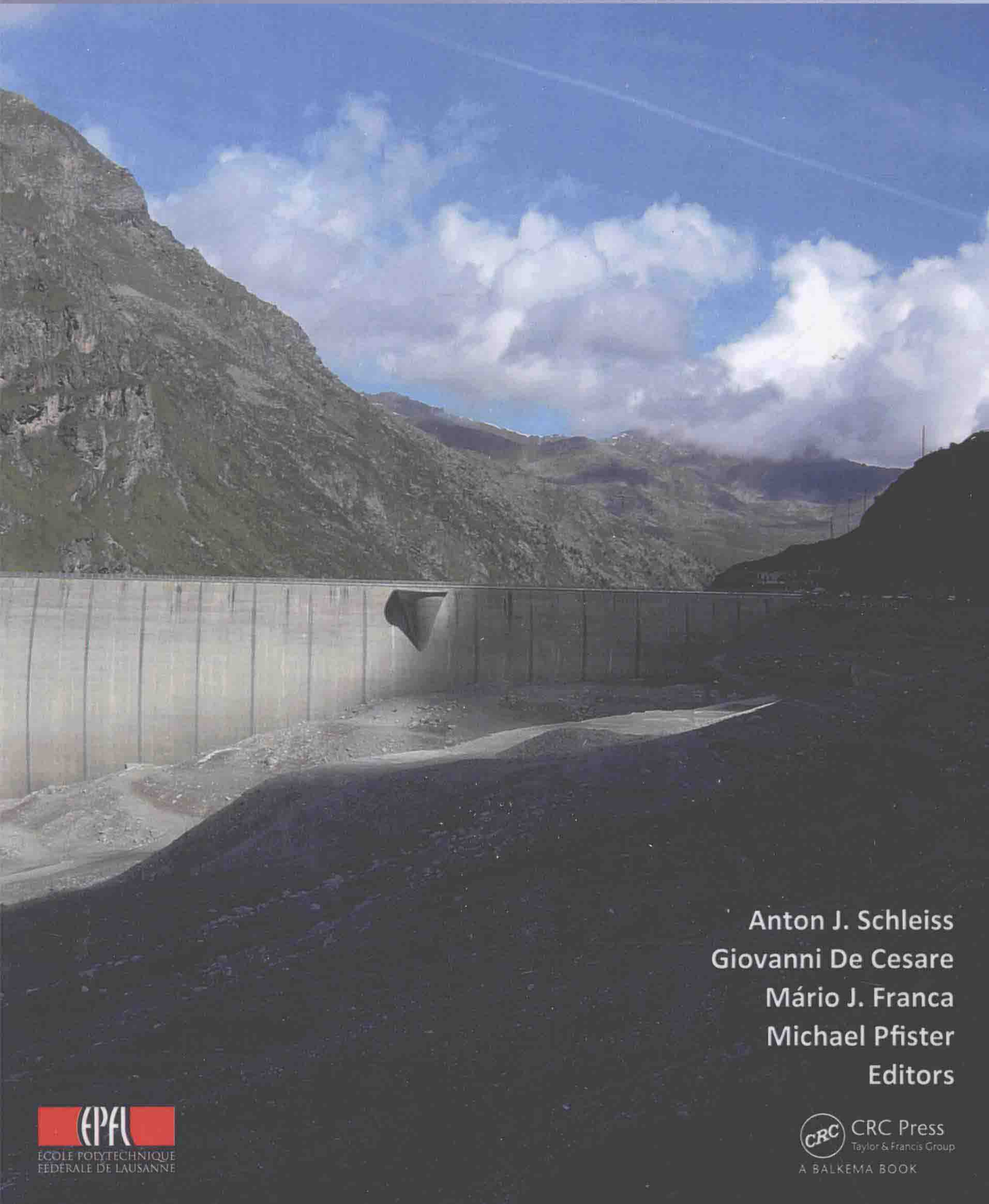
Reservoir Sedimentation



Anton J. Schleiss
Giovanni De Cesare
Mário J. Franca
Michael Pfister
Editors

EPFL
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

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Editors

Anton J. Schleiss, Giovanni De Cesare, Mário J. Franca & Michael Pfister

Laboratoire de Constructions Hydrauliques (LCH)
École Polytechnique Fédérale de Lausanne (EPFL), Switzerland

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Preface

Despite the mechanisms of reservoir sedimentation being well known for a long time, sustainable and preventive measures are rarely taken into consideration in the design of new reservoirs. To avoid operational problems of powerhouses, sedimentation is often treated for existing reservoirs with measures which are efficient only for a limited time. Since most of the measures will lose their effect, the sustainable operation of the reservoir and thus the water supply, as well as production of valuable peak energy is endangered. Today's worldwide yearly mean loss of reservoir storage capacity due to sedimentation is already higher than the increase of capacity by the addition of new reservoirs for irrigation, drinking water, and hydropower. Depending on the region, it is commonly accepted that about 1–2% of the worldwide capacity is lost annually. In Asia, for example, 80% of the useful storage capacity for hydropower production will be lost by 2035. The main sedimentation process in narrow and long reservoirs is the formation of turbidity currents, transporting fine sediments near to the dam every flood season, increasing sediment levels up to 1 m per year. The outlet devices including intakes and bottom outlets are often affected after only 40 to 50 years of operation, even in catchments with moderate surface erosion rates. The effects of climate change will considerably increase the sediment yield of reservoirs in the future, mainly in Alpine regions due to glacier retreat and melting of permafrost grounds.

The today's challenge of dam owners and engineers is to guarantee with adequate mitigation measures, the future sustainable use of the vital reservoirs supplying water for drinking, food and energy production. Research and development is still urgently needed to identify efficient mitigation measures adapted to the main sedimentation processes involved in reservoirs.

During the Seventh International Conference on Fluvial Hydraulics "River Flow 2014" at École Polytechnique Fédérale de Lausanne (EPFL), Switzerland, scientists and professionals from all over the world addressed the challenge of reservoir sedimentation in a special session and exchanged their knowledge and experiences. The conference was organized under the auspices of the Committee on Fluvial Hydraulics of the International Association for Hydro-Environment Engineering and Research (IAHR). Invited and selected contributions, which give an overview on the latest developments and research regarding reservoir sedimentation including case studies, are presented in this book, hoping that they can contribute to better sustainable use of the vital reservoirs worldwide. We acknowledge the support of the Swiss Federal Office for the Environment, BG Consulting Engineers, and Hydro Exploitation SA as main sponsors for the Proceedings and the River Flow 2014 Conference. Further sponsoring was obtained from e-dric.ch, IM & IUB Engineering, Basler & Hofmann, Aqua-Vision Engineering and Met-Flow SA.

The Laboratory of Hydraulic Constructions (LCH) of EPFL carried out the organization of the special session on reservoir sedimentation in the frame of River Flow 2014.

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Table of contents

Preface vii

Organization ix

Sponsors xi

Reservoir sedimentation

Sustainable water supply, climate change and reservoir sedimentation management: Technical and economic viability 3
G.W. Annandale

Three-dimensional numerical modeling of flow field in rectangular shallow reservoirs 11
T. Esmaeili, T. Sumi, S.A. Kantoush, A.J. Schleiss & S. Haun

Meandering jets in shallow rectangular reservoir 21
Y. Peltier, S. Erpicum, P. Archambeau, M. Pirotton & B. Dewals

Combination of 2D shallow water and full 3D numerical modeling for sediment transport in reservoirs and basins 31
G. Wei, M. Grünzner & F. Semler

Photometric analysis of the effect of substrates and obstacles on unconfined turbidity current flow propagation 37
J.M. McArthur, R.I. Wilson & H. Friedrich

Advances in numerical modeling of reservoir sedimentation 45
S. Kostic

Innovative in-situ measurements, analysis and modeling of sediment dynamics in Chambon reservoir, France 53
M. Jodeau, M. Cazilhac, A. Poirel, P. Negrello, K. Pinte, J.-P. Bouchard & C. Bertier

Measurements of spatial distribution of suspended sediment concentrations in a hydropower reservoir 63
S. Haun & L. Lizano

Case studies of reservoir sedimentation as a consequence of soil erosion 71
V. Hrissanthou

The impact of flow transformations and reservoir floor topography on reservoir deposition patterns in high energy environments 81
F. Weirich

Reservoir sedimentation and erosion processes in a snow-influenced basin in Southern Spain 91
A. Millares, M.J. Polo, A. Moñino, J. Herrero & M.A. Losada

Suspended sediment dynamics of Ribarroja Reservoir (Ebro River, Spain) 99
M. Arbat-Bofill, E. Bladé, M. Sánchez-Juny, D. Niñerola & J. Dolz

The use of Flow Assisted Sediment Transport (FAST) to remove sediment from reservoirs in Southern California, USA 109
F. Weirich

Two approaches to forecasting of sedimentation in the Stare Miasto reservoir, Poland 119
T. Dysarz, J. Wicher-Dysarz & M. Sojka

Influence of geometry shape factor on trapping and flushing efficiencies 129
S.A. Kantoush & A.J. Schleiss

Flushing of coarse and graded sediments – a case study using reduced scale model 139
J.R.M. Almeida, J.J. Ota, F.R. Terabe & I.I. Muller

1D modelling of fine sediments dynamics in a dam reservoir during a flushing event 147
L. Guertault, B. Camenen, A. Paquier & C. Peteuil

Numerical analysis of sediment transport processes during a flushing event of an Alpine reservoir 155
G. Harb, C. Dorfmann, J. Schneider & H. Badura

Modelling suspended sediment wave dynamics of reservoir flushing 163
T.H. Tarekegn, M. Toffolon, M. Righetti & A. Siviglia

Numerical modeling of suspended sediment transport during dam flushing: From reservoir dynamic to downstream propagation 175
G. Antoine, A.-L. Besnier, M. Jodeau, B. Camenen & M. Esteves

St-Egrève reservoir – modelling of flushing and evolution of the channel bed 185
E. Valette, P. Tassi, M. Jodeau & C. Villaret

Sequential flushing of Verbois and Chancy-Pougny reservoirs (Geneva, Switzerland) 195
E.F.R. Bollaert, S. Diouf, J.-L. Zanasco & J. Barras

Simulation of the flushing into the dam-reservoir Paute-Cardenillo 203
L.G. Castillo, J.M. Carrillo & M.A. Álvarez

Comprehensive numerical simulations of sediment transport and flushing of a Peruvian reservoir 211
A. Amini, P. Heller, G. De Cesare & A.J. Schleiss

Sediment bypass tunnels to mitigate reservoir sedimentation and restore sediment continuity 221
R.M. Boes, C. Auel, M. Hagmann & I. Albayrak

Modeling long term alternatives for sustainable sediment management using operational sediment transport rules 229
S.A. Gibson & P. Boyd

Global analysis of the sedimentation volume on Portuguese reservoirs 237
F. Taveira-Pinto, L. Lameiro, A. Moreira, E. Carvalho & N. Figueiredo

Reservoir sedimentation management at Gebidem Dam (Switzerland) 245
T. Meile, N.-V. Bretz, B. Imboden & J.-L. Boillat

Keyword index 257

Author index 259

Reservoir sedimentation

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Sustainable water supply, climate change and reservoir sedimentation management: Technical and economic viability

G.W. Annandale
Golder Associates Inc., Denver, Colorado, USA

ABSTRACT: The paper considers the effects of climate change and reservoir sedimentation on water supply reliability and sustainability. From a global fresh water supply perspective it is argued that river water has the greatest potential for sustainable development. The known fact that reservoir storage is required to reliably supply water from rivers leads to the conclusion that provision of such space will become even more important in the future due to the uncertainties of increased hydrologic variability associated with climate change. The limited availability of dam sites emphasizes the need to indefinitely maintain reservoir storage space for use by future generations, thereby ensuring sustainable development. The current undesirable situation that is characterized by more reservoir storage space being lost to sedimentation than is added through construction of new facilities points to the importance of implementing reservoir sedimentation management techniques. Historically, its implementation has been hampered by an incorrect perception that reservoir sedimentation management is not economically viable. To transform this view it is necessary to acknowledge the dual nature of reservoir storage, i.e., it can be either renewable or exhaustible depending on design and operating decisions. Correct characterization of reservoir storage space and implementation of principles of the economics of exhaustible resources quantifies the value to reservoir sedimentation management, previously ignored. Sustainable and reliable supply of fresh water in the future demands changes in engineering and operating paradigms and changes in the ways dams and their reservoirs are economically evaluated.

1 INTRODUCTION

Global fresh water supply is in crisis, due to increasing world population, non-sustainable development and use of water resources and the imminent threat associated with climate change. This paper provides a high-level review of the potential sustainability of abundantly available fresh water sources and identifies the preferred source for future development, i.e., river water. It confirms the need for storage to reliably supply fresh water from rivers and clearly demonstrates that the need for large reservoir storage spaces will increase in the future to reliably supply fresh water from rivers under climate change scenarios. The limited availability of suitable dam sites to develop the required reservoir storage space and the threat of reservoir sedimentation, which reduces available reservoir storage space, emphasizes the importance of sustainable development. With reservoir sedimentation being the single greatest threat to losing reservoir storage space, the importance of reservoir sedimentation management is emphasized. Indefinitely preserving reservoir storage space for use by future generations is of critical importance. Viable reservoir sedimentation management techniques exist, but their implementation has been hampered in the past due to the incorrect perception that such management approaches are not economically viable. This notion originates from standard discounting procedures used in economic analysis, which merely represents current cultural values but is not in compliance with the principles of sustainable development, i.e., a desire for fairness between current and future generations—a concept known as creation of intergenerational equity. By highlighting the dual nature of reservoir storage space it is argued that correct use of the principle of the economics of exhaustible resources results in decisions favoring the use of reservoir sedimentation management technology to ensure sustainable development of water resource infrastructure.

2 SUSTAINABLE FRESH WATER SOURCES

The two principal and most abundantly available sources of fresh water are groundwater and river water. Identification of the source with the greatest potential for sustainable development requires consideration of principles proposed by Herman Daly, an economist who participated in the development of sustainable development policy guidelines for the World Bank. He proposed for sustainable development to occur that a) renewable resources should be used at a *rate* that is smaller than their *rate* of regeneration, b) exhaustible resources should be used at a *rate* that is smaller than the *rate* of development of renewable substitutes, and that c) pollution should not exceed the *rate* by which the environment can assimilate it.

Due to the hydrologic cycle both groundwater and surface water may be viewed as renewable and both have the potential for sustainable development if the *rate* of usage does not exceed the *rate* of replenishment. Globally, it has been found that groundwater is not sustainably developed nor used. Gleeson et al. (2012) found that 3.5 times more groundwater is globally used than what is replenished. Konikow (2011) sets average groundwater depletion since 1900 at about 4,500 km^3, which equals the net storage space of all large reservoirs on earth. This non-sustainable use of groundwater is attributed to the large difference between global replenishment rates of groundwater (about 1,400 years) (Shiklomanov & Rodda 2003) and daily usage rates. In contrast Shiklomanov & Rodda (2003) estimates the global replenishment rate of river water at about 16 to 18 days, which is much closer to the daily rate of abstraction of water. This indicates that river water has a much greater potential for sustainable development.

3 NEED FOR STORAGE

By selecting river water as the preferred source for sustainable development of water supply systems the indispensable need for storage to reliably supply fresh water is acknowledged. Storage is required to smooth out seasonal variations in river flow, which in some places may also vary significantly from year to year. Regions with high inter-annual hydrologic variability require

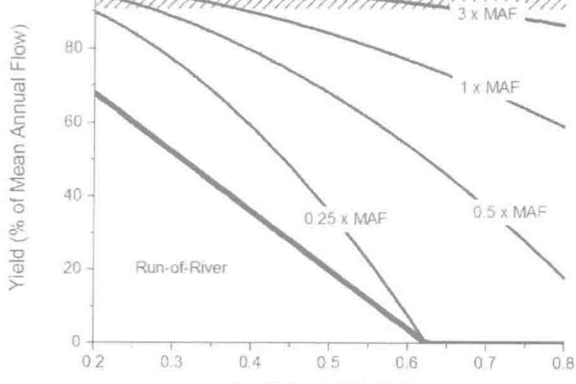

Figure 1. Relationship between yield, annual coefficient of variation of river flow (standard deviation divided by the mean) and reservoir storage volume (expressed in terms of mean annual flow – MAF) for 99% reliability of supply. Bold line separates run-of-river and multiple-year storage states (Annandale 2013).

large reservoir storage volumes to enable reliable supply of water during multiple-year droughts. Figure 1, based on the Gould-Dincer approach (McMahon et al. 2007) distinguishes between run-of-river and storage requirements, dependent on inter-annual hydrologic variability.

4 CLIMATE CHANGE AND ROBUST INFRASTRUCTURE

Global increases in hydrologic variability due to climate change (i.e., more intense and longer droughts, and greater floods) will have the greatest impact on water supply reliability. Although it is uncertain by how much hydrologic variability will increase, an impression of its impacts can be found by delineating how regions currently experiencing multiple-year droughts might expand. Figure 2(a) approximates regions of the world currently experiencing on a regular basis multiple-year droughts (two years or longer). Figure 2(b) is an estimate of how the area of such regions might expand if global hydrologic variability would increase by 25% (Annandale 2013). The figure implies that regions of the world currently using run-of-river projects or small reservoirs to reliably supply water will require much larger storage reservoirs in the future. For example, using the Gould-Dincer approach (McMahon et al. 2007), Figure 3 shows that if the annual coefficient of variation of riverflow increases from 0.4 to 0.5, then the yield will decrease from 60% of the Mean Annual Flow (MAF) to about 35% MAF for a reservoir with a volume equaling 0.25 MAF. In contrast, when using a reservoir with a volume equaling one times the MAF, the yield will decrease from 90% to about 85% of the MAF. Yield is therefore much less sensitive to increased hydrologic variability when

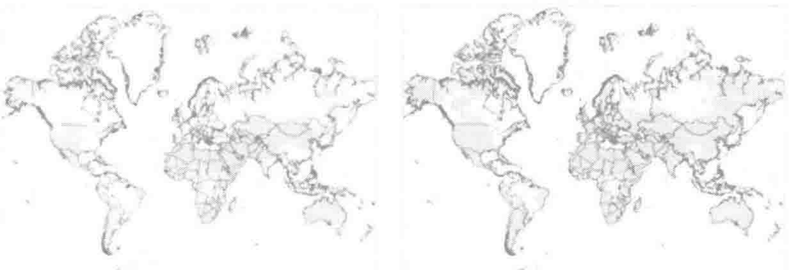

Figure 2. (a) Estimated delineation of regions experiencing multiple-year droughts on a regular basis. (b) Estimated expansion of regions that will experience multiple-year droughts for an assumed global increase in hydrologic variability equaling 25% (Annandale 2013).

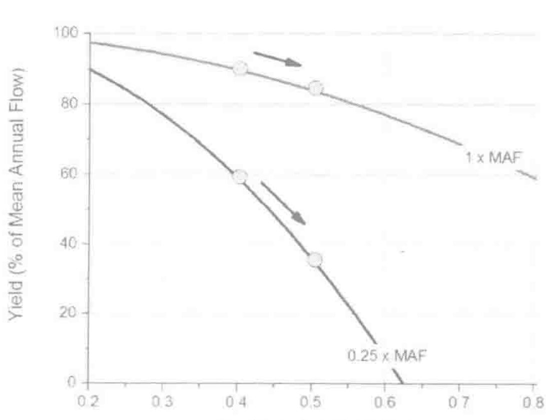

Figure 3. Sensitivity of yield to increased hydrologic variability from reservoirs with volumes equaling 0.25 and 1.00 times the MAF (99% reliability).

using large storage spaces than smaller ones. Large reservoir volumes therefore characterizes robust infrastructure, resistant to the effects of climate change.

5 SUSTAINABLE DEVELOPMENT

Sustainable development as defined by the Brundtland Commission (United Nations 1987) requires fairness between generations, i.e., creation of intergenerational equity. To create intergenerational equity in an era of climate change will necessitate having available enough reservoir storage for use by future generations. Not having enough storage will prevent future generations from reliably supplying fresh water from rivers.

Current trends in net reservoir storage space indicate that enough storage may not be available in the future. The combined effects of a reduced global rate of dam construction since about the 1980s and storage loss to reservoir sedimentation resulted in a global net decrease in reservoir storage (Fig. 4). The only way to reverse this undesirable trend is to construct more reservoirs and to implement reservoir sedimentation management approaches that will indefinitely preserve reservoir storage space. The limited availability of suitable dam sites for construction of reservoirs emphasizes the importance of implementing reservoir sedimentation management technology in both existing and future projects.

6 RESERVOIR SEDIMENTATION MANAGEMENT

Multiple reservoir sedimentation management techniques exist and their technical viability have been proven (Morris & Fan 1997; Sumi 2003; Palmieri et al. 2003; Annandale 2011). Techniques may be categorized into groups representing catchment management, prevention of sediment deposition and removal of deposited sediment. Each of these categories contains a number of techniques, as summarized in Figure 5. Catchment management aims are reducing sediment yield, i.e., the amount of sediment that may flow into a reservoir. Techniques that may be used to accomplish this goal include reforestation (revegetation of catchments), construction of check dams, contour farming and warping. Prevention of sediment deposition in reservoirs can be accomplished through bypassing sediment around a reservoir (using tunnels, river modification, sediment exclusion and off-channel storage) and by sluicing and

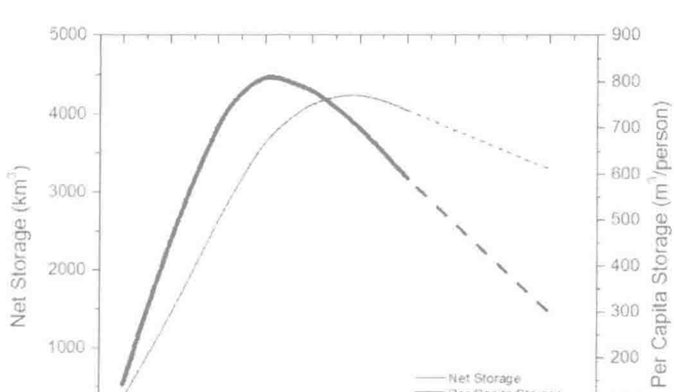

Figure 4. Trends in net global total and per capita net reservoir storage (developed from White 2001 and assuming 1% annual loss to sedimentation).

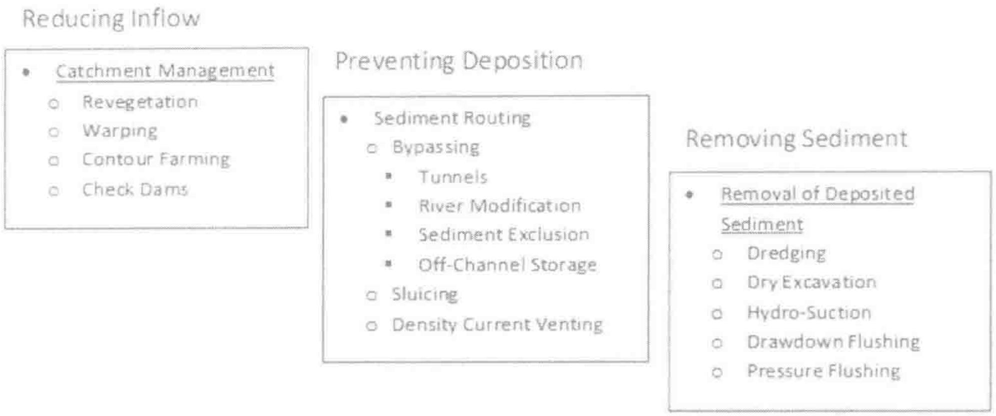

Figure 5. Three categories of reservoir sedimentation management techniques.

density current venting. Various techniques can be used to remove sediment that has already deposited in reservoirs. These include drawdown flushing, pressure flushing, dredging, dry excavation and hydrosuction. Selecting the right technique is project specific, a topic that is beyond the scope of this paper.

7 DUAL NATURE OF STORAGE

A question requiring addressing is why reservoirs continue to lose storage space due to sedimentation in spite of the fact that multiple techniques are available to either prevent sedimentation or, at least, minimize the magnitude of storage loss. Part of the reason for this undesirable state of affairs can be found in a common design paradigm and belief that little can be done to prevent reservoir sedimentation. This attitude results in dam designs that are not amenable to reservoir sedimentation management.

Another reason is that the economic analysis techniques that are used to assess the economic value of dams and reservoirs do not promote sustainable development. Conventional discounting techniques merely reflect existing cultural values that place greater importance on the present than on the future, a position that is in conflict with the tenets of sustainable development.

To address this issue it is necessary to revert to the sustainable development principles proposed by Daly, and firstly determine whether reservoir storage space is an exhaustible or a renewable resource. As already indicated, the limited number of suitable dam sites available for construction of reservoir storage implies that reservoir storage space may be an exhaustible resource. However, closer examination shows that this is not strictly true. Reservoir storage space potentially has a dual character; it can be either exhaustible or renewable depending on design and operating decisions.

If a dam designer or operator accepts that storage loss due to sedimentation is inevitable and makes no attempt to develop sustainable designs or implement operating procedures that will either prevent or minimize storage loss to sedimentation, then the reservoir storage space is deliberately and consciously classified as an exhaustible resource. On the other hand, if a dam designer prepares designs facilitating reservoir sedimentation management and an operator implements management strategies that either prevent or minimize the effects of reservoir sedimentation, then the reservoir storage space is classified as a renewable resource.

These deliberate design and operating decisions, classifying a reservoir as either exhaustible or renewable, have significant implications for the economic analysis of dams and their reservoirs, thereby determining whether reservoir sedimentation management is economically viable.

Conventional approaches to assess the economic value of a project entail quantifying its net present value. This is accomplished by making use of discounting techniques. The net present value of a project is determined by subtracting discounted future costs from discounted future benefits. If the net present value thus determined is positive, a project may be viewed as economically viable.

By critically examining this approach it can be concluded that discounting in economic analysis merely represents current cultural attitudes that value the present more than the future. This can be seen in Figure 6, which shows the change in the present value of $1,000 over time, discounted at 6%. The fact that the present value of this amount of money rapidly decreases over time shows that greater value is placed on receiving benefits earlier rather than later. Therefore, the economic value of a project can be increased by scheduling benefits to occur as soon as possible in a project timeline and expenses as far into the future as possible.

The cost to future generations of losing a natural resource (i.e., the loss of reservoir storage space to sedimentation) is never accounted for in the economic analysis of dam and reservoir projects. The standard reasoning is that the present value of such a loss, which may occur 70 or 100 years from now, is insignificant. Such reasoning is not in line with the concept of sustainable development, i.e., it does not create intergenerational equity (United Nations 1987). Forcing future generations to bear the cost of discarded natural resources for the benefit of current generations is not in line with the desire to establish fairness between generations. The fact that reservoir storage space has a dual character and the fact that its characterization as either a renewable or exhaustible resource depends on deliberate decisions by dam designers and operators invalidates the reasoning common to standard economic analysis.

A deliberate decision by dam designers and operators to accept storage loss to reservoir sedimentation as inevitable, thereby consciously classifying the reservoir storage space as an exhaustible resource, demands implementation of the Hotelling Principle (Hotelling 1931). This fundamental principle of the economics of exhaustible resources (Solow 1974) indicates that the price of an exhaustible resource increases with the discount rate, which has significant implications to the economic analysis of dam and reservoir projects. If the price of an exhaustible resource increases with the discount rate, then the present value of that resource remains constant (Gopalakrishnan 2000). Figure 6 compares the present value of an exhaustible resource using the Hotelling Principle to the present value determined using conventional discounting. The present value of $1,000 using the Hotelling Principle remains $1,000 regardless of time.

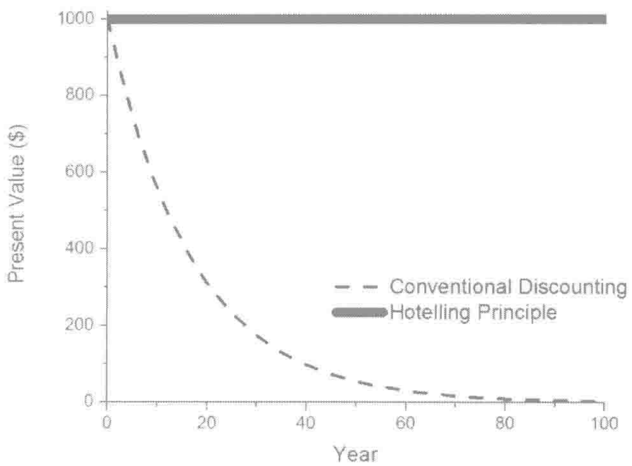

Figure 6. The present value of $1,000 using conventional discounting techniques (for a discount rate of 6%) and using the Hotelling Principle.