Cost of siltation in Sardar Sarovar reservoir: implications for catchment treatment

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Estimates on lost reservoir capacity in India provide an alarming picture. There are several instances of soil erosion and sedimentation with run-off water. The cost of sediment removal from a large reservoir may be high, in addition to cost of dam construction. The present article estimates the loss to economy by siltation of Sardar Sarovar reservoir through loss of electricity generation and agricultural productivity. The article also suggests adoption of intensive soil and moisture conservation measures on scientific lines from protection viewpoint.

Keywords: Catchment treatment, sedimentation removal, siltation, reservoir, soil erosion.

ONE of the most important objectives of constructing and maintaining soil and moisture conservation measures in the catchment of a reservoir is to avoid loss of live storage capacity caused by high rate of sediment deposition behind the dam. There are several impacts of soil erosion and sedimentation on 'production and consumption' in the region affected by reservoir. This includes reservoir siltation leading to loss of hydropower generation capacity, reduction in irrigation water supply affecting agricultural production, and impact on drought or flood cycles. The annual loss of live storage capacity in India is estimated at 1.3 billion cubic metres (bcm) according to the National Commission for Integrated Water Resources Development, Government of India[1]. Other estimates of lost live storage capacity indicate 1.95 BCM (ref. 1). Sedimentation effects in most reservoirs worldwide, not just in India, are affecting their capacity. It is difficult to replace the lost capacity of a reservoir. Treatment of river catchment in terms of soil conservation could be an alternative to desiltation of reservoir. The present article estimates the marginal cost of siltation in the Sardar Sarovar Project (SSP) reservoir, which is being constructed on the Narmada river in Gujarat.

Materials and methods

Study area

The present study was confined to the SSP catchment area lying in Gujarat. This is a unique, multi-state, multipurpose river valley project to harness the untapped waters of River Narmada for the survival of millions of people by providing irrigation water and energy. The catchment area of the SSP is 88,000 sq. km in Gujarat.

The Narmada basin extends over an area of 98,796 sq. km and lies between long. 72°32′–81°45′E and lat. 21°20′–23°45′N on the northern extremity of the Deccan Plateau. The basin covers large areas in Madhya Pradesh (MP), Gujarat and Maharashtra (Figure 1). It has an elongated shape with a maximum length of 953 km from east to west and a maximum width of 234 km from north to south. The basin has five well-defined physiographic zones. They are (i) the upper hilly areas covering the districts of Shahdol, Mandla, Durg, Balaghat and Seoni in MP, (ii) the upper plains covering the districts of Jabalpur, Narsimhapur, Sagar, Damoh, Chhindwara, Hoshangabad, Betul, Raisen and Sehore in MP, (iii) the middle plains covering the districts of East Nimar, part of west Nimar, Dewas, Indore and Dhar in MP, (iv) the lower hilly areas covering part of the West Nimar and Jhabua in MP, Dhulia in Maharashtra and parts of Baroda in Gujarat, and (v) the lower plains covering mainly the districts of Bharuch and part of Baroda in Gujarat. The Narmada basin consists mainly of black soil. The rainfall is heavy ranging between 1400 and 1650 mm in the upper hilly areas; in the middle it ranges between 1000 and 1400 mm and in the lower plains it varies between 650 and 1000 mm.

The SSP catchment is characterized by typical undulating hilly terrain comprising ridges and deep valleys dominantly occupied by well to excessively drained soils. Surface and subsurface stoniness of the soil profiles is the common feature in almost all the micro-catchments, which limits the soil depths at many places. Soil depth varies widely in the catchment area from very shallow to shallow at top of the hillocks to moderate to very deep at the bottom. Rock outcrops are common, suggesting that soils are severely eroded[2]. The top storey has species with

