ENVIRONMENTAL FLOW ASSESSMENT FOR A HYDROPOWER PROJECT ON A HIMALAYAN RIVER

A THESIS

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WATER RESOURCES DEVELOPMENT

by

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CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the thesis entitled **ENVIRONMENTAL FLOW ASSESSMENT FOR A HYDROPOWER PROJECT ON A HIMALAYAN RIVER** in partial fulfilment of the requirement for the award of the Degree of Doctor of Philosophy and submitted in the Department of Water Resources Development and Management of the Indian Institute of Technology Roorkee, Roorkee is an authentic record of my own work carried out during a period from July, 2004 to April, 2009 under the supervision of Dr. U. C. Chaube, Professor and Dr. S. K. Mishra, Associate Professor, Department of Water Resources Development and Management, Indian Institute of Technology Roorkee, Roorkee.

The matter presented in this thesis has not been submitted by me for the award of any other degree of this or any other Institute.

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This is to certify that the above statement made by the candidate is correct to the best of our knowledge.

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ABSTRACT

The flows of the world's rivers are increasingly being modified through impoundments, abstractions, return flows, inter-basin diversions, and flood control structures (Dyson et al., 2003; Postel and Richter, 2003). It is estimated that more than 60% of the world's rivers are fragmented by hydrological alterations (Ravenga et al., 2000). This has led to widespread degradation of aquatic ecosystems (Millennium Ecosystem Assessment, 2005).

Tropical monsoon hydrology in India necessitates development of storage and flow diversion schemes for multipurpose utilization of water. A large number of hydropower schemes on the Himalayan rivers are in different stages of development. These river valley schemes will cause flow related impacts due to storage, flow diversion, tunnelling, muck disposal etc. There may be critical reaches in which altered flows are not able to sustain the riverbed ecology and riparian environment existing prior to implementation of the storage and diversion schemes.

Environmental flows (EF) are the water that is left in a river eco-system or released into it for the specific purpose of managing the condition of that ecosystem. A wide range of outcomes, from environmental protection to serving the needs of people, are to be considered for the setting of an environmental flow. There is no simple figure that can be given for the environmental flow requirements of rivers and environmental water requirements of catchments. Much depends on stakeholders' decisions about the future character and health status of these ecosystems.

RESEARCH GAPS

Review of available literature on environmental flow assessment (EFA) shows that:

1. The status of EF research in India may be characterized as being in its infancy because of very limited knowledge base (NCIWRDP, 1999). EF in India has usually been understood as the minimum flow to be released downstream from a dam as compensation for riparian right without considering impacts on river ecosystem.
2. Efforts made by scientists in different parts of the world on EFA (methods, methodologies, approaches) vary in terms of knowledge base. Further, the EF studies and guidelines are region specific.
3. Socio-economic and water quality aspects of environmental flows also need to be considered in Indian context because of social and religious significance of rivers. Only a few methodologies consider these aspects in EFA.

4. Water requirement of human, livestock and vegetation in tributaries catchments (terrestrial ecosystem) related with a river reach may be termed as environmental water requirements (EWR) as these support distinct ecologies. Limited literature is available on EWR of terrestrial ecosystem. Distinction between EWR and EFR is important as the water requirements of terrestrial ecosystems are currently not explicitly considered (Smakhtin and Anputhas, 2006). Components of a hydropower project and related impacts are spread over the tributary catchments of a river reach. Therefore, EWR also needs to be assessed in addition to EFR as both are interlinked.
5. In previous hydrological studies of Satluj basin, differences in land use, rainfall pattern, snow area coverage of different tributary catchments have not been considered in assessment of low flows.
6. Usually environmental flows are prescribed in terms of hydrologic indices which may not adequately represent hydraulic habitat requirements of aquatic life.

STUDY AREA

For the purpose of this research work, the study area consists of the Satluj river reach and interim catchment related with the Nathpa Jhakri Hydroelectric Project (NJHEP) and Rampur Hydroelectric Project (RHEP). The study reach is part of middle Himalayas. The NJHEP is in operation stage and the diverted water (at Nathpa dam) is released back into Satluj after power generation at Jhakri. RHEP is under construction. The RHEP will make use of the water released in the tail race pool after power generation at Jhakri. Thus, RHEP will cause reduction in Satluj river flow downstream of Jhakri and up to Bael where the water will be released back into Satluj after power generation. Most of the project components are underground.

FIELD INVESTIGATIONS

Reconnaissance survey: Reconnaissance survey of the Satluj river between Nathpa dam and Jhakri power house was carried out for understanding the NJHEP and its environment.

Collection of soil samples and grain size analysis: Eight soil samples from various locations (Satluj river bed, banks of Satluj river and the streams) were collected for establishing the relationship between soil moisture retention capacity and soil texture. Brooks and Corey model has been used to estimate SMRC and HC of soils in study area using soil physical and chemical properties.

Village level survey: The survey was carried out to assess (i) dependability of people and animals on Satluj water for meeting their water requirements; (ii) source and adequacy of water supply in tributary catchments; (iii) change in crop type and crop areas if any and (iv) existing animal population.

Efforts were made to obtain considered opinions of villagers in a collective manner.

Monitoring of tributary discharges: Discharge of 13 tributaries of Satluj river have been monitored during the periods; October to December (2005), January to April (2006) and December (2006) to February (2007) on ten daily scale using current meter.

Sampling of benthic flora and fauna: Field observations on biodiversity (benthic) of Satluj river have been carried out at several sites during February to April 2006 and during December 2006. Sampling for abundance of macroinvertebrates was also conducted during December 2006.

River bed profile: River bed profile (transverse cross-sections of the Satluj river bed) at four locations in initial 10.8 km reach d/s of Nathpa dam have been surveyed. Longitudinal section of the Satluj river from Nathpa to Rampur has been prepared based on available data.

FLOW RELATED IMPACTS ON AQUATIC BIODIVERSITY

There is a potential lag effect in biological response to flow alteration. The NJHEP has come in operation stage in the year 2003. Therefore, present prediction and quantification of the biotic response to flow alteration could be done only with limited ability. Principles proposed by Bunn and Arthington (2002) form the basis for this assessment.

(i) Reduced flows immediately downstream of dam explains absence of hydropsyche.

(ii) Sudden increases in flow downstream of Nathpa dam may cause significant downstream drift of macroinvertebrates.

(iii) Hydrologic factors for fish being scanty in the study reach of river Satluj are (i) unstable flow regime (ii) continuous physiological stress due to loss of energy in maintaining their position in fast flowing waters (iii) frequent change in structure and consistency of river bed caused by high velocity of flow during floods.

(iv) The release of cooler water downstream of Jhakri power house can influence the spawning behaviour of fish and life history process of invertebrates in the downstream. After implementation of RHEP, cooler water downstream of Jhakri power house will be diverted into tunnel which may favour spawning of fish in Satluj reach upto Bael.

(v) Nathpa dam has transformed small length of the river Satluj into a pool habitat on upstream. Conversion of lotic to lentic habitat will result in the loss of fishes adapted to turbid riverine habitats. Creation of standing water body upstream of Nathpa dam is likely to favour introduced species. However, downstream of Nathpa dam long-term success of invading or introduced species is unlikely due to unstable flow regime.

WATER QUALITY INDEXING AND FLOW RELATED IMPACTS

The silt flushing discharge (81 cumec) from desilting chamber will have high silt content (70 to 80 g/l) causing high turbidity upto Jhakri (~ 80 g/l) beyond which it will reduce to 10 g/l due to return of desilted water from power house at Jhakri after power generation. However, after commissioning of Rampur Hydroelectric Project, the Satluj river will continue to have high turbidity even beyond Rampur town.

In the present study, three indices have been used to assess water quality; namely NSF-WQI, CPCB-WQI and Satluj-WQI. NSF-WQI is based on 9 parameters, all of which may not be important with reference to bathing and river ecology. CPCB-WQI is an index suitable for assessing bathing water quality. It does not include turbidity. Therefore, a new index (Satluj-WQI) based on 5 parameters (DO, BOD, pH, Faecal coliform and turbidity) is proposed in the context of EFA.

The Satluj WQI standard value has been proposed considering river bathing standards as per CPCB criteria and Aquatic Life Turbidity Criteria (for lean season and rainy season). Though, the Satluj WQI is higher than Satluj WQI standard at all the locations and also during rainy season and lean season, excessive turbidity due to silt flushing during the post-project condition will have adverse impact on aquatic life. The lean season Satluj WQI at D/S of Rampur for the post-NJHEP and post-RHEP conditions just meets the standard and therefore represents the critical condition, with respect to river bathing and aquatic life.

ENVIRONMENTAL WATER REQUIREMENT OF TERRESTRIAL ECOSYSTEM

The annual evapotranspirative demand of vegetation is 64 MCM. It is based on classification of area under ten land uses in the tributary catchments and estimation of actual evapotranspiration under different land uses. The domestic water needs of human population (2.813 MCM), animal water need (0.67 MCM) are based on estimated population and daily water requirements for summer and winter seasons.

Analysis of 26 years concurrent rainfall data at Nichar and Rampur shows that the area is prone to meteorological drought. Improvement in soil moisture characteristics is essential as the soils are shallow and evapotranspirative demand of natural vegetation is high.

The extensive tunnelling and other underground excavations (6.0 MCM) in the area have had adverse effect on subsoil water regime and recharging capacity. Based on field observations it has been found that springs and streams have either dried up or lean season flow have reduced. This has had adverse impact on meeting human and animal water needs in the tributary catchments.

Natural vegetation at the muck disposal sites has been destroyed by the dumped material. The analysis shows that the available water holding capacity of the dumped muck is less than 0.08 (vol./vol.) and organic matter content is negligible. Agronomic measures adopted by NJHEP for vegetation growth at the muck disposal sites have not been successful. Measures to improve available water holding capacity are (i) to reduce percentage of coarse particles to less than 15 % by mixing particles of appropriate size so that the top 2m depth contains soil texture of the type similar to that existing in the area, (ii) to incorporate large quantities of dead roots, peat or other organic material.

RIVER MAPPING AND LEAN SEASSON LOW CHARACTERISTICS

As an improvement over the previous hydrological studies of Satluj basin, the methodology proposed in this study is based on correlation between discharges of tributaries having similar catchment characteristics. Distinction has been made on the basis of (i) rainfed and snowfed catchments; (ii) durations with and without snowmelt contribution.

Specific discharge (discharge per unit catchment area) duration curves of Sholding, Gaanvi, Bhaba and Baspa streams are quite similar and hence discharge data of these streams can be used to estimate discharges of other streams on per unit catchment area basis. Difference in the values of Q90/Q50 for tributaries on right bank (Gaanvi , Bhaba) and left bank (Sholding , Baspa) indicate different normalized baseflow contributions from these catchments and it might be attributed to the amount of precipitation varying with the location of these catchments, whether in forward or leeward zones (Singh and Singh, 2001).Therefore, tributaries in the study area are divided into (i) Left bank tributaries having snow melt contribution, (ii) Right bank tributaries having snow melt contribution and (iii) Tributaries having no snow melt contribution.

Estimated tributary discharges have been used in lean season flow mapping of Satluj river from Nathpa to Jhakri. Important conclusions of river mapping are:

(i) Contributions to lean season flow of Satluj river are mainly from Shilaring stream, Sorang stream, Kut stream, Gaanvi stream, Manglad stream and Sumej stream.

(ii) Flow contribution from October upto January is mainly from ground water which gets nearly depleted by end of January. Beyond January, flow contribution is mainly from snow melt and winter rain.

(iii) Satluj river reach from Nathpa to the confluence of Sorang Stream (about 10.8 km) is a critical reach in the context of environmental flow. Flow in this reach is leanest in January and February months.

Low flow characteristics of Satluj river at three locations i.e. (i) Nathpa, (ii) d/s of confluence of Sholding stream and (iii) Rampur have been analyzed. Flow variability (represented by ratio Q20/Q90) has significantly increased in post-NJHEP condition. The ground water contribution to Satluj flow (represented by ratio Q90/Q50) is relatively higher in post-NJHEP condition compared to pre-NJHEP condition.

ASSESSMENT OF ENVIRONMENTAL FLOWS

The environmental flows have been assessed using three methods viz. (i) lookup tables, (ii) Environmental Management Class based FDC approach and (iii) hydraulic habitat analysis. The hydraulic habitat analysis is recommended for environmental flow assessment. The environmental flow may be prescribed as below:

(i) Release d/s of Nathpa dam should be at least 7 cumec. This release alongwith tributary inflows will cause submergence of 41.7% to 72.5% of bed width in the critical reach (10.8 km d/s of Nathpa dam) in the month having lowest flow. This amount of bed submergence is considered to be satisfactory in consideration of habitat requirement of aquatic life.

(ii) The velocity of 1.2 m/s should be maintained in consideration of silt flushing and maintenance of dissolved oxygen content and aquatic life.

(iii) Satluj WQI should be higher than 47 (for rainy season) and 55 (for lean season) based on CPCB criteria for outdoor bathing and Aquatic Life Turbidity Criteria

Loss in power generation due to environmental flow release downstream of Nathpa dam is likely to occur during September to April. In this period flow at Nathpa dam is not sufficient to meet diversion requirement (405 cumec) for power generation of 1500 MW and environmental flow requirement (7 cumec) downstream of Nathpa dam.

Each unit of flow released d/s of Nathpa dam (as environmental flow requirement) instead of being utilized for power generation will result in a loss of 3.711 MW. The power loss corresponding to environmental flow of 7 cumec is 26 MW.

RESEARCH CONTRIBUTION

i) The study contributes to limited literature on EFA in India and particularly to the Himalayan region wherein a large number of hydropower projects are being implemented.

ii) The study is important as it attempts to incorporate hydrologic, hydraulic and ecological aspects in EFA and provides scientific basis for prescription of EF.

iii) Present study analyzes environmental water requirements of the tributary catchments also which are distinct from environmental flow requirement.

iv) As an improvement over the previous hydrological studies of Satluj basin, the methodology proposed in this study is based on consideration of (i) rainfed and snowfed catchments; (ii) durations with and without snowmelt contribution.

v) A new index incorporating turbidity parameter (Satluj water quality index) has been proposed in the context of EFA.

Key Words: Environmental flow, Ecosystem, Environmental water requirement, Hydraulic habitat analysis, Hydropower, Nathpa Jhakri Hydroelectric Project,

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(PRADEEP KUMAR)

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SYMBOLS

%	Percent
^0C	Degree celcius
10Q10	10-day minimum flow corresponding to 10 year return period
10Q2	10-day minimum flow corresponding to 2 year return period
A	Catchment area
D	Maximum depth of flow
E_p	Pan evaporation
h	Matric potential
H	Elevation from mean sea level
H_R	elevation at Rampur from mean sea level
IBOD	Sub-index of biochemical oxygen demand
Icoli	Sub-index of faecal coliform
IDO	Sub-index of dissolved oxygen
IpH	Sub-index of pH
m	Order of event
MAM10	Mean annual 10-day minimum flow
MRO	Monsoon flow of Satluj river at Nathpa
MRO_{Rampur}	Monsoon flow of Satluj river at Rampur
N	Total number of event
NMRO	Non-monsoon flow of Satluj river at Nathpa
p	probability
P	Precipitation
Q	Discharge
Q_{20}	Discharge corresponding to 20% exceedence probability
Q_{50}	Discharge corresponding to 50% exceedence probability
$Q_{7,10}$:	Average 7-day annual minimum flow
Q_{90}	Discharge corresponding to 90% exceedence probability
$Q_{d,T}$:	d-day, T-year low flow
Qnd	Discharge of Satluj river downstream of Nathpa
Qndm	Minimum required release downstream of Nathpa
Qnt	Discharge of Satluj river going into tunnel
Qnu	Discharge of Satluj river upstream of Nathpa
Qsd	Discharge of Sholding Stream downstream of tunnel intake
Qss	Discharge of Satluj river downstream of Sholding confluence

Qst	Discharge of Sholding Stream going into tunnel
Qsu	Discharge of Sholding Stream upstream of tunnel intake
R	Rainfall
R_N	Average rainfall
t	time
T	Total bed width of river
T_{max}	mean monthly maximum temperature
T_{Rmax}	mean monthly maximum temperature at Rampur
W	Top width of water flowing in a river
W_i	Weightage associated with ith water quality parameter
δ	temperature lapse rate
θ	Soil moisture content

ACRONYMS

AET	:	Actual evapotranspiration
AMF	:	Absolute minimum flow
av.	:	Average
BBM	:	Building Block Methodology
BFI	:	Base flow index
BOD	:	Biochemical oxygen demand
CA	:	Catchment area
CAT	:	Catchment area treatment
ch.	:	Chainage
cm	:	centi metre
CPCB	:	Central Pollution Control Board
cumec	:	cubic metre per second
CV	:	Coefficient of variation
CWC	:	Central Water Commission
d/s	:	Downstream
DHI	:	Danish Hydraulic Institute
DO	:	Dissolved oxygen
DRIFT	:	Downstream Response to Imposed Flow Transform
DRM	:	Desktop Reserve Model
DWAF	:	Department of Water Affairs and Forestry
e.g.	:	For example
EF	:	Environmental flow
EFA	:	Environmental flow assessment
EFR	:	Environmental flow requirement
EMC	:	Environmental management class
EPAM	:	Expert Panel Assessment Method
et al.	:	and others
EWR	:	Environmental water requirement
FDC	:	Flow duration curve
FREND	:	Flow Regimes From Experimental And Network Data
g	:	gram
GLS	:	Generalized least square
ha	:	hectare
HC	:	Hydraulic conductivity

HPSEP&PCB	:	Himachal Pradesh State Environment Protection and Pollution Control Board
HRT	:	Head race tunnel
i.e.	:	That is
IFIM	:	Instream Flow Incremental Methodology
IFR	:	Instream flow requirement
IHA	:	Indicators of hydrological alteration
IUCN	:	International Union for Conservation of Nature and Natural Resources
IWMI	:	International Water Management Institute
JTU	:	Jackson Turbidity Unit
km	:	kilo metre
kW	:	kilo watt
L	:	litre
LB	:	Left bank
LFFC	:	Low flow frequency curve
LFFC	:	low flow frequency curve
LIFE	:	Lotic Invertebrate Index for Flow Evaluation
lpd	:	litre per day
lpm	:	litre per minute
lps		litre per second
m	:	metre
m^3	:	cubic metre
m^3/s	:	cubic metre per second
MAR	:	Mean annual runoff
max.	:	Maximum
MCM	:	Million cubic metre
MDF	:	Mean daily flow
min.	:	Minimum
mm	:	milli metre
MoEF	:	Ministry of Environment and Forests
MW	:	Mega watt
NCIWRDP	:	National Commission for Integrated Water Resource Development Plan
NH	:	National highway
NJHEP	:	Nathpa Jhakri Hydroelectric Project
No.	:	number
NSF	:	National Sanitation Foundation

NTU	:	Nephelometric turbidity unit
OLS	:	Ordinary least square
PET	:	Potential evapotranspiration
pH	:	cologarithm of dissolved hydrogen ions (H^+)
PHABSIM	:	Physical Habitat Simulation Model
RAV	:	Range of variability
RB	:	Right bank
RHEP	:	Rampur Hydroelectric Project
s	:	second
S. No.	:	Serial number
SDDC	:	Specific discharge duration curve
SMRC	:	Soil moisture retention capacity
SPAM	:	Scientific Panel Assessment Method
sq.	:	Square
u/s	:	Upstream
UK	:	United Kingdom
USA	:	United States of America
viz.	:	namely
vol.	:	Volume
WAMP	:	Water Allocation and Management Planning
WAPCOS	:	Water and Power Consultancy Services
WLS	:	Weighted least square
WQI	:	Water Quality Index

CHAPTER - 1
INTRODUCTION

1.1 BACKGROUND

The flows of the world's rivers are increasingly being modified through impoundments such as dams and weirs, abstractions for agriculture and urban water supply, drainage return flows, maintenance of flows for navigation, and structures for flood control (Dyson et al., 2003; Postel and Richter, 2003). These interventions have caused significant alteration of flow regimes mainly by reducing the total flow and affecting the variability and seasonality of flows. It is estimated that more than 60 % of the world's rivers are fragmented by hydrological alterations (Ravenga et al., 2000). This has led to widespread degradation of aquatic ecosystems (Millennium Ecosystem Assessment, 2005).

Right from the place of its origin to its outfall in the sea (or a bigger river), a naturally flowing fresh water river provides the habitat for a variety of diverse life forms. In many developing countries, a river also meets the needs of people on its banks. The livelihoods of many fisher folk, boatmen and farmers are supported by the river. Hundreds of religious and cultural events are organized regularly on river banks. All these benefits are provided by naturally flowing rivers without any costs being incurred, and these benefits are for all times. When the flow of rivers is reduced by storage and diversion and joined by water from polluted streams, many of these benefits are sacrificed.

Variability and seasonality of flows in tropical countries such as India is characterised by a high percentage of annual rainfall (70 % to 85 %) occurring in monsoon season (June/July to September/October). Tropical monsoon hydrology necessitates development of storage and flow diversion schemes on rainfed and perennial rivers for multipurpose utilization of water particularly for hydropower generation and irrigation for which high demand exists throughout the year. Himalayan rivers being snowfed are characterised by perennial flows and steep gradients offering abundant scope for hydropower development. A large number of hydropower schemes in the Himalayan mountainous region spread over parts of India, Nepal, Bhutan and Pakistan are in different stages of development.

A hydropower generation scheme in the Himalayan mountainous region usually consists of a control structure on the river (dam with or without significant storage), a water conveyance system (tunnel, canal) and a power house. The power house is located at a distance in downstream where topographical head difference between dam location and power house location is utilised for power generation and water is returned to the river. In several cases, water conveyance system and power house are located underground. A river reach is deprived of its natural flows due to diversion at control structure. Further, flow in the tributaries within a river reach may get modified due to various construction activities and also if tributary flows are diverted into the conveyance system. Thus, the natural flow regime is altered not only in a river reach downstream of control structure but at several places within a catchment associated with the project layout. Figure 1.1 depicts layout of a hydropower project and flow related impacts.

There may be critical reaches in the river where altered flows are not able to sustain the ecosystem services existing prior to implementation of the hydropower scheme. The developmental planning process in eco-sensitive and fragile Himalayan mountainous region should ensure that the biodiversity and ecological integrity of the aquatic and terrestrial ecosystems are protected and conserved.

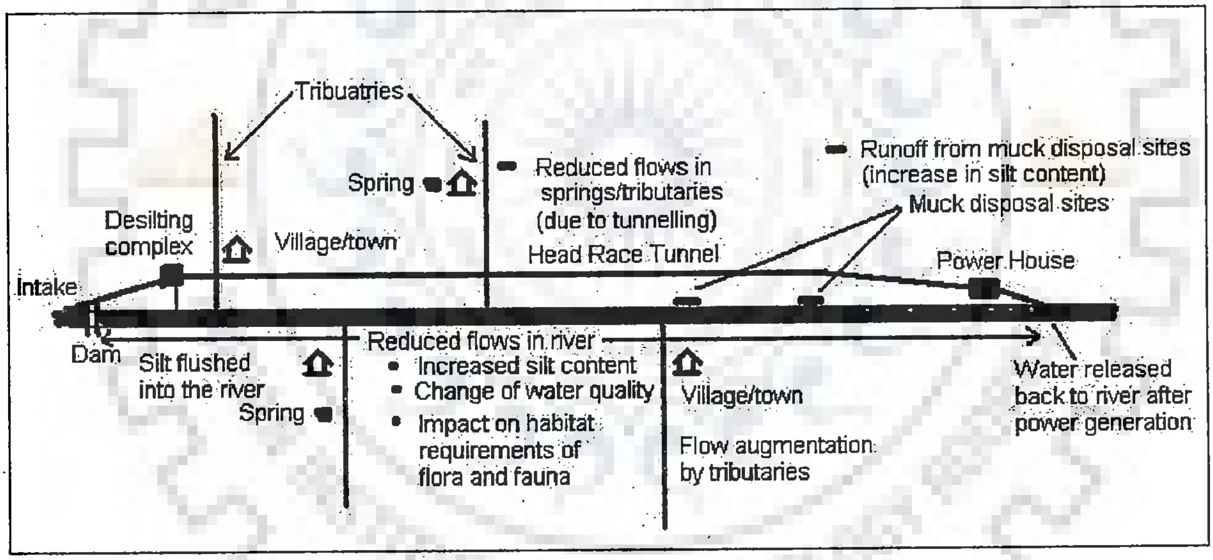


Figure 1.1: Layout of a hydropower project and flow related impacts

Ecosystem Services: An ecosystem is a natural unit consisting of all plants, animals and micro-organisms (biotic factors) in an area functioning together with all of the non-living physical (abiotic) factors of the environment. A river reach may be considered as aquatic ecosystem and its catchment as terrestrial ecosystem. These two ecosystems support distinct ecologies and are influenced by a hydropower project.

Globally, there is a growing acceptance of the need to safeguarding ecosystems when managing waters to meet human demands (Dugan et al., 2002; Instream Flow Council, 2002; Postel and Richter, 2003; Dyson et al., 2003). A goal of integrated water resources management is to ensure that the efficient use of water and related resources does not compromise the sustainability of vital ecosystems (GWP, 2000; GWP, 2003). This entails finding the balance between the short-term needs of social and economic development and the protection of the natural resource base for the longer term. An important challenge is, therefore, to balance water allocation between different users and uses (GWP, 2000). Ecosystems are the silent water users who have frequently been omitted from water allocation decision-making. Ecosystems, however, provide a wide range of valuable services to people (GWP, 2003; Millennium Ecosystem Assessment, 2005). In India, the livelihood of rural people to a large extent depends directly on the provision of ecosystem services. The marginalization of ecosystems in water resources management and the associated degradation or loss of ecosystem services, have resulted in economic costs, in terms of declining profits, remedial measures, damage repairs and lost opportunities. The highest costs, however, are typically borne by people depending directly on ecosystem services (Emerton and Bos, 2005; Millennium Ecosystem Assessment, 2005; Pearce et al., 2006).

In several cases, maintaining ecosystems has proven to be a more cost-effective way of providing services than employing artificial technologies (Emerton and Bos, 2005). Thus, recognizing the full value of ecosystem services, and investing in them accordingly, can safeguard livelihoods and profits in the future, save considerable costs and help achieve sustainable development goals. Failing to do so may seriously jeopardize any such efforts (Russell et al., 2001; Costanza, 2003; Dyson et al., 2003; Emerton and Bos, 2005; Millennium Ecosystem Assessment, 2005; Pearce et al., 2006).

Many factors, such as water quality, sediments, food-supply and biotic interactions, are important determinants of riverine ecosystems. However, an overarching master variable is the river's flow regime (Poff et al., 1997; Bunn and Arthington, 2002). This recognition of flow as a key driver of riverine ecosystems has let to the development of the environmental flows concept (Dyson et al., 2003). A wide range of outcomes, from environmental protection to serving the needs of industries and people, are to be considered for the setting of an environmental flow. There is no simple figure that can be given for the environmental flow requirements of rivers. Much depends on stakeholders' decisions about the future character and health status of these ecosystems.

1.2 ENVIRONMENTAL FLOW ASSESSMENT

Terms such as instantaneous flow, daily flow, weekly flow, seasonal (fortnightly, monthly, wet season, lean season) flow are used to express magnitude of flow. Seasonal flows have been usually studied in the context of water use planning and water management. Insufficient rather than excessive water is the concern not only in design for water use but also in managing the instream flow for ecological and environmental sustainability. Therefore, new dimensions such as river maintenance flows, environmental flows, and managed flows have been added to the analysis of lean season flows.

An environmental flow is the water regime provided within a river to maintain ecosystems and their benefits where there are competing water uses and where flows are regulated. Environmental flows provide critical contributions to river health, economic development and poverty alleviation. They ensure the continued availability of the many benefits that healthy river and groundwater systems bring to society.

Environmental flows serve to represent water allocation for ecosystems. As ecosystems, in turn, provide services to people, providing for environmental flows is not exclusively a matter of sustaining ecosystems but also a matter of supporting livelihoods of village people who make direct use of river water for variety of purposes including religious worship. There is, however, a lack of methods to demonstrate the inherently multidisciplinary link between environmental flows and ecosystem services. The present study aims at filling this knowledge gap.

For day-to-day management of particular rivers, environmental requirements are often defined as a suite of flow discharges of certain magnitude, timing, frequency and duration. These flows ensure a flow regime capable of sustaining a complex set of aquatic habitats and ecosystem processes and are referred to as "environmental flows", "environmental water requirements", "environmental flow requirements", "environmental water demand", etc. (Knights, 2002; Lankford, 2002; Dyson et al., 2003; Smakhtin et al., 2004a, 2004b). Many methods for determining these requirements have emerged in recent years. They are known as environmental flow assessments (EFA).

1.3 REASEARCH GAPS

Review of available literature on environmental flow assessment (Chapter 2 and chapter 3) shows that:

1. The status of EF research in India may be characterized as being in its infancy because of very limited knowledge base (NCIWRDP, 1999). EF in India has usually been understood as a flow, which is to be released downstream from the dams as a riparian right.
2. Efforts made by scientists in different parts of the world on EFA (methods, methodologies, approaches) vary in terms of use of biotic data and socio-economic aspect of EF. Further, the EF studies and guidelines are region specific.

