REVIEW OF GREENHOUSE GAS EMISSIONS FROM THE CREATION OF HYDROPOWER RESERVOIRS IN INDIA

Background Paper

India: Strategies for Low Carbon Growth

June 2008
The World Bank

CONTENTS

Acknowledgements

This report was produced as a background paper for the study, *India: Strategies for Low Carbon Growth*. The team that has worked on this paper comprises the following World Bank staff and consultants: Bjorn Svensson, Judith K. Plummer and Rohit Mittal. Valuable comments were received from Alessandro Palmieri, Lars Odegard and Vahid Alavian. In addition, that study benefited from the support of Kseniya Lvovsky as former Task Team Leader for the Study, Mr. Kwawu M. Gaba as the current Task Team Leader, Mr. Charles J. Cormier as the current co-Task Team Leader, Karin Kemper and Salman Zaheer as responsible Sector Managers, and Isabel Guerrero, Country Director India.

List of Abbreviations

CDM	Clean Development Mechanism
CH4	Methane
CO_2	Carbon Doxide
FRL	Full Reservoir Level
GHG	Green House Gases
GW	Giga Watt
GWh	Giga Watt Hour
HPP	Hydro Power Project
kWh	Kilo Watt Hour
ICOLD	International Commission on Large Dams
IHA	International Hydropower Association
IPCC	Intergovernmental Panel on Climate Change
MW	Mega Watt
N_2O	Nitrogen Oxide
NPP	Net Primary Production
UNESCO	United Nations Educational, Scientific and Cultural Organization

1.0 Background

This is a preliminary report for the World Bank regarding emissions of greenhouse gases from hydropower reservoirs in India. The objective of the work, according to the terms-of-reference, is, *inter alia*, to examine the available data and available methodologies in order to produce an estimate of net methane emissions from reservoirs now and in the future in India, or to create a range of estimates based on particular assumptions.

This work will also provide:

- Guidance on the effect of climatic conditions where the reservoir is located;
- Guidelines on how to consider evolution of methane emission with time as pre-reservoir vegetation decomposes, taking into consideration that methane also derives from decomposing organic matter being imported from upstream catchments;
- Criteria for predicting the formation of anoxic layers in the reservoir, including recommendations on how to avoid it or to mitigate the effects (oxygenation, multiple level intakes, etc.); and
- To put methane emissions from artificial reservoirs in perspective by providing estimates of emission reduction by submergence of existing wetlands, when that is the case.

The discovery that reservoirs might sometimes constitute important sources of greenhouse gases to the atmosphere is fairly recent. Although the observation immediately induced intensive studies in several countries with extensive hydropower resources, the scientific knowledge of the phenomenon is still inferior relative to for example similar emissions from agriculture. Thus, Indian rice paddies have been intensely studied in this respect (the current estimate is that about 4Tg of methane is emitted annually from rice paddies in the country), while studies of emissions from reservoirs have so far been neglected. However, future reservoirs, and particularly those intended to support hydropower plants with Clean Development Mechanism (CDM) as a financial option, will have to be evaluated in terms of their contribution to climate change. The CDM requires a detailed account of the balance of greenhouse gases.

Unfortunately, there is no widely accepted methodology for estimating greenhouse gas emissions from existing or planned reservoir projects. Those inventory methods which have been suggested, e.g., by Intergovernmental Panel on Climate Change (IPCC), does not reflect the complete chemical and physical mechanisms involved and tend to overestimate emissions by not taking full account of the natural emissions. In addition, system boundaries are usually too narrow. Reservoirs influence entire river systems downstream from the inlet, and some effects are actually transmitted to the sea.

A series of UNESCO-International Hydropower Association (IHA) workshops are being launched to cope with the uncertainties related to estimates of greenhouse gas emissions from reservoirs. The ambition is to develop a standardised methodology which can be used to distinguish reservoirs that are significant sources of greenhouse gases and to identify mechanisms that need to be included in inventories of reservoirs for this purpose. This work is expected to produce recommendations for reservoir inventories in the near future. Until then, a critical evaluation of published results in combination with general ecological knowledge seems to be the only means of analysing the role of reservoirs in a changing climate.

2.0 Mechanisms behind Increased Emissions of Greenhouse Gases from Reservoirs

When organic soils and vegetation are flooded, decomposition processes commence. As long as oxygen is available, the decomposition of organic matter will result in emissions of carbon dioxide. Net emissions from reservoirs are then simply related to the extra carbon contained in the inundated vegetation and can be easily calculated if the original carbon content and its oxidation rate in the water is known. Observations indicate that most of the easily degraded organic matter has disappeared after about 10 years, while wooden material like tree trunks is more or less refractory, i.e., remains over a very long period of time and thus does not contribute significant amounts of atmospheric greenhouse gases.

In temperate regions, oxygen dissolved in the water is usually large enough to balance decomposition processes. However, in tropical environments, where reservoirs tend to become more or less permanently stratified and the temperature is comparatively high, oxygen will be rapidly used up near the bottom resulting in the initiation of quite different microbial activities, where the end product is methane, a greenhouse gas with a heating potential 23 times higher than that of carbon dioxide. Methane is either diffused through the water column or, more importantly, forms bubbles that emerge from the bottom to the water surface. Methane dissolved in the water mass is rapidly oxidised when passing oxygenated water, whereas bubbles largely resist oxidation. At depths larger than approximately 20 m, the pressure is too high for bubbles to form so there only dissolved methane can exist.

The implication of these observations is that net contributions of greenhouse gases to the atmosphere from man-made lakes are the sum of release of extra carbon dioxide and the fraction of carbon leaving the water surface as methane. In deep reservoirs, methane contributes insignificant amounts of gas to the atmosphere. In this context it should also be mentioned that certain environmental conditions can amplify methane emissions. The water hyacinth is a floating exotic aquatic weed that has invaded many water bodies in India. When covering the water surface the water hyacinth reduce the aeration of the water and decomposing water hyacinths consume large amounts of oxygen.

Detailed studies of reservoirs have, however, shown that the picture is more complicated than described above. Organic matter in reservoirs does not consist of flooded vegetation only. It also derives from so-called allochthonous material, entering the reservoirs through tributaries and emanating from upstream catchments. This organic matter is continuously replenished and is exposed to the same processes as flooded vegetation. As long as the decomposition of the allochthonous material results in the formation of carbon dioxide only, reservoirs will not contribute to emissions of extra greenhouse gas to the atmosphere though, because the carbon dioxide would have formed anyway somewhere within the aquatic system. If, however, a fraction of the decomposed material results in the formation of methane, an increased burden of atmospheric greenhouse gases will result. Again, in deep and stratified reservoirs, the methane is trapped near the bottom and only small amounts will reach the water surface. In shallow reservoirs with anoxic bottom water, however, oxidation processes are insufficient to keep pace with methanogenesis and significant amounts of methane might then leave the water surface.

It should be mentioned that methane is also naturally emitted from certain ecosystems, notably wetlands. Inasmuch as such environments are inundated, methane emissions can actually decrease after reservoir flooding provided the depth of the reservoir is large enough and the anoxic layer is not too extensive.

In aquatic as well as terrestrial ecosystems there are organisms with the capacity to use dissolved carbon dioxide to synthesise new organic, so-called autochthonous, matter. Hence, on average there will be a net sequestration of carbon that partly counterbalance the decomposition processes. In arid environments, aquatic primary production is higher than in the surrounding terrestrial environment, and reservoirs created in such environments might actually constitute sinks for atmospheric carbon. Likewise, particulate organic matter (both autochthonous and allochthonous) will sink to the bottom and become buried in the sediments. This route of carbon flow also constitutes a net sink which can be quite significant, leading to removals of a few to several hundred grams of carbon per square meter every year, depending on the ambient climatic and hydrochemical conditions.

From what has been described above, one can draw the conclusion that reservoirs' contribution to atmospheric greenhouse gases is extremely variable. The topography, climate, soil and geological conditions as well as land-use constitute the ultimate factors responsible for the fate of carbon in reservoirs. In addition, reservoir operation may also be of great importance. If, for example, reservoirs supply hydroelectric power stations and use water withdrawn from near the bottom where anoxic conditions prevail, vast amounts of methane may be released below the water outlets or spillways.

3.0 Characteristics of Indian Reservoirs and their GHG Emissions

In India, impoundments cover about 5 million hectares, the majority being located in the southern part of the country. About half of this area is occupied by reservoirs that support hydropower plants, notwithstanding that the majority of dams satisfy multipurpose needs. The hydropower potential of India is estimated at about 149 GW of which about 23 percent has been exploited. The untapped potential is mainly in alpine environments in the northern part of the country.

Indian reservoirs represent the whole spectrum of different reservoir types found in the world. Some are located in alpine environments and share the same features that are typical of northern temperate reservoirs, i.e., can be assumed to release insignificant amounts of greenhouse gases. On the other extreme one finds reservoirs in arid environments, where sequestration probably dominates over release of carbon. Between these extremes are reservoirs located in wet, humid or dry tropical environments. Their performance in terms of emission of greenhouse gases is more difficult to appreciate. Table 1 provides an overview of the characteristics of reservoirs in different Indian states. The data derives from ICOLD's (International Commission on Large Dams) most recent compilation. Unfortunately, data related to Indian dams and reservoirs are incomplete and sometimes erroneous. Obvious errors have been discarded from the table.

Ocular inspections of satellite photos (Google Earth) in combination with information on prevalent climatic conditions indicate that reservoirs in Uttaranchal, Tamil Nadu, Sikkim, Rajasthan, Punjab, Karnataka, Jammu/Kashmir, Himachal Pradesh, Gujarat, and Arunachal Pradesh represent categories of surface waters where net emissions of greenhouse gases, to judge from experiences from other parts of the world, are generally low, and probably comparable to those from natural lakes. These reservoirs represent about 40 percent of the total storage capacity or 11 percent of the total area occupied by reservoirs in the country. The discrepancy between these two percentages indicates that reservoirs in the actual states are deep compared to remaining reservoirs.

Table 1: Distribution and Characteristics of Indian Reservoirs (Reservoir Data from ICOLD, 2007)

State	Total no of reservoirs	of which complete data are available	Reservoirs with hydropower	Climate zone	Total storage capacity (BCM) (1)	No of reservoirs younger than 10 yrs
West Bengal	28	3	1	mainly humid subtropical	1,48	0?
Uttaranchal	15	11	7	mainly highland	3,06	0?
Uttar Pradesh	135	70	5	humid subtropical	15,35	0
Tripura	1	0	1	humid subtropical	0,31	0
Tamil Nadu	88	64	45	mainly tropical dry	6,5	0?
Sikkim	1	0	?	highland	0	0?
Rajasthan	84	52	1	mainly arid	8,28	0
Punjab	3	0	1?	arid and humid subtropical	2,37	1
Orissa	151	120	6	tropical wet & dry	17,22	0
Meghalaya	4	0	3	humid subtropical	0,7	0
Manipur	3	0	?	humid subtropical	0,4	0?
Maharashtra	1658	710	33	mainly tropical wet & dry	25,52	75
Madhya Pradesh	1259	1124	7	mainly humid subtropical	17,16	18
Kerala	44	20	14	tropical wet	5,38	0
Karnataka	177	162	10	mainly semi-arid	33,63	0?
Jammu & Kashmir	7	1	1	highland	0	0?
Himachal Pradesh	5	5	5	mainly highland	13,92	0
Gujarat	545	29	2	mainly arid	16,14	0?
Goa	6	6	0	tropical wet	0,04	0?
Chattisgarh	37	31	3	mainly humid subtropical	6,22	0
Bihar & Jharkhand	104	53	5	humid subtropical	4,31	2?
Assam	3	2	2	humid subtropical	0,01	0?
Arunachal Pradesh	1	0	1	highland	0	0?
Andhra Pradesh	121	85	10	mainly tropical wet & dry	27,31	0
Andaman & Nicobar Islands	1	0	?	mainly tropical wet & dry	0	0?
Sum	**4481**	**2548**	**>162**		**206,54 (2)**	**~100**

(1) Source: Central Water Commission, 2006

(2) The storage capacity, when minor irrigation tanks and impoundments are included, amounts to 213 BCM. Ongoing projects will add 76 BCM more.

As a matter of fact, there are clear relationships between the main purpose with reservoirs in India and their volume to surface area ratio. [It should be remembered that reservoir capacity refers to live storage as opposed to reservoir volume which also includes dead storage. Data used in this study and deriving from ICOLD's database exclusively deals with live storage only, which means that depth calculations are conservative, i.e., underestimate the real depth.] Reservoirs used for irrigation have an average depth of 7.4m, all states taken together. Hydroelectric reservoirs and those that serve the purpose of both providing water for irrigation and power have an average depth of 18m. About 50 percent of the latter kinds of reservoirs are located in the states mentioned above, where environmental conditions favour low emissions of carbon gases. As concluded earlier, dissolved methane is rapidly oxidised in oxygenated water. Aerobic conditions, extending to a depth of about 5 m from the water surface, have proven sufficient for the full elimination of methane before it reaches the water surface. Therefore, reservoir depth *per se* is crucial for a reservoir's potential to emit methane.

As seen in Table 1, few reservoirs are younger than 10 years, notwithstanding the ongoing creation of new reservoirs and the possible time lag between ICOLD's compilation and the timetable of reservoir filling. In other words, decomposing flooded vegetation and soil organic matter probably play a minor role for the overall carbon balance in existing Indian reservoirs.

The most potent, but least easily evaluated source of atmospheric methane from Indian reservoirs is probably the degassing of hypolimnetic (=deriving from near the bottom) water when passing the tailrace or downstream river reaches or canals. The significance of this source is related to the shape of the reservoir, its hydraulics and the design of the reservoir outlet. While many other contributions of reservoir emissions of greenhouse gases can be deduced from general experience and easily obtained information, estimates of emissions due to degassing must be based on analyses of complex site-specific information. Such information is currently not available for Indian reservoirs, or for tropical reservoirs in other countries except for a few intensively studied ones in South America for that matter.

4.0 Conclusions and Recommendations/ Suggested Next Steps

1. Estimates of greenhouse gas emissions from Indian reservoirs are underway – (see Annex 1). These estimates involve a high degree of uncertainty, among other things depending on the fact that reliable information is available for comparatively few reservoirs. It is clear, however, that previous estimates that have been circulated in the press overstate emissions from reservoirs in India. In particular, hydropower reservoirs are to a large extent located in regions where natural conditions restrict processes that give rise to methane emissions. In addition, such reservoirs are deep and old, factors that also reduce emissions of greenhouse gases. In order to allow more precise estimates it is suggested that the characteristics of major reservoirs (at least those with a surface area $\geq$100 km^2) be updated. Data of particular interest are surface area, reservoir length, average depth and renewal/throughflow rate. These measures allow a simplified analysis of the risk of stratification of reservoirs, a prerequisite for the formation of anoxic, methane generating bottom water as emphasised by Ledec and Quintero in a World Bank report published 2003.

2. Since methane production is related to the amount of organic matter in reservoirs it is of value to know the size of the catchment upstream from the reservoirs from where the organic material derives.

3. It can be suspected that one of the most important pathways for methane from the water to the atmosphere is the degassing of water that passes hydropower turbines. Measurements of methane concentrations near the intake of several power plants should illuminate how important this pathway is.

4. Information on sedimentation rates in reservoirs should be gathered together with estimates of the organic content in order to allow calculations of carbon sequestration in sediments.

5. Information on the stratification of reservoirs in India should be gathered. It is likely that the stratification differs between regions/states.

6. Guidelines that allow proper consideration of the greenhouse effect should be produced to assist future environmental impact assessments.

Annex 1: Predicting Emissions of Greenhouse Gases from Future Hydropower Projects in the Middle Reaches of Sutlej River

1.0 Background

Two workshops hosted by UNESCO/IHA have analysed the scientific basis for estimating emissions of greenhouse gases from freshwater reservoirs[1]. "With regards to the three species of gases of interest (N_2O, CO_2 and CH_4), the participants concluded the following:

- Data were presented on the recordings of N_2O related to freshwater reservoirs in each of the major climate types. Very small N_2O emissions had been recorded. It is well established that the major sources of nitrogen are agricultural fertilizers and urban waste discharges coming from the upstream watershed. It was concluded that N_2O emissions need not be included in future reservoir induced GHG research.

- For CO_2, it was noted that emissions measured at the reservoir surface largely represented the product of the natural carbon cycle. In a small number of temperate and cold/boreal reservoirs, absorption of CO_2 had been recorded at the reservoir surface. Measurements on newly created reservoirs showed an increase of CO_2 emissions with peak values during the first years after impoundment. It was understood that this pulse represented the decomposition of submerged flora, although a substantial portion of the remaining biomass will not decompose and will be preserved by the reservoir water. Another source of the CO_2 is the release of carbon from soils in the drawdown zone. In all reservoirs, the peak of this activity occurred generally within the first two or three years after commissioning. It was agreed that the net CO_2 emissions were not significant in relation to the lifespan of most reservoirs.

- CH_4 is the most significant GHG in relation to reservoirs. In cold/boreal and temperate reservoirs, little CH_4 emissions have been recorded. In some cold/boreal reservoirs, CH_4 emissions have been detected following the break-up of the winter ice cover. In some tropical reservoirs, however, significant CH_4 emissions have been recorded. There is a high temporal variability in CH_4 emissions, which needs further investigation. In at least one case (Petit Saut, French Guyana), significant CH_4 'degassing' emissions have been recorded downstream of the reservoir. However, based on a limited set of published measurements, it seems that some tropical reservoirs exhibited very low CH_4 emissions."

Run-of-the-river hydropower plants do not cause net emissions of GHG except the comparatively small amounts of such gases released as a result of manufacturing of equipment and construction work, including transportation. The total amounts of such emissions usually fall below 10 g CO_2-equivalents per kWh[2].

---

[1] http://www.unesco.org/water/ihp/pdf/ghg_participants_statement.pdf

[2] Svensson, B. (2005). Greenhouse gas emissions from hydroelectric reservoirs: A global perspective. pp. 25-37, In: dos Santos, M.A. & Rosa, L.P. (Eds.) Global warming and hydroelectric reservoirs. Proceedings of International Seminar on Greenhouse Fluxes from Hydro Reservoirs & Workshop on Modeling Greenhouse Gas Emissions from Reservoir at Watershed Level. Rio de Janeiro, Brazil, 8-12 August 2005. COPPE/UFRJ, Eletrobrás. 197 pp.

The harnessing of Sutlej River for energy purpose includes, *inter alia*, three hydropower plants located between longitudes 77°35'E to 77°43'E and latitudes 31°23'N to 31°30'N, viz. the Luhri (capacity rated at 775 MW), Nathpa (1500 MW) and Khab (1020 MW). The Khab Dam Project will use a reservoir covering a surface area of 1000 ha and with a gross storage amounting to 625 Mm^3, while the other two projects are regarded as run-of-the-river HPP although Nathpa includes a small dam lake with a gross storage of 3.43 Mm^3, and covering a surface area of 22.86 ha. The three projects span altitudes from 2760 m (Khab at FRL) to 710 m (Luhri)[3].

The meteorological conditions display large variations within the actual reaches of the Sutlej River although the warm-temperate climate zone is dominant. Air temperatures vary between near 0°C in the winter to >40°C in the summer, while the water temperature varies between about 10-20°C[4].

Sutlej is a braided river and lacks aquatic macrophytes. The amount of organic matter in the water mass is also low. This is because the water is nutrient poor. High turbidity during most of the year also reduces light penetration which disfavours algal growth[4].

The river valley between Khab and Luhri is steep, with slopes as great as 70°. The climate is generally arid, and riparian vegetation is sparse.

2.0 Factors that Influence Emission of Greenhouse Gases

Net increases of GHG emissions come from flooded, decomposing vegetation and other organic matter trapped in the reservoir sediments. Large depth, high turnover of the water mass and low temperature reduce formation of methane, the most important GHG in connection with river regulation. Removal of the vegetation before flooding will also reduce GHG emissions.

The natural flow in the Sutlej River peaks in the summer and is typically between 400 and 1,500m^3/s (extremes as high as 5,000m^3/s have been recorded in recent years), whereas in the winter discharges are normally between 70 and 130m^3/s[5]. There is usually no riparian vegetation below the average summer water level. The seasonal flow variation has a pattern that favourably acts to reduce methane emissions since comparatively high temperatures coincide with high turnover rate of the water mass, while in the winter temperature will be low enough to maintain well oxygenated water.

Particles suspended in the water will sink to the bottom in standing water, a phenomenon that increase the transparency of the water and facilitate primary production. Therefore, more carbon will be available in a volume of water following river regulation.

---

[3] Rampur Hydropower Project: Executive Summary of EA. Available at http://www-wds.worldbank.org/external/default/WDSContentServer/WDSP/IB/2007/08/03/000011823_20070803113548/Rendered/INDEX/E14650v7.txt

[4] Joshi, C.B. (1996). Hydro-biological profile of river Sutlej in its middle stretch in western Himalayas. - Uttar Pradesh Journal of Zoology 16:97-103.

[5] Kumar, R. et al. (2007). Flash-Flood Warning for the Upper Sutlej River Basin, Northern India. - National Surface Water Conference & Hydroacoustics Workshop, April 2-6, 2007, St. Louis, Missouri, USA. U.S. Geological Survey (USGS), 8 pp.

A theoretical estimate based solely on a relationship between average net primary production and latitude [Net Primary Production (NPP - g C per m^2 per yr) = 852 – 11.7*latitude][6], and assuming that 20% of NPP is embedded in the sediments[7], gives a net burial of about 100gC per m^2 annually. However, because of the low concentration of nutrients, it is likely that this amount overestimates the carbon storage in the Khab Reservoir.

Warm temperate forests in their natural state is estimated to contain 371t C/ha[8]. The forests along the Sutlej River have been heavily logged and largely consist of shrubs nowadays. Erosion has probably depleted the soil organic matter, including litter and debris. In addition a broad zone on both sides of the river is barren due to the annual flooding. Perhaps less than 200 t C/ha remains. This means that the Khab reservoir, unless the area is cleared of vegetation, would inundate 200,000 t of carbon at most. The decomposition of flooded vegetation is usually completed in less than 10 years, when about 50 % of the organic matter has disappeared. The remaining fraction is resistant and will not contribute significant amounts of greenhouse gas.

How much of the carbon will be emitted as methane to the atmosphere? Since the average depth of the reservoir is 62.5m methane emissions through bubbling need not be considered. The only mechanisms that would release methane to the atmosphere are diffusion through the water mass or degassing below the power station. The importance of these two pathways depends on the oxygen content near the bottom of the reservoir.

The inlet to the reservoir will be well oxygenated at all times. The renewal rate of the reservoir in winter is about 70 days, while in the summer it is only 7 days. Methane formation is a slow process compared to aerobic degradation of organic matter. It is likely that oxygen will be sufficient to prevent methanogenesis in the winter since the reservoir will not be stratified at this time of the year and because of the low temperature. In the summer, on the other hand, when the risk of stratification of the water mass is normally larger, the water renewal rate will most likely be high enough to replenish well oxygenated water and prevent massive methane formation.

This rough estimate indicate that without forest clearance the specific emissions of CO_2 from the Khab Power station would be in the order of 1g per kWh (given an estimated annual energy generation of 3522 GWh and a reservoir life expectance of 100 years). This figure will be even lower if the entire cascade of power generation is considered. If we assume that 5% of the carbon will be emitted as methane, the specific emissions will reach about 1.5g CO_2-equivalents per kWh; not considering the carbon permanently buried in the sediments.

3.0 Design Criteria that could Reduce Methane Emissions

It is unlikely that reservoirs and power stations in the Sutlej River will emit large amounts of methane, the only GHG that needs to be considered in hydropower projects. Because of the steep river valleys in the Himalaya region, depth will always be large enough to prevent

---

[6] Lewis, W. M., Jr. (1987). Tropical limnology. - Annual Review of Ecology and Systematics 18:159-184.

[7] Information given at the UNESCO/IHA workshop in Iguaçu, Brazil in October 2007.

[8] Estimates of preanthropogenic carbon storage in global ecosystem types compiled by Jonathan Adams, Environmental Sciences Division, Oak Ridge National Laboratory, TN 37831, USA.

ebullition of methane and dissolved methane will be oxidised before reaching the water surface.

The only remaining escape route for methane in this region is degassing below the power station. It is, however, impossible to judge weather this is a real risk since the hydraulics of reservoirs in this part of the world has not been modelled. Before this has been done one can only speculate what design modifications that could reduce methane emissions. Surface intakes would definitely do the job, but pose practical difficulties. Alternatively, one could force well aerated surface water to a bottom intake by installing a shaft or a screen that separates the water masses.