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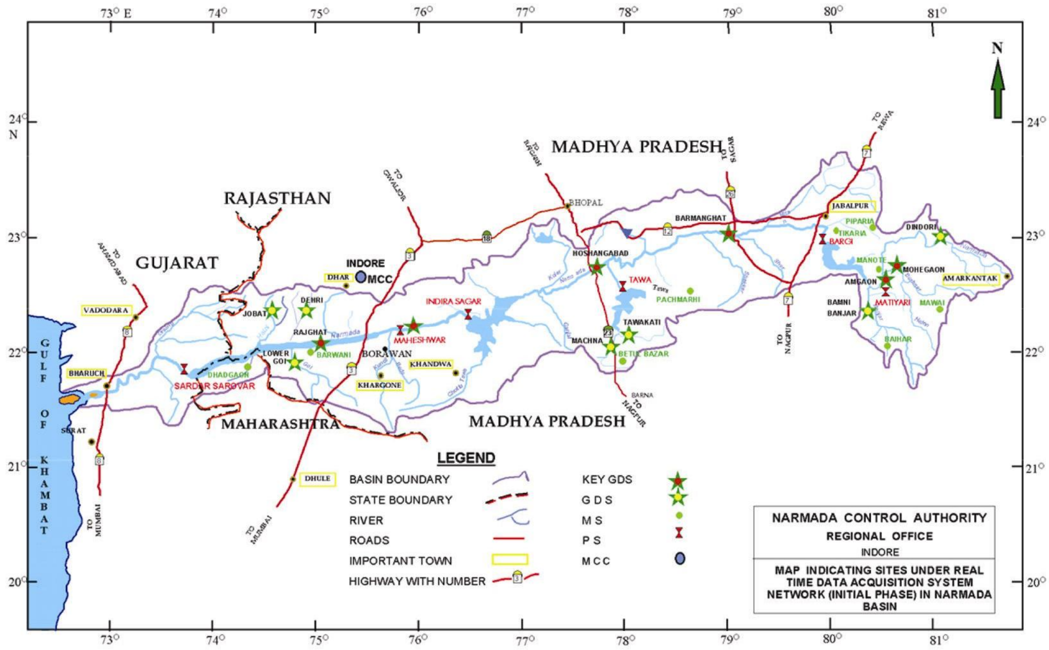


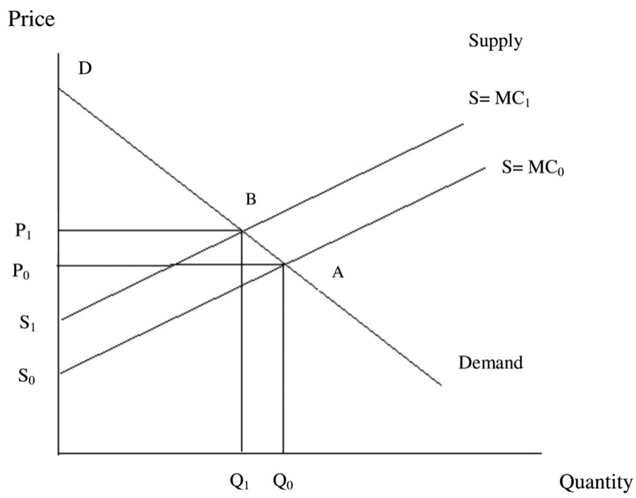
Figure 1. Index map of Narmada basin (Narmada Control Authority, 2000).

good canopy cover and clumped distribution. The mid story, on the other hand, has mixed vegetation. The species have good canopy cover; however, they do not have clumped distribution. The ground cover during rainy season is observed to have high ground coverage with contiguous distribution[2].

Extensive treatment work in the catchment area of SSP has been taken up by authorities of the Sardar Sarovar Narmada Nigam Ltd, Gandhinagar for conservation of soil and moisture. According to the second interim report of the committee for assessment of planning and implementation for SSP submitted to the Ministry of Environment and Forests (New Delhi), Gujarat[3] had carried out treatment work in the whole area during 1990–1995 whereas Maharashtra covered about 46,000 ha (68% of its area) during 1992–2002. The Narmada Valley Development Authority (NVDA) in MP covered only 161,000 ha (38%) out of 429,000 ha under the project. The impoundment of reservoir is more than 80%, whereas the total catchment area treatment work carried out by the three concerned states is reported to be 45% (ref. 3).

Valuation approach

Sedimentation in reservoirs behind dams has been recognized throughout Southeast Asia as a major consequence of land degradation and erosion in upper watersheds[4]. The potential economic losses in terms of losses in hydroelectric power, irregular or inadequate flow of irrigation water, reduced flood control and impact on drinking water supply have been considered to be significant.



At MC_0 (no loss of reservoir capacity) – Consumer surplus is area DP_0A; At MC_1 (loss of reservoir capacity) – Consumer surplus is area DP_1B. Change in consumer surplus (due to loss of reservoir capacity) – Area P_1P_0AB. At MC_0 (no loss of reservoir capacity) – Producer surplus is area P_0AS_0. At MC_1 (loss of reservoir capacity) – Producer surplus is area P_1BS_1. Change in producer surplus (due to loss of reservoir capacity) – Area P_1BS_1 – area P_0AS_0.

Figure 2. Illustration of dam reservoir sedimentation loss estimation.

Losses due to sedimentation has been estimated in terms of losses in hydropower and irrigation. The approach for valuation of economic losses is illustrated in Figure 2. Considering the objective of the dam to be delivering water for irrigation, the demand curve represents the demand for irrigation water from the dam. Initially, without reservoir sedimentation, the dam is able to supply Q_0 amount of water at price P_0 to satisfy this demand. However, sedimentation of the reservoir reduces its storage capacity and may affect the planned lifetime of the reservoir. All these impacts would effectively increase the marginal costs of delivery of irrigation water. This is represented by an increase in the marginal cost of delivered water, from $S = MC_0$ to $S = \mathrm{MC}_1$. The reduced supply of water from the dam results in a net loss in consumer surplus. At MC_0 (no loss of reservoir capacity), the consumer surplus is represented by area DP_0A. At MC_1 (loss of reservoir capacity), the consumer surplus is reduced to an area DP_1B. Therefore, the loss of consumer surplus (due to loss of reservoir capacity) can be given by an area P_1P_0AB. Similarly, At MC_0 (no loss of reservoir capacity), the producer surplus is shown by area P_0AS_0. At MC_1 (loss of reservoir capacity), the producer surplus is given by area P_1BS_1.

Hence, loss of producer surplus (due to loss of reservoir capacity) can be shown by the difference of the areas P_1BS_1 and P_0AS_0. This approach can be extended to estimate the off-site costs of reservoir sedimentation in terms of all other uses such as hydroelectricity generation, flood control and domestic water supply. The most common method is to measure these impacts in terms of the value of foregone net benefits from reductions in storage of the reservoir caused by sedimentation.

Data collection

The Central Soil & Water Conservation Research & Training Institute, Vasad constructed run-off and silt measuring structures at selected micro watersheds and measured the rainfall, run-off and silt loss continuously during rainy season. The data on siltation into the reservoir were collected from the report submitted by the Centre to SSNNL.

The data on gross storage and dead storage capacity were collected from secondary source[5]. Further, the outputs of hydroelectricity generation and irrigation benefits were also collected from secondary sources[5,6]. The values of benefits are estimated from the data presented in these records. The present study is confined to the losses due to reduction in hydropower generation and irrigation. The water used in hydropower can also be utilized for irrigation benefits. Therefore, annual losses are computed by adding the losses on account of reduction in hydroelectricity and irrigation benefits. It is assumed that the reductions in benefits are permanent. By reducing the reservoir capacity, siltation reduces the area which can otherwise be irrigated and this also impairs the existing irrigation infrastructure. The canals, their distributaries and water courses get filled with silt. As a result, the efficiency and economy of the whole irrigation system is adversely affected. The malfunctioning of Kosi canal system is an example, where high sedimentation load led to choking of the system. This resulted in closure of the canal system affecting irrigation potential[7]. Similarly, the silt-laden reservoir water adversely affected hydropower generation, as the volume of water available for power generation was reduced.

The basic assumption of the analysis is that the flow of these benefits is related to the remaining volume of storage in the reservoir. It is difficult to determine the precise relationship between active, dead and total reservoir capacity, and the effects of increased sedimentation in the absence of information available. Therefore, the losses of dead and total reservoir capacity are taken as the upper and lower bounds for the impact of sedimentation. It is assumed that these reductions include the actual losses in active storage and thus hydroelectric and irrigation benefits. The dead storage of a reservoir is the portion of total reservoir storage capacity that is allocated to storing sediment. Usually, engineers plan for a certain amount of dead storage in a reservoir based on existing sedimentation rates, with the remaining storage capacity assumed to be valid. An ‘unplanned’ increase in sedimentation due to greater soil erosion upstream increases the dead storage component of a reservoir. This, in turn, means that more active storage becomes ‘inactive’ and thus, there is a consequent loss of water available for hydropower, irrigation and other economic benefits[4].

Results and discussion

Sardar Sarovar Project: features and proposed benefits

The SSP constructed across the River Narmada is a concrete gravity dam, 1210 m in length and with a maximum height of 163 m above the deepest foundation level. The full reservoir level (FRL) of the SSP is fixed at RL 138.68 m. The maximum water level is 140.21 m and minimum draw-down level is 110.64 m. The normal tail water level is 25.91 m. The gross storage capacity of the reservoir is 0.95 M ha m and live storage capacity is 0.58 M ha m. The dead storage capacity below minimum draw-down level is 0.37 M ha m. The reservoir occupies an area of 37,000 ha and has a linear stretch of 214 km of water and an average width of 1.77 km.

Irrigation: SSP has been planned to provide irrigation facilities to 1.845 m ha of land, covering 3112 villages of 73 taluks in 15 districts of Gujarat. It will also irrigate 75,000 ha in the strategic desert districts of Barmer and Jalore in Rajasthan and 37,500 ha in the tribal, hilly tract of Maharashtra through lift irrigation. While 75% of the command area in Gujarat is drought-prone, the entire command area of 75,000 ha in Rajasthan is drought-prone. Assured water supply is supposed to make this area drought proof.

Table 1. Storage losses in SSP

Initial gross storage capacity (M ha m) (*a*)	Average sediment rate (M ha m) (*b*)	Annual total storage loss (%) (*b*/*a**100)	Initial dead storage capacity (M ha m) (*c*)	Annual dead storage loss (M ha m) (*b*/*c**100)
0.95[#]	0.0047	0.0495[@]	0.37[#]	1.27

[#]http://www.sardarsarovardam.org/. [@]Based on maximum rate of silting 5.34 ha-m/100 km^2/year (Parmar *et al.*[12]; Sena *et al.*[2]).

Hydropower: There are two powerhouses, viz. river bed powerhouse and canal head powerhouse with an installed capacity of 1200 MW and 250 MW respectively. The power is shared by three states, MP – 57%, Maharashtra – 27% and Gujarat – 16%. This provides a useful packing power to the western grid of the country which has limited hydel power production at present. A series of micro hydel power stations are also planned on the branch canals where convenient gradients are available.

Flood protection: It is contemplated to provide flood protection to riverine reaches measuring 30,000 ha covering 210 villages in Bharuch city and a population of 400,000 in Gujarat.

Drinking water supply: A special allocation of 0.86 million acre feet of water has been made to provide drinking water to 135 urban centres and 8215 villages (45% of total of 18,144 villages in Gujarat) within and outside the command area in Gujarat, covering the present population of 18 million and prospective population of over 40 million by the year 2021. All the villages and urban centres of the arid region of Saurashtra and Kachchh and all ‘no source’ villages and villages affected by salinity and fluoride in North Gujarat are contemplated to be benefited. Water supply requirement of several industries is also to be met from the project giving a boost to all-round production.

Valuation of lost benefits due to siltation

Hydropower loss: There are various estimates about power generation and its valuation. Gujarat Urja Vikas Nigam Ltd (GUVNL) has entered into a power purchase agreement (PPA) with SSNNL for the purchase of power at the rate of Rs 2.05/unit. GUVNL has also sought the approval of the Gujarat Electricity Regulatory Commission (GERC) for the PPA with SSNNL[8]. In FY 2005–06, the Maharashtra State Electricity Company purchased 17,062 MU of electricity at a total cost of Rs 3263 crores. This works to Rs 1.91/unit (ref. 9). These values have been used to estimate the loss in hydro power benefits due to siltation.

Valuing irrigation losses: Enhanced irrigation over an area of 1,905,500 ha is expected to increase with Sardar Sarovar Narmada Canal water, which has been estimated to increase agricultural production valued at Rs 85 billion[6,10]. This implies a potential increase in irrigated area valued at Rs 44,608/ha. There is also lower estimate of enhanced irrigation potential of 1,84,5000 ha (ref. 11). With this irrigation potential estimate, the estimated potential increase in irrigated area is valued at Rs 46,070/ha. These lower and higher values have been used to estimate the loss in irrigation potential due to siltation in the dam.

Estimation of losses

Estimates of loss in storage in the reservoir are given in Table 1. The initial gross storage capacity of the dam is 0.95 M ha m. Average rate of siltation in the sub-watersheds gauged by Central Soil & Water Conservation Research & Training Institute, Vasad is estimated to be less than 5.34 ha-m/km^2/year of slit going into the reservoir[2,12]. Therefore, considering a sediment loss of 5.34 ha-m/km^2/year, total annual sediment of 4.69×10^{-3} M ha m from the catchment area lying in Gujarat is estimated to go into the reservoir. With this estimate, the total annual storage loss works out to be 0.49%. Similarly, the annual dead storage loss works out to be 0.13%. These values of storage losses have been considered lower and upper limits and are used for estimating the hydropower and irrigation potential losses on account of sedimentation in the SSP reservoir in Gujarat. Table 2 gives the estimation of annual hydropower and irrigation losses. Different scenarios have been examined based on estimates by different experts[6,10]. The hydropower generation estimates for both deficit rainfall and excess rainfall years have been considered[6]. Similarly, two scenarios of irrigation potential generated from the dam have been considered[6,11]. Based on loss of total storage, the estimated output of hydropower loss varies from 4.2 M kWh in a deficit monsoon year to 4.98 M kWh in a surplus monsoon year. This works out to be in the range Rs 8.1–8.68 million per annum during deficit monsoon. For surplus monsoon scenario, these values vary between Rs 9.51 and 10.2 million per annum. Similarly, hydropower loss estimate based on loss of dead storage varies from 10.9 to 12.7 M kWh during deficit and surplus monsoon years respectively. This works out to be Rs 20.7–22.2 million per annum during deficit monsoon. For surplus monsoon scenario, these annual values vary between Rs 24.4 and 26.2 million. The Government of Maharashtra has fixed a single part tariff of Rs 4.18/unit for purchase of power from SSP[9]. At this price, the estimated annual hydropower losses due to siltation work out to be

Table 2. One-year hydropower and irrigation losses

	Hydropower loss (range)		Irrigation loss (range)		Total capitalized value	
	Deficit monsoon	Surplus monsoon	Lower	Higher	Low	High
Existing output (a)*	856 M kWh	1007 M kWh	1,845,000# ha	1,905,500* ha		
Value (Rs/unit) (b)*						
(i) Lower value	1.91/kWh	1.91/kWh	44,608/ha	44,608/ha		
(ii) Higher value	2.05/kWh	2.05/kWh	46,070/ha	46,070/ha		
Based on loss of total storage (%) (c)	0.495	0.495	0.495	0.495		
Lost output (a*(c/100))	4,234,226	4,981,152	9126	9425		
Annual cost (Rs million)	(I)		(II)		(I) + (II)	(I) + (II)
(i) Lower value	8.08	9.51	407.10	420.45	416.62	428.54
(ii) Higher value	8.68	10.21	420.45	434.23	430.66	442.91
Based on loss of dead storage (%) (e)	1.27	1.27	1.27	1.27		
Lost output (a*(e/100))	10,871,663	12,789,444	2469	2550		
Annual cost (Rs million)						
(i) Lower value	20.76	24.42	1045.27	1079.55	1069.70	1100.31
(ii) Higher value	22.28	26.21	1079.53	1114.93	1105.75	1137.22

*Berga *et al.*[6]; #http://www.sardarsarovardam.org/; a, b, c, e are notations used for explaining computation of 'lost output'.

Rs 17.7 million and Rs 45.4 million in a deficit monsoon scenario and Rs 20.8 million and Rs 53.4 million in a surplus monsoon scenario considering loss in total storage and dead storage respectively. Similarly the loss of irrigation potential varies between 44,608 and 46,070 ha. This is estimated in the range Rs 407–434 million based on loss of total storage and Rs 1045–1114 million based on loss of dead storage. Total capitalized value of loss is the sum of hydropower loss and irrigation potential loss. The lower value of loss is estimated in the range Rs 1105–1137 million, based on dead storage loss.

Conclusion

Non-adoption of proper soil and water conservation measures, including forest plantation, in the catchment area of the Sardar Sarovar reservoir will result in annual loss of Rs 1105–1137 million by accounting for loss in power generation and reduction in irrigated area alone in the command area. However, these losses can be minimized by treating the catchment area with appropriate location-specific soil and water conservation measures.

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