment discharge, the pool level fluctuates significantly, resulting in the following problems:
  - The annual energy output of the project will be reduced somewhat, although the total energy output is larger in the long term.
  - The water level in the flood season is reduced, so it is necessary to design a turbine with a large discharge capacity to compensate for the reduction of head.
  - The variation of the water level in the reservoir is quite large, so the design of the turbine is more difficult than under typical conditions.

Because the flow with high sediment concentration may pass through the turbine, abrasion of the runner and other turbine parts may be serious, resulting in reduced efficiency and lifespan of the turbine. Cooling water systems may be choked by sediment particles.

- *Conflicts with irrigation.*—Because discharging sediment requires a large amount of water, conflicts between sediment discharge needs and irrigation needs may develop.
- *Changes in the downstream channel.*—Reservoirs under the operating rule of impoundment and detention alter the relationship between waterflow and sediment loads released from the reservoir, but the change is not as large as that under the operating rule of impoundment. Nearly clear water will be released from impounding reservoirs, resulting in downstream channel degradation. If a reservoir is operated in two stages, impoundment in the first stage followed by impoundment and detention in the second stage after the deposition of considerable volumes of sediment in the reservoir, the discharged sediment load will induce a new problem in the downstream river channel, which would have adjusted to the conditions of clear water releases.

## 6.10 Cost of Sedimentation Prevention and Remediation

Cost and other economic considerations are driving factors in determining the type, amount, and timing of remediation of reservoir sedimentation. Reservoir dredging and other remediation measures can be very costly, sometimes even exceeding the initial cost of constructing the reservoir. Capital, like many other commodities, is a limited resource and is best expended where there is the expectation of greatest benefit. Unfortunately, the benefits of remediation measures are not always obvious to those who manage the purse strings, and funding for remedial work is, therefore, difficult to obtain, even in wealthy countries. It is up to the sedimentation engineer and reservoir operators to justify the need for remediation and to evaluate the costs and economic benefits of remediation to obtain funding approvals, regardless of whether the reservoir is privately or publicly owned (Harrison, 1996).

There can be substantial indirect economic losses associated with lost water supplies or lost hydrogeneration due to sedimentation. In underdeveloped regions of the world, there may not be alternative power or alternative water supplies when normal reservoir operations are shut down, resulting in interruption of service to customers for extended periods of time. The societal costs of such interruptions can range from personal hardship, to the shutting down of businesses and factories, to loss of life. Unreliable water and electric power supplies, for whatever reason, also may constrain the economic development of regions. In developed regions, other reservoirs and alternative power supplies, such as nuclear or fossil-fueled plants, would likely make up for sediment-related losses of supply. However, such alternatives might come at a substantially greater cost.

Costs for remedial actions vary widely. Dredging may range in cost from less than $2 to more than $50 per cubic meter, depending on site conditions and quantities. Flushing and sluicing options may, or may not, be less costly than dredging, depending on the value of the lost water, lost power generation, and environmental impacts. Also, flushing and sluicing may require substantial expenditures for constructing new, low-level sluice openings at a dam, if they were not provided in the original design. Watershed restoration programs may be relatively inexpensive for the reservoir operator if other beneficiaries can be enlisted to share in the costs. However, watershed management may take many years to become significantly effective, requiring interim dredging or other measures to continue operation of the reservoir. Strategies combining two or more types of remediation may be undertaken to achieve the most cost-effective, long-term solution, such as watershed management and sediment passthrough. The best and most cost-effective remediation plans for such reservoirs must be determined by identifying and evaluating all the alternatives and the resources available for implementation. However, even the best plans are of little value if no funds are available for implementation. In that case, compromises may be necessary (Harrison, 1996).

## 6.11 Reservoir Sustainability Criteria

Criteria to ensure the sustainability of reservoirs can be divided into three categories: safety, reduction of sediment inflow, and environmental compatibility. Safety standards must be met for dams, rock slopes, earthquakes, floodflows, structural behavior, aging, and rehabilitation. Safety concerns should be addressed in the engineering design, construction, and operation of dam projects (Veltrop, 1996).

A variety of methods have been applied over the years to reduce sediment inflow. These include erosion control through soil conservation, contour building and terracing of steep slopes in catchment areas, trapping sediments behind check or debris dams, reforestation or revegetation of denuded areas, and providing vegetation screens of shrubs or weeds. Because control of large drainage areas is difficult, prevention of sediment inflow is often impractical. Therefore, efforts to remove sediments from reservoirs abound.

Sustainability also requires: (1) studies and implementation of mitigatory measures to counter the impacts of dams and reservoirs on the natural environment (maintenance of ecosystems, water quality, temperature, etc.), (2) social acceptance, (3) quality of life, and (4) economic justification and financial support. Public acceptance of dams and reservoirs requires that these engineering works be in tune with the current ideas and values of society.

Sustainable use of reservoirs also requires:

- Greater use of hydrometeorological forecasts to improve the efficiency of reservoir operation
- Optimum operation of reservoirs to resolve conflicting release requirements, including establishing seasonal minimum instream releases
- Ecologically friendly operating rules
- Operational control of water levels to influence the habitat of disease carriers
- Reduced water losses through evaporation control
- Documented socioeconomic impacts of reservoir sedimentation, including the cost of storage loss

## 6.12 Technical Tools

Computer models are useful tools to simulate and predict the effects of erosion and sedimentation on the sustainable development and use of reservoirs. They are technical tools that enable planners, engineers, and policymakers to select an optimum solution among different alternatives. There are two types of computer models related to erosion and sedimentation: (1) those related to the erosion and sedimentation processes in rivers and reservoirs, and (2) those related to economic analysis of sustainable development and use of reservoirs. A brief introduction of some of the models, especially those developed by the U.S. Bureau of Reclamation, is given in the following sections.

### 6.12.1 GSTARS 2.0/2.1 Models

A generalized erosion and sedimentation model for alluvial rivers should be able to:

- Compute hydraulic parameters for open channels with fixed, as well as movable, boundaries
- Compute water surface profiles in the subcritical, supercritical, and mixed flow regimes (i.e., in combinations of subcritical and supercritical flows without interruption)
- Simulate and predict the hydraulic and sediment variations, both in the longitudinal and the transverse directions

- Simulate and predict the change of alluvial channel profile and cross-sectional geometry, regardless of whether the channel width is variable or fixed

- Incorporate site-specific conditions such as channel side stability and erosion limits

- Simulate bed sorting and armoring

The Generalized Stream Tube model for Alluvial River Simulation Version 2.0 (GSTARS 2.0), released by Reclamation (Yang et al., 1998), and its improved version GSTARS 2.1 (Yang and Simões, 2000) have the above capabilities. The stream tube concept was used in GSTARS 2.0/2.1 for water and sediment routing in a semi-two-dimensional manner. The adjustment of bed provides the variation in the vertical direction. Conjunctive use of energy and momentum equations enable computation of water surface profiles through subcritical, critical, and supercritical flows without interruption. The use of minimum total stream power theory (Yang and Song, 1986) provides the theoretical basis for the determination of channel width and depth adjustments. GSTARS 2.0/2.1 contains the following sediment transport formulas from which a user may choose:

- Ackers and White's 1973 method
- Engelund and Hansen's 1972 method
- Krone's 1962 and Ariathurai and Krone's 1976 methods for cohesive sediment transport
- Laursen's 1958 formula
- Meyer-Peter and Müller's 1948 formula
- Parker's 1990 method
- Revised Ackers and White's 1990 method
- Toffaleti's 1969 method
- Yang's 1973 sand and 1984 gravel transport formulas
- Yang's 1979 sand and 1984 gravel transport formulas
- Yang's 1996 modified formula for sediment-laden flows

Non-equilibrium sediment transport can also be simulated based on the theory introduced by Han (1980).

Some of the possible applications and features of GSTARS 2.0/2.1 are:

- The model can be used for water surface profile computations with or without sediment transport.

- It can compute water surface profiles through subcritical and supercritical flow conditions, including hydraulic jumps, without interruption.

- It can compute the longitudinal and transversal variations of flow and sediment conditions in a semi-two-dimensional manner, based on the stream tube concept. If only one stream tube is selected, the model becomes one dimensional. If multiple stream tubes are selected, both the lateral and vertical bed elevation changes can be simulated.

- The bed sorting and armoring computation based on sediment size fractions can provide a realistic simulation of the bed-armoring process.

- The model can simulate channel geometry changes in width and depth simultaneously, based on minimum total stream power.

- The channel side stability option allows simulation of channel geometry change, based on the angle of repose of bank materials and sediment continuity.

GSTARS 2.0/2.1 is a general numerical model developed for a personal computer to simulate and predict river morphologic changes caused by natural and engineering events. Although GSTARS 2.0/2.1 is intended to be used as a general engineering tool for solving fluvial hydraulic problems, it does have the following limitations from a theoretical point of view:

- GSTARS 2.0/2.1 is a quasi-steady flow model. Water discharge hydrographs are approximated by bursts of constant discharges. Consequently, GSTARS 2.0/2.1 should not be applied to rapid, varied, unsteady flow conditions.

- GSTARS 2.0/2.1 is a semi-two-dimensional model for flow simulation and a semi-three-dimensional model for simulation of channel geometry change. It should not be applied to situations where a truly two-dimensional or truly three-dimensional model is needed for detailed simulation of local conditions. However, GSTARS 2.0/2.1 should be adequate for solving most river engineering problems.

- GSTARS 2.0/2.1 is based on the stream tube concept. The phenomena of secondary current, diffusion, and superelevation are ignored.

GSTARS 2.0 is written for DOS PC operation. An improved and revised version, GSTARS 2.1, for Windows operation with graphic interface, was released by Reclamation in the year 2000 (Yang and Simões, 2000) to replace GSTARS 2.0.

### 6.12.2 GSTARS3 Model

The Generalized Sediment Transport model for Alluvial River Simulation Version 3.0 (GSTARS3) was developed by Reclamation to simulate the process of river and reservoir sedimentation (Yang and Simões, 2002). In addition to the capabilities of GSTARS 2.1 and GSTARS 2.0, GSTARS3 has the ability to simulate the formation of deltas, non-equilibrium sediment transport in a reservoir, the exchange of sediment across stream tubes, more extensive cohesive material transport capabilities, and fractional transport of sediment mixtures of vastly different sizes. GSTARS3 has the ability to simulate different reservoir operation schemes, including sluicing to remove sediment from a reservoir. Yang and Simões (1999) provided a summary report on the development of GSTARS 2.0, 2.1, and 3. Chapter 5 gives the basic principles and approaches used in sediment transport computer models, including those used in GSTARS 2.0/2.1/3.

### 6.12.3 GSTAR-1D Model

A new model developed by Reclamation is GSTAR-1D. GSTAR-1D was developed in cooperation with the U.S. Environmental Protection Agency for use in Total Maximum Daily Load (TMDL) studies. Its development was driven by the need to incorporate more physical processes associated with cohesive sediment transport and the ability to model unsteady flow. The user's manual and program have been released by the Bureau of Reclamation (Yang et al., 2004, 2005). In addition to most of the capabilities of GSTARS 2.1, GSTAR-1D has the following features:

- Computation of water surface profiles in single channels, simple channel networks, and complex networks
- Steady and unsteady flow models
- Cohesive sediment aggregation, deposition, erosion, and consolidation
- Multiple bed layers
- Flood plain simulation
- Exchange of water and sediment between main channel and flood plains
- Ability to limit erosion and deposition at cross-sections
- Point and non-point sources of flow and sediments
- Internal boundary conditions, such as time-stage tables, rating curves, weirs, culverts, bridges, dams, and radial gates

### 6.12.4 GSTAR-W Model

Another model being developed by Reclamation is GSTAR-W (Yang, 2002). This is an erosion and sedimentation model for river systems in a watershed. GSTAR-W will integrate capabilities of GSTARS 2.1, GSTARS3, and GSTAR-1D for river and reservoir systems in a watershed for the determination of TMDL under different hydrologic, hydraulic, topographic, and geologic conditions at any location in a watershed. The concepts, theoretical basis, and approaches used in the GSTAR-W model are summarized by Yang et al. (2003).

### 6.12.5 Economic Model

To determine the sustainability of a reservoir requires an economic model, in addition to hydraulic and sedimentation models. An economic model should select the size and other controllable characteristics of a reservoir, sediment management strategy, and the useful life of the reservoir to maximize the net benefits. Palmieri et al. (1998) express this concept by the following equation:

$$\begin{aligned}\text{maximize} \int_0^T & NB\left(P,CD,CH,CP_0,CP_t,X_t\right)e^{-rt}dt \\ & -C_0\left(P,CD,CH,CP_0\right)+SV\left(P,CD,CH,CP_0\right)e^{-rT}\end{aligned} \tag{6.7}$$

subject to

$$\begin{aligned} dCP/dt &= -M_t + X_t \\ CP_t &\geq 0 \end{aligned} \tag{6.8}$$

where $NB$ = net benefits (i.e., benefits - costs of operating and maintaining the dam),
$P$ = vector of prices,
$CH$ = vector of site characteristics,
$CD$ = vector of dam characteristics and functions,
$CP_0$, $CP_t$ = initial reservoir capacity and remaining capacity at time $t$, respectively,
$M_t$ = mean sediment yield at time $t$,
$X_t$ = sediment removal at time $t$,
$C_0$ = initial setup costs,
$r$ = interest rate,
$SV$ = salvage value,
$T$ = operating lifetime, and
$t$ = time.

The economic model can be used to select the optimum initial design reservoir capacity $CP_0$, dam characteristics and functions $CD$, sediment removal $X_t$, and a reservoir economic operating lifetime $T$.

## 6.13 Summary

This chapter provides a brief review and summary of technology available in the sustainable development and use of reservoirs where erosion and sedimentation should be considered. This study reached the following conclusions:

- The concept of "dead storage" for reservoir sedimentation of limited useful life is not consistent with the concept of sustainable use of reservoirs.

- The concept of sustainability should be used for future reservoir planning, design, and operation.

- Thorough and systematic approaches should be used in evaluating the impacts of erosion and sedimentation on sustainable development and use of reservoirs.

- Different engineering methods are available to remove or reduce the amount of sediment in a reservoir.

- River hydraulics and sediment transport computer models are available, or are being developed, to make detailed analyses and predictions of the impacts of river morphology and sedimentation processes on sustainable use and operation of a reservoir. The minimum energy dissipation rate theory, or the simplified versions of minimum unit stream power and minimum total stream power, can be used as a theoretical basis for developing these models.

- An economic model to maximize the net benefit should be used in the selection of reservoir size and useful life, subject to controllable reservoir characteristics and management strategy.

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