3. Socio-economic and water quality aspects of environmental flows are important in Indian context because of social and religious significance of rivers. Only a few methodologies consider these aspects in EFA.
4. Water requirement of human, livestock and vegetation in tributaries catchments (terrestrial ecosystem) related with a river reach may be termed as environmental water requirements (EWR) as these support distinct ecologies. Limited literature is available on EWR of terrestrial ecosystem. Distinction between EWR and EFR is important as the water requirements of terrestrial ecosystems are currently not explicitly considered (Smakhtin and Anputhas, 2006). Components of a hydropower project and related impacts are spread over the tributary catchments of a river reach. Therefore, EWR also needs to be assessed in addition to EFR as both are interlinked.
5. In previous hydrological studies of Satluj basin, differences in land use, rainfall pattern, snow area coverage of different tributary catchments have not been considered in assessment of low flows.
6. Usually environmental flows are prescribed in terms of hydrologic indices which may not adequately represent hydraulic habitat requirements of aquatic life.

1.4 OBJECTIVES

The primary purpose of this study is to contribute to the research work on EFA and EWR in Himalayan region through analysis of flow related impacts of a hydropower project. Specific objectives of the research work are:

1. To review available EFA methodologies in terms of applicability, strengths and limitations and the status of EFA in India;
2. To collect data from natural environment and analyze the flow related impacts (on aquatic biodiversity, water quality) of a hydropower project;
3. To assess environmental water requirements of terrestrial ecosystem (tributary catchments);
4. To analyze the low flow characteristics of Satluj river and related tributaries in the specific river reach and assess environmental flows using suitable methods.

1.5 ORGANIZATION OF THE THESIS

The thesis is arranged in nine chapters as follows:

Chapter 1: The first chapter provides background for the research problem and the objectives which are proposed to be achieved in this research work.

Chapter 2: In this chapter, review of literature is presented in two parts; first part covers review of low flow hydrology and second part covers a critical analysis of available environmental flow assessment (EFA) methodologies. At the end, the EFA methodologies have been summarized identifying the strengths and limitations as well as requirement of input data and the outcomes of the EFA methodologies.

Chapter 3: This chapter deals with the current status of environmental flow assessment in India.

Chapter 4: This chapter deals with (i) the study area in terms of location, climate, catchment characteristics and hydrologic characterization (ii) details of field investigations carried out for the study.

Chapter 5: The chapter deals with analysis of aquatic biodiversity and water quality in the study area and impact of altered flow regime due to diversion of Satluj flow at Nathpa. The study is based on analysis of sample data (sampling of biodiversity, water quality and village level survey) and secondary data available in literature.

Chapter 6: This chapter analyses pattern of human habitations, accessibility to Satluj river, impact of tunnelling on sources of water, and annual water demand of animals, human beings and vegetation in the context of environmental water requirements of terrestrial ecosystem.

Chapter 7:.This chapter deals with the river mapping of Satluj river reach from Nathpa to Jhakri and lean season flow analysis.

Chapter 8: Based on the analysis carried out in previous chapters, environmental flow assessment in the Satluj river reach influenced by the hydropower projects is discussed in this chapter.

Chapter 9: This chapter presents the summary and important conclusions drawn from the study.

CHAPTER – 2

A CRITICAL REVIEW OF ENVIRONMENTAL FLOW ASSESSMENT METHODOLOGIES

Several methods/methodologies have been proposed in the literature for assessment of environmental flows. These methods range from simplistic use of the hydrological record to establish minimum and flushing flows to sophisticated procedures linking changes in river discharge with geomorphological and ecological response. Some methods consider socio-economic aspects also such as DRIFT, BBM. The hydrologic index methods and hydraulic rating methods are based entirely on hydrologic analysis of hydrologic data such as discharge, velocity, depth of flow, wetted perimeter, and wetted area at different cross sections of the river reach. Recent studies have combined a number of methods within a broader methodological framework designed to provide comprehensive recommendations on water allocations for ecosystem protection.

The review of literature is presented in two parts; first part covers brief review of low flow hydrology (Section 2.1 to Section 2.2) and second part covers a critical analysis of available environmental flow assessment (EFA) methodologies (Section 2.3 to Section 2.7). At the end, the EFA methodologies have been summarized identifying the strengths and limitations as well as requirement of input data and the outcomes of the EFA methodologies (Section 2.8).

2.1 RELEVANCE OF LOW FLOW HYDROLOGY IN THE CONTEXT OF ENVIRONMENTAL FLOWS

Low flow hydrology covers the analysis of river flows during dry weather. Mean annual runoff in volume or in equivalent discharge terms are used as upper bound of low flow hydrology. Environmental flows have often been prescribed in terms of percentile flows such as 95%, 80% dependable flows which under natural conditions pertain to dry weather.

Long-term hydrologic data (mainly stream flow) are the main input data in several EFA methods. Such data are usually not available for catchments in many parts of the world particularly in Himalayan mountainous region. Therefore, appropriate methods for assessment of flows in ungauged catchments are needed. Reliability of EFA depends on reliability of low flow assessment. Low flow regional regression models represent a relationship between low stream flow statistics and watershed characteristics. The watershed characteristics are used to describe the various processes that influence streamflow during low flow events. These processes need to be quantified in a way so as to be effectively represented within a regional regression model.

In steeply sloping terrain, fracture zones above the main water table may transport subsurface water laterally. Stream channels that intersect these fracture zones receive the laterally flowing subsurface water. The amount of seepage a stream receives from such fracture zones depends on the lateral flow rate of water through the fractures as well as the density and size of the fractures. Bingham (1986), Aucott et al. (1987), Rogers and Armbruster (1990) and Ries (1994) provide further discussion regarding the discharge rates exhibited by various geological features.

Large scale blasting operations are carried out under ground to accommodate various components of an underground hydro power scheme. New fracture zones are created which may alter the subsurface flow regime. Very limited studies are available on influence of under ground construction on subsurface flows. Chapter 6 provides further discussion on this important aspect.

Near channel storage areas, such as permanently wetted channel bank soils, alluvial valley fills, and wetlands, accumulate and store water during precipitation events. As stream flow subsides during the low flow period, water that has accumulated in the near channel storage areas may be discharged into the stream, and therefore may contribute to sustaining stream flow (Smakhtin, 2001).

In Himalayan region, melt water from glaciers, snow, and ice formations serve as main source of stream flow during summer. The influence of melt water on low flow events has been examined in several studies (Gerard, 1981; Gurnell, 1993; Hopkinson and Young, 1998; Jain, 2001).

Ground water, lakes, wetlands and glaciers serve as sources of stream flow input during low flow periods. In cold regions, processes made possible by low temperatures contribute to stream flow losses during low flow periods. For instance, the formation of permafrost reduces the amount of ground water available for discharge into stream channels. Precipitation in the form of snow provides temporary storage of water, which may remain unavailable for stream recharge until it has melted. Lastly, ice formation over stream channels also serve as a source of water loss (Smakhtin, 2001).

2.2 LOW FLOW ESTIMATION TECHNIQUES

Generally, low flow stream flows are described using the seven-day, ten-year low stream flow statistic ($Q_{7,10}$). Riggs (1985) defined the $Q_{7,10}$ as the average 7-day annual minimum at a 10-year recurrence period. Many federal and state environmental

Table 2.1: Categorization of EFA methodologies

Organization	Category	Sub-category	Example
IUCN (Dyson et al. 2003)	Methods	Look-up Tables	Hydrological (e.g. Q95 index); Ecological (e.g. Tennant Method)
		Desktop Analysis	Hydrological (e.g. Richter Method); Hydraulic (e.g. Wetted Perimeter Method); Ecological
		Functional Analysis	Building Block Methodology (BBM); Expert Panel Assessment Method (EPAM); Benchmarking Methodology
		Habitat Modelling	Physical Habitat Simulation Modelling (PHABSIM)
	Approaches		Expert Team Approach; Stakeholder Approach (expert and non-expert)
	Frameworks		Instream Flow Incremental Methodology (IFIM); Downstream Response to Imposed Flow Transformation (DRIFT)
World Bank (Brown and King, 2003)	Perspective Approaches	Hydrological Index Methods	Tennant Method
		Hydraulic Rating Methods	Wetted Perimeter Method
		Expert Panels	
		Holistic Approaches	Building Block Methodology (BBM)
	Interactive Approaches		Instream Flow Incremental Methodology (IFIM); Downstream Response to Imposed Flow Transformation (DRIFT)
IWMI (Tharme, 2003)	Hydrological Index Methods		Tennant Method
	Hydraulic rating Method		Wetted Perimeter Method
	Habitat Simulation Methodologies		Instream Flow Incremental Methodology (IFIM)
	Holistic Methodologies		Holistic Approach; Instream Flow Incremental Methodology (IFIM); Downstream Response to Imposed Flow Transformation (DRIFT); Building Block Methodology (BBM); Expert Panel Assessment Method (EPAM); Scientific Panel Assessment Method (SPAM); Habitat Analysis Method

Following EFA methods/methodologies have been reviewed in this chapter covering their origin, development, strengths and limitations:

- Lookup Tables prescribed in UK, Australia, USA
- Desktop Methods based on Hydrological Data (Range of Variability Approach, Base Flow Index, flow duration curve based approach)
- Desktop Methods based on Hydrological and Ecological Data (Lotic Invertebrate Index for Flow Evaluation (LIFE))
- Hydraulic Rating Method
- Habitat Simulation Methodologies

- Holistic methodologies – These include:
  - Holistic Approach (Arthington et al., 1992a) – bottom up method
  - Downstream Response to Imposed Flow Transformations (King et al., 2003) – top down method
  - Instream Flow Incremental Methodology (Bovee, 1986; Bovee et al., 1998) – bottom up method
  - Building Block Methodology (King and Tharme, 1994; King and Louw, 1998) – bottom up method
  - Expert Panel Assessment Method (Swales and Harris, 1995) – bottom up method
  - Scientific Panel Assessment Method (Thoms et al., 1996) – bottom up method
  - Habitat Analysis Method (Walter et al., 1994; Burgess and Vanderbyl, 1996) – bottom up method

2.4 HYDROLOGICAL INDEX METHODS

These are the simplest and most widespread EFA methods also referred to as desk-top or look-up table methods. These methods rely primarily on historical flow records. Environmental flow is usually given as a percentage of average annual flow or as a percentile from the flow duration curve, on a seasonal or monthly basis. Commonly, the Environmental Flow is represented as a proportion of flow (often termed the 'minimum flow', e.g. Q95 – the flow equalled or exceeded 95 percent of the time) intended to maintain river health. Most methods simply define the minimum flow requirement; however, in recognition of the 'Natural Flow Paradigm' more sophisticated methods have been developed that take several (upto 32) flow characteristics into account (such as low flow durations, rate of flood rise/fall etc).

Hydrological Index Methods provide a relatively rapid, non-resource intensive, but low resolution estimate of environmental flows. Therefore the methods are most appropriate at the planning level of water resources development, or in low controversy situations where they may be used as preliminary estimates.

Montana or Tennant Method: Tennant (1976) considered the three factors of wetted width, depth and velocity as being crucial for fish wellbeing. Tennant (1976) measured variables concerning physical, biological and chemical parameters along 58 transects from 11 different streams at 38 different discharges (a total of 196 miles of stream). These data were gathered in three north-western states of the United States and augmented with additional data collected from a further 21 states.

Tennant (1976) proposed that certain flows could achieve the maintenance of particular amounts of habitat as given in Table 2.2. Tennant considered biota other than fish in the formulation of these standards but was concerned chiefly with the maintenance of in-stream secondary production and recreational salmonid fisheries.

Tennant (1976) recognised that the flat allocation of a single discharge to a modified flow regime effectively removed all trace of any pre-existing pattern of seasonality. Therefore, Tennant proposed a series of different flows for two six-month blocks (Table 2.2).

Table 2.2: Proportion of mean annual flow to achieve the maintenance of differing levels of habitat quality

Flow category	Recommended baseflow regime (%)	
	October to March	April to September
flushing or maximum	200	200
optimum	60–100	60–100
outstanding	40	60
excellent	30	50
good	20	40
fair or degrading	10	30
poor or minimum	10	10
severe degradation	<10	<10

Disadvantages

Tennant (1976) suggested that the method is most applicable for mountain streams with 'virgin' flow. If the flow regime is already partly regulated, then suggested allocations may be too low. Prewitt and Carlson (1980) suggested that in streams where losses to offstream uses and diversions are poorly known, there is a high potential for under-allocation. This has serious consequences in areas for which there is poor or little accurate quantitative data on actual volumes abstracted.

The Montana Method is dependent on the provision of extensive flow data. In many regions of world, such long term flow records are not available. Furthermore, where long time series of data are available, care must be taken in choosing which period of record is used as the basis for water allocations. Therefore, the choice of segment of streamflow data upon which to base an environmental allocation seems critical.

The relationship between habitat suitability and proportions of mean annual flow, which forms the basis of the Montana Method, has not been examined in India. Moreover, in regions with variable flows (i.e. the mean flow is substantially different to the median flow), application of the Montana Method may result in allocations more generous than are required (Richardson, 1986; Tharme, 1996).

The Montana Method has been criticised for offering an assessment of only low to moderate resolution, encompassing limited temporal differences in flow allocations (Stalnaker and Arnette, 1976). In other words, only two 'seasonal' flows are possible, The Montana method is generally for baseflows only and has little provision for recommending other ecologically important flows (e.g. spates and floods).

Arthington et al. (1992a) regarded the adoption of 20th, 50th and 80th percentile flows (drought, median and flood flows respectively) as defining the boundary conditions within an environmental flow allocation and, further, that the incorporation of variability within the monthly flow was needed. Incorporation of monthly percentile flows allows the maintenance of the natural temporal pattern of intra-annual variation. Furthermore, additional volumes may also be added to monthly allocations to achieve specific ecological purposes or to accommodate for downstream abstraction or diversion (Arthington et al., 1992a; Swales et al., 1994).

2.4.1 Look-up Tables

France: A Hydrological index is used in France, where the Freshwater Fishing Law (June, 1984) required that residual flows in bypassed sections of river must be a minimum of 1/40 of the mean flow for existing schemes and 1/10 of the mean flow for new schemes (Souchon and Keith, 2001).

UK: In regulating abstractions in the UK, an index of natural low flow has been employed to define the environmental flow. Q95 (i.e. that flow which is equalled or exceeded for 95% of the time) is often used. However, in other cases, indices of rarer events (such as mean annual minimum flow) have been used. The figure of Q95 was chosen purely on hydrological grounds. However, the implementation of this approach often includes ecological information (Barker and Kirmond, 1998).

USA: Tennant (1976) developed a method using calibration data from hundreds of sites on rivers in the mid-western states of the USA to specify minimum flows to protect a healthy river environment. Percentages of the mean flow are specified that provide different quality habitat for fish e.g. 10% for poor quality (survival), 30% for moderate habitat (satisfactory) and 60% for excellent habitat. The indices have been adapted for other climatic regions in North America and have been widely used in planning at the river basin level.

Indices based purely on hydrological data are more readily calculated for any new region, as flow data tend to be generally available. Look up tables do not necessarily take account of site specific conditions. Therefore these are particularly appropriate for low controversy situations. They also tend to be precautionary.

2.4.2 Desktop Analysis

Desktop methods can be sub-divided into (a) those based purely on hydrological data, and (b) those that employ both hydrological and ecological data.

Desktop methods based on hydrological data

Desktop methods examine the whole river flow regime rather than using simple pre-derived statistics. A fundamental principle is to maintain integrity, natural seasonality and variability of flows, including floods and low flows (e.g. drying out where rivers are ephemeral).

(A) Range of Variability Approach (RVA):

Range of variability Approach developed by Richter et al. (1997) uses the indicators of hydrological alteration (IHA) as given in Richter et al. (1996). They developed a hydrological method intended for setting benchmark flows on rivers, where protection of the natural ecosystem is the primary objective. Development of the IHA approach concentrated on identification of the components of a natural flow regime, indexed by magnitude (of both high and low flows), timing (indexed by monthly statistics), frequency (number of events), duration (indexed by moving average minima and maxima) and rate of change. The method used gauged or modelled daily flows and a set of 32 indices (Richter et al., 1996). Each index was calculated on an annual basis for each year in the hydrological record and thus concentrates on inter-annual variability in the indices. The question to be addressed is how much deviation from natural ranges of these parameters is too much? Where no ecological information is available to answer this question, the RVA uses a default range of variation based +/-1 standard deviation from the mean or between the 25^{th} and 75^{th} percentiles.

(B) Desktop Reserve Model (DRM):

Hughes and Munuster (2000) and Hughes and Hannart (2003) developed a desktop method for rivers in South Africa. The user calculates a hydrological index (i.e. coefficient of variation of flows divided by the base flow index; CV/BFI) using river flow data at the site. Then, curves are employed to define the percentages of mean annual runoff (MAR) volume that is required for different components (low flows and floods) of the environmental flow regime. Recently, Hughes et al. (in press) have developed an operating rule model to simulate time series of reservoir releases for instream flow requirements.

BFI is a non-dimensional ratio which is defined as the volume of baseflow divided by the volume of total streamflow (or alternatively, as the ratio between the average discharge under the separated baseflow hydrograph and the average discharge of the total hydrograph). In catchments with high groundwater contribution to streamflow, BFI may be close to 1, but it is equal to zero for ephemeral streams. Some sources list characteristic values of BFI for a number of rivers in certain regions (FREND, 1989; Smakhtin and Watkins, 1997). BFI was found to be a good indicator of the effects of geology on low-flows and for that reason is widely used in many regional low-flow studies.

(C) Flow Duration Curve Based Study

A flow duration curve (FDC) is a plot of flow vs percentage time equalled or exceeded. This can be prepared using the entire time series data of flow or the flow data pertaining to a specific period (such as a month) in different years. Further, it can be developed for a particular site or combining data for different sites on per unit catchment area basis in a hydrometeorologically homogeneous region.

Stalnaker and Arnette (1976) suggested that the use of flow duration curve analysis is problematic unless the hydrological pattern of the stream in question is similar to that of the region for which it was developed. In the United States several methods have been devised, including the original procedure, which modify flow duration curve analysis to account for such differences in stream size and region (Tharme, 1996).

Flow duration curve analysis does seek to reintroduce some level of seasonality back into the modified flow regime and this is its greatest strength. A major disadvantage, however, is a questionable identification of exactly what flows are necessary to maintain certain aspects of the aquatic environment. In addition, flow duration curve analysis, as it stands, does not explicitly allow for a consideration of inter-annual variation of discharge.

A major assumption of flow duration curve analysis is that the most frequent conditions over a period of record are suitable for all life history stages without any examination of short-duration perturbations and species responses (Richardson, 1986). Moreover, it also assumes that the prolonged imposition of a certain flow has the same ecological effect as a group of repeated but temporally discrete events of the same magnitude. There is little theoretical or empirical basis for these assumptions.

(D) Environmental Management Class (EMC) based FDC Approach

Smakhtin and Anputhas (2006) reviewed various hydrology based environmental flow assessment methodologies and their applicability in Indian context. Based on the study, they suggested a flow duration curve based approach which links environmental flow requirement with environmental management classes.

This EFA method is built around a period-of-record FDC and includes several subsequent steps. The first step is the calculation of a representative FDC for each site where the environmental water requirement (EWR) is to be calculated. In this study, the sites where EF is calculated are coincident with the major flow diversion. The sites with observed flow data are further referred to as 'source' sites. The sites where reference FDC and time series are needed for the EF estimation are further referred to as 'destination' sites. In this case, the destination site is significantly impacted by upstream basin developments (such as flow diversion). Therefore, representative 'unregulated' monthly flow time series, or corresponding aggregated measures of unregulated flow variability, like FDCs, have to be simulated/derived from available observed (source) records.

All FDCs in this study are represented by a table of flows corresponding to the 17 fixed percentage points: 0.01, 0.1, 1, 5, 10, 20, 30, 40, 50, 60, 70, 80, 90, 95, 99, 99.9 and 99.99 percent. These points (i) ensure that the entire range of flows is adequately covered, and (ii) easy to use in the context of the following steps. FDC tables were calculated directly from the observed record or from part of the record which could be considered 'unregulated'. Normally the earlier part of each record - preceding major dams' construction – was used to ensure that monthly flow variability, captured by the period-of-record FDC, is not seriously impacted.

For each destination site, a FDC table was calculated using a source FDC table from either the nearest or the only available observation flow station upstream. To account for land-use impacts, flow withdrawals, etc., and for the differences between the size of a source and a destination basin, the source FDC is scaled up by the ratio of 'natural' long-term mean annual runoff (MAR) at the outlet and the actual MAR calculated from the source record. The application of such ratio effectively 'naturalizes' the observed flow source time series and 'moves' it to the basin outlet.

The scaling up of the curves is effectively equivalent to the scaling of the actual time series. It is important to stress that both the calculated FDC and the corresponding time series reflect the flow amounts and variability which no longer exist at the outlets of river basins. They are perceived to represent the hydrological reference conditions that existed in the past prior to major basin developments.

EF aim to maintain an ecosystem in, or upgrade it to, some prescribed or negotiated condition/status also referred to as "environmental management class (EMC)". The higher the EMC, the more water will need to be allocated for ecosystem maintenance or conservation and more flow variability will need to be preserved.

Placing a river into a certain EMC is normally accomplished by expert judgment using a scoring system. Alternatively, the EMCs may be used as default 'scenarios' of environmental protection and corresponding EWR and EF - as 'scenarios' of environmental water demand.

Six EMCs are used in this study and six corresponding default levels of EWR may be defined. The set of EMCs (Table 2.3) is similar to the one described in DWAF (1997). It starts with the unmodified and largely natural conditions (rivers in classes A and B), where no or limited modification is present or should be allowed from the management perspective. In moderately modified river ecosystems (class C rivers), the modifications are such that they generally have not (or will not – from the management perspective) affected the ecosystem integrity. Largely modified ecosystems (class D rivers) correspond to considerable modification from the natural state where the sensitive biota is reduced in numbers and extent. Seriously and critically modified ecosystems (classes E and F) are normally in poor conditions where most of the ecosystem's functions and services are lost. Rivers which fall into classes C to F would normally be present in densely populated areas with multiple man-induced impacts. Poor ecosystem conditions (classes E or F) are sometimes not considered acceptable from the management perspective and the management intention is always to "move" such rivers up to the least acceptable class D through river rehabilitation measures (DWAF, 1997). This restriction is not however applied in this report, primarily because the meaning of every EMC is somewhat arbitrary and needs to be filled with more ecological substance in the future. Some studies use transitional EMCs (e.g., A/B, B/C, etc.) to allow for more flexibility in EWR determinations. It can be noted, however, that ecosystems in class F are likely to be those which have been modified beyond rehabilitation to anything approaching a natural condition.

It is possible to estimate EWR corresponding to all or any of the above EMCs and then consider which one is best suited/feasible for the river in question, given existing and future basin developments. On the other hand, it is possible to use expert judgment and available ecological information in order to place a river into the most probable/achievable EMC.

Default FDCs representing a summary of EF for each EMC are determined by the lateral shift of the original reference FDC – to the left, along the probability axis. The mentioned 17 percentage points on the probability axis: 0.01, 0.1, 1, 5, 10, 20, 30, 40, 50, 60, 70, 80, 90, 95, 99, 99.9 and 99.99 percent are used as steps in this shifting procedure. A FDC shift by one step means that a flow which was exceeded, 99.99 percent of the time in the original FDC will now be exceeded 99.9 percent of the time, the flow at 99.9 percent becomes the flow at 99 percent, the flow at 99 percent becomes the flow at 95 percent, etc. A linear extrapolation is used to define the 'new low flows' at the lower tail of a shifted curve. The entire shifting procedure can be easily accomplished in a spreadsheet.

Table 2.3: Environmental Management Classes (EMC) and corresponding default limits for FDC shift

EMC	Ecological description	Management perspective
A: Natural	Pristine condition or minor modification of in-stream and riparian habitat	Protected rivers and basins. Reserves and national parks. No new water projects (dams, diversions, etc.) allowed
B: Slightly modified	Largely intact biodiversity and modified habitats despite water resources development and/or basin modifications	Water supply schemes or irrigation development present and/or allowed
C: Moderately modified	The habitats and dynamics of the modified biota have been disturbed, but basic ecosystem functions are still intact. Some sensitive species are lost and/or reduced in extent. Alien species present	Multiple disturbances associated with the need for socio-economic development, e.g., dams, diversions, habitat modification and reduced water quality
D: Largely modified	Large changes in natural habitat, modified biota and basic ecosystem functions have occurred. A clearly lower than expected species richness. Much lowered presence of intolerant species. Alien species prevail	Significant and clearly visible disturbances associated with basin and water resources development, including dams, diversions, transfers, habitat modification and water quality degradation
E: Seriously modified	Habitat diversity and availability modified have declined. A strikingly lower than expected species richness. Only tolerant species remain. Indigenous species can no longer breed. Alien species have invaded the ecosystem	High human population density and extensive water resources exploitation
F: Critically modified	Modifications have reached a critical modified level and ecosystem has been completely modified with almost total loss of natural habitat and biota. In the worst case, the basic ecosystem functions have been destroyed and the changes are irreversible	This status is not acceptable from the management perspective. Management interventions are necessary to restore flow pattern, river habitats, etc. (if still possible/feasible) – to 'move' a river to a higher management category

Source: Smakhtin and Anputhas (2006)

The difference between the default shifts of the reference FDC for different environmental classes is set to be one percentage point. In other words, a minimum lateral shift of one step (a distance between two adjacent percentage points in the FDC table) is used. This means that for a class A river the default environmental FDC is determined by the original reference FDC shifted one step to the left along the probability axis. For a class B river the default environmental FDC is determined by the original reference FDC shifted two steps to the left along the probability axis from its original position, etc.

An environmental FDC for any EMC only gives a summary of the EF regime acceptable for this EMC. The curve however does not reflect the actual flow sequence. At the same time, once such environmental FDC is determined, it is also possible to convert it into the actual environmental monthly flow time series. The spatial interpolation procedure described in detail by Hughes and Smakhtin (1996) can be used for this purpose. The underlying principle in this technique is that flows occurring simultaneously at sites in reasonably close proximity to each other correspond to similar percentage points on their respective FDCs.

Desktop methods based on hydrological and ecological data

Methods that use ecological data tend to be based on statistical relationships between independent variables such as flow to biotic dependent variables. The latter could be simple, such as total abundance or species richness, or more complicated matrices calculated from lists of taxa observed in the samples. The advantages of this type of approach is that it directly addresses the two areas of concern (flow and ecology) and takes into account, directly, the nature of the river in question. However, there are some disadvantages:

(a) It is difficult or impossible to derive biotic indices that are sensitive only to flow and not to other factors (e.g. habitat structure, water quality). Hence, biotic indices designed for water-quality monitoring purposes should be used with great caution (Armitage and Petts, 1992).

(b) Lack of both hydrological and biological data is often a limiting factor; sometimes routinely collected data may be gathered for other purposes and not be suitable.

(c) Time series of ecological data may well not be independent, which can violate the assumptions of classical statistical techniques.

A method developed in the UK in this category that involves the use of available ecological data is the Lotic Invertebrate Index for Flow Evaluation (LIFE) (Dunbar et al., 1998). It is designed to be used with routine macro-invertebrate monitoring data. A metric of perceived sensitivity to water velocity scores all recorded UK taxa on a six-point scale. For a sample, the score for each observed taxon is weighted based on its abundance, and mean score per taxon is calculated. The system works with either species or family level data. For monitoring sites where historical time series of flows are known, the relationship between LIFE score and preceding river flow may be analysed. Moving averages of preceding flow have shown good relationship with LIFE scores over a range of sites. The exact manner in which LIFE score variation can be used to manage river flows is still to be determined. Nevertheless, the principle is believed to be sound and LIFE has the major advantages of utilizing the data collected by existing bio-monitoring programmes so is compatible with the European Water Framework Directive.

2.5 HYDRAULIC RATING METHODS

As discussed above, difficulties exist in relating changes in the flow regime directly to the response of species and communities; hence, approaches have been developed that use habitat for target species as an intermediate step. Within the total environmental niche required by an individual animal or plant living in a river, it is the physical aspects that are affected by changes to the flow regime.

The most obvious physical dimension that can be changed by altered flow regimes is the wetted perimeter area of submerged river bed of the channel. Hydraulic rating methods provide simple indices of available habitat (e.g. wetted perimeter) in a river at a given discharge. Graphs of discharge and wetted perimeter provide a basic tool for environmental flow evaluation. As a rule of thumb, shallow, wide rivers tend to show more sensitivity of their wetted perimeter to changes in flow than do narrow, deep rivers.

Gippel and Stewardson (1998) have highlighted the problems of trying to identify thresholds (critical discharges below which wetted perimeter declines rapidly) that can be used to define minimum environmental flows.

Hydraulic rating methods are based on historical flow records (stage-discharge rating curve) and cross-section data. They model hydraulics as function of flow and assume links between hydraulics (wetted perimeter, depth, velocity) and habitat availability of target biota. In other words, they use hydraulics as a surrogate for the biota. Environmental flow is given either as a discharge that represents optimal minimum flow, below which habitat is rapidly lost, or as the flow producing a fixed percentage reduction in habitat availability. In recent years, hydraulic rating methods have been superseded by Habitat Simulation Methodologies or absorbed within Holistic Methodologies.

Wetted Perimeter Method: The wetted perimeter method (Reiser et al., 1989) is the most commonly applied hydraulic rating method. Environmental flows are determined from a plot of the hydraulic variable(s) against discharge, commonly by identifying curve breakpoints where significant percentage reductions in habitat quality occur with decreases in discharge. It is assumed that ensuring some threshold value of the selected hydraulic parameter at a particular level of altered flow will maintain aquatic biota and thus, ecosystem integrity.

The wetted perimeter or area method has been used in Australia (e.g. Tunbridge, 1988; Tunbridge and Glenane, 1988; Anderson and Morison, 1989; Davies and Humphries, 1995) however in these studies, this method was not the sole criterion upon which the environmental flow was ultimately based.

The wetted perimeter or area method usually involves the placement of a single transect per site at a location on the river most responsive to changes in flow. The relationship between wetted perimeter and discharge is then determined from measurements taken at several different stage heights. There are several important assumptions associated with use of the wetted perimeter or wetted area approach. First, it is assumed that single transects per site are adequate to describe the changes within that site that occur with changing discharge. Second, since those locations that are most responsive to changes in discharge are riffles, then the focus of the study tends to be on this habitat type. It is assumed, therefore, that consideration of one habitat type only is sufficient to fulfil the requirements of other biotopes or habitat types. Third, the most important assumption is that stream area (or perimeter) is a surrogate for many other factors or processes that determine overall stream health or ecological integrity. When considered together, these inherent assumptions result in a highly simplified perception of the stream environment encompassed within a single variable.

The wetted perimeter or area method is based on a series of observations of changes in stream habitat structure with changing discharge and collectively grouped under the heading of wetted perimeter theory (Stalnaker and Arnette, 1976). In this sense, it is similar to Tennant's (1976) proposal that there are general relationships between habitat quality and some aspect of the flow regime (in this case proportion of the mean annual flow). In wetted perimeter theory, there is an association between wetted perimeter and discharge, wherein wetted perimeter increases rapidly with increasing discharge, from a base level of zero flow and reaches an inflection point, where after increases in wetted perimeter occur much more slowly until bankful stage is reached. This inflection point is taken to represent the optimal discharge. Tunbridge (1988), in a report on the environmental flow needs of freshwater rivers and lakes of south-western Victoria, found that such inflections in the relationship between flow and wetted perimeter were often absent or poorly defined.

Gippel et al. (1992) noted that reliance on the maintenance of some identified percentage of 'optimum habitat' at a series of river reaches could result in the situation where it is impossible to simultaneously accommodate each reach because of spatially varying 'optimum' discharges (i.e. a site located downstream of another requiring less water in order to maintain optimum habitat). Poorly developed species-specific habitat requirements will only increase the potential for errors of this type.

Gippel et al. (1992) were highly critical of the multiple transect approach employed by Hall (1989, 1990, 1991), Hall and Harrington (1991) and Tunbridge (1980), noting that in all of these studies, measured velocities were not the mean velocity but rather the velocity recorded at 0.1 X depth from the stream bottom. Gippel et al. (1992) noted that one of the assumptions in multiple transect analyses is that water velocity (particularly that at 0.1 X depth) rises proportionally with increasing stage height, and also noted that this was unlikely to be so.

Gore and Nestler (1988) suggested that the multiple transect method was prone to error because of the assumed proportional change in some habitat variables with increasing stage height. In addition, Tharme (1996) warns that the distance between transects and the total number of transects for each stream reach is critical in determining the reliability of estimated changes in habitat structure.

2.6 HABITAT SIMULATION METHODOLOGIES

Habitat simulation methodologies are widely used and based on hydrological, hydraulic and biological response data. They model links between discharge, available habitat conditions (including hydraulics) and their suitability to target biota. Environmental flow is predicted from habitat-discharge curves or habitat time and exceedence series.

PHABSIM (Physical HABitat SIMulation model) (Bovee, 1986) is the most commonly applied habitat simulation methodology. Habitat simulation methodologies also make use of hydraulic habitat-discharge relationships, but provide more detailed, modelled analyses of both the quantity and suitability of the physical river habitat for the target biota. Thus, environmental flow recommendations are based on the integration of hydrological, hydraulic and biological response data. Flow-related changes in physical microhabitat are modelled in various hydraulic programs, typically using data on depth, velocity, substratum composition and cover; and more recently, complex hydraulic indices (e.g. benthic shear stress), collected at multiple cross-sections within each representative river reach. Simulated information on available habitat is linked with seasonal information on the range of habitat conditions used by target fish or invertebrate species, commonly using habitat suitability index curves (Groshens and Orth 1994). The resultant outputs, in the form of habitat-discharge curves for specific biota, or extended as habitat time and exceedence series, are used to derive optimum environmental flows. The habitat simulation-modelling package PHABSIM (Bovee, 1982; Bovee et al., 1998; Milhous *et al.* 1989; Stalnaker *et al.* 1994), housed within the Instream Flow Incremental Methodology (IFIM), is the pre-eminent modeling platform of this type. The relative strengths and limitations of such methodologies are described in King and Tharme (1994); Tharme (1996); Arthington and Zalucki (1998); Pusey (1998) and they are compared with the other types of approach in Tharme (2003).

2.7 HOLISTIC METHODOLOGIES

Holistic Methodologies are actually frameworks that incorporate hydrological, hydraulic and habitat simulation models. They are the only EFA methodologies that explicitly adopt a holistic, ecosystem based approach to environmental flow determination. A wide range of holistic methodologies has been developed and applied, in Australia, South Africa and United Kingdom.

Ecosystem components that are commonly considered in holistic assessments include geomorphology, hydraulic habitat, water quality, riparian and aquatic vegetation, macroinvertebrates, fish and other vertebrates with some dependency upon the river/riparian ecosystem (i.e. amphibians, reptiles, birds, mammals). Each of these components can be evaluated using a range of field and desktop techniques (Tharme, 1996; Arthington and Zalucki, 1998; Tharme, 2003) and their flow requirements are then incorporated into EFA recommendations, using various systematic approaches as discussed in more detail below.

2.7.1 Holistic Approach

The Holistic Approach to environmental flow assessments was formulated in late 1991 at a Brisbane workshop involving Australian and South African water scientists. It consists of flexible conceptual framework for bottom up construction of EF regime on a month-by-month and element-by-element basis on best available scientific data. There are three major assumptions underlying the Holistic Approach (Arthington et al., 1992b):

1. Water belongs to the environment and therefore other users of that water can only be accommodated from that quantity not required by the river.
2. There is more water in riverine systems than is strictly needed for maintenance of the riverine ecosystem.
3. If the essential features of the natural flow regime can be identified and adequately incorporated into a modified flow regime, then the extant biota and functional integrity of the ecosystem should be maintained.

The primary feature of the Holistic Approach is the hydrological analysis of historical unregulated flow records for the river in question. These data are used to set boundary conditions for any modified flow regime. A proposed flow regime will only be ecologically acceptable if it does not contain flow events which are outside the historical pattern. For example, if a particular modified flow regime contains elements (sequences of days of set discharge) which have never occurred in the historical record, then that modified flow regime as it stands is ecologically unacceptable.

The Building Block Methodology and Holistic Approach are essentially based on expert opinion, except that the processes by which those opinions are incorporated into a flow strategy are better documented and based (preferably) on sound quantitative data. It is to be noted that the Holistic Approach is, in itself, not a set of prescribed rigid and well-defined methods but rather a philosophical framework capable of incorporating a range of methods.

A riverine ecosystem consists of such components as the source area, river channel, riparian zone, floodplain, groundwater, wetlands and estuary, as well as any particularly important features such as rare and endangered species. The holistic approach is based on theoretical concepts and understanding of the processes governing river ecosystems.

The main idea of the approach is to identify the essential features of the natural hydrological regime, define their influence on key geomorphological and ecological characteristics of the riverine ecosystem, estimate each flow attribute and progressively sum and combine them to construct a modified flow regime. The basic hydrological features suggested initially for inclusion in a modified flow regime were low flows, wet season flows (including the first major flood of the wet season, various medium-sized floods and some very large floods) and any other special-purpose flows of particular importance for the river in question (Arthington et al., 1992a). The modified flow regime is constructed month by month (or on a shorter time scale where relevant) and flow element by flow element, each flow element representing a well-defined feature of the flow regime understood or believed to achieve particular ecological, geomorphological or water quality objectives in the modified river system. The annual water needs of the riverine ecosystem are the sum of the low flow requirements throughout the year plus the additional wet-season flows, ranging from small freshes to floods. To this sum might be added the requirements for flushing flows or any other special-purpose flows to achieve particular objectives which are not likely to be achieved by the other flow provisions. It is assumed in the methodology that very large floods would not be restrained by dams or other infrastructure and so would occur more or less naturally as a component of the modified flow regime (Arthington et al., 1992a).

The total water requirements of the riverine ecosystem would ultimately be defined in terms of monthly flow allocations (or on a shorter time scale where relevant), and monthly maximum and minimum flows, desirable levels of flow variability and the timing, frequency, duration and hydrograph shapes of floods and flushing flows (Arthington et al., 1992a). It is implicit in the methodology that these attributes of the modified flow regime must lie within the range of values characterising the historical pattern, on the assumption that if a particular modified flow regime contains elements (eg. Sequences of days of set discharge) which have never occurred in the historical record, then that modified flow regime is ecologically unacceptable (Pusey, 1998).

Recent Developments of the Holistic Approach:

Some critics feel that the Holistic Approach is primarily hydrological (Jowett, 1997) because the tools to integrate biology fully do not exist now, and the method "does not explicitly indicate the biological implications of flow decisions" (Young et al. 1995). Whereas many recommendations must be based on opinion or 'best scientific information' in poorly studied systems, links between flow and outcomes for the aquatic ecosystem have been quantified in recent applications of the approach (Davies et al. 1996). The scope for using a wide array of quantitative methods and tools under the umbrella of the holistic framework is obvious, and widely accepted (Swales and Harris, 1995; Young et al., 1995; Tharme, 1996; Bunn, 1998; Dunbar et al., 1998).

Young et al. (1995) queried the concept of the 'natural' flow regime and how to decide on that state, especially given various scenarios of climate change. Several methodologies (Habitat Analysis Method, Flow Restoration Methodology) incorporate the development of a hydrological model with a daily time step representing the entire catchment as an integral and essential part of environmental flow assessment. Despite the obvious advantages of access to such models, ecologists are concerned about their accuracy, especially at very low and very high flows. Other concerns are that the effects of such factors as deforestation, changes in land use, and presence of offstream storages on the flow regime are generally not accommodated in the models, and that the lengths of record used to simulate extended historical flow sequences may not be long enough to capture cyclic and episodic flow patterns and events. The effects of climate change have not been incorporated into hydrologic models thus far.

Young et al. (1995) suggested that there is a mismatch between the analysis of the natural flow regime using daily flow records and description of the modified flow regime largely expressed as monthly or seasonal flows. Recent developments using a combination of simulation and stochastic dynamic programming techniques provide a methodology for delivering environmental flows on a daily basis in a highly variable environment (Arthington et al., 1998a; Dudley et al., 1998; Scott, 1998; Scott et al., 1998). The Flow Restoration Methodology also aims to deliver water for environmental purposes on a daily basis (Arthington, 1998a).

Jowett (1997) has objected that the Holistic Approach is primarily hydrological and it precludes the possibility that a riverine ecosystem can be enhanced by other than a natural flow regime.

2.7.2 Instream Flow Incremental Methodology (IFIM)

The Instream Flow Incremental Methodology (IFIM) is a framework for addressing the impacts on river ecosystems of changing a river flow regime. The US Fish and Wildlife Service developed IFIM (Bovee, 1986; Bovee et al., 1998). In some states of the USA, the use of IFIM has become a legal requirement for assessing the impacts of dams or abstractions.

Advantages of IFIM include it being a comprehensive framework for considering both policy and technical issues and its problem-orientated structure. Its implicit quantitative nature integrating micro and macro-habitat is generally considered an advantage. Furthermore, its scenario-based approach is favoured for negotiations between water users, but may be less suitable in setting flow regimes to comply with ecological objectives.

Disadvantages of IFIM partly arise from its comprehensive nature. A full study takes a considerable time and because of the wide range of issues included, provides numerous avenues for criticism. Furthermore, it is important to understand the limitations of the models used, what they include, omit or simplify, and any further issues arising from the linkages of models. Quantification of uncertainty is an element that has been frequently overlooked. Many "IFIM" studies have been criticised, but these criticisms have often arisen because the framework was not applied in its entirety. Often, emphasis has been placed on Step 3 – Modelling, at the expense of the other critical steps.

The Five Phases of the In-stream Flow Incremental Methodology (IFIM) include:

Phase 1. Identifying problems

The problems are identified and broad issues and objectives are related to legal entitlement identification.

Phase 2. Project planning and catchment characterisation

The technical part of the project is planned in terms of characterising the broad-scale catchment processes, species present and their life history strategies, identifying likely limiting factors, collecting baseline hydrological, physical and biological data.

Phase 3. Developing models

Models of the river are constructed and calibrated. IFIM distinguishes between microhabitat, commonly modelled using an approach such as PHABSIM, and macro-habitat, which includes water chemistry/quality and physico-chemical elements such as water temperature. A structure for specifying channel and floodplain maintenance flows is present, but there is little guidance on specific methods. Hydrological models of alternative scenarios, including a baseline of either naturalised or historical conditions, drive the habitat models. The models are integrated, using habitat as a common currency.

Phase 4. Formulating and testing scenarios

Alternative scenarios of dam releases or abstraction restrictions are formulated and tested using the models to determine the impact of different levels of flow alteration on individual species, communities or whole ecosystems.

Phase 5. Providing inputs into negotiations

The technical outputs are used in negotiations between different parties to resolve the issues set out in step one.

As with the multiple transect method, the location of study sites is critical in determining the outcome and utility of the IFIM procedure. It is assumed that the discharge-related changes in habitat that occur in the reference site may be extrapolated elsewhere in the catchment with confidence. Another similarity to the multiple transect method is that study sites are usually chosen on the basis of whether the habitat structure is likely to be responsive to changes in discharge. For this reason, most sites included in IFIM studies are riffles or runs (King and Tharme, 1994; Tharme, 1996). This may be appropriate if riffle dwelling species are the major focus or target but is unlikely to be the case when riffles do not normally contain the target taxa. This focus on riffle/run habitat underscores the absolute necessity of preliminary studies to ascertain macrohabitat conditions within the study river.

The procedure used in the IFIM to simulate changes in microhabitat conditions with changing discharge is contained within the module known as PHABSIM II (Physical Habitat Simulation), which consists of 240 separate programs covering depth, velocity, substrate and cover. Simulations are usually based upon transect data collected on one occasion (i.e. one discharge) and a series of measurement relating discharge to river stage height. Thus transect placement, transect number and the accuracy of measurements have great potential to influence subsequent habitat simulation. King and Tharme (1994) recommend that an experienced hydraulics expert be involved in the initial phase of habitat quantification.

Simulating the changes in suitability of a river reach for a particular species involves two separate procedures. The first is known as hydraulic simulation and the second is known as habitat simulation. In the hydraulic simulation phase, the stream reach is divided up into a series of cells defined by the number of measurements taken in the initial survey process. Well-defined hydraulic relationships such as between stream slope, bed roughness and water velocity and depth are then applied to simulate the changes that occur within the stream channel at different discharge points. Two assumptions are critical in this process. First, it is assumed that conditions measured at one point extend both laterally and longitudinally to the field of coverage of the next point of measurement; and second, that mean water velocities in individual cells change in the same way as do mean velocities for a cross-section.

Criticisms of the IFIM process relate to the actual hydraulic simulation phase and include concerns about the validity of the assumption that Manning's *n* remains constant at different discharge levels, the degree of precision at boundary layers and the assumption that channel shape does not change with increasing discharge (Shirvell, 1986; King and Tharme, 1994; Tharme, 1996). In addition, the hydraulic simulation does not perform well in non-standard situations such as rapid expansions or contractions in channel width or the presence of secondary channels (i.e. Parallel anabranches) (King and Tharme, 1994).

Pusey et al. (1993) stressed that unless hydraulic/habitat simulation techniques can be expanded to include such complex structures as woody debris, macrophyte beds and leaf litter, their full utility will not be realized. Such in-stream features are not only important substrates for microorganisms and macroinvertebrates and important sites of primary production (Thorpe and Delong, 1994), but may also serve as food and ultimately determine in-stream secondary production. Leaf litter is especially important in this regard as it may have a fundamentally important role in the delivery of organic carbon to downstream food webs (Vannote et al., 1980).

The most heavily criticized component of the IFIM process is the habitat simulation phase. The habitat simulation phase essentially combines the information derived from the hydraulic simulation phase with data on the preferred physical microhabitat of the target taxa to assess how much of the preferred microhabitat is available at different discharges (King and Tharme, 1994).

Biological information on the habitat requirements of target taxa is summarized in a series of curves. In this case, it is indicated that flows below 0.25 m sec-1 are not suitable for this species, nor are flows above 1 m sec-1. Curves with a narrow range theoretically indicate well-developed preferences for a particular range of conditions whereas broad curves indicate little preference.

Assessment of changes in habitat suitability in the IFIM is achieved by examining discharge-related changes in weighted usable area. Weighted usable area is most often taken to represent a measure of the amount of habitat within the study reach that is suitable for use by a target taxon, and is derived by application of the depth, velocity and substrate preference indices to the simulated conditions at each discharge. For example, Gan and McMahon (1990a) list an example wherein a 10 m^2 cell of stream bed had simulated depth, velocity and substrate conditions corresponding to depth, velocity and substrate preference indices of 0.9, 0.85 and 1.0 respectively. Thus this cell had an overall suitability of 0.9 X 0.85 X 1.0 = 0.765 and therefore 7.65 m^2 of that cell could be considered suitable.

IFIM was originally developed for small simple coldwater streams with a snow-melt hydrology. Gan and McMahon (1990b) indicated that its applicability in ephemeral streams may be limited. In addition, the simulation models were found to perform poorly at low flows. Fluvial systems which are characterized by long periods of no or low flow may therefore not be appropriate systems in which to apply the IFIM. Moreover, flood flows tend to be turbulent rather than gradually varying, thus making them difficult to model hydraulically. Rapid scour and deposition during floods and changing levels of channel hydraulic roughness due to varying amounts of suspended material may also decrease the ability of the model to simulate changes in habitat at high flows in a meaningful way.

2.7.3 Downstream Response to Imposed Flow Transformation (DRIFT)

The Downstream Response to Imposed Flow Transformation (DRIFT) framework (King et al., 2003) was developed in South Africa. It is scenario-based, providing decision-makers with options (scenarios) of future flow regimes for the river of concern, together with the consequences for the condition of the river. Probably it's most important and innovative feature is a strong socio-economic module, which describes the predicted impacts of each scenario on subsistence users of the resources of a river.

DRIFT has four modules:

(i) **Biophysical:** Within the constraints of the project, scientific studies are made in all aspects of the river ecosystem: hydrology, hydraulics, geomorphology, water quality, riparian trees and aquatic and fringing plants, aquatic invertebrates, fish, semi-aquatic mammals, herpetofauna and microbiota. All studies are linked to flow; so as to predict how any part of the ecosystem will change in response to specified changes in flow.

(ii) **Socio-economic:** Social studies are made of all river resources used by common property users for subsistence, and the river-related health profiles of these people and their livestock. The resources used are costed. All studies are linked to flow, to predict how the people will be affected by specified river changes.

(iii) **Scenario-Building:** For any future flow regime the client would like to consider, the predicted change in condition of the river ecosystem is described using the database created in module (i) and (ii). The predicted impact of each scenario on common property subsistence users is also described, together with its uncertainty. DRIFT provides a routine for optimizing the flow regime that gives maximum benefits for a given volume of water available.

(iv) **Economics:** The compensation costs of each scenario for common property users are calculated.

If there are no common property subsistence users, modules (ii) and (IV) can be omitted. Although DRIFT is usually used to build scenarios, its database can equally be used to set flows for achieving specific objectives. The DRIFT Solver can optimize ecological condition through combinations of dam releases of different timings, magnitudes and durations, given a set annual environmental allocation of water.

2.7.4 The Building Block Methodology (BBM)

The Building Block Methodology has been developed by South African water scientists. King and Tharme (1994) and King and Louw (1998) provide a full description of the methodology. There are three major assumptions underlying the methodology:

1. The riverine biota can cope with naturally occurring baseflow conditions but may be reliant on other higher flow conditions in order to fulfil important life history needs.
2. The identification and incorporation of these important flow characteristics will help to maintain the river's natural biota and processes.
3. Certain flows influence channel morphology more than others and their incorporation into a modified flow regime will aid maintenance of natural channel structure and the diversity of the physical biotopes within the river (King and Tharme 1994; Tharme 1996).

The objective of the Building Block Methodology is to determine ecologically acceptable, modified flow regimes for impounded rivers and other situations where flows are regulated. Application of the methodology provides advice on the IFR of a river through a systematic sequence of activities involving three main phases.

1. A comprehensive information gathering phase undertaken by experts in their fields (fluvial geomorphology, hydraulic modelling, aquatic ecology, aquatic chemistry, hydrology, water engineering, social and recreational aspects). Coordination of activities is achieved through an IFR planning meeting, and this phase of the BBM culminates in a comprehensive 'Starter Document' provided to all participants prior to a structured IFR workshop.

Pre-workshop activities also involve the selection of IFR sites. They are selected to capture and represent spatial geomorphological and biological variation along the river and its major tributaries. The Starter Document serves to achieve three objectives: it informs all participants about the river; it encourages the experts to focus on the river's flow requirements; and it remains as a lasting synthesis of knowledge on a specific river at a specific time (King and Tharme, 1994).

2. The IFR workshop generally involves about 20 people, representing agency water managers and engineers, the consulting engineers appointed for the specific development, and the disciplinary experts. The workshop commences with a rapid overview of the Starter Document and, usually, a field visit to each instream flow site along the river. A chairperson and facilitator then guide the workshop participants through the various steps of the Building Block Methodology to reach a consensus on a recommended modified flow regime for the river. This is based on monthly flows and special purpose flows over shorter time spans, each component of flow being specified in terms of magnitude, time of year, duration, and rate of rise and fall of flood flows. Flow regimes are developed for river maintenance and for drought conditions.

   A 'motivation' is provided for each specified flow by its proponent, and these are recorded in workshop report. Recommendations are designed to achieve a particular 'desired future state' for the river along each reach, given its existing ecological condition and the importance of the reach and river in the broader context of riverine conservation and social uses of the river (King and Louw, 1998). The construction of flow regime is quantitative in that conversion of much of the ecological knowledge about the river into recommended environmental flows depends on accurate river cross-sections and stage-discharge rating curves, while recommendations for certain high flows depend on accurate hydrological data (King and Tharme, 1994).

   Each workshop takes two to four days, depending upon the size of the catchment, its geomorphological and ecological heterogeneity, and the number and location of proposed water developments. A technical report is produced after the workshop, recording the processes used, the inputs of experts, and the outcomes in terms of in-stream flow recommendations.

3. The third phase constitutes a series of activities that link the environmental flow considerations to the engineering activities taking place in the catchment. Hydrological yield analysis (Hughes et al., in press), assessment of conflicts with potential consumptive users, and a coarse flow-related assessment of the implications of IFR recommendations for the complete river system are combined to produce a description of the 'working guide desired state', with its IFR (King and Louw, 1998).

Two or three other possible states which would require more or less water than the IFR are also described, each linked to its probable physical, ecological, social and economic consequences. Outcomes from these assessments are then linked to a public participation process, ending with a decision on whether or not the project will proceed and the IFR will be met. If the project proceeds with agreement to meet the IFR, planners use the IFR tables to reserve water for the river (King and Louw, 1998).

2.7.5 Expert Panel Assessment Method (EPAM)

The Expert Panel Assessment Method (Swales and Harris, 1995) was developed in Australia. The suitability of stream flows for the survival and abundance of native fish was taken as the primary criterion of the suitability of the discharge as an environmental flow, because "fish communities are generally acknowledged to be a good indicator of overall environmental quality or river 'Health', and respond to direct and indirect stresses of the entire aquatic ecosystem" (Swales and Harris, 1995).

In the first test of the Expert Panel Assessment Method, flows were manipulated experimentally below six headwater water storages on tributaries of the Murray-Darling River in eastern New South Wales. Arrangements were made in the winter of 1992 for four different flow releases to be made from the storages, "representing the 80%, 50%, 30% and 10% flow percentiles" determined from flow duration curves for each river (Swales and Harris, 1995). The suitability of selected flows for maintaining habitat quality, fish and invertebrates (as food for fish) was assessed visually during a field inspection and scored by two independent expert panels comprising specialists in fish biology, invertebrate ecology and fluvial geomorphology. The panels were asked to assess the suitability of flows on a seasonal and non-seasonal basis.

The most significant outcome of this trial was the consistent recommendation by panel members that the natural seasonal patterns of river flows should be restored (lowest flows in summer, intermediate in spring and autumn and highest in winter months). In this trial of the Expert Panel Assessment Method, congruence between the recommendations of the two separate panels was assumed to represent a validation of the method (Swales and Harris, 1995). However, panel rankings of the various flows varied considerably. Visual inspection of the resultant scores derived for 'non seasonal' flows indicates that perhaps only two of the six comparisons can be considered as being remotely similar. Bishop (1996) applied a statistical test to determine the degree of congruence between the scores derived from the individual panels and found that only one out of 18 of the comparisons (non-seasonal and seasonal comparison combined) showed a significant association at the $p<0.05$ level. Clearly, the two expert panels had differing expert opinions on the same flows (Pusey, 1998).

Bishop (1996) suggested that variation in panel scores may arise from variation in the specialist's knowledge base, from the subjective manner in which flows are scored, from the difficulty in assessing stream habitat from the stream bank and, lastly, from conflicts between the direct experience of each expert and the hydrological data supplied to the team.

Cooksey (1996) provided a critique of the Expert Panel Assessment Method from the perspective of behavioural psychology based on similarities between the methodology and other group techniques. One area of concern raised by Cooksey (1996) was the role of interpersonal dynamics in the assessment process and the potential for a single dominant personality to influence assessments made by other panel members. In addition, consensus in judgement may represent 'collective bias' rather than agreement upon fact. Group dynamics play a fundamentally important role in collective decision-making when anonymity is not guaranteed. Cooksey (1996) also criticized the use of a rank-based system, particularly when the suitability of a set flow is determined 'on-site'. Such a system, especially when rankings are produced rapidly, tends to result in rankings which are derived intuitively rather than rationally. Intuitive assessments generally occur 'covertly' and their basis is difficult to publicly retrace. Abstract rating scales tend to reinforce this intuitive process.

Bishop (1996) also presents an example where expert experience and intuition were overridden by the provision of erroneous hydrological data. Other criticisms of the Expert Panel Assessment Method offered by Cooksey (1996) include the choice of experts, the value systems of the supposed experts and the mechanisms by which consensus is achieved.

EPAM has several benefits, which include:

• direct communication of specialist knowledge from recognised experts;
• ensures incorporation of interdisciplinary judgements;
• relatively inexpensive and rapid; and
• provides direct links between scientists and managers.

2.7.6 Scientific Panel Assessment Method (SPAM)

The Scientific Panel Assessment Method (Thoms et al., 1996) is similar to the Expert Panel Assessment Method approach but differs considerably in some key aspects. Foremost among these differences is that the Scientific Panel Assessment Method, as applied in the Barwon-Darling River, is not a visual assessment of trial releases. Rather, it incorporates visual inspection of key sites with the collection and interpretation of field data and background information gathered from prior empirical studies and the theoretical literature. In essence, it is a more refined and transparent version of the Expert Panel Assessment Method.

Thoms et al. (1996) distinguished the Scientific Panel Assessment Method from the Habitat Assessment Method of Walter et al. (1994). The Barwon-Darling study attempted to take an holistic view of the system by considering key ecosystem components (fish, trees, macrophytes, invertebrates and geomorphology) and their responses to three 'habitat elements': flow regime, flood hydrograph and physical structure. Thoms et al. (1996) noted that, in the past, environmental flow studies have focused too narrowly on the provision of minimum flows and suggested that this is an inappropriate focus in dryland river systems given their high degree of flow variability. Accordingly, the Scientific Panel Assessment Method considered many aspects of the flow regime including, but not limited to, total discharge, floods of various return periods and magnitude, drought frequency, seasonality and many aspects of the flood hydrograph. Each of these attributes of the flow regime was related to the needs of fish, trees, macrophytes, invertebrates and geomorphology in a useful cross-tabulation. For example, the potential interactions between the flow attributes and aspects of the resident fish populations, such as breeding, migration, species distributions, gene flow, trophic responses and larval recruitment, were all considered.

The Barwon-Darling study considered such fundamental aspects of ecosystem function as the movement of energy and carbon between the terrestrial and aquatic environment, and the bases for the various food webs existing within the river and their relationship to flow. This represents an advance on earlier work under the Expert Panel Assessment Method, which was narrowly focused on the maintenance of areas in which fish feed or which are suitable for the production of aquatic invertebrates upon which fish feed.

2.7.7 Habitat Analysis Method

The Habitat Analysis Method was developed by the former Queensland Department of Primary Industries, Water Resources, to determine environmental flow requirements as part of the Water Allocation and Management Planning (WAMP) initiative (Burgess and Vanderbyl, 1996).

The centrepiece of the method is a Technical Advisory Panel workshop run to achieve four distinct outcomes: (i) identification of generic habitat types existing within the catchment; (ii) determination of the flow-related ecological requirements of each habitat;

(iii) development of bypass flow strategies to meet those requirements; and (iv) development of a monitoring strategy to check the effectiveness of flow strategies.

Several basic assumptions from the Holistic Approach have been built into the Habitat Analysis Method, as given below:

1. Environmental flows and river management should attempt to mimic the natural flow regime (Arthington et al. 1992a; Arthington and Pusey 1993)
2. The need to consider the aquatic biota in terms of sustainable and resilient populations (Blühdorn and Arthington 1994b).
3. Flows which maintain habitats in good condition provide a 'surrogate' means of determining environmental flows for riverine biota.
4. Water can be described in terms of flow: water levels, flow velocity, timing of flows (seasonal, diurnal), rates of change of flow and volume.
5. Water can be described in terms of quality: suspended solids, turbidity, salinity, nutrient levels, temperature, pH and other chemical properties.
6. In some cases, flows released for consumptive use may satisfy environmental requirements en route through the natural watercourse.

The Technical Advisory Panel workshop is preceded by a data collection phase when the following information is collated:

- catchment and watercourse maps;
- locations of water infrastructure and management nodes
- longitudinal sections of major streams
- streamflow data at management points within the catchment highlighting key features of catchment flow regimes such as seasonality;
- history of infrastructure development;
- current water management rules;
- State of the Rivers reports and water quality reports;
- overview of river morphology and bank stability
- broad survey of fish populations in catchment;
- list of important riverine habitat;
- list of rare and endangered species; and
- a summary of relevant government policies and plans for wetland and river management.

Slides of representative habitats and satellite imagery of river reaches are also assembled before the workshop.

The workshop process produces a matrix of habitat types (waterholes, riffles, impoundments, backwaters, wetlands, brackish zone, estuarine zone, mangroves) *versus* critical environmental flow requirements (e.g. critical water levels, acceptable ranges, timing and duration of flows). Bypass flow strategies are then proposed to meet the flow requirements of each habitat, initially by identifying broad management responses (eg. Minimising temperature variation, maintaining specific water depths, mimicking natural flow events). The objective at this point is "to develop flow provisions which are not too complex, so that all panel members can see the links back to the critical flow requirements" of habitats (Burgess and Vanderbyl, 1996).

The outcomes of these processes would typically include environmental flow provisions for waterhole, riffle zone and wetland management, inclusion of part of the first major flow of the season, based on the suggestion that the first major flood of the wet season may be important as a source of suspended solids, nutrients and carbon, as well as providing cues for fish migration and spawning (Arthington et al., 1992a). Channel maintenance flows are also recommended. At this point, any rare and endangered species are considered to determine the implications of the proposed environmental flow options for maintenance of species of special status. Burgess and Vanderbyl (1996) emphasise that it is important to exclude rare and endangered species from the initial workshop discussions so as not to consciously develop provisions specifically for them. This is in keeping with the key principles of the method, namely, to provide for the needs of the 'riverine ecosystem' using habitat as the 'indicator' for estimating environmental flow requirements, rather than focusing on the needs of individual species or communities.

The impact of providing each environmental flow option is then assessed by considering its effectiveness in meeting critical environmental requirements (i.e. 'sensitivity'), water resource entitlements (i.e. 'yield and reliability') and the capacity of infrastructure outlet works ('physical limitations and costs'). These impact assessments allow for rational debate of the issues during the community consultation phase.

The final step is to present options for the specified environmental flow provisions back to the expert panel members, to verify that they are consistent with the original intentions of the workshop, and to quantify sensitivity levels associated with effectiveness in meeting critical environmental flow requirements (Burgess and Vanderbyl, 1996). This feedback loop is achieved either by reconvening the workshop or by circulating a report and seeking comments from the panel members. At this point the environmental flow provisions and options regarding these provisions are presented to a formal stakeholder consultation process designed to assist in determining an acceptable balance between all water uses. The outcomes from this final phase are formal specifications of the environmental flow provisions to be included in any water management plan (Burgess and Vanderbyl, 1996).

2.8 SUMMARY

Efforts made by scientists in different parts of the world on EFA (methods, methodologies, approaches) vary in terms of available data and knowledge base particularly with regard to the biotic data and socio-economic importance of EF. Some of these are subjective in nature. Further, impacts of application of these EFA methodologies in river reaches are not yet fully known.

The EFA methodologies discussed in the previous sections have been summarized identifying the strengths and limitations as well as requirement of input data and the outcomes of the EFA methodologies as shown in Table 2.4.

Table 2.4: Input, output, strengths and limitations of various EFA methodologies

Method	Input	Output	Strengths	Limitations
Lookup Tables (hydrologic index method)	Monthly/seasonal flow duration curve; Average annual flow	exceedence probability flows (percentile flows)	Relatively rapid, non-resource intensive; appropriate at planning level or in low controversy situation; Tennant method is most applicable for mountain streams with virgin flow.	Low resolution estimate of EF. High potential for under-allocation when uses and diversions are poorly known, Little provision for recommending spates and floods. Based on assumed relationship between habitat suitability and proportions of mean annual flow. Allocations are more generous than required in regions with variable flows.
Desktop Methods using hydrologic data	Gauged or modelled daily/weekly/monthly flow data	Percentage of mean annual runoff, FDCs in relation to EMC	Useful when no ecological information available; A relatively rapid, non-resource intensive; Appropriate at planning level or in low controversy situation; Examine whole range of river flow regime rather than simple pre-derived statistics of lookup tables	Low resolution estimate of EF; Based on assumed relationship between habitat suitability and proportions of mean annual flow.
Desktop Methods using hydrological and ecological data	Hydrologic and ecological data	Relationship between score of observed taxon and river flow	Utilizes the existing ecological and hydrological data; Flow and ecology are directly addressed;	Difficult to derive biotic indices that are sensitive only to flow; time series of ecological data may not be independent and thus may violate assumptions of statistical techniques
Hydraulic Rating Method	Hydrologic and hydraulic data and hydraulic relation to habitat	Relation between discharge and % reduction in hydraulic habitat availability	Hydraulics is used as a surrogate for the biota; Provides simple indices of available habitat	Inflection points in relationship between flow and wetted perimeter may be absent or poorly defined. Poorly developed species-specific habitat requirements increase the potential for errors; distance between transects and the total number of transects is critical in determining the reliability of estimated changes in habitat structure
Habitat Simulation Methodologies	discharge; hydraulic related biological response: biota	Habitat-discharge curve ; Habitat-time curve	Deals with micro-habitat; environmental flow recommendations are based on the integration of hydrological, hydraulic and biological response data	Requires hydrologic, hydraulic and biological response data at multiple cross-sections and habitat simulation modelling
Holistic Approach	Expert opinion, fluvial geomorphology, hydraulic, ecology, hydrologic, social and recreational aspects, field visits	EF regime on a month-by-month and element-by-element basis; Alternate water use scenarios	Incorporates more detailed assessment of flow variability than early BBM studies; includes method for generating trade-off curves for examining alternative water use scenarios; applicable to regulated/unregulated rivers and for flow restoration; high potential for application to other aquatic ecosystems; recommends a monitoring programme as a crucial component; allows for using a wide array of quantitative methods and tools	Some risk of inadvertent omission of critical flow events; lack of structured set of procedures and clear identity for EFM hinders rigorous routine application; it is based on quantification of links between flow and outcomes for aquatic ecosystem which may not be correctly known.

Table 2.4 continued ...

Method	Input	Output	Strengths	Limitations
Building Block Methodology	Expert opinion, fluvial geomorphology, hydraulic, ecology, hydrologic, social and recreational aspects, field visits	Rapid advice on EF, physical, ecological, social, economic consequences of a water resource project, scenario-based assessments of alternative flow regimes	Rigorous and extensively documented (manual and case studies available); prescriptive bottom-up approach; includes social component (dependent livelihoods); incorporates a monitoring programme; high potential for application to other aquatic ecosystems; links to public participation processes; less time, cost and resource intensive than DRIFT; applicable to regulated or unregulated rivers and in flow restoration context; now incorporates a method facilitating top-down	Limited potential for examination of alternative scenarios relative to DRIFT; risk of omission of critical flow events (common to all holistic methodologies)
Expert Panel Assessment Method	Expert opinion, visual assessment of trial releases, available data	Professional judgement, EFR using fish communities as indicators	Good for initial assessment; site-specific focus; rapid and inexpensive; low resource intensity; makes use of field-based ecological interpretation of different multiple trial flow releases from dams, at one or a few sites, to determine EFR (expressed as flow percentiles);	Limited resolution of EF output; aims to address river ecosystem health, rather than to assess multiple ecosystem components; strongly reliant on professional judgement; no explicit guidelines for application; poor congruence in opinion of different panel members (due to subjective scoring approach, individual bias)
Scientific Panel Assessment Method	Same as above + collection and interpretation of field data, prior empirical studies, theoretical literature	Recommendations on many aspects of flow regime, flow related ecological requirements, flow strategies	More refined and transparent version of EPAM; key features of the ecosystem and hydrological regime and their interactions at multiple sites are used as basis for EFA; includes stakeholder-panel member workshop; well defined EFA objectives; potential for inclusion of other ecosystem components; moderately rapid, flexible and resource-intensive	Limited use of field data; poor definition of output format for EFR; less quantitative supporting evidence
Habitat Analysis Method	Hydrologic and hydraulic data, Panel expertise, infrastructure dev. In catchment, water quality, morphology, fish population, important habitat	Critical flow requirements of habitats and sensitivity levels	Relatively rapid, inexpensive, basin-wide reconnaissance method for determining preliminary EFRs at multiple points in catchment; Technical Advisory Panel Workshop based method, superior to simple hydrological EFMs; field data limited or absent; represents a simplified version of the Holistic Approach	Inadequate for comprehensive EFAs; little consideration of specific flow needs of individual ecological components; requires standardisation of process and refinement of flow bands linked to habitats

Table 2.4 continued ...

Method	Input	Output	Strengths	Limitations
Instream Flow Incremental Methodology	Hydrologic, hydraulic data at multiple transects, target taxa	Discharge related changes in usable area (measure of habitat) for target taxa	Considers both policy and technical issues; integrates micro and macro habitat; useful in negotiations; institutionalised and being applied in a inflexible fashion	Wide range of issues included providing avenues for criticism; more emphasis on modelling at the expense of other critical steps;
Downstream Response to Imposed Flow Transformation	Hydrologic, hydraulic, geomorphologic and water quality data, aquatic and health profiles of water users, animals, socio-economic data	Scenarios of future flow regimes and consequences for condition of river, impacts on subsistence users of river resources	Rigorous and well-documented top-down, scenario-based process; appropriate for comprehensive EFAs (1-3 years) based on several sites within representative and critical river reaches; ability to address socio-economic links to ecosystem; scope for comparative evaluation of alternative modified flow regimes; potential for application to other aquatic ecosystems; output is suitable for negotiation of tradeoffs; links to external public participation process and macro-economic assessment; applicable to regulated or unregulated rivers and for flow restoration; recommends a monitoring programme;	Resource intensive; limited inclusion of flow indices describing system variability; requires documentation of generic procedure for wider application.

CHAPTER - 3

ENVIRONMENTAL FLOW PRACTICE IN INDIA

The status of EF research in India may be characterized as being in its infancy because of very limited knowledge base. The Report of National Commission for Integrated Water Resource Development Plan (NCIWRDP, 1999) has stated that it was not possible to estimate the amount of water needed for environmental purposes as the knowledge base for making any approximate calculation of this requirement was very limited. Minimum flow requirement in Indian rivers has been discussed at several forums but primarily in the context of water quality. The Supreme Court of India in a judgment of year 1999, directed the government to ensure a minimum flow of 10 cubic meters per second (m^3/s) in the Yamuna River at New Delhi for improving its water quality (Smakhtin and Anputhas, 2006).

3.1 PRACTICES IN SOME DEVELOPED COUNTRIES

France:

Freshwater fishing law of June 1984 requires that residue flows in bypassed sections of river must be a minimum of 1/40 of the mean flow for existing schemes and 1/10 of the mean flow for new schemes. Since NJHEP is an existing scheme, residue flow d/s of Nathpa dam should be 1/40 of long-term mean flow.

USA:

Tennant Method: Percentages of the mean flow are specified that provide different quality habitat for fish e.g. 10% for poor quality (survival), 30% for moderate habitat (satisfactory) and 60% for excellent habitat. The indices have been adapted for other climatic regions in North America and have been widely used in planning at the river basin level. However, they are not recommended for specific studies and where negotiation is required.

Instream Flow Incremental Methodology (IFIM): The US Fish and Wildlife Service developed IFIM. In some states of USA, use of IFIM has become a legal requirement for assessing the impacts of dams or abstractions.

South Africa:

Building Block Methodology (BBM) has been adopted as the standard method for intermediate and comprehensive determination of the ecological reserve under the new South African Water Law. Details of the BBM are given in Section 2.6.4, Chapter 2. Environmental flow is known as 'ecological Reserve' in South Africa. It is estimated for a water body and then only the difference between the total available water resource (natural flow) and the Reserve is considered to be utilizable. Such pro-environment position is unlikely to succeed in India, in the conditions of increasing water scarcity.

UK:

The Environment Agency of England and Wales is responsible for ensuring that the needs of water users are met whilst safeguarding the environment. It has specified percentages of natural Q_{95} flow that can be abstracted for different environmental weighting bands. Application of this method for EFA of Satluj river is discussed in Chapter 8.

3.2 NEED OF EFA AND CONSTRAINTS IN INDIAN CONTEXT

Necessitated by tropical monsoon hydrology in India, a very large number of river valley projects have been constructed for irrigation, flood control and hydropower generation. Floodplains have been cut out by embankments along rivers. Land based infrastructure development activities continue to increase sediment loads of rivers. Also, because of urbanization, industrialization and agricultural intensification, rivers are getting higher discharges of domestic and industrial effluents, fertilizers and pesticides. Out of the 30 world river basins marked as global level priorities for the protection of aquatic biodiversity by Groombridge and Jenkins (1998), nine are from India due to their extensive and continuing development. These basins include Cauvery, Ganges-Brahmaputra, Godavari, Indus, Krishna, Mahanadi, Narmada, Pennar and Tapi. With an exception of Ganges-Brahmaputra, all the above basins have also been categorized as "strongly affected" by flow fragmentation and regulation (Nilsson et al., 2005).

Environmental flow in India has usually been understood as a flow, which is to be released downstream from the dams for environmental maintenance. Such releases have often been minimal implying maximum abstraction. Overall, there has been limited appreciation of the nature of rivers as ecosystems whose ecological integrity depends upon their physical, chemical, biological characteristics and interactions with their catchment. In majority of dams in India, there is no legal stipulation that a certain share of the water must be reserved for downstream rivers. Once the water has been diverted, then, for long stretches, rivers exist only as dirty, polluted nallahs, acquiring a substantial flow only during a short span of rainy days.

Iyer (2005) has highlighted the importance of in-stream flows in India for different purposes: "Flows are needed for maintaining the river regime, making it possible for the river to purify itself, sustaining aquatic life and vegetation, recharging groundwater, supporting livelihoods, facilitating navigation, preserving estuarine conditions, preventing the incursion of salinity, and enabling the river to play its role in the cultural and spiritual protection agencies in USA use the $Q_{7,10}$ when developing water quality standards. A review of methods of hydrological estimation at ungauged sites in India is discussed in Jha and Smakhtin (2008). A discussion of several methods for estimating low stream flow statistics is presented below:

2.2.1 Low Flow Duration and Frequency Curves for Gauged Sites

A flow duration curve (FDC) is a cumulative frequency curve, which depicts discharge as a function of the percentage of time that the discharge is exceeded. In general, the portion of the FDC corresponding to low flows is determined as the part of the curve consisting of stream flows below the median flow point (Smakhtin, 2001).

Low Flow Frequency Curve (LFFC) can also be used to describe the low flow regime of a river. A LFFC describes the frequency distribution of annual minimum stream flow events. Typically, LFFCs are used to develop non-exceedence probability statistics, such as the $Q_{7,10}$ which estimate the average interval in years that a stream falls below a specific discharge (Smakhtin, 2001). Researchers have examined the suitability of LFFCs constructed from the minimum flow series of a number of different averaging intervals (Whitehouse et al., 1983; McMahon and Mein, 1986).

Estimation of low stream flow statistics by both the FDC and LFFC techniques involves fitting a theoretical probability distribution (Weibul, Gumbel, Person and Log-Pearson Type-III, and lognormal distributions) to the available stream flow data. Various tests are available in textbooks of statistical hydrology (Ayyub and McCuen, 2002; McCuen et al., 1981) for fitness of theoretical probability distribution.

Researchers have attempted to determine the most appropriate probability distribution for describing the annual minimum flows in different geographic regions. There is no single probability distribution which could provide best fit for stream flow data of all the rivers. Tasker (1987) used stream flow data from 20 Virginia rivers and concluded that the 3-parameter Weibul and log-Pearson Type-III best described the 7-day annual minimum stream flow series. Vogel and Kroll (1989) tested the performance of probability distributions at 23 Massachusetts sites. They recommended the 2- and 3-parameter lognormal, Weibul and log-Pearson Type-III distributions.

2.2.2 Low Flow Regional Regression Models for Ungauged Sites

Quantifying low stream flow statistics by frequency analysis requires a historical stream flow record. At ungauged sites, where no stream flow record exists, regional regression models are commonly used for low flow estimation. A regional regression model defines a stream's low flow statistic as a function of watershed characteristics (Stedinger et al., 1993). Regional regression models most often take the form:

$$Q_{d,T} = a X_1^b X_2^c \ldots$$

Where $Q_{d,T}$ is the d-day, T-year low flow statistic acquired from gauged flow records, X_i are measurable watershed characteristics, and a, b, c are model parameters obtained from the regression analysis. In this equation, $Q_{d,T}$ variable is the response variable and the X_i variables are the explanatory variables.

Regionalization is based on the premise that watersheds with similar characteristics will have similar stream flow responses. Thus a low flow regional regression equation developed using stream flow data from gauged sites should adequately describe low flows at ungauged sites occurring within the same hydrometeorologically homogeneous region.

Low flow regional regression models are constructed using multiple regression analysis. Multiple regression analysis entails: (i) selection of a regression model type; (ii) estimation of regression model parameters; (iii) assessment of parameter significance; and (iv) assessment of estimation errors. Traditionally, regression model parameters have been estimated using ordinary lest squares (OLS) techniques (Thomas and Benson, 1970; Hardison, 1971).

Two of the assumptions governing OLS regression are: (i) model residuals have a constant variance; and (ii) model residuals are independent. In practice, both of these assumptions are often violated. Variations in the accuracy of stream flow statistic estimators, which are mainly due to variation in stream flow record length at different gauges, causes the model residuals to have a non-constant variance. In addition, the stream flows within the same hydrological region are often highly correlated; therefore, model residuals are not independent.

Taskar (1980) developed a weighted least squares (WLS) procedure as a means of resolving the problems posed by stream flow records of unequal lengths. Further improvements to regional regression models were realized with the development of generalized least squares (GLS) procedures.

GLS procedures remedy issues regarding unequal record lengths and cross correlation between concurrent flows. Kroll and Stedinger (1998) provided a discussion detailing the advantages of GLS procedures over OLS, as well as the circumstances when OLS procedures are adequate and when GLS procedures are necessary.

Researchers have developed regional regression models for various regions. In each instance, the regression models were constructed by including watershed characteristics as explanatory variable.

Barnes (1986) concluded that the percentage of basin underlain by stratified drift, mean basin elevation, and mean annual precipitation were significant in describing the low flow regime of the lower Hudson river basin in New York.

Arihood and Glatfelter (1991) developed regional regression equations for 82 sites in Indiana. They found the contributing drainage area, as well as a regionalized value of the low flow duration ratio, which is the 20% flow duration divided by the 90% flow duration, were significant in describing low flows in Indiana.

Vogel and Kroll (1992) determined that low flow statistics of streams in central western Massachusetts are highly correlated with drainage area, average basin slope, and baseflow recession constant.

Ries (1994) constructed regional regression equations for streams in Massachusetts. Ries found the watershed characteristics that best described the low flow regime to be drainage area, area of stratified-drift deposits per unit of stream length, and a surrogate for the effective head of the aquifer in the stratified drift deposits.

Prior research has indicated that regional regression models poorly estimate low stream flow statistics. Standard errors of regional regression models tend to be relatively high. Regional regression models constructed by Barnes (1986), Arihood and Glatfelter (1991), and Ries (1994) produced standard errors as high as 51%, 61% and 98.5% respectively. Thomas and Benson (1970) have also documented standard errors in excess of 100%. The high standard errors may result from the exclusion of important explanatory variables. Another reason may be that the watershed characteristics data contained within the explanatory variables have not been of high enough quality.

2.3 CATEGORIZATION OF ENVIRONMENTAL FLOW ASSESSMENT (EFA) METHODOLOGIES

The development of environmental flows assessment (EFA) methodologies began in USA in the late 1940s, mainly as a result of new environmental and freshwater legislation accompanying the peak of the dam-building era in USA. Australia and South Africa are the other advanced countries with respect to development and application of EFA methodologies (Tharme, 2003).

In several countries, the main objective of EFA has been to define a minimum acceptable flow based on predictions of instream habitat availability matched against the habitat preferences of one or a few species of fish (Jowett, 1997; Pusey, 1998).

Since fish species such as trout and salmon are very sensitive to flow, it has been argued that if the flow is appropriate for them, it will probably serve most other ecosystem needs. However, scientific literature reveals that this may not necessarily be so, and flow management is best addressed for the entire ecosystem. Recent EFA methodologies increasingly take a holistic approach (Brown and King, 2003; Instream Flow Council, 2002) as discussed later.

Perspective and interactive approaches: Perspective EFAs recommend a single environmental flow. By using this perspective approach, however, insufficient information is supplied on the implications of not providing the recommended flow. Interactive EFAs focus on establishing the relationship between river flow and one or more attributes of the river system. This relationship may then be used to describe environmental/ecosystem implications (and resulting social/economic implication) of various flow scenarios. Interactive methodologies thus facilitate the exploration of trade-offs of several water allocation options.

Bottom-up and top-down approaches: The basis of most EFA is a bottom-up approach, which is the systematic construction of a modified flow regime from scratch on a month-by month (or more frequent) and element-by-element basis, where each element represents a well defined feature of the flow regime intended to achieve particular objectives. In contrast, top-down approaches define the environmental flows requirement in terms of accepted departures from the natural (or other reference) flow regime. Thus, top-down approaches are less susceptible to omission of critical flow features than bottom-up approaches.

Methods and methodologies: Tharme (2003) distinguished the two levels of EFA as "methods" (procedures or techniques used to measure, describe or predict changes in important physical, chemical or biological variables of the stream environment) and "methodologies" (collection of several instream flow methods which are arranged into an organized iterative process which can be implemented to produce results). Several reviews concerned with environmental flow assessment methodologies have been published (Tharme, 1996; Jowett, 1997; Dunbar et al., 1998; Tharme, 2003; Acreman and Dunbar, 2004; Jha et al., 2008).

EFA methodologies have been classified in several ways by different organizations as shown in Table 2.1. The categorization by IWMI is based on the required input data and not on the methodological characteristics, which may change over time and be overlapping (Louise, 2006). Therefore, categorization by IWMI is followed in this chapter.

lives of the people." There are several constraints and factors in which India differs from developed countries such as USA, UK, Australia that have taken a lead in addressing the problem of EFR.

Religious importance: Unlike other countries, rivers in India have a great religious significance for a vast population. Indian society attaches great cultural and religious importance to rivers. Rivers are worshipped as mother and many of the customs and festivals are linked with them. Most of the Hindu festivals are associated with bathing in holy ponds and rivers. A large number of pilgrims assemble on the banks of rivers and ponds to take holy dip. For this purpose, river flows and water quality particularly during lean season have to be maintained.

Agrarian economy: Agriculture is the largest user of water. Economy of the country is dependent on agriculture to a large extent. Irrigated agriculture serves a variety of societal aims such as food security, drought protection, employment generation etc. Trade off between agriculture and ecology is made difficult by existing socio-political situation in the country.

Tropical monsoon hydrology: In most part of India 80 to 90% of annual rainfall (and therefore the natural flow) occurs in monsoon season (June/July to September/October). Water demand exists throughout the year necessitating storage of monsoon runoff. Existing surface storage capacity of 213 bcm is just 11% of the annual flow of 1869 bcm. In Murray-Darling basin in Australia, the storage capacity is 150% of the annual flow (CWC, 2007).

Exploitation of ground water: There is over exploitation of ground water in several river basins in the country. As a result, the base flow in rivers has decreased over the years and some of the river reaches become dry during non monsoon season. Instream flow requirements have consequently increased.

Sewage disposal in rivers:. Untreated waste water from towns and villages is often directly disposed in the rivers as treatment of sewage to desired standards is expensive thus adversely affecting river ecology and increasing the Instream flow requirements. Conservation and restoration of rivers has been limited to "cleaning" of rivers by legally enforcing the treatment of industrial effluents. These efforts have met with limited success in river conservation.

Water is a State subject: In the Constitution of India, water is a State subject meaning thereby that State is responsible for development and utilisation of river water within its jurisdiction. Several of the rivers are interstate in character. Water resource development and utilisation in upstream state causes reduction in available flows in the downstream state. The EF is required to be met out of the total water availability in the basin. Negotiation on the State's shares is often a long-drawn and politically sensitive process.

3.3 PRESENT STATUS OF EFA IN INDIA

India faces a number of water related challenges, including increasing water scarcity and competition for water between different sectors and riparian states. Balancing the water requirements of the environment and other uses is becoming critical in many of the river basins in India due to increase in population and associated water demands. The status of EF research in India may be characterized as being in its infancy because of very limited knowledge base. The concept of the intrinsically invaluable role of natural flow of rivers has been emphasized in several policy statements in the recent past as discussed below. Unfortunately, this is not being applied in project planning. A large number of hydropower projects are being developed in Himalayan region without understanding of the value of fresh water ecosystems to poor people in the downstream, other forms of life, and to the entire environment for all time to come. National policies/guidelines on environmental management are briefly reviewed below:

3.3.1 Constitutional Provisions

Article 51-A (g), stipulates the duty of every citizen to "protect and improve the natural environment including forests, lakes, rivers and wildlife and to have compassion for living creatures." Water (Prevention and Control of Pollution) Act (1974, 1988) seeks to maintain or restore wholeness of water. Central and State Pollution Control Boards have been established under this act.

The present national policies for environmental management are contained in the National Forest Policy, 1988, the National Conservation Strategy and Policy Statement on Environment and Development, 1992, Policy Statement on Abatement of Pollution,1992. Some sector policies such as the National Agriculture Policy, 2000; National Population Policy, 2000; and National Water Policy, 2002 have also contributed towards environmental management.

3.3.2 National Water Policy (2002)

The following statements of National Water Policy are relevant to environmental flows:

- Water is part of a larger ecological system. Realizing the importance and scarcity attached to fresh water, it has to be treated as an essential environment for sustaining all life forms

- In para 5, it accords ecology a relatively much lower and fourth priority (after Drinking water, Irrigation and Hydro-power) but indirectly recognizes water use for fresh water" ecosystems
- In para 6.3, it states "preservation of the quality of environment and the ecological balance should be a primary consideration" and goes on to add that the adverse impact on the environment, should be minimized and should be offset by adequate compensatory measures
- In para 14, it states that effluents should be treated to acceptable levels and standards before discharging them in to natural streams and that minimum flow should be ensured in the perennial streams for maintaining ecology and social considerations

3.3.3 National Environment Policy (2006)

In light of present knowledge and accumulated experience, the National Environment Policy seeks to extend the coverage, and fill in gaps that still exist in various policy statements,. It does not displace, but builds on the earlier policies. The policy document covers strategies and actions to be taken by municipalities, major cities, state and local governments for urban areas. The policy document does not contain specific details or recommendations with regard to environmental flows. Following policy statements are relevant to river ecology:

Principles

Human beings are at the centre of concerns for sustainable development. They are entitled to a healthy and productive life in harmony with nature.

Where there are credible threats of serious or irreversible damage to key environmental resources, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation.

Environmental standards must reflect the economic and social development situation in which they apply. Standards adopted in one society or context may have unacceptable economic and social costs if applied without discrimination in another society or context.

Strategy and actions for river systems

- Promote research in glaciology to evaluate the impacts of climate change on glaciers and river flows.
- Promote integrated approaches to management of river basins by the concerned river authorities, considering upstream and downstream inflows and withdrawals by season, interface between land and water, pollution loads and natural regeneration

capacities, to ensure maintenance of adequate flows, in particular for maintenance of in-stream ecological values, and adherence to water quality standards throughout their course in all seasons.

- Consider and mitigate the impacts on river and estuarine flora and fauna, and the resulting change in the resource base for livelihoods, of multipurpose river valley projects, power plants, and industries.
- Integrate conservation and wise use of wetlands into river basin management involving all relevant stakeholders, in particular local communities, to ensure maintenance of hydrological regimes and conservation of biodiversity.
- Incorporate a special component in afforestation programmes for afforestation on the banks and catchments of rivers and reservoirs to prevent soil erosion and improve green cover.
- Take measures to prevent pollution of water bodies from other sources, especially waste disposal on lands.

3.3.4 Ministry of Environment and Forests (Govt. of India)

Ministry of Environment and Forests, Govt. of India (MoEF, 2006) provides guidelines for EIA of development projects including river valley projects. However, the document does not specify EFR nor does it provide guidelines for assessment of environmental flows. Govt. of India has constituted Water Quality Assessment Authority (WQAA) in the year 2001 under the chairmanship of Secretary, MoEF exercising powers under the Environment (Protection) Act 1986 for several functions. Some of these relevant to EFR are as given below:

- To direct various agencies to standardize methods for water quality monitoring
- To ensure quality of data generation and utilization thereof
- To take measures so as to ensure proper treatment of waste water with a view to restoring the water quality of the river water bodies to meet the designated best uses
- To maintain minimum discharge for sustenance of aquatic life forms in riverine system
- To utilize self assimilation capacities at the critical river stretches
- To deal with any environmental issues concerning surface and ground water quality referred to it by Central Government or State Government relating to the respective areas, for maintaining and/or restoration of quality to sustain designated best-uses.

3.3.5 CWC Guidelines and Recommendations

Central Water Commission (CWC, 2007) carried out studies on minimum flows in various Indian rivers (i) In Himalayan rivers such as; Bhagirathi, Alaknanda, Tons, Giri (ii) in other rivers; Krishna and Godavari basins, (iii) southern tributaries of Yamuna and Tapi. Results of the studies are given in Annexure 3.1. The studies indicated that in the case of Himalayan rivers the virgin flows are very high due to snow melt contributions. However it may not be possible to maintain this condition in the lower reaches due to large existing utilizations. Therefore CWC recommends different minimum flow criterion for the Himalayan rivers in mountainous reaches and other rivers. CWC used the following guiding principles for EFA:

1. The maintenance of minimum flow in the river during the lean season should be accepted as an important objective for maintenance of river regime and water quality and thereby of pollution abatement.
2. The objective of restoring the flow in the river to what it was before any diversion projects is unattainable, for that would mean dismantling the existing irrigation systems.
3. Ecology is just another claimant for water. Standard principle for resolving river water dispute is "existing use will be negotiated". Therefore, the existing irrigation use should be protected and the nature sector can only claim a portion of the balance water available.
4. There cannot be one single formula to determine EFR for all the rivers. Ecology of each river, some times different reaches within a river, has to be studied and EFR computed accordingly.
5. EFR concept is applicable only to such rivers that do not go completely dry during lean seasons. For rivers that go completely dry, the riverine ecology ceases to exist and this need not be corrected by artificial means.

Based on the studies, the CWC has recommended the following hydrological indices for EFA:

Himalayan Rivers

- Minimum flow to be not less than 2.5% of 75% dependable Annual Flow expressed in cubic meters per second.
- One flushing flow during monsoon with a peak not less than 250% of 75% dependable Annual Flow expressed in cubic meters per second.

Other Rivers

- Minimum flow in any ten daily period to be not less than observed ten daily flow with 99% exceedance. Where ten daily flow data is not available this may be taken as 0.5% of 75% dependable Annual Flow expressed in cubic meters per second.

- One flushing flow during monsoon with a peak not less than 600% of 75% dependable annual Flow expressed in cubic meters per second

CWC has recommended to adopt a simple method for working out the minimum flows.. It felt that the Tennant Method is the only method which can be followed at present.

CWC guidelines are based on opinions of water resource experts in India. This approach suffers for the same drawbacks of behavioural psychology as in the Expert Panel Assessment method (Swales and Harris, 1995) and Scientific Panel Assessment method (Thoms et al, 1996). Cooksey (1996) provides a critique of such methods (Section 2.7.5 and Section 2.7.6, Chapter 2)

3.3.6 Water Policy of Himachal Pradesh

The study area is located in the state of Himachal Pradesh in India. In projects for hydropower generation involving impounding of water, adequate water is required to be released round the year to meet the needs of downstream users. The "Environmental Discharge" shall not be less than 15% of the available discharge at any given time. In forest areas the extraction of water shall be planned keeping in view the needs of the flora and fauna of the area. The involvement and participation of beneficiaries and other stakeholders will be encouraged at the project planning stage itself.

3.3.7 Guideline of Pollution Control Board of Himachal Pradesh

In the context of hydropower scheme (NJHEP) taken up for this research work, the Himachal Pradesh State Environment Protection and Pollution Control Board (HPSEP&PCB) has specified minimum releases to be made from the Nathpa dam as 15% threshold value of the minimum flow observed in lean season.

3.4 SUMMARY

Socio-economic welfare of the vast population in India is directly related to water resources and hydropower development. Ecology is accorded a relatively much lower (fourth) priority in National Water Policy document (2002). However water use for fresh water ecosystems has been indirectly recognized in various national and state level policy statements reviewed in this chapter.

Several of the methodologies (particularly holistic methodologies) reviewed in Chapter 2 require extensive data (hydrological, hydraulic and ecological) which usually are not available for Himalayan region. The EFA practice in India has recent origin and EF have been prescribed in terms of hydrological indices by Central Water Commission, the apex water body in India.

CHAPTER - 4

STUDY AREA, BASELINE DATA AND FIELD INVESTIGATIONS

4.1 THE SATLUJ BASIN

4.1.1 Satluj Basin in Tibet

The Satluj river (Figure 4.1) rises as Langchhen Khabab river from Mansarovar lake in the Tibetan Plateau at an elevation of about 4572 m. It forms one of the five main tributaries of Indus river. Satluj river travels about 322 km in the Tibetan province of Nari-Khorsam forming a plateau of successive deposits of boulders, gravel clay and mud. The flow of Satluj obtained mainly from snow and glaciers has cut a deep valley through these deposits going upto about 914 m deep at places. The entire catchment area in Tibet plateau (36075 sq. km) and some area in India in the downstream are mostly without rainfall and have a cold desert climate. This results in low flow in the Satluj river until it is joined by its major tributary Spiti near Namgia in India.

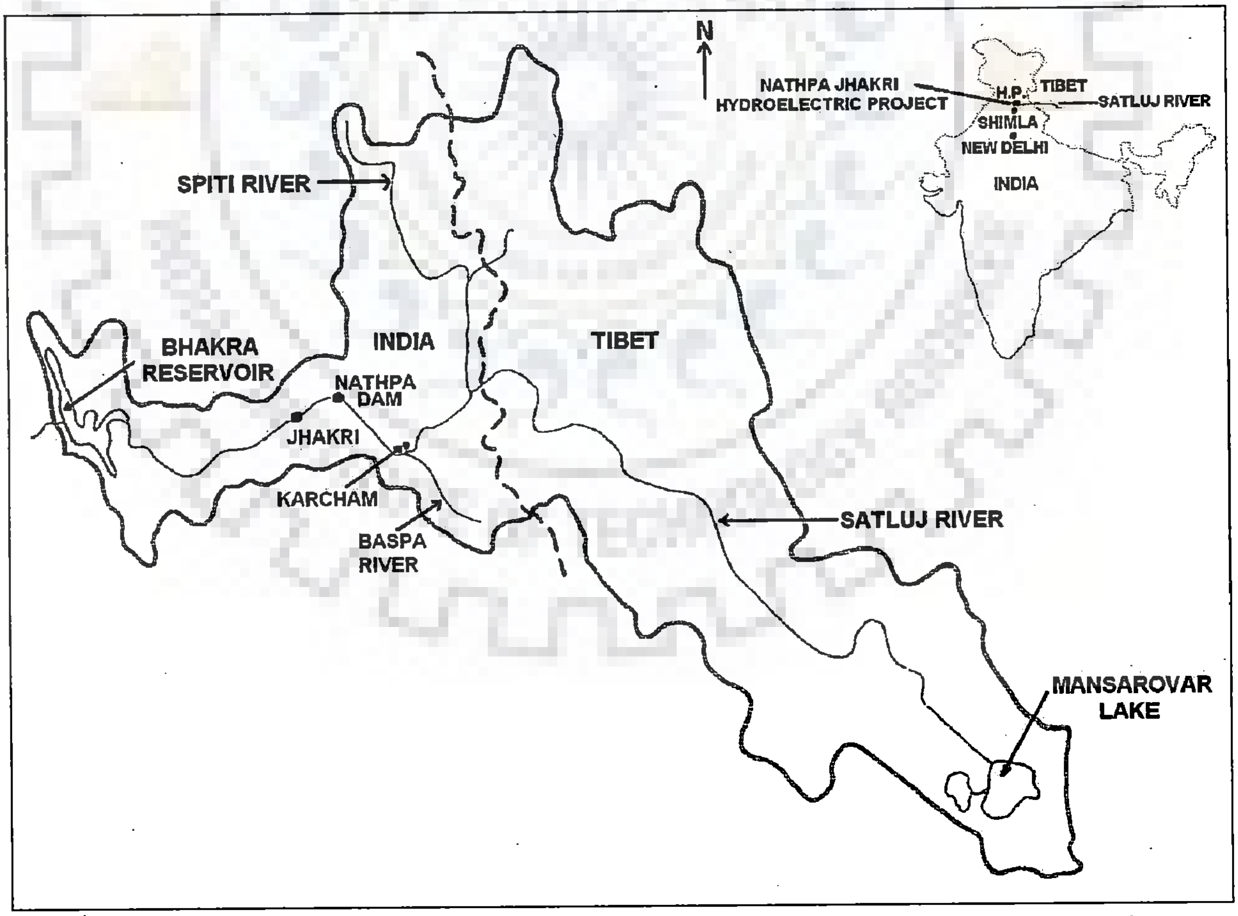


Figure 4.1: Satluj basin upto Bhakra dam

4.1.2 Satluj Basin in India

Indian part of the Satluj basin is elongated in shape and covers outer Himalayas (Shivalik ranges), middle Himalayas (Dhauladhar range) and greater Himalayas (Greater Himalayan range and Zaskar range). The great or main Himalayan range is comprised of snow clad peaks, glaciers and deep valleys. Middle Himalayas in the east part of Himachal Pradesh gives way to a series of mountain ranges of the lower Himalaya. There are Naga Tibba range, the Shimla hills and the Churdhar range. Outer Himalayas are extensive in Kangra, Hamirpur, Una, Mandi, Bilaspur, Solan and Sirmour districts.

The elevation of catchment varies widely from about 500 m at Bhakra dam site to 7000 m in greater Himalayas although only a very small area exists about 6000 m. Mean elevation of the basin is about 3000 m. The gradient is very steep in upper reaches and gradually reduces downstream.

The Satluj river enters India in the state of Himachal Pradesh near Shipkila. It flows along a southwestern course in Kinnaur district of Himachal Pradesh. The river has carved spectacular gorges where it has cut across the Zaskar, main Himalaya and Dhauladhar ranges. It flows at the base of the Shimla ridge and enters the lower hills in Bilaspur area where the gigantic Bhakra dam has been constructed across it. The total catchment area of Satluj river upto Bhakra dam is about 56874 sq. km, of which 22305 sq. km is in India including Spiti basin. The river then enters the plains of Punjab to finally drain into the Indus river in Pakistan. Alpine, Subalpine, temperate and sub tropical forests are formed at different elevations. The important settlements along Satluj river upto Bhakra dam site are Namgia, Kalpa, Jhakri, Rampur and Bilaspur.

Major tributaries of Satluj river upto Nathpa dam

Spiti river: It rises from the glaciers in the northern slopes of the main Himalayan range in Spiti area. It joins the Satluj at Namgia soon after the latter river enters Indian territory.

The valley of the Spiti river lies in trans-Himalayan tract of Himanchal Pradesh and thus resembles the Tibetan tract depriving it from the benefit of the southwest monsoons. The mountains are barren and largely devoid of a vegetative cover. The area is a rain deficient cold desert. The river attains peak discharge in late summers when snow on the mountains melts. The Spiti river may freeze occasionally in winter. The main settlements that have come up along the Spiti river and its tributaries are Hansi and Dhankar Gompta.

Baspa river: It rises in the main Himalayan range in the extreme north-eastern corner of Himanchal Pradesh. The main river flows along a NNW direction past a steep gorge having good vegetative cover on either side. Steep slopes and U-shaped valleys occur in the upper catchment of this river. Further downstream it has cut a spectacular gorge. River terraces are found at many places in the Baspa valley.

4.2 HYDROPOWER DEVELOPMENT IN SATLUJ BASIN

Several hydroelectric schemes on river Satluj and its tributaries are in different stages of implementation (Figure 4.2). In most of these schemes, river water is diverted for power generation and returned to the river at a downstream location depriving the river of its natural flow in specific reaches. Bhakra, Kol and Suni dams are storage type hydro power schemes. Even if the individual schemes may not be to significantly detrimental the physical and biotic environment, the combined effect of these schemes could be significant on a basin scale. Therefore it is necessary to assess the impact of each scheme. In this context, Nathpa-Jhakri hydro electric project has been selected for the case study.

4.3 THE STUDY AREA

For the purpose of this research work, the study area consists of the Satluj river reaches and interim catchments related with the Nathpa Jhakri Hydroelectric Project (NJHEP) and Rampur Hydroelectric Project (RHEP). The study reach is part of middle Himalayas also known as lesser Himalayas. It lies between outer Himalayas and the perpetual snow covered ranges of greater Himalayas.

The NJHEP is in operation stage and the diverted water (at Nathpa dam) is released back into Satluj after power generation at Jhakri. RHEP is under construction. The RHEP will make use of the water released in the tail race pool after power generation at Jhakri. Thus, RHEP will cause reduction in Satluj river flow downstream of Jhakri and up to Bael where the water will be released back into Satluj after power generation. The combined effect of NJHEP and RHEP is that the Satluj river will be deprived of the natural flows to the extent of 405 cumec in the reach from Nathpa to Jhakri (34 km) and then from Jhakri to Bael (23 km). Brief details of these projects are given below:

Nathpa Jhakri Hydroelectric Project

The 1500 MW Nathpa Jhakri Hydroelectric Project (NJHEP) is a run-of the river project on the river Satluj with a dam near village Nathpa in district Kinnaur and an underground power house near village Jhakri in district Shimla. The project layout and longitudinal section of the project are shown in Figure 4.3. The project area is on Hindustan Tibet road NH-22 approximately 150 km from Shimla.

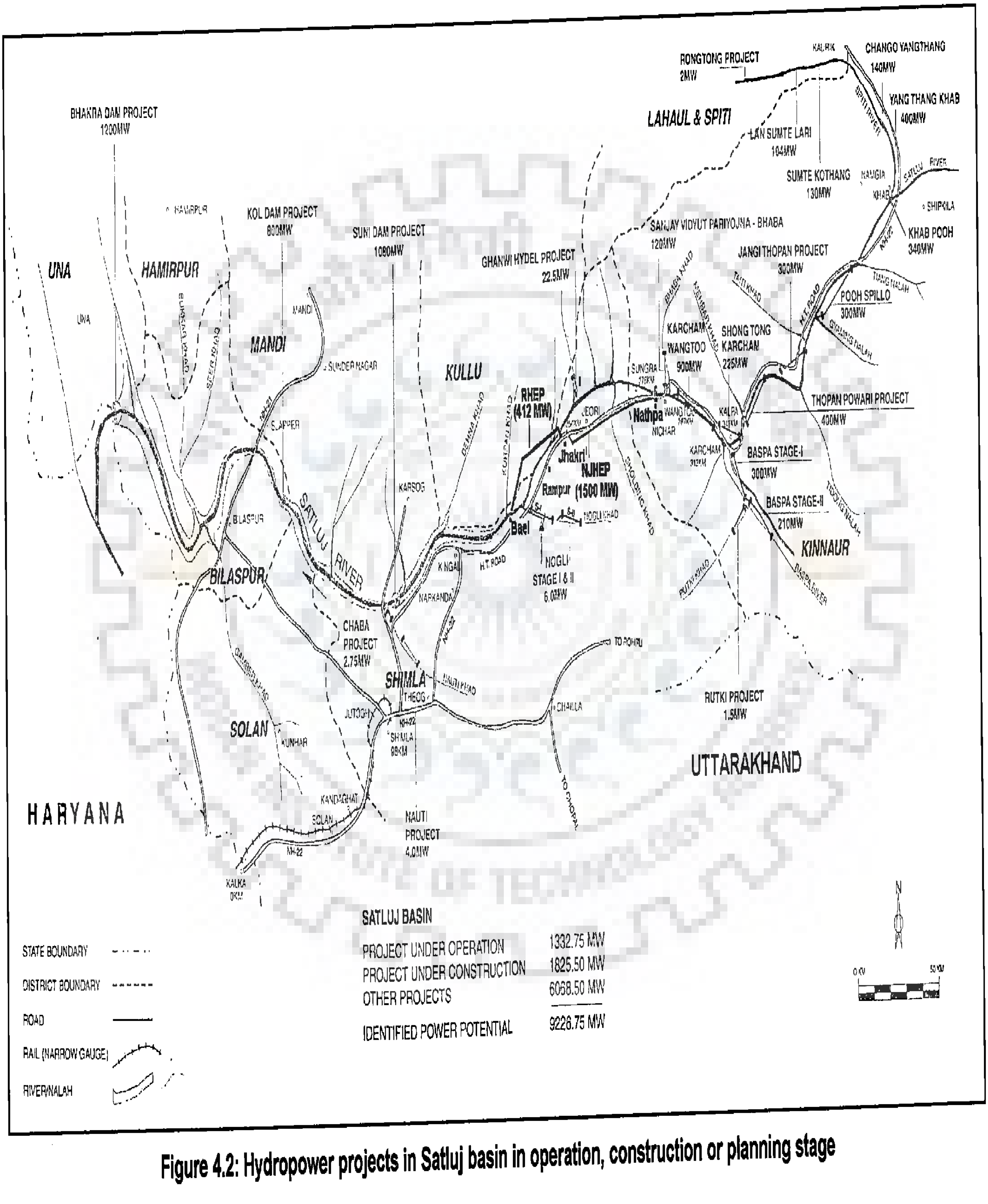
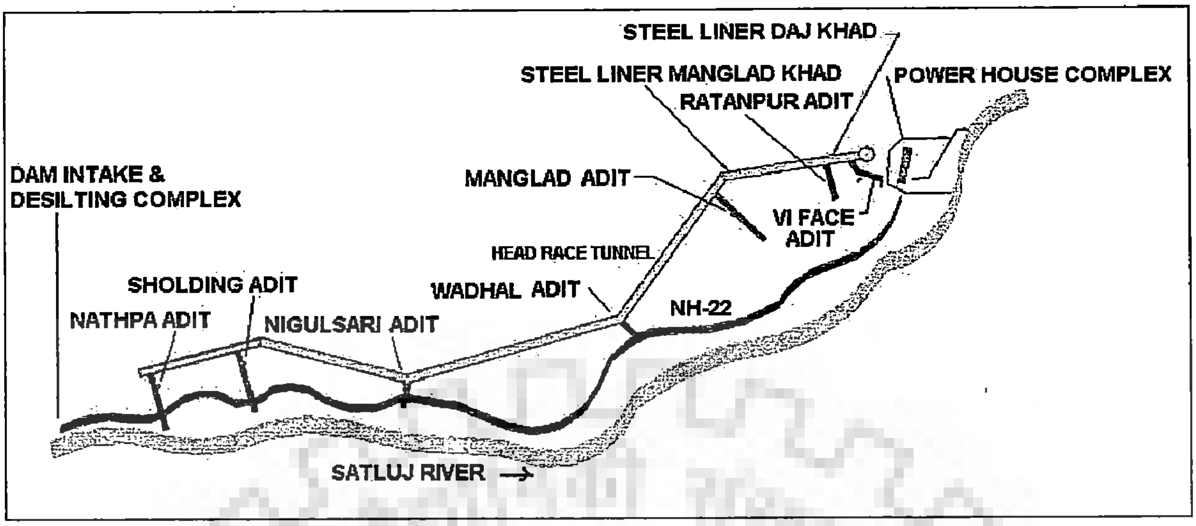
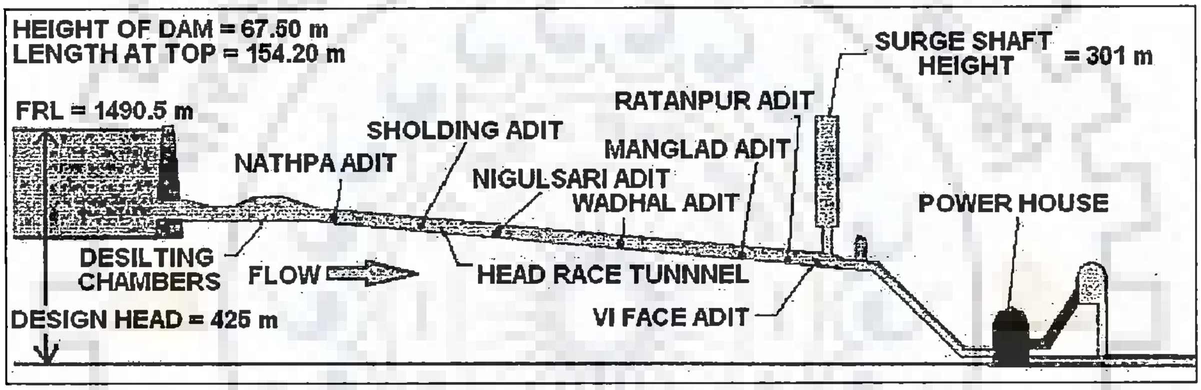


Figure 4.2: Hydropower projects in Satluj basin in operation, construction or planning stage



(A) Layout



(B) Longitudinal section

FIGURE 4.3: Layout and longitudinal section of NJHEP

About 405 cumecs of water is required to harness the installed capacity of the project. During monsoon season, the flow of the river varies from 700 to 2500 cumecs, and from 100 to 150 cumecs during the lean months. In the lean period, the entire water in the river at Nathpa is required for power generation. In between Nathpa and Jhakri there are several small streams locally known as streams. Flow of Sholding stream is also diverted into head race tunnel (HRT) during lean period.

The river reach between Nathpa and Jhakri is situated in steep mountain terrain. The study area falls in three tehsils i.e. Rampur tehsil of Shimla district, Nichar tehsil of Kinnaur district and Nirmad tehsil of Kullu district. District and tehsils are administrative units. A district has 3 to 6 tehsils. In elevation, the first 100 m from the river bed is predominantly rocky and do not support much of the vegetation. There is great variation of altitude with rugged terrains and hard climatic conditions in the study area.

Most of the sediment of Satluj river (almost 90%) is contributed by the upper reaches falling in Tibet. Horticulture is almost nil on right bank of Satluj river. There is more forest area on right bank compared to left bank and land holdings are also less. After Jeori, right bank has the green forests. Main face of right bank is overlain by pastures at places, but the back side has dense forests.

Rampur Hydroelectric Project

The Rampur project (Figure 4.2) is designed to divert 383.88 cumecs of de-silted water of the Satluj from the tailrace pool of NJHEP to the Rampur Intake structure from where the water is conveyed (from left bank to the right bank) through a 484 m HRT and 43.2 m cut and cover conduit. A 10.5 m dia headrace tunnel of 15.08 km conveys the water to a surface power station near Bael. Water is then returned to the Satluj river. The project is under construction stage. On completion, the project would utilise a gross head of 138 m to generate approximately 1969.69 Gwh of design energy in a 90% dependable year. The catchment area of the Satluj upto Nathpa-Jhakri is 49,800 sq. km. and upto Rampur HEP is 50,800 sq. km.

4.4 BASELINE DATA AND INFORMATION

Baseline data (numeric data and descriptive information) for pre- and post-project situation has been procured for assessment of the impacts of altered flow regime. Those impacts which might have direct or indirect relation to flow regime of Satluj river are relevant for the present study.

The baseline data consists of (i) physiography of Satluj river basin and its tributary sub-basins particularly in the study reach (ii) meteorological data, (iii) data on flow regime, (iv)direct/indirect water use by human, animal population and vegetation, (v) water quality, (vi) benthic flora, fauna and (vii) soil characteristics.

4.4.1 Data Procurement

The data/information was procured from several agencies, and discussions held with various experts. Reports and other documents collected from various agencies are shown in Annexure 4.1. Availability status of hydrologic data for the Satluj catchment is given in Annexure 4.2. Availability of meteorological data (temperature and rainfall at Nichar, Jhakri and Rampur) for the Satluj catchment is given in Annexure 4.3. Long term (ten daily) discharges are available only for Sholding (1970 to 1996) and Gaanvi (1976 to 2005) streams. In addition short term data for Shilaring stream, Sorang stream, Sailan stream and Chaunda stream is also available.

4.5 FIELD INVESTIGATIONS

4.5.1 Reconnaissance Survey

Reconnaissance survey of the Satluj river between Nathpa dam and Jhakri power house was conducted. The details are given in Table 4.1. A number of perennial and non-perennial streams join Satluj between Nathpa and Jhakri. Shilaring, Sholding, Sorang and Gaanvi are important tributaries. Figure 4.4 shows the tributaries and villages in the study area.

Table 4.1: Reconnaissance survey of study area

S. No.	Station/Stream	km	RB/LB	Observations during reconnaissance survey in March 2005
1.	Nathpa dam	0	-	Height of dam 67.50 m, pool of water d/s of dam and then dry bed, Bhaba HEP outfall u/s of Nathpa dam
2.	Three tributaries	<1	RB	Rainfed, non-perennial, negligible flow
3.	Shilaring stream	5	RB	Snow fed, perennial, right bank severely eroded, hill slopes covered with debris or boulders due to construction of road to Nathpa village, a hydropower project (5 MW) near village Rakshad is proposed
4.	Sholding stream	10	LB	Snow fed, Satluj river bed and valley widens in this reach, very little flow during non-monsoon as all water diverted to HRT, river bed comprises of gravels and silt
5.	Chhota Khambha & Bara Khambha streams	13	RB	Rainfed, approach road to Nigulsari Adit, debris from road construction dumped on sides of river
6.	Nigulsari stream (Chaunda khad)	16	LB	Snowfed, a small hydropower project (2.4 MW) is proposed
7.	Sorang stream	20	RB	Snowfed, almost vertical hills, 100MW HEP is proposed
8.	Tikadda stream	22	RB	Rainfed and perennial, rocky bed of Satluj
9.	Kapurang stream (Chaura khad)	24	LB	0.9 MW project on Sailan stream (tributary of Chaura khad) is proposed, vegetation on terraces visible, inhabitation on right bank of Satluj valley, pine forest between elevation 2600 to 3000 m
10.	Kut stre am	25	RB	Snowfed
11.	Shimla stream	26	LB	Rainfed, at the boundary of Shimla and Kinnaur districts
12.	Dhara li stream	27	LB	good vegetation on LB, terraced agriculture on RB
13.	Ratu stream	30	RB	Rainfed
14.	Gaan vi stream	33	RB	Snow fed, Gaanvi HEP of 22.5 MW
15.	Unoo stre am (Rai khad)	34	LB	Silty water, agriculture on terraces, near Jeori village
16.	Mang lad stream	37	LB	Snow fed, muck dumping site is planted with Rubinia, Chir and Grass, slopes are provided with toe wall
17.	Kao wil stream	38	RB	Rainfed
18.	Daaj stream (Gasso khad)	42	LB	Rainfed, water used for water mill, agriculture on terraces
19.	Sumej strea m	43	RB	Snow fed, used for water supply to SJVNL township (Jhakri), small shrubs and grasses on side banks

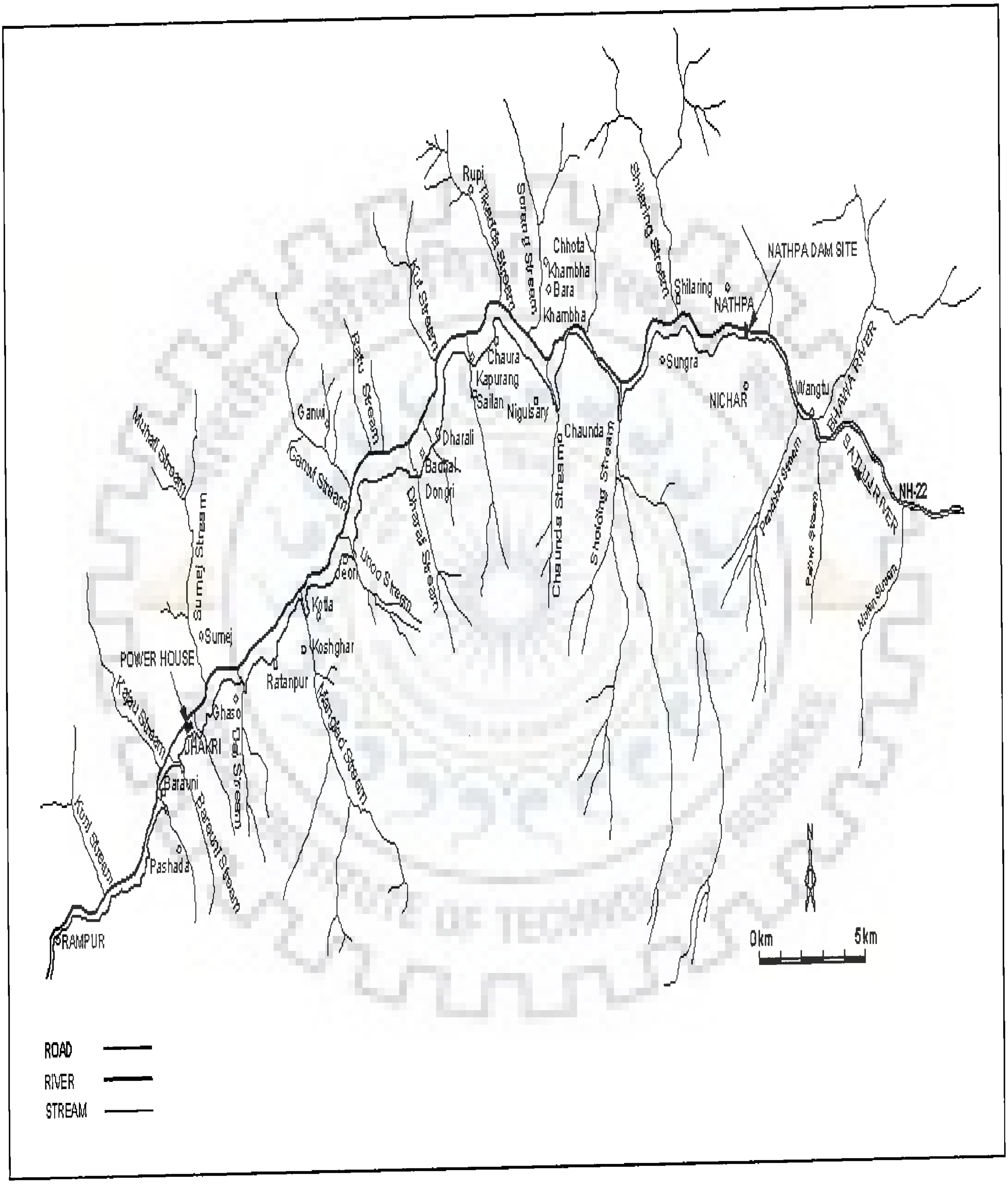


Figure 4.4: Tributaries and villages in the study area

4.5.2 Collection of Soil Samples and Grain Size Analysis

In the mountainous region, soils are generally under three land uses i.e. forest, grasses and cultivation. These land uses have important role in conditioning the soil and ultimately affecting its moisture retention and transmission characteristics. For the sustainable use of the scarce soil and water resources, proper knowledge of moisture retention and transmission characteristics is essential as the soils are shallow and rainfall is intense and highly variable in the Himalayan mountainous catchments.

Soil moisture retention characteristic (SMRC) expressing the relationship between matric potential (h) and moisture content (θ) is of prime importance in modelling water and solute movement in the unsaturated soil zone. Because of the time and expenses involved in making direct measurements, Brooks and Corey (1964) model has been used to estimate SMRC and HC of soils in study area using soil physical and chemical properties. Details of Brooks and Corey model and its application are given in Annexure 4.4.

For this purpose, soil samples from Satluj river bed, left and right banks of Satluj river and streams were collected for establishing the relationship between soil moisture retention capacity and soil texture. Eight soil samples from the Nathpa-Jhakri river reach were collected for grain size analysis. Sampling sites (Figure 4.5) were selected as to represent soils in the valley along the whole river reach. The grain size distributions of these samples are shown in Figure 4.6. Depending on similarity in sampling sites, the soil samples were classified into five categories:

- (i) Staluj river bed near Nathpa (T1),
- (ii) Satluj river side slopes (T2, T3 and T4),
- (iii) Sholding Stream bank (T5),
- (iv) Chaunda Stream bank (T6) and
- (v) Dharali Stream and Unoo Stream banks (T7, T8)

4.5.3 Village Level Survey

Socio economic aspect of EF is particularly important in Indian context. Unlike other EFA methodologies, DRIFT EFA (Chapter 2) has a socio economic module. Social studies are required of water resources used by common property users for subsistence, and the river-related health profiles of these people and their livestock. Such studies are linked to flow of the river and its tributaries, to predict how the people will be affected by altered flow regime.

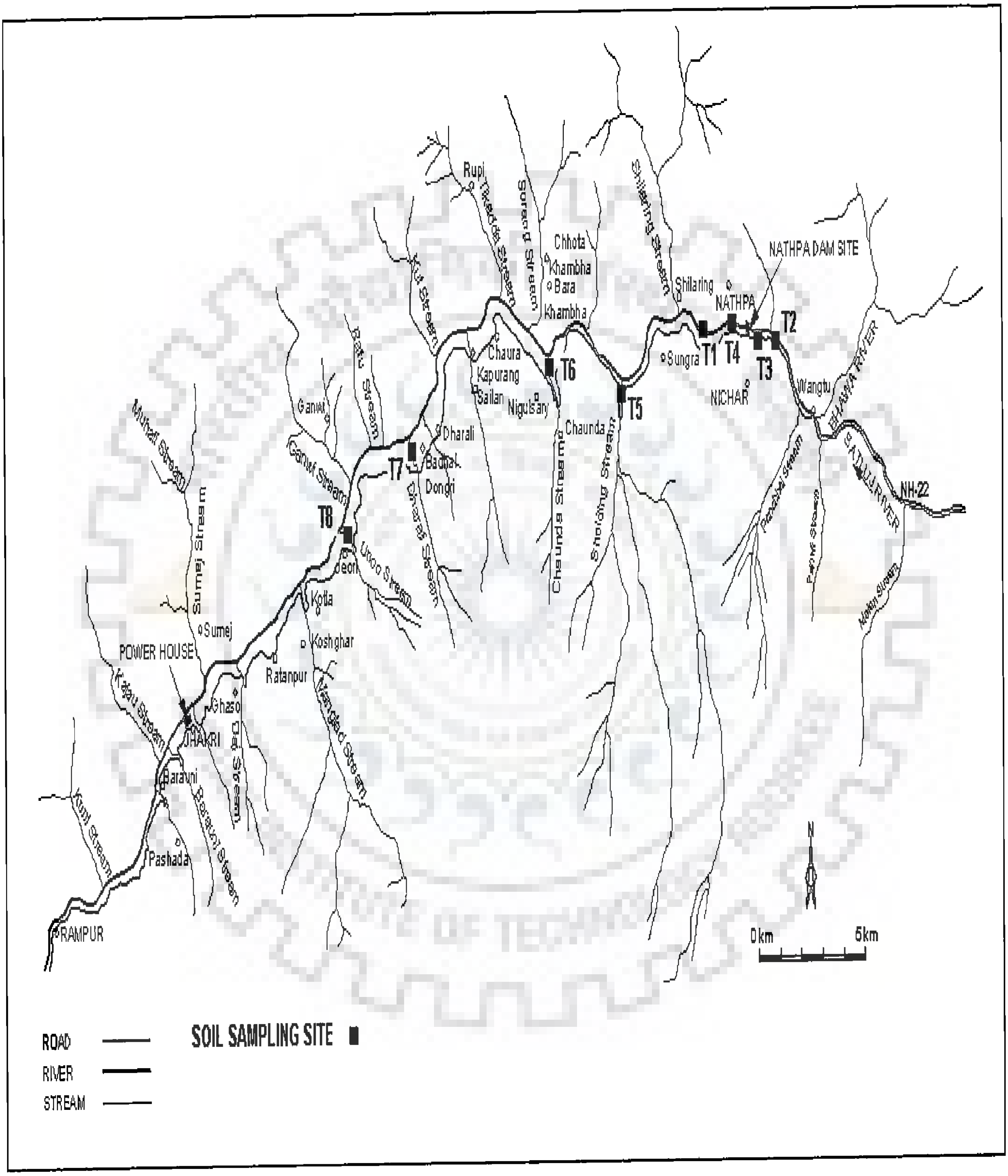
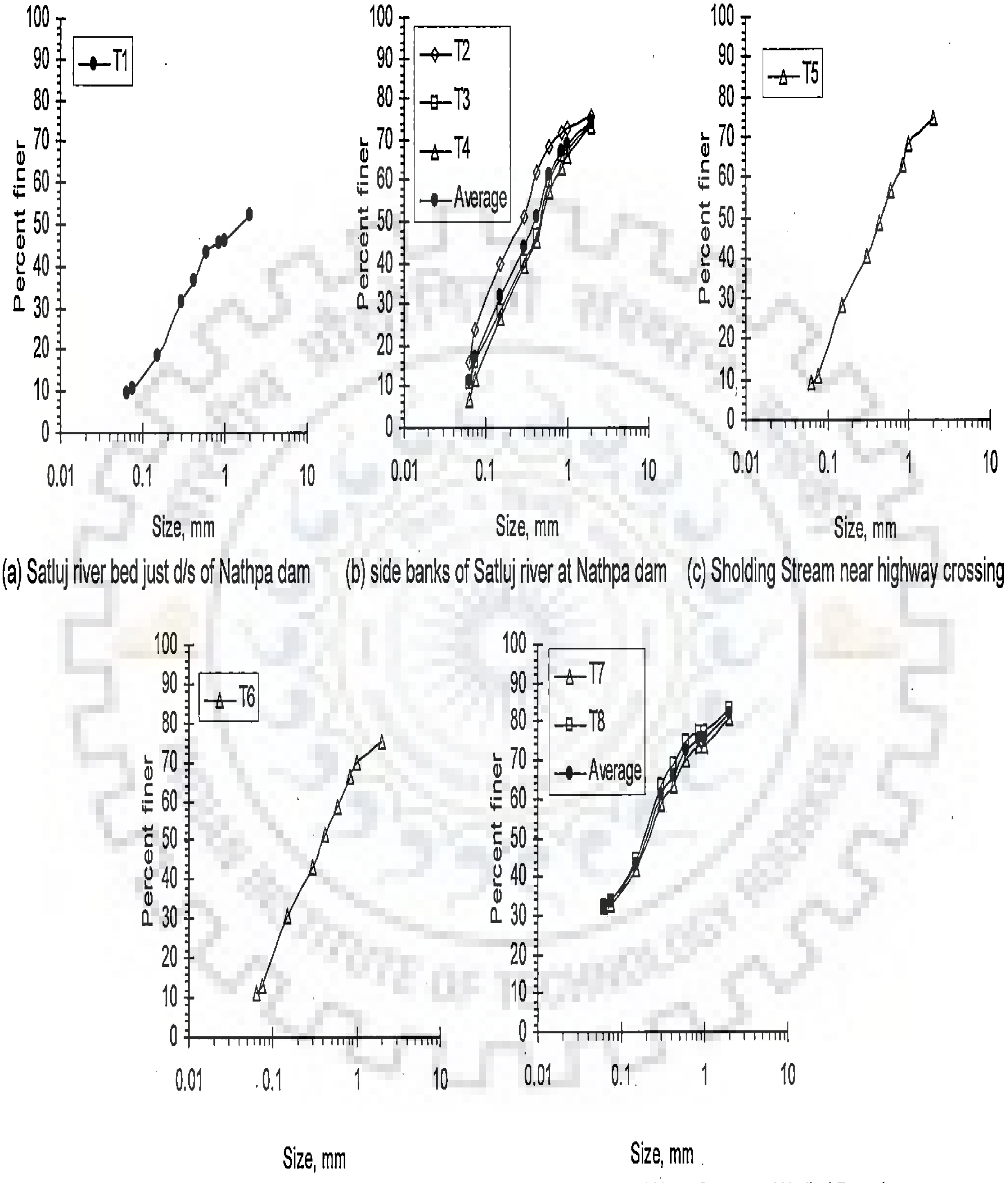


Figure 4.5: Soil sampling sites



(a) Satluj river bed just d/s of Nathpa dam (b) side banks of Satluj river at Nathpa dam (c) Sholding Stream near highway crossing

(d) Chaunda Stream near Nigulsari village (e) Dharali Stream and Unoo Stream at Wadhal Dongri village and Jeori town

Figure 4.6: Percentage finer curves for the soils in study area

Main objective of the village level survey was to make reliable assessment of (i) dependability of people and animals on Satluj water for meeting their water requirements; (ii) source and adequacy of water supply in tributary catchments; (iii) change in crop type and crop areas if any and (iv) animal population, fodder requirements, grazing area. For this purpose a performa was designed to carry out village level sample survey of Kandhar, Paunda/Bhabanagar, Chhota Khambha/Bada Khambha, Nigulsari, Chaura, and Badhal villages in the study reach (Annexure 4.5). Five villages are in Nichar block and four villages are in Rampur block.

Efforts were made to contact educated/responsible persons and talk to them in a group so that collected information is not vitiated by discrepancies and incomplete or casual statements by individuals. Thus, while talking to group of persons in a village, effort was made to ascertain that villagers give their considered opinions in a collective manner. Results of survey have been used in study of environmental water requirement of tributary catchments (Chapter 6).

Findings of village level survey:

1. Human habitations are located at higher altitudes compared to Satluj river and away from Satluj river. These habitations are concentrated along roads which are the only transport routes
2. Springs and streams are main source of water for drinking, irrigation, livestock. Water supply is adequate in winter but inadequate in summer
3. Flows in springs and streams have decreased over the years. Several springs have dried up in the post project condition
4. Hill slopes are used for grazing in summer whereas in winter, leaves and grasses are stocked. The grazing areas in general are away from Satluj river
5. A large number of goats and sheeps are domesticated for the purpose of milk, meat and wool
6. Most of the people are involved in agriculture and dairy farming. Fishing in Satluj river is not a source of livelihood in the surveyed villages
7. Small land holdings are scattered around human habitations. Cereals such as wheat, jau, maize etc. are generally grown along with some vegetables. Paddy is also grown in some patches near to perennial streams. Apple and plum are main horticultural crops.
8. Over the years, area under cultivation has increased particularly area under apple fruit crop. There is no change in type of cereal crops.

4.5.4 Monitoring of Tributary Discharges

Long term (ten daily) discharges are available only for Sholding and Gaanvi Streams. In addition short term data for Shilaring stream, Sorang stream, Sailan stream and Chaunda stream is also available. Discharge of other streams have been monitored as part of field work for this research in lean season using current meter. The monitored data for the periods October-December (2005), January-April (2006) and December (2006) to February (2007) on ten daily scale are given in Appendix 4.6 and Appendix 4.7.

The main purpose of discharge monitoring was to assess surface water availability at different locations along the river during post-project situation. River mapping and lean season flow analysis is given in Chapter 7.

4.5.5 Sampling of Benthic Flora and Fauna

Field observations on biodiversity (benthic) of Satluj river were carried out at several sites during February to April 2006 and during December'06 as per details given below. Location of sampling sites are shown in Figure 4.7.

Field Observations during February to April 2006

Site No.	Distance from Nathpa dam	Site location	Weather	Temp. of river water
F1	100 m	Downstream of Nathpa dam	Clear sunny	~ 7 ^{0}C
F2	11 km	Near the confluence of Chaunda stream with Satluj	Clear sunny	7 to 8.5 ^{0}C
F3	25 km	Near the confluence of Unoo stream with Satluj	Clear sunny	7 to 8.5 ^{0}C
F4	32 km	Near the confluence of Sumej stream with Satluj	Clear sunny	~ 8.5 ^{0}C
F5	33 km	Near Jhakri	Clear sunny	9^{0}C
F6	-	Nogli, Sumej and kajo streams between Jhakri and Rampur	Clear sunny	9^{0}C

Sampling for abundance of macroinvertebrates during December 2006

Site No.	Site	Distance from Nathpa dam
S1	Upstream of Shilaring stream confluence with Satluj	2.9 km
S2	Downstream of Shilaring stream confluence with Satluj	3.0 km
S3	Upstream of Chaunda stream confluence with Satluj	10.8 km
S4	Downstream of Chaunda stream confluence with Satluj	11.0 km
S5	Near the confluence of Gaanvi stream with Satluj	23.2 km

The sampling of benthic life included identification and abundance of species of flora and fauna present in the river reach. Results of sampling are discussed in Chapter 5.

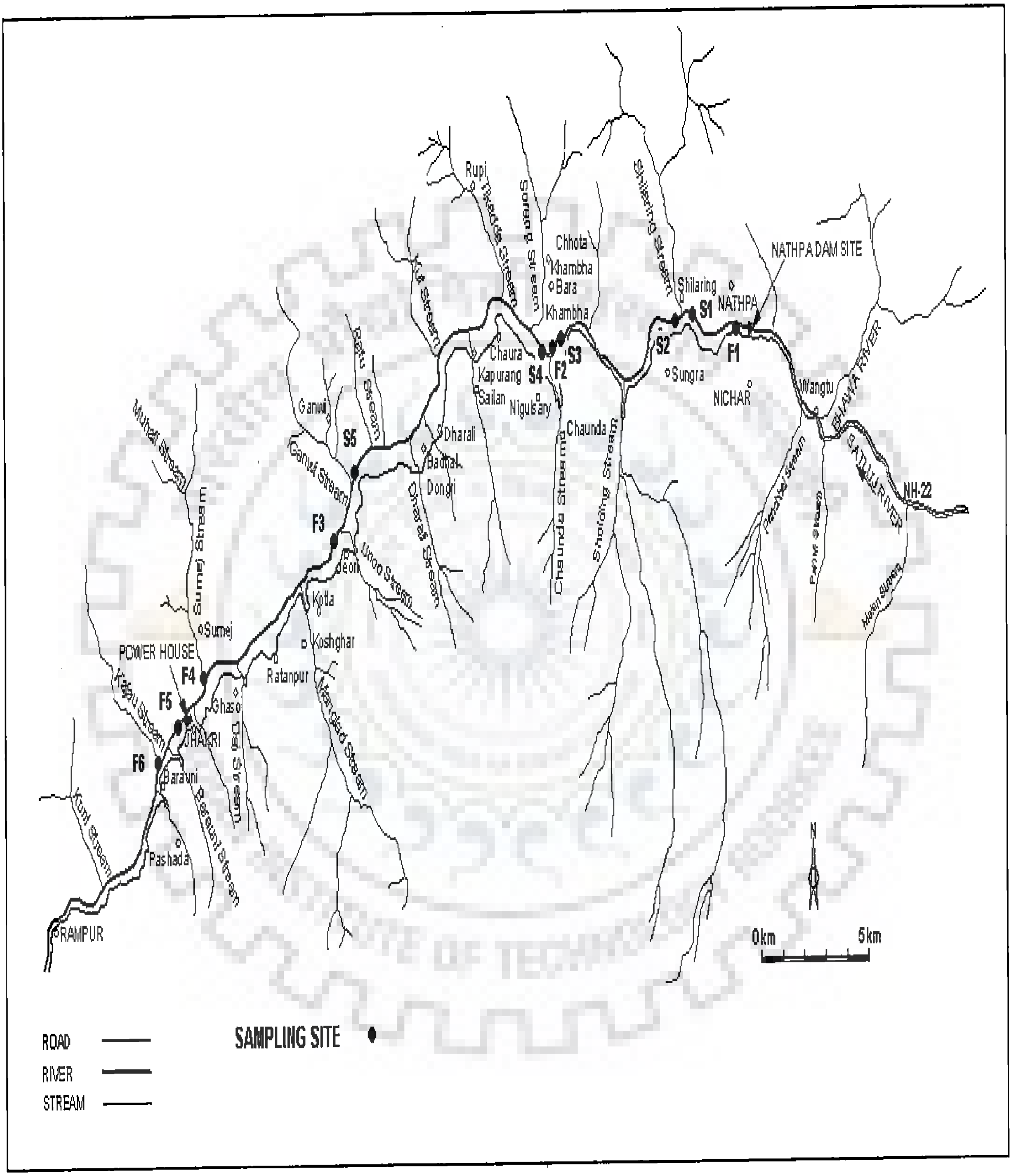


Figure 4.7: Sampling sites for flora and fauna

4.5.6 River Bed Profile

River bed profile (transverse cross-sections of the Satluj river bed) at four locations in initial 10.8 km reach d/s of Nathpa dam were surveyed. Longitudinal section of the Satluj river from Nathpa to Jhakri has been prepared based on available data. The hydraulic habitat analysis using river bed condition, river cross-sections and longitudinal section is given in Chapter 8. The river bed and banks are largely rocky and the flow is negligible immediately downstream of Nathpa dam but increases along the reach downstream.

4.6 PRECIPITATION CHARACTERISTICS

4.6.1 Seasonal Meteorological Behaviour

For the study of temporal distribution, a hydrologic year consists of winter (December-March), pre-monsoon (April-June), monsoon (July-September) and post-monsoon (October-November) seasons.

Winter season (December-March): The precipitation during this season is caused by extratropical weather system originating from Caspian sea and approaches India from the west. As the season advances, these disturbances come lower and lower and, by the end of December, they cover more or less whole Himalaya.

The precipitation is generally in the form of snow in the greater Himalayas, snow and rain in the middle Himalayas, and light to moderate rain over the outer Himalayas and the adjoining north Indian plains. The average frequency of occurrences of these disturbances is found to vary from 3 to 5 each month, and it reduces as the season advances. The precipitation decreases considerably as these disturbances move eastward along the Himalaya because of increasing distance from the source of moisture.

Premonsoon season (April-June): Generally this season lasts for about a period of 3 months from April to June and is considered as a transit period between winter and southwest monsoon. Light to moderate rains are essentially caused by air mass convective storms. The convection increases because of increasing trend of temperature in Himalayan region in this season.

Monsoon season (July-September): Normally precipitation over the Himalaya is caused by the moist air currents from Bay of Bengal in this season. Sometimes, in association with certain weather situations both branches of monsoon, the Bay of Bengal and Arabian sea, arrive simultaneously in this region heralding the onset of monsoon. Rainfall decreases westward because of increasing distance from the source of moisture, viz., Bay of Bengal and Arabian sea, which results in less amount of moisture content in air currents. This is the season of abundant rain compared to other seasons and rivers are generally flooded. Snow and glaciers at very high altitudes continue melting during this season. The monsoon normally starts withdrawing from this region towards the end of September. Monsoon currents become practically dry as most of the moisture content they initially carried is precipitated during their passage over the plains and mountain ranges of the Himalayas. It results in insignificant rainfall in the trans-Himalayan region.

Post Monsoon season (October-November): During this season, clear autumn weather sets in and there is generally little rainfall. This is the driest season in the entire Himalayas as well as in the plain areas. Cloud cover is the least in the month of November when skies are clear to lightly clouded for more than 25 days in a month.

4.6.2 Analysis of Seasonal Precipitation

Concurrent precipitation data of 26 years are available for two stations viz. Rampur and Nichar are given in Annexure 4.8. Rampur is representative of lower part and Nichar is representative of upper part of the study area. Table 4.2 shows mean annual and mean seasonal rainfall (R_N) and number of years (n) as percentage of total number of years (N) when seasonal/annual precipitation is less than 75% of mean rainfall. The table also provides values of coefficient of variation (ratio of standard deviation to mean) and correlation coefficients between precipitation at Nichar and Rampur. The results are summarized below:

(i) Average annual rainfall at Rampur (873 mm) is slightly higher than that at Nichar (855 mm) mainly because of higher rainfall during monsoon at Rampur. This does not include precipitation in the form of snowfall.

(ii) Rainfall at Rampur in all seasons is highly erratic as the seasonal coefficients of variation are significantly high. Post-monsoon and winter rains at Nichar are also highly erratic. Only small amount of rainfall is received during post-monsoon period (October-November) at Rampur and Nichar.

(iii) There is good correlation between post-monsoon rainfall at Nichar and Rampur. Rainfall in other seasons at Nichar are poorly correlated with rainfalls at Rampur indicating the effect of altitude and aspect. Annual rainfalls at these two stations are also poorly correlated.

(iv) India Meteorological Department has given following two criteria for identification of proneness of an area to meteorological drought:

  (a) Drought is a situation occurring in any area where annual rainfall is less than 75% of normal in 20% or more of the years examined.

(b) If annual or seasonal coefficient of variation (standard deviation divided by mean rainfall) is 30% or more, the rainfall is said to be erratic and the area is classified as drought prone.

Based on the above mentioned criteria, the study area is prone to meteorological drought. However, long-term data is needed for ascertaining it. Further, a meteorological drought is different from hydrological and agricultural droughts. Rainfed agriculture is not sustainable, due to agroclimatic constraints and lack of irrigation facilities.

Table 4.2: Seasonal rainfall characteristics at Nichar and Rampur

	Nichar					Rampur				
	Winter	Pre-monsoon	Monsoon	Post-monsoon	Total	Winter	Pre-monsoon	Monsoon	Post-monsoon	Total
RN, mm	223.17	251.55	328.68	51.61	855.01	255.44	178.18	401.13	38.33	873.08
0.75RN, mm	167.38	188.66	246.51	38.71	641.25	191.58	133.64	300.85	28.75	654.81
n	8.00	7.00	8.00	11.00	4.00	9.00	11.00	8.00	15.00	5.00
n/N	30.77	26.92	30.77	42.31	15.38	34.62	42.31	30.77	57.69	19.23
Std. Dev., mm	100.32	86.87	118.36	39.29	178.28	125.33	105.17	258.22	39.97	331.98
CV, %	44.95	34.53	36.01	76.13	20.85	49.06	59.02	64.37	104.28	38.02
Correlation coefficient						0.346	0.170	0.511	0.830	0.225

R_N : average rainfall; n : number of years when rainfall is less than $0.75R_N$
Std. Dev : standard deviation; CV : coefficient of variation

4.6.3 Spatial Distribution of Precipitation

Climate

Numerous small climate differences occur over short horizontal distances controlled by altitude, local relief and mountain barrier effect most important being altitude and aspect. Climate varies from hot and moist tropical climate in lower valleys to cool temperate climate at about 2000 m and tends towards polar as the altitude increases beyond 2000 m.

Subtropical	450 – 900 m
Warm temperate	900 – 1800 m
Cool temperate	1800 – 2400 m
Cold high mountain	2400 – 4000 m
Snowy and frigid	above 4000 m

The altitude controls not only temperature but also the rainfall. Furthermore, the south facing slopes are sunnier and also get more rain. Owing to large differences in seasonal temperatures and great range of elevation in the catchment, snowline is highly variable, descending to an elevation of about 2000 m during winter. The permanent snow line in this part of Himalayan range is about 5400 m. Snow covered area is confined to Spiti, Baspa and upper Satluj sub basins. About 11% area of the total Satluj catchment lies under glaciers.

Because of rugged terrain and inaccessibility to the higher reaches, a poor snow gauge network is found at high altitude where high snowfall is experienced. Cumulative isohyetal pattern of rainfall (mm) for the period of 10 years (October 1986 to September 1996) over Indian part of Satluj basin upto Bhakra dam (NIH, 1998-99) is shown in Figure 4.8. The lower catchment (Kasol to Bhakra) experiences very high rainfall. The general trend of rainfall exhibits that lower and middle parts of the basin experience more rainfall, whereas upper part of the basin experiences less rainfall.

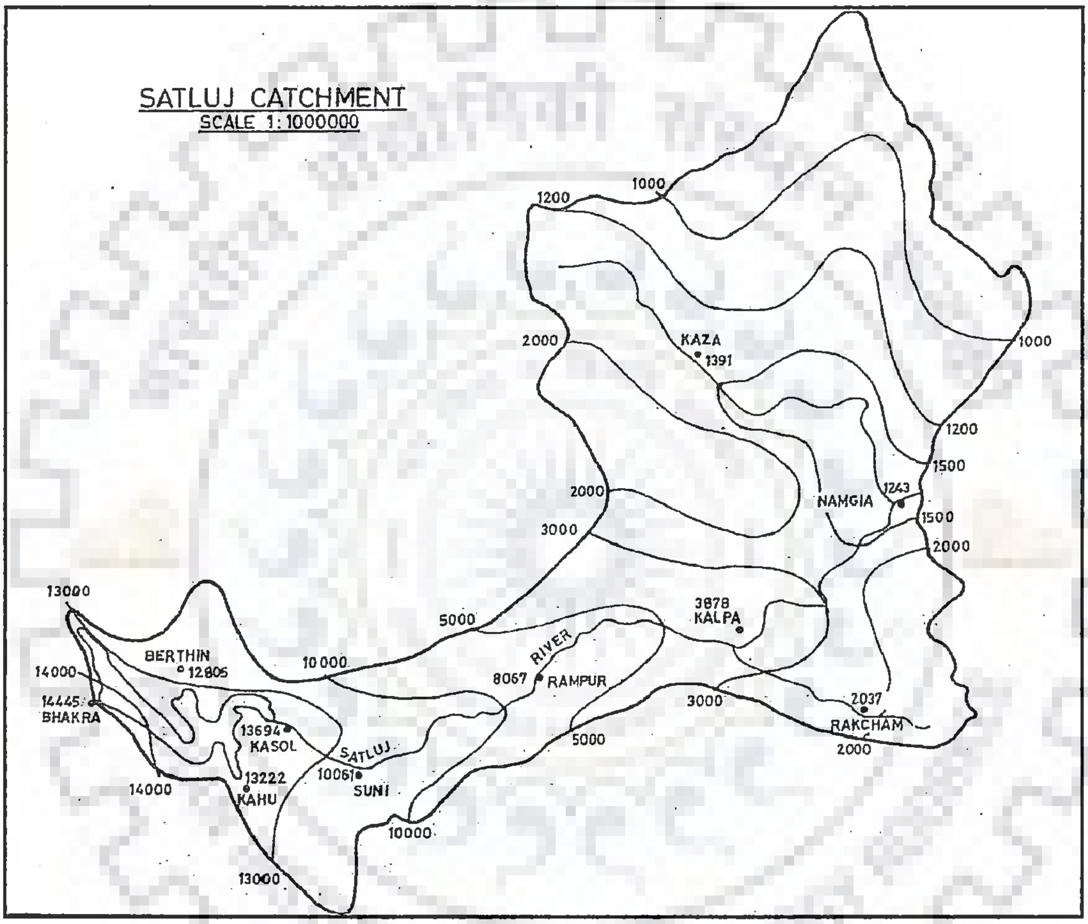


Figure 4.8: Ten years cumulative isohyetal pattern of rainfall (mm) over Satluj basin

Several authors have studied spatial and seasonal distribution of rainfall over Satluj basin. The important conclusions drawn based on the studies of Singh and Kumar (1996), Singh and Kumar (1997), NIH (1998-99), Singh and Singh (2001), Singh and Jain (2002) are as follows:

1. The rainfall distribution with altitude on the leeward side of outer Himalayas shows that the rainfall in all seasons increases linearly with elevation in Satluj basin. The rainfall on the windward side is higher than that on the leeward side. Both higher number of rainy days and high rainfall intensity are responsible to increase the rainfall with altitude in the outer Himalayan range.

2. In the greater Himalayan range, rainfall decreases with elevation exponentially in the post- and pre-monsoon seasons, and so does the annual rainfall. In the monsoon, no specific trend is seen.
3. Over all ranges of Himalayas in the Satluj basin, monsoon rainfall contributes maximum (45-71 %) to the annual rainfall. Minimum rainfall is experienced in the post-monsoon season in the outer and middle Himalayas because of less moisture content availability in this season. In the greater Himalayan range, minimum rainfall is experienced in the winter season because most of the precipitation falls as snow. Contribution of pre-monsoon rainfall to annual rainfall increases from outer Himalayas to greater Himalayas and becomes significant in the greater Himalayan range. Contribution of winter rainfall is also significant in the middle Himalayan range.

4.6.4 Precipitation Effect on River Flow and Agriculture

The study reach is part of middle Himalayas also known as lesser Himalayas. It lies between outer Himalayas and the perpetual snow covered ranges of greater Himalayas. Snow, ice and glacier fields in Satluj basin form the natural reservoirs of fresh water contributing significantly to the perennial water resource at Nathpa and in downstream. Melting provides stream flows from March to September every year.

Hydraulic gradients and rapid stream response result in flash floods due to rainfall with steep rise in the hydrograph. Owing to steep mountain slopes between Nathpa and Jhakri, most of the rainfall drains off with little ground water recharge compared to plain regions.

The varied topography in the study area in combination with temporal and spatial characteristics of precipitation have resulted in various agroclimatic zones. Agriculture is not sustainable due to highly erratic nature of seasonal rainfall in study area (Table 4.1). In parts where vegetation cover does not exist on soil (deforested, mined areas, muck disposal sites, quarry sites) high intensity rains during monsoon season cause heavy soil erosion. On the other hand, where good vegetation cover exists, loss of soil moisture recharge through evapotranspiration is high. In both cases lean season availability of water is adversely affected.

4.7 LONG-TERM CHANGES IN RAINFALL

Kumar et al. (2005) have carried out trend analysis of seasonal and annual rainfall data of eleven stations in Himachal Pradesh for the period of 84 years (1901-1984). Trend analysis of rainfall at Kilba (in the valley) and Shimla (on hill) is relevant for the study area. The results are given in Table 4.3.

At Kilba: Whereas monsoon rainfall has decreased, there has been significant increase in winter rain. The station receives more rainfall in winter compared to monsoon season. Lower monsoon rainfall is due to rain shadow effect.

Table 4.3: Mean and long-term trends of rainfall at Shimla (elevation 2205 m) and Kilba (elevation 2030 m)

Item	Period	Parameters	Winter	Pre-monsoon	Monsoon	Post-monsoon	Annual
Rainfall at Shimla Elev.2205m	1901-1984	Mean (cm)	20.75	26.99	95.46	4.95	148.16
		Trend (cm/100 years	-15.19	8.77	-39.27	1.71	-43.98
Rainfall at Kilba Elev.2030m	1901-1984	Mean (cm)	32.88	16.69	20.31	4.33	74.21
		Trend (cm/100 years	25.27	0.15	-6.61	2.95	21.76

At Shimla: Kumar et al. (2005) have indicated decrease in monsoon and annual rainfall at Shimla to be 39.27 cm/100 year and 43.98 cm/100 year respectively based on analysis of data from 1901 to 1984.

The study suggested that:

(i) Long-term changes in rainfall pattern are taking place in the region.

(ii) There is a long-term decreasing trend in winter and monsoon rainfall and increasing trend in post-monsoon rainfall in the region.

(iii) These could have major implications with regard to drinking water supplies from springs and water availability for irrigation and power generation.

(iv) The changes may have adverse effect on soil moisture levels.

CHAPTER – 5

FLOW RELATED IMPACTS ON AQUATIC BIODIVERSITY AND WATER QUALITY

5.1 INTRODUCTION

River ecology has been the focus of recent EFA methodologies such as Lotic Invertebrate Index for Flow Evaluation (LIFE) (Dunbar et al., 1998) and various methods based on holistic approach (Tharme, 2003). However lack of both hydrological and biological data is often a limiting factor and sometimes routinely collected biological data may not be suitable for the recent EFA methodologies. Some critics feel that the EFA methods requiring data on aquatic diversity (such as Holistic Approach based methods) are primarily hydrological (Jowett, 1997) because the tools to integrate biology fully do not exist now, and the methods "do not explicitly indicate the biological implications of flow decisions" (Young et al., 1995). Therefore EFR recommendations have often been based on expert opinion or 'best scientific information' in poorly studied systems. However links between flow and outcomes for the aquatic ecosystem have been quantified in recent applications of the approach (Davies et al., 1996).

EFA methodologies and country practices on EFA (Chapter 2, Chapter 3) do not consider maintenance of water quality by dilution as part of environmental flow. Though EF is not required to solve the river water quality problems by dilution; anticipated water quality consequences of modified flows are very much relevant as rivers in India have great religious significance. Further, untreated waste water is often disposed in the rivers adversely affecting river ecology. Conservation and restoration of rivers in India has been limited to "cleaning" of rivers by legally enforcing the treatment of industrial effluents. These efforts have met with limited success in river conservation.

The chapter deals with analysis of aquatic biodiversity and water quality in the study area and impact of altered flow regime due to diversion of Satluj flow at Nathpa. The study is based on analysis of sample data (sampling of biodiversity, water quality and village level survey) and secondary data available in literature. Planktonic community has been primarily considered as indicators of aquatic health because of their sensitivity to change in flow regimes.

5.2 BIODIVERSITY BEFORE WATER DIVERSION

(i) Micro Flora and Fauna

The benthic micro-flora consist of attached algae which grow as a thin film on all kinds of solid objects in the streams and even on sand and mud patches. Among the benthic micro-flora, diatoms is the dominant group especially the epiphytic and epilithic genera represented by Navicula, Gyrosigma, Nitzschia and Suriella. During the months of February and March every stone at the bottom remains covered with dark green to blackish green patches of blue-green algae (Myxophyceae). The other genera of importance recorded were Tetraspora, Ulothrix and Oedogonium amongst green algae (Chlorophyceae). The benthic micro-fauna, which occurred in association with algal film, include Arcella, Difflugia and Monostyla mainly as stray specimens.

(ii) Macrophytes:

The macrophytes which remain attached to rocks, boulders and stones etc. belong to various genera of Bryophyta (Mosses).These macrophytes are essentially inhabitants of fast flowing and turbulent streams receiving snow melt and spring waters .The mosses are indeed the most characteristic macrophytes of the turbulent streams .These mosses grow on stones and boulders which project a few centimetres above the surface of the water.

iii) Macro-Fauna:

The benthic macro fauna principally consists of (a) invertebrates and (b) vertebrates. Vertebrates are animals having a back bone including mammals, birds, reptiles, amphibians and fishes. Macro fauna in Satluj river comprises mainly of aquatic insects (invertebrates) and fishes (vertebrates).

(a) Macro vertebrates: The macro vertebrates encountered in river Satluj and its tributaries are Amphibia (Tadpoles of Rana) and fishes {brown trout (Salmo trutta fario), snow trout (Schizothorax richardsonii) in young stages, Nemacheilus gracilis, Nemacheilus stolizkae, Nemacheilus botia, Glyptothorax stoliczkae, Glyptothorax conirostre}.

Biological productivity is low due to low temperature in the study reach. Snow trout and brown trout do not grow to a large size when compared to slow meandering zone of river Satluj in the lower elevations. The sport fishery constituted by brown trout is confined mainly in river Baspa and its tributaries.

(b) Macro invertebrates: Amongst the invertebrates; naids, larvae and imagos of various insect orders contributed about 87.5% of total animals. The quantitative and qualitative analysis is given in Table 5.1. It is found that naids of Ephemeroptera and Plecoptera show a downward tendency in their occurrence from upper to lower stretches while the abundance of larvae of Trichoptera was in a reverse order. The other invertebrates recorded were tricladid Turbellaria and naids of Odonata.

Macroinvertebrates play significant role in stream ecosystems. As a group, macroinvertebrates are the primary food source for most stream fishes. Their taxonomic, habitat, and life-history diversity ensures that an array of food types is available to many fish species over the entire annual cycle. They also conduct the less apparent but no less important work of decomposing leaf litter and small particles of organic debris on the stream bottom or in the water column, and of grazing stream algae, fungi and bacteria. Considerable information is available on invertebrate responses to a variety of environmental conditions, and thus invertebrates may be used as indicators of stream conditions.

Table 5.1: Quantitative and qualitative analysis of benthic invertebrates in river Satluj and its tributaries

S. No.	Stream	Number of samples	Numerical count/sq. m	Wet weight of biomass, g	Qualitative (%)					
					Ephemeroptera	Plecoptera	Trichoptera	Coleoptera	Diptera	Miscellaneous
Upstream of dam										
1	River baspa, Sangla	10	89	1.250	63.5	12.1	13.0	0.2	9.6	1.6
2	Hurba Stream, Sangla	8	172	1.354	53.5	15.6	20.4	0.5	10.0	-
3	Rukti Stream, Sangla	12	230	0.490	87.8	1.0	0.9	0.3	4.4	-
4	Wangad Gad, Wangtu	6	157	1.174	89.0	2.7	5.0	0.1	2.4	-
Between Nathpa dam and confluence of tail race from power house at Jhakri										
5	Sholding Stream	8	189	2.085	46.4	3.2	42.3	1.9	6.2	-
6	Nigulsari Stream	8	172	3.154	36.1	1.1	46.2	3.5	10.6	2.5
7	Dharali Stream	6	134	3.650	34.8	-	48.2	2.5	13.4	1.1
8	Manglad Stream	8	129	2.295	41.2	0.5	42.8	3.1	10.0	2.4
Downstream of Jhakri										
9	River Satluj, Nogli	6	60	0.540	61.8	2.2	21.6	1.2	12.9	0.3
10	Nogli Stream	7	156	1.242	34.2	2.6	42.5	1.5	15.0	4.2
11	Macheda Stream	4	118	2.950	28.2	0.8	51.8	2.5	11.5	5.2
12	Behra Stream	6	127	2.850	27.8	1.4	38.2	8.5	20.2	3.9
13	Swari Nala, Luhri	4	134	2.180	23.9	0.6	56.8	10.2	7.1	1.4
14	River Satluj, Luhri	4	72	0.885	54.6	0.4	30.2	1.2	13.6	-

Source: WAPCOS (1999)

The physical and chemical parameters are reflected in the quantity and quality of animal communities in a mountain stream. The faunal communities have to adapt to the various hydrological parameters of fast-flowing riverine conditions. They face hazards of great magnitude including variable velocities of water flow, occurrence of periodic floods including flash floods due to cloud bursts and continuous rolling of bottom material consisting of boulders, stones, gravel etc. accentuated during floods. The impact of rolling action of bottom material on benthic animals has been studied in river Beas which is an identical riverine system (Khan and Tandon, 1941). High floods cause dislodging of benthic animals. However, such conditions remain for a short period of time. The biotic communities generally reappear after 105 to 122 hours during and after rains and 78 hours during snow melting turbulence.

The turbulent river Satluj and its tributaries have provided micro-habitats for the denizens to get suitably adapted to the environment. The various micro-habitats are water falls, rapids, riffles, eddies and pools.

5.3 BIODIVERSITY AFTER WATER DIVERSION

Field observations have been carried out during February to April 2006 at 6 sites (F1 to F6) as shown in Figure 4.7 (Chapter 4). Summary results of field observation are given below:

Benthic Flora:

1. Dominant groups of phytoplanktons found during post-project situation are same as existing in pre-project condition. Blue green algae have economic importance in fixation of atmospheric nitrogen.
2. Bryophyta (macrophyte) have been observed alongside the river bank. These plants are ambhibious in nature and grow in moist shady places. Species found are Riccia fluitans, Marchantia simlana, Pellia endiviae folia and Madotheca.
3. Equisetum is the single pteridophyte found at all the sites. Plant is bushy having root, hair, stem and leaves. Height ranges from a few centimeters (E. scripoides) to few meters (E. giganteum). It is an economically important plant.

Benthic Fauna:

4. Arcella (protozoa) in the study area was found growing at least 20 m away from river bank. Diffusei is free living and feeds upon algae. Hence, it is in plenty where algae are in abundance. Planaria and Coleoptera were also found.
5. Ephemeroptera: Dominant groups were of Baetis and Epeorous. In case of Trichoptera dominant group was Rhicophila; incase of Coleoptera, dominant group were Gyrinidae and Psephenidae. In case of Diptera, dominant groups were Blepharoceridae and Leptidae.

Fishes:

6. For fish survey (Plate 5.1), Jhala (a net of 1.5 m dia) was used for 5 to 6 hours continuously at each of the six sites on different dates during the period. During these field observations, no fish was observed at the first three sites i.e. from downstream of Nathpa dam to confluence of Unoo stream with Satluj.

   However, fishes were observed in Nogli stream, Sumej stream and Kajo stream near its confluence with Satluj river. The sole fish species observed was a trout which belongs to taxonomic family Cyprinidae and sub-family schizothoracinae. It is a small sized migratory fish variety locally known as "asla". Literature review (DHI, 2006) shows that reaches downstream of Jhakri show presence of relatively more fish species due to favourable temperature regime and less turbulent flow conditions.

5.3.1 Abundance of Macroinvertebrates

Samples of macroinvertebrates were collected from 5 sites (S1 to S5) as shown in Figure 4.7 (Chapter 4). These samples were analysed in laboratory as discussed below to quantify abundance of macroinvertebrates.

Methodology

A sample consisted of collection of 20 sub-samples each of (0.25 x 0.25) m^2 taken from all microhabitat types. The procedure results in sampling of approximately 1.25 m^2 stream bottom area. Net of mesh size 500µm was used for collecting the macroinvertebrates. Boulders or cobbles in the area were picked up and organisms vigorously washed by hand into the net. Finally, the substrate with smaller boulders was disturbed by kicking systematically across the area 3-4 times such that the invertebrates wash downstream into the net. The organisms were then picked from the net surface and preserved in 80% ethanol or 4% formaldehyde. These samples were brought to the laboratory for processing. The collected macroinvertebrates were sorted and identified to operational taxonomic unit (at least to family level with the help of regional keys) in the laboratory using dissecting microscope for identifying the fauna. The aquatic macroinvertebrate samples are shown in Plate 5.2 and Plate 5.3.

Results

The results of laboratory analysis of samples were arranged for each taxonomic group in terms of (i) total number of animals under each taxonomic group and (ii) percentage abundance of each taxonomic group and are given in Table 5.2. The taxonomic groups found were Trichoptera, Diptera, Ephemerotera, Coleoptera, Plecoptera, Odonata, Oligochaeta, Heteroptera and Gastropoda. The percentage abundance of taxonomic groups at each site is compared in Figure 5.1.

Only two taxonomic groups (Diptera and Ephemeroptera) are found at each site, yet, on the basis of percentage abundance, the major taxonomic groups were found to be Trichoptera, Diptera, Ephemeroptera, Coleptora and Odonata. From upper to lower portion of Nathpa-Jhakri reach, percentage abundance of Diptera increases whereas Ephemeroptera shows the reverse trend. Exception is seen at site 1 (just downstream of Nathpa dam) which may be due to the alteration of natural condition of initial reach. Percentage abundance of other groups does not show any definite trend from upper to lower reach.

Table 5.2: Total number count and % abundance for each taxonomic group in Satluj river between Nathpa and Jhakri

Taxonomic Group	Site - I		Site-II		Site-III		Site-IV		Site-V	
	Total Number count	% Abundance	Total Number count	% Abundance	Total Number count	% Abundance	Total Number count	% Abundance	Total Number count	% Abundance
Trichoptera	37	3.78	0	0	0	0	38	12.71	35	5.85
Diptera	100	10.2	4	7.27	8	16.67	179	59.87	521	87.12
Ephemeroptera	841	85.82	48	87.27	38	79.17	39	13.04	30	5.02
Coleoptera	1	0.1	0	0	0	0	15	5.02	2	0.33
Plecoptera	0	0	0	0	0	0	0	0	4	0.67
Odonata	0	0	3	5.45	1	2.08	2	0.67	6	1
Oligochaeta	1	0.1	0	0	1	2.08	0	0	0	0
Heteroptera	0	0	0	0	0	0	25	8.36	0	0
Gastropoda	0	0	0	0	0	0	1	0.33	0	0
Total	980		55		48		299		598	

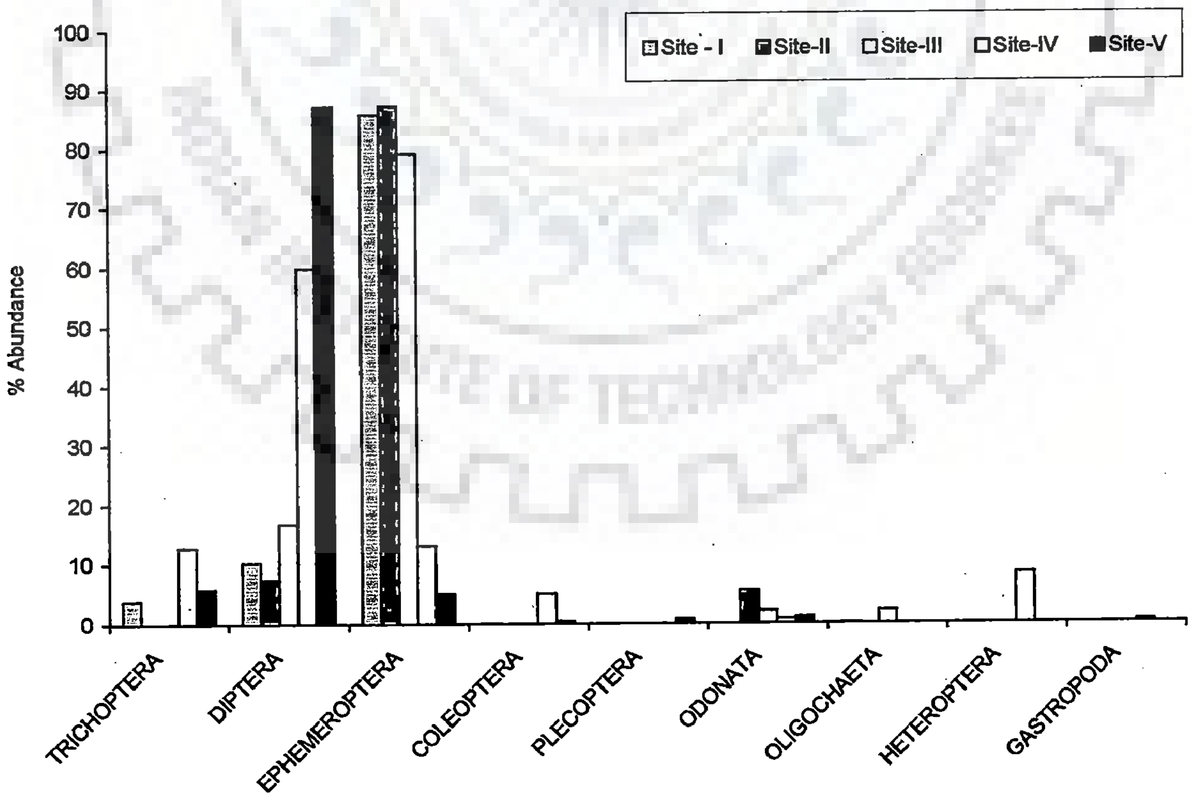


Figure 5.1: Abundance of different taxonomic groups

5.4 IMPACT OF ALTERED FLOW REGIME ON AQUATIC BIODIVERSITY

The Himalayan region is usually regarded as a cold water regime. The rivers usually have higher dissolved oxygen content, high transparency, very low biochemical and chemical oxygen demands and relatively low productivity (Jhingran and Sehgal, 1978 and Sehgal, 1983). High velocity and turbulence of water current is a major constraint in the primary productivity of the aquatic bodies of this region. In the recent years, interest to know the general eco-biological characteristics of the Himalayan streams has increased and growing information is now available for some water bodies from this region (Sharma and Bhadra, 1986; Nautiyal and Nautiyal, 1995; Moog and Sharma, 1996; Sharma, 1996; Nautiyal et al., 1998; Kishore et al., 1998 and Bhatt et al., 2000; Sharma, 2005).

Available information on aquatic biodiversity during pre and post project situation has been used to assess impact of altered flow regime in Satluj river. Principles proposed by Bunn and Arthington (2002) form the basis for this assessment.

5.4.1 Impact on Physical Habitat and Biotic Composition

Effect of velocity of flow: Average flow velocity downstream of Nathpa dam upto a release of 3 cumec is in the order of 1 m/s further reducing downstream. Beyond release of more than 3 cumec, the average flow velocity is in order of 0.8 to 1.2 m/s; for discharge of 4 cumec and 10 cumec respectively. When 1500 cumec is discharged from Nathpa dam, the velocity of flow is more than 12.7 m/s.During the field observations, it was found that at low discharges, velocity profile in transverse direction at a section could be highly variable as the river reach is in bolder stage.

Hydropsyche needs high flow rate both for its net construction and respiration. Very little discharge immediately downstream of dam explains absence of hydropsyche. Trotsky and Gregory (1974) has also reported that *Hydropsyche* was heavily reduced below a dam with very low daily flows.

Influence on food and substrate: The growth of periphyton and filamentous algae has increased during lean season because of the reduced turbulence in flow, decreased substrate redeposition, and reduced scouring effect of transported inorganic material, for which the Nathpa reservoir serves as trap. This offers potential opportunities for species using algae as food or substrate, such as chironmids, gastropods, Psychomyiidae, *Ephemerella* spp., *Heptagenia* spp., and *Baetis* spp., for increasing in abundance.

Influence on aquatic plants: Lean season flows are significantly reduced. Therefore, excessive growth of submerged aquatic macrophytes downstream of Nathpa dam is not expected. Inundation upstream of Nathpa dam may encourage many plant species promoting diversity.

Influence on aquatic invertebrates: Sudden increases in flow downstream of Nathpa dam may occur due to emergency shut down of tunnel diversion and in the downstream of Jhakri due to return of water after power generation (while stepping up power generation). This can cause significant downstream drift of macroinvertebrates. Burn and Arthington (2002) state that as much as 14% of the standing crop of benthic biota can be eliminated each month due simply to drift resulting from increased shear stress.

All the taxonomic groups of macroinvertebrates observed in the study reach during post-project condition are same as during pre-project condition (Table 5.3 and Table 5.4). These are not affected by altered flow regime.

Influence on fish: Village level survey and field observations did not indicate abundance of fish in the study reach even though presence of these in upstream and downstream of the study reach is reported in literature. Literature also suggests that snow and brown trouts are found in streams near confluence with Satluj as they provide more favourable habitat. Newly emerging and juvenile fish (if any) hiding in the streams substrate during winter are extremely susceptible to being stranded in the substrate during flow reductions.

Hydrologic factors for fish being scanty in river Satluj are as follows:

- Unstable flow regime is not favourable for fish habitats. Breeding and propagation of cold water fish is hindered by occurrence of floods.
- Most of the energy of cold water fishes is utilized in maintaining their position in fast flowing waters creating continuous physiological stress.
- Velocity of flow varies not only along the river due to change in gradient but also across the section (due to boulders).
- Structure and consistency of river bed changes frequently due to rolling of boulders caused by high velocity of flow during floods which could be about 12.7 m/s for a flood of 1500 cumec (DHI, 2006).

5.4.2 Impact on Life History Strategies

- Satluj river has unstable flow regime. Rates of water level fluctuation, disturbance frequency (flood and spates) and intensity (velocity and shear stress) in the reach affect seedling survival, as well as plant growth rates. This explains poor biodiversity in the Satluj river reach.
- Stream fishes are expected to recruit by spawning due to reduced and relatively stable stream flows when their spawning habitats are least likely to be scoured out. Small insect nymphs and invertebrates may get introduced due to reduced velocity.
- The release of cooler water downstream of Jhakri power house can influence the spawning behaviour of fish and life history process of invertebrates in the

downstream. Cold water releases have been found to delay spawning by up to 30 days in some fish species. After implementation of Rampur Hydroelectric Project, cooler water downstream of Jhakri power house will be diverted into tunnel favouring spawning of fish in Satluj reach upto Bael (the outfall d/s of RHEP power house).

5.4.3 Impact on Longitudinal and Lateral Connectivity

Longitudinal connectivity

- Nathpa dam has transformed small length of the river Satluj into a pool on upstream, supplementing the riverine environment with pool habitats.
- Conversion of lotic to lentic habitat on upstream of Nathpa dam will result in the loss of fishes adapted to turbid riverine habitats.

Literature shows that river impounding and blocking of fish passage are often followed by disappearance or decline of major migratory species in river reaches upstream of barriers. Even small instream barriers such as V-notch gauging weirs can impede the movement of fish. Therefore certain minimum release on continuous basis is necessary for movement of migratory species.

Lateral connectivity

Nathpa dam (without storage) has only small effect to dampen flood peaks and in reducing the frequency, extent and the flood plain inundation. Flood plains in the reach from Nathpa and Jhakri are very much limited. Therefore, possibility of fish getting trapped in isolated flood plain bodies is very small. However, in the reach downstream of Jhakri Satluj flows through relatively wider valley and fish existence is also found in the reach.

5.4.4 Exotic and Introduced Species

The term exotic (i.e. non native) species is defined as those that are not indigenous. Creation of standing water body upstream of Nathpa dam favours introduced species many of which are most abundant in lakes. However, downstream of Nathpa dam long-term success of invading or introduced species is unlikely due to inherent low productivity of cold water and unstable flow regime.

5.5 WATER QUALITY ANALYSIS

The quality of water in natural water ways usually is evaluated in relation to chemical and physical criteria. Bacteriological parameters frequently are included in evaluation of recreational waterways. The objective of this study is to evolve water quality indices and to compare the quality of water of the Satluj river at different locations in pre and post commissioning of the Nathpa Jhakri Hydroelectric Project.

5.5.1 Need for Water Quality Index

Whereas water quantity is determined by a single parameter – the volume or rate of flow during a given time period, the water quality is described in terms of concentration of several constituents (20 odd common constituents to hundreds). Comparison of water quality in terms of a list of constituents is not easy. For example a water sample containing six components in 5% higher than permissible (hence objectionable) levels; pH, hardness, chloride, sulphate, iron and sodium may not be as bad for drinking as another sample with just one constituent – mercury at 5% higher than permissible. Water quality indices aim at giving a single value to the water quality on the basis of one or the other system which translates the list of constituents and their concentrations present in a sample into a single value. In the present study, two existing indices have been used for assessing water quality; these are NSF-WQI and CPCB-WQI. In addition, a new index is proposed in the context of environment flow requirement.

5.5.2 NSF Water Quality Index (NSF-WQI)

Brown et al. (1970) developed an index based on nine parameters, developing a common scale, and assigning weights for which elaborate Delphic exercises were performed. This effort was supported by the National Sanitation Foundation (NSF). For this reason, this index is referred as NSF-WQI and also as Brown's Index in literature.

A list of nine parameters (Table 5.3) was chosen as most significant by Brown et al. (1970). In addition, Brown et al. (1970) stated that if total content of detected pesticides or toxic elements (of all types) exceeds 0.1 mg/L, the water quality index will be automatically registered to zero.

The index (NSFWQI) is calculated as follows:

$$\text{NSFWQI} = \sum_{i=1}^{n} w_i q_i$$

where,

q_i = the quantity of the i^{th} parameter

(a number between 0 to 100 read from the appropriate subindex graph)

w_i = weight of the I^{th} parameter

The Water Quality Index uses a scale from 0 to 100 to rate the quality of the water. The overall WQI score is compared against the following scale (Table 5.4) to determine how healthy the water is at a given time.

Table 5.3: Weights for parameters included in Brown's NSF-WQI

Parameters	Weights
Dissolved oxygen	0.17
Faecal coliform density	0.15
pH	0.12
BOD (5-day)	0.10
Nitrates	0.10
Phosphates	0.10
Temperature	0.10
Turbidity	0.08
Total solids	0.08
Total	1.00

Table 5.4: NSF-WQI scale

Index value	NSF Water Quality	Suitability for activities involving direct human contact, recreation, bathing etc.	Suitability for support of aquatic life
91-100:	Excellent water quality	Suitable	High diversity of aquatic life
71-90:	Good water quality		
51-70:	Medium or average water quality		Less diversity, have increased algae growth
26-50:	Fair water quality	Marginally suitable	Low diversity
0-25:	Poor water quality	Not suitable, abundant quality problems	Limited number of aquatic life forms

5.5.3 Water Quality Index of Central Pollution Control Board, India (CPCB-WQI)

CPCB-WQI is primarily based on the WQI of National Sanitation Foundation (Abbasi, 2002). However, slight modifications were made in terms of assignment of weightages so as to conform to the water quality criteria for different categories of water uses set by the Central Pollution Control Board, India. Four important water quality parameters- dissolved oxygen (DO), biochemical oxygen demand (BOD), pH and faecal coliform were selected through Delphi. A weighted sum aggregation function was used to evaluate the overall water quality index.

The index was developed to evaluate the water quality profile of river Ganga in its entire stretch and to identify the reaches where the gap between the desired and the existing water quality is significant enough to warrant urgent pollution control measures (Sarkar and Abbasi, 2006).

The index had the weighted multiplication form:

$$W.Q.I = \sum_{i=1}^{N} w_i I_i$$

Where I_i = sub index for i th water quality parameter

W_i = weight associated with i th water quality parameter and

P = number of water quality parameters

A list of four parameters was selected through Delphi. Sub-Index values were obtained by using sub index equations as shown in Table 5.5.

Table 5.5: Sub-index equations of the CPCB-WQI

Parameter	*Range applicable*	*Equation*	*Correlation*
DO	0–40% saturation	IDO = 0.18 + 0.66 (% sat)	0.99
	40–100% saturation	IDO = - 13.5 + 1.17 (% sat)	0.99
	100–140% saturation	IDO = 163.34 - 0.62 (% sat)	–0.99
BOD (mg/l)	0–10	IDO = 96.67 – 7.00 x (BO)	–0.99
	10–30	IBOD = 38.9 – 1.23 x (BOD)	–0.95
pH	2–5	IpH = 16.1 + 7.35 x (pH)	0.925
	5–7.3	IpH = - 47.61 + 20.09 x (pH)	0.99
	7.3–10	IpH = 316.96 – 29.85 x (pH)	–0.98
	10–12	IpH = 96.17–8.00 x (pH)	–0.93
Faecal coliform	$1–10^3$	Icoli = 97.2 – 26.80 x log (coli)	–0.99
	$10^3–10^5$	Icoli = 42.33 – 7.75 x log (coli)	–0.98
	$> 10^5$	Icoli = 2	

Source: Sarkar and Abbasi (2006)

To assign weightages, significance ratings were given to all the selected parameters. A temporary weight of 1 was assigned to the parameter which received highest significance rating. All other temporary weights were obtained by dividing each individual mean rating with the highest. Each temporary weight was then divided by the sum of all weights to arrive at the final weights. These weights were modified to suit the water quality criteria for different categories of uses. The weights and modified weights are illustrated in Table 5.7.

The classification of water *vis a vis* the final index values is given in Table 5.6.

Table 5.6: Water class as per CPCB-WQI score

S. N	WQI	Description	Class
1	63 – 100	Good to excellent	A
2	50 – 63	Medium to good	B
3	38 – 50	Bad	C
4	38	Bad to very bad	D,E

5.5.4 Inclusion of Turbidity in WQI for Environmental Flow

Turbidity means the optical condition of waters caused by suspended or dissolved particles or colloids that scatter and absorb light rays instead of transmitting light in straight lines through the water column. Turbidity may be expressed as nephelometric turbidity units (NTUs) measured with a calibrated turbidity meter.

NSF-WQI is useful in the context of drinking water supply. CPCB considers four parameters (DO, BOD, pH and faecal coliform) for the purpose of maintaining quality of river water for mass bathing and recreation only. Sediment concentration of flows downstream of dams and barrages is influenced; not only by the releases from the dam but also due to addition of sediments (i) flushing from desilting chambers and (ii) runoff from mined areas and muck disposal sites

Out of 486 cumec flow diverted from Nathpa dam, 81 cumec is returned to Satluj river for flushing out deposited sediments in desilting chambers. Silt load of river Satluj in monsoon months ranges from 15 g/L to 50 g/L. In non-monsoon months, it varies from less than 1 g/L to 5 g/L. The 81 cumec discharge from desilting chamber has high silt content of the order of 70 to 80 g/L. Therefore Satluj river will have high turbidity upto Jhakri (~ 80 g/L) beyond which it will reduce to 10 g/l due to return of diverted flow after power generation. However after construction of Rampur Hydroelectric project, silt concentration will continue to be high in the down stream reach upto Bael. Therefore, turbidity is an important parameter which should be considered while assessing the quality of flow. In this context, a new index (Satluj-WQI) has been proposed and the modified weights are given in Table 5.7.

Table 5.7: Weights assigned to different water quality parameters in CPCB-WQI and Satluj-WQI

Parameters	Weights assigned		
	NSF-WQI	CPCB-WQI	Satluj-WQI
DO	0.17	0.31	0.27
Faecal coliforms	0.15	0.28	0.24
pH	0.12	0.22	0.19
BOD	0.1	0.19	0.16
Turbidity	0.08	0.00	0.13
Total	0.62	1.00	1.00

5.6 WATER QUALITY INDICES OF SATLUJ RIVER

5.6.1 Water Quality Data

Himachal Pradesh State Environment Protection and Pollution Control Board (HPSEPPCB) has carried out water quality sampling at four locations (U/S of Nathpa dam, D/S of Nathpa dam, U/S of Jhakri and D/S of Jhakri) during pre-project and at three locations (Wangtu Bridge U/S of Nathpa dam, U/S of Rampur and D/S of Rampur) during post-project condition. The results of water quality sampling for pre-project and post-project conditions are given in Annexure 5.1 and Annexure 5.2 respectively.

5.6.2 Water Quality Indices

Water quality data available for post-commissioning stage is not adequate; hence NSF-WQI, CPCB-WQI and Satluj-WQI have been estimated for pre-commissioning stage. The values of CPCB-WQI, NSF-WQI and Satluj-WQI for pre-commissioning stage are given in Table 5.8 and are also shown in Figure 5.2. The Satluj-WQI is found to be more consistent with NSF-WQI (better correlation coefficient and lower standard error and root mean square error) than consistency of CPCB-WQI with NSF-WQI. However, CPCB-WQI and Satluj-WQI values are little higher than NSF-WQI. This is due to the fact that CPCB-WQI and Satluj-WQI consider lesser number of water quality parameters and hence getting relatively higher weightages compared to the weightages assigned to these parameters in NSF-WQI.

Table 5.8: CPCB-WQI, NSF-WQI and Satluj-WQI for pre-project condition

Source	Location	Period	NSF-WQI	CPCB-WQI	Satluj-WQI
HPPCB	Nathpa U/S	May, 2002	73.62	85.86	77.51
	Nathpa D/S	May, 2002	69.95	81.76	73.88
	Jhakri U/S	May, 2002	72.31	79.38	81.65
	Jhakri D/S	May, 2002	69.60	77.45	73.37
HPPCB	Nathpa U/S	July, 2002	66.58	74.80	68.29
	Nathpa D/S	July, 2002	62.24	72.96	66.97
	Jhakri U/S	July, 2002	66.05	72.70	66.81
	Jhakri D/S	July, 2002	63.85	72.84	66.29
HPPCB	Nathpa U/S	Sep-Oct, 2002	64.96	91.44	62.49
	Nathpa D/S	Sep-Oct, 2002	80.77	89.70	85.55
	Jhakri U/S	Sep-Oct, 2002	70.67	78.55	74.42
	Jhakri D/S	Sep-Oct, 2002	75.41	82.66	78.61
HPPCB	Nathpa U/S	Nov-Dec, 2002	76.49	81.31	82.09
	Nathpa D/S	Nov-Dec, 2002	72.46	73.54	75.34
	Jhakri U/S	Nov-Dec, 2002	73.02	77.24	76.96
	Jhakri D/S	Nov-Dec, 2002	75.00	75.73	75.72
HPPCB	Nathpa U/S	Feb, 2003	73.75	73.36	77.63
	Nathpa D/S	Feb, 2003	71.89	71.70	75.66
	Jhakri U/S	Feb, 2003	78.54	79.94	79.77
	Jhakri D/S	Feb, 2003	76.13	77.25	76.12
HPPCB	Nathpa U/S	Mar, 2003	64.33	74.61	71.14
	Nathpa D/S	Mar, 2003	61.1	74.96	68.54
	Jhakri U/S	Mar, 2003	67.23	80.39	75.65
	Jhakri D/S	Mar, 2003	62.73	67.05	59.63
HPPCB	Nathpa U/S	Apr, 2003	63.27	78.48	73.65
	Nathpa D/S	Apr, 2003	70.52	77.82	73.2
	Jhakri U/S	Apr, 2003	60.74	70.95	66.99
	Jhakri D/S	Apr, 2003	64.82	69.86	69.95
			Standard Error	5.032	3.168
			RMSE	9.550	4.878
Correlation Coefficient between NSF-WQI and CPCB-WQI/Satluj-WQI				0.483	0.858

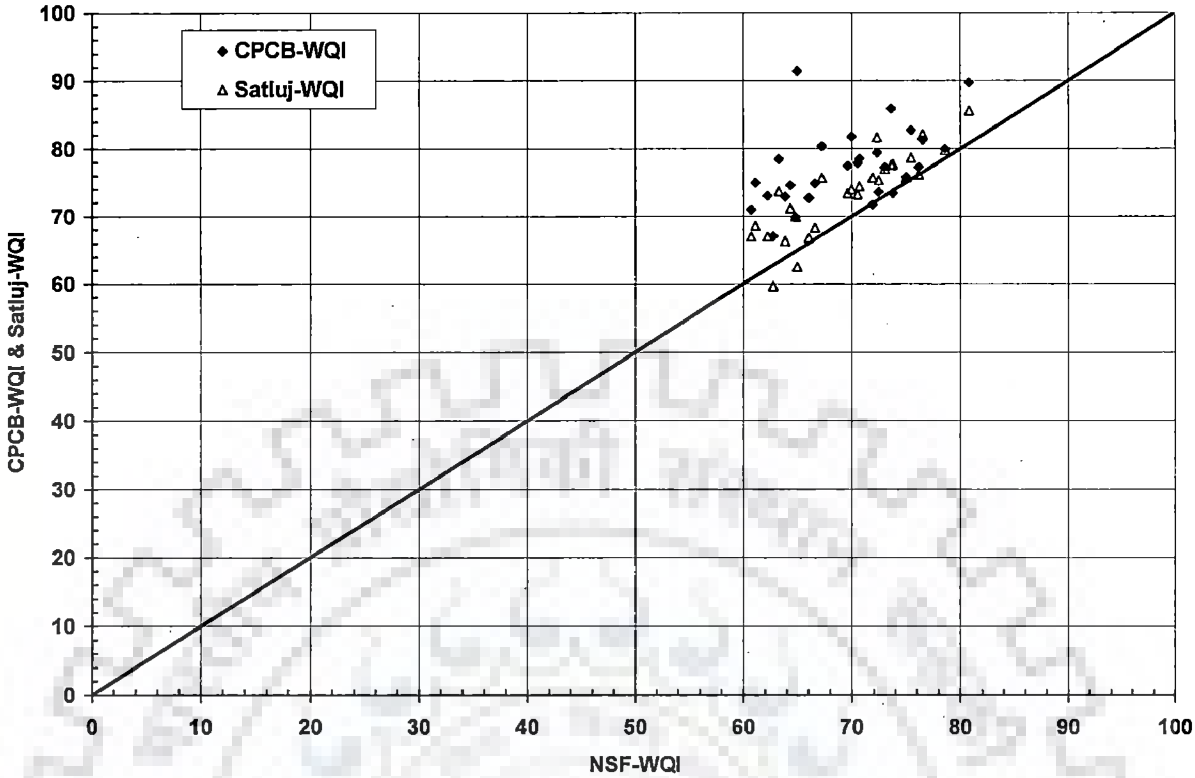


Figure 5.2: Comparison of Satluj-WQI and CPCB-WQI with NSF-WQI for pre-project condition

5.7 CHANGE IN SATLUJ-WQI DUE TO ALTERED FLOW REGIME

5.7.1 Permissible Limit on Turbidity

Background turbidity means turbidity in the immediate vicinity of and outside the area of influence of the discharge or discharges from the source or sources under consideration. For establishing permissible limits, background turbidity may be calculated as the up-stream historical turbidity associated with low flows, excluding episodic run-off events, for the season(s) or period(s) for which the turbidity discharge limit is established. If background data are unavailable, 1 NTU may be used as a default value.

Aquatic life turbidity criteria in fresh water rivers in India are not available. Such criteria have been evolved in some developed countries and are available on websites. For the purpose of this study, the turbidity criteria as followed by Department of Ecology, State of Washington, USA (http://www.ecy.wa.gov/ecyhome.html) have been taken and are given in Table 5.9.

Table 5.9: Aquatic Life Turbidity Criteria

Use Category	Percent Saturation
1. Char Spawning and Rearing 2. Core Summer Salmonid Habitat 3. Salmonid Spawning, Rearing, and Migration 4. Non-anadromous Interior Redband Trout	Turbidity shall not exceed: • 5 NTU over background when the background is 50 NTU or less; or • A 10% increase in turbidity when the background turbidity is more than 50 NTU.
1. Salmonid Rearing and Migration only 2. Indigenous Warm Water Species	Turbidity shall not exceed: • 10 NTU over background when the background is 50 NTU or less; or • A 20% increase in turbidity when the background turbidity is more than 50 NTU.

Source: http://www.ecy.wa.gov/ecyhome.html

In case of NJHEP, background turbidity is taken as the turbidity measured at Wangtoo which is U/S of the Nathpa dam. The average background turbidity measured at Wangtoo are as given below:

Season	Background turbidity	Upper limit of turbidity as per Aquatic Life Turbidity Criteria
Lean season (January-February)	10 NTU	15 NTU
Rainy season (July-August)	600 NTU	660 NTU

5.7.2 Satluj-WQI Standard for River Bathing and Aquatic Life

The Satluj WQI standard considering river bathing standards as per CPCB criteria and Aquatic Life Turbidity Criteria (for lean season and rainy season) have been calculated following the procedure given in Section 5.5.4. The results are given below:

	Water quality data					
	pH	DO	BOD	Faecal Coliform	Turbidity	Satluj WQI standard
		mg/L	mg/L	MPN/SPC/100mL	JTU/NTU	
Lean Season	7.5	5	3	500	15	55
Rainy Season	7.5	5	3	500	660	47

5.7.3 Satluj WQI for Pre and Post Project Conditions

Observed water quality data for pre and post project conditions at different locations on Satluj river (Annexure 5.1 and Annexure 5.2) have been used to calculate Satluj WQI. The Satluj WQI at U/S of Nathpa dam, D/S of desilting complex of NJHEP, D/S of Jhakri and D/S of Rampur are compared in Figure 5.3 (rainy season) and Figure 5.4 (lean season).

The Satluj WQI is higher than Satluj WQI standard at all the locations and also during rainy season and lean season. It is mainly because the water quality parameters (DO, BOD, pH, Faecal coliform) are well within acceptable limits even though turbidity of Satluj river is very high. The excessive turbidity during the post-project condition will have adverse impact on the aquatic life. The lean season Satluj WQI at D/S of Rampur for the post-NJHEP and post-RHEP condition just meets the standard as shown in Figure 5.5. This may be attributed to higher turbidity and higher faecal coliform expected in the post-RHEP situation.

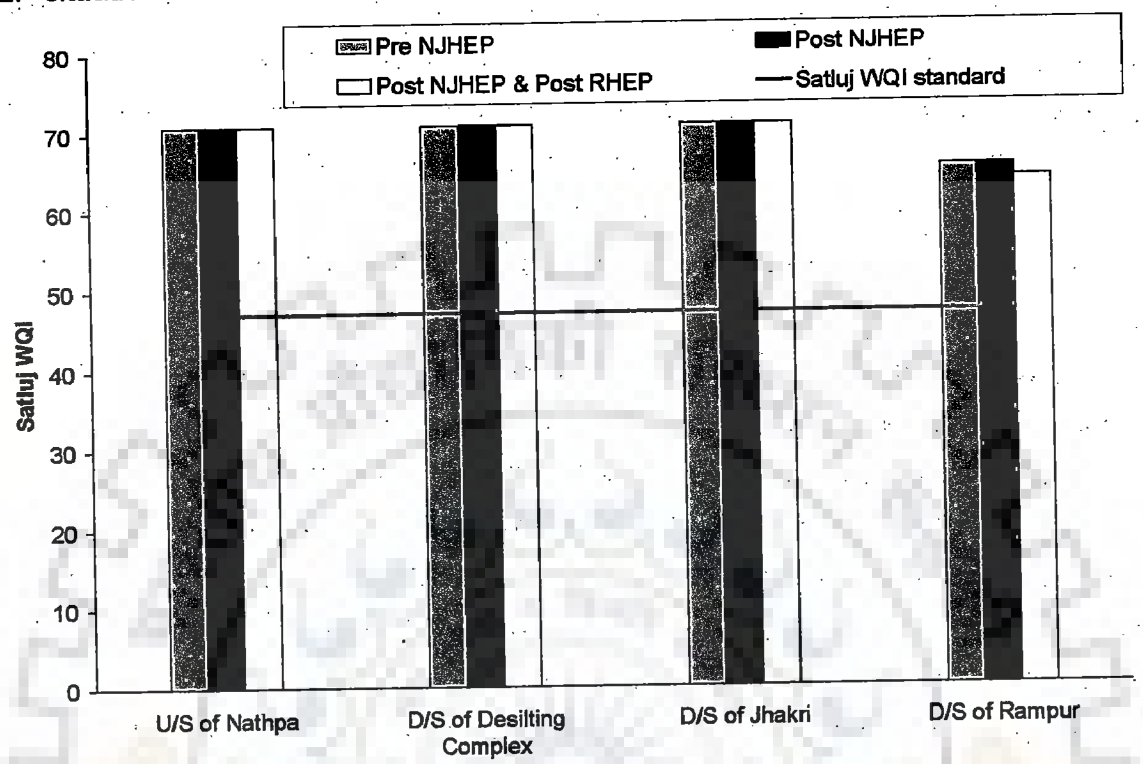


Figure 5.3: Satluj WQI at various locations for pre and post-project conditions of NJHEP and RHEP during rainy season

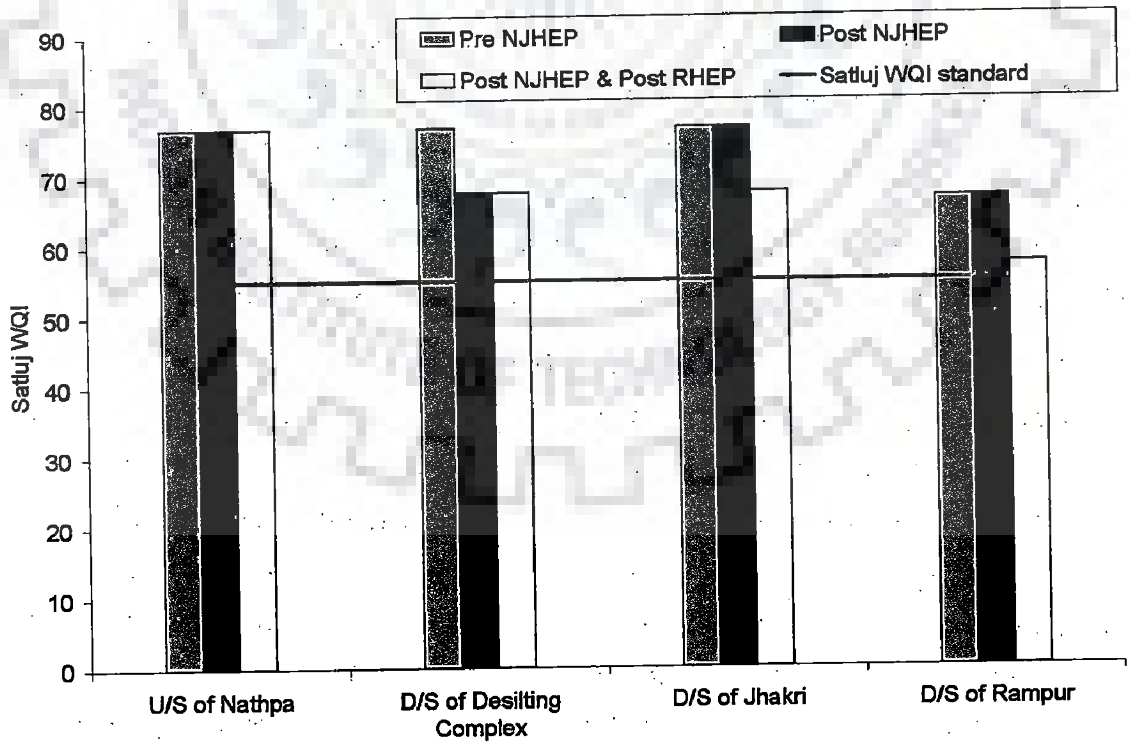


Figure 5.4: Satluj WQI at various locations for pre and post-project conditions of NJHEP and RHEP during lean season

5.8 CONCLUSIONS

5.8.1 Flow Related Impacts on Aquatic Biodiversity

There is a potential lag effect in biological response to flow alteration. The project has come in operation stage in the year 2003. Therefore, assessment of the biotic response to flow alteration could be done only with limited ability. Principles proposed by Bunn and Arthington (2002) have been applied to assess the impacts.

Reduced flows immediately downstream of dam explain absence of hydropsyche. Trotsky and Gregory (1974) has also reported that *Hydropsyche* was heavily reduced below a dam with very low daily flows.

Sudden increases in flow downstream of Nathpa dam may cause significant downstream drift of macroinvertebrates. Burn and Arthington (2002) state that as much as 14% of benthic biota can be eliminated each month due to drift.

Hydrologic factors for fish being scanty in the study reach of river Satluj are (i) unstable flow regime (ii) continuous physiological stress due to loss of energy in maintaining their position in fast flowing waters (iii) frequent change in structure and consistency of river bed caused by high velocity of flow during floods.

The release of cooler water downstream of Jhakri power house can influence the spawning behaviour of fish and life history process of invertebrates in the downstream. After implementation of RHEP, cooler water downstream of Jhakri power house will be diverted into tunnel which may favour spawning of fish in Satluj reach upto Bael.

Nathpa dam has transformed small length of the river Satluj into a pool habitat on upstream. Conversion of lotic to lentic habitat will result in the loss of fishes adapted to turbid riverine habitats. Creation of standing water body upstream of Nathpa dam is likely to favour introduced species. However, downstream of Nathpa dam long-term success of invading or introduced species is unlikely due to unstable flow regime.

5.8.2 Water Quality Indexing and Flow Related Impacts

Water quality indices aim at giving a single value to the water quality by translating the concentrations of several constituents into a single value. In the present study, two existing indices have been used for assessing water quality; these are NSF-WQI and CPCB-WQI. In addition, a new index (Satluj-WQI) is proposed in the context of environment flow requirement. Satluj-WQI is found to be more appropriate in comparison to CPCB-WQI in the context of EFA as it considers turbidity also.

The Satluj WQI standard value has been calculated considering river bathing standards as per CPCB criteria and Aquatic Life Turbidity Criteria (for lean season and rainy season).

The Satluj WQI is higher than Satluj WQI standard at all the locations and also during rainy season and lean season. It is mainly because the water quality parameters (DO, BOD, pH, Faecal coliform) are well within acceptable limits even though turbidity of Satluj river is very high. The excessive turbidity due to silt flushing during the post-project condition will have adverse impact on the aquatic life. The lean season Satluj WQI at D/S of Rampur for the post-NJHEP and post-RHEP condition just meets the standard as shown in Figure 5.5. This may be attributed to higher turbidity and higher faecal coliform expected in the post-RHEP situation.

Plate 5.1: Sampling of fish using Jhala (a net)

Plate 5.2: Sampling of macroinvertebrates using net of mesh size 500µm

Plate 5.3: Sample of macroinvertebrates assembled in enamelled tray

CHAPTER - 6

ENVIRONMENTAL WATER REQUIREMENTS OF TERRESTIAL ECOSYSTEM

Several EFA methodologies have been reviewed in Chapter 2. Some of the EFA methodologies incorporate socio-economic component also such as: (i) DRIFT (Section 2.5.3, Chapter 2) and (ii) BBM (Section 2.6.1, Chapter 2)

Water requirement of human, livestock and vegetation in tributaries catchments within a river reach directly influence flow regime of main river. Such water requirements may be termed as environmental water requirements (EWR) of terrestrial ecosystem as these support distinct ecologies of the tributary catchments. The EWR of aquatic ecosystem may then be understood as environmental flow requirement (EFR) of main river to distinguish it from EWR of the tributary catchments. This distinction is important as the requirements of terrestrial ecosystems are currently not explicitly considered, and, second, that at present the *'environmental flow requirements'* and *'environmental water requirements'* are normally taken as synonyms (Smakhtin and Anputhas, 2006).For catchment level studies, EWR is also important in addition to EFR as both are interlinked.

There are several tributaries/springs which contribute to flow of Satluj river between Nathpa and Jhakri. Human and livestock population make use of flow in these tributaries and springs. Flow pattern in the tributaries and springs have got modified due to project activities. As part of this research work village level survey was carried out (Chapter 4). Summary results of the survey are given in Table 6.1.

This chapter analyses pattern of human habitations, accessibility to Satluj river, impact of tunnelling on sources of water, and annual water demand of animals, human beings and vegetation in the context of EWR of terrestrial ecosystem.

6.1 SATLUJ AS SOURCE OF WATER FOR HUMAN POPULATION

The physical conditions of mountain environment have exercised an important influence on distribution of human settlements in Nathpa-Jhakri reach. Areas of rugged relief, forests and snow do not have human habitations. Most of the population (except nomads) reside in rural habitations varying in size from isolated hamlet to agglomerated settlements. The houses are scattered near the patches of available arable lands, near the source of water and near the roads.

Villages have developed along a highway (NH-22) from Jhakri to Nathpa and in upper reaches. The main road (NH-22) itself is at a significantly higher elevation compared to river bank. Satluj river is accessible to these human habitations only at few locations. River Satluj is not the source of water for use by human population upstream of

Table 6.1: Summary of village level survey

S. No.	Information Source	Block/ Village/ road connectivity	Distance from Satluj river bank (km)	Water Supply			crops		Animals	
				Daily need per person (litre)	Source	Adequacy as perceived by villagers	Type	Change in type, area	Type	No.
1	L. Das Secretary Yog Mandal	Nichar - Kandhar - 2 km	6	100	Spring Kandhar Nala	Yes but discharge decreased	Wheat, jau, makki, chaulai, Phaphda, apple, vegetables	Increase in apple area	Goat Sheep cow	650 850 450
2	B. S. Negi Gram Pradhan	Nichar - Ponda - 0 km	2.5	100	Spring Sholding Nala	Inadequate in summer, 7-8 springs dried	Wheat, makki, jau, apple, vegetable	Increase in apple area	Goat Sheep cow	7000 200
3	Farmer's group	Nichar Chhota Khambha 1 km	10	50 (W) 100 (S)	Spring Sarati Nala	Inadequate in summer	Wheat, makki, jau, apple, vegetable	More area under apples and vegetables	Goat Sheep cow	2000 100
4	Mahendra Singh Gram Pradhan	Nichar Nigulsari 0 km	< 1	150 (W) 300 (S)	Spring Chaunda khad	Yes but 1 spring dried	Wheat, makki, jau, apple, vegetable, paddy	No change in crop type but crop area increased	Goat Sheep cow Buffalo	12500 1000 1000
5	Farmers group	Nichar Chaura 0 km	2	100 (W) 150 (S)	4 springs Chaura khad	Inadequate	Wheat, makki, jau, apple, vegetable, paddy	No change	Goat Sheep cow	5400 5400 150
6	R. C. Soni Gram Pradhan	Rampur Badhal 0 km	< 1	125 (W) 175 (S)	15 springs Dharali khad	Decrease in Dharali khad flows, 4 springs dried	Apple, nashpati, ado, khurmani	More area under vegetables and fruits	Goat Sheep cow Mule	2000 2000 350 150

W: winter, S: summer

Table 6.1 continued ...

S. No.	Information Source	Block/ Village/ road connectivity	Distance from Satluj river bank (km)	Water Supply			crops		Animals	
				Daily need per person	Source	Adequacy as perceived by villagers	Type	Change in type, area	Type	No.
7	Surendra Shop Owner	Rampur Jeori/Tayal 0 km	< 1	75 (W) 100 (S)	1 spring Unoo khad	Inadequate in summer	wheat, paddy, vegetables, apple	Increase in crop area	Goat	1600
									Sheep	1600
									cow	1000
									Buffalo	400
8	Farmers group	Rampur Rattanpur 0 km	< 1	60 (W) 100 (S)	Handpump Spring	Adequate	Wheat, paddy, vegetables, plums	Increase in crop area	Goat	NA
									Sheep	NA
9	Farmers group	Rampur Gasso 0 km	< 1	100 (W) 150 (S)	8-10 springs	Springs dried. Khad discharge decreased	Wheat, jau, makki, vegetables, plum	No change	Goat	100
									Sheep	100
									cow	150

W: winter, S: summer

Jhakri. Rampur is a major town located in proximity of Satluj river. In addition, a township has developed at Jhakri as a sequence of NJHEP. Cultural and religious activities in these towns may be directly related to Satluj river

6.2 WATER REQUIREMENT OF ANIMAL POPULATION

6.2.1 Animal Population

Major livestock animals in the area are cow, buffalo, sheep, goat, and draft animal (viz., horses, ponies, mules, and donkeys). The population of sheep and goat is significantly higher than that of other animals (Table 4.3, Chapter 4). Sheep and goats are used for meat, milk, and wool, and their droppings for fertilizer in the fields.

Distribution of human and livestock population in different forest divisions (Table 6.2) shows that human population is very low in Sarahan wild life division. The availability of forestland per unit livestock in Nichar area (2.51 ha/livestock) is greater than that in Rampur area (0.5 ha/livestock). Table 6.3 shows the composition of various types of livestock.

Table 6.2: Human and livestock population in forest divisions

Item	Rampur division	Nichar division	Sarahan wildlife division	Total
Area included in CAT (ha)	12427	117513	50300	180240
Forest area in CAT plan	7771	111511	41749	161031
Human population	21195	23861	7213	52269
Livestock population	15409	44438	40831	100678
Ratio of livestock to human population	0.73	1.86	5.66	1.93
Livestock population (no./ha)	1.24	0.378	0.81	0.56
Forest area available per unit livestock (ha/unit)	0.5	2.51	1.02	1.6

Source: CAT Plan (2004-05)

Table 6.3: Population of different livestock

Item	Cattle	Buffalo	Sheep	Goats	Others	Total
CAT plan estimate for Nichar (CAT Plan, 2004-05)	9985	03	22207	10765	1478	44438
% of total	22.5	Negligible	50	24.2	3.3	100
WAPCOS estimate for study area (WAPCOS, 1999)	40576	830	49638	23389	3000	116933
% of total	34.7	0.71	42.45	20.0	2.12	100

Census data for Kinnaur district shows decadal increase of 9.912% in human population from the year 1991 to year 2001. Increase in population of Nichar subdivision is 11.6% from the year 1991 to year 2001. Animal population in the year 2008 have been estimated assuming decadal growth rate of 10 % in the Nichar and Sarahan areas and growth rate of 15 % per decade in the Rampur area (Table 6.4).

Table 6.4: Animal population in the area (for the year 2008)

Area	Growth rate per decade	Growth rate for 5 years	Animal Population	
			2003*	2008
Rampur Tehsil	15%	7.5%	18252	19049
Nichar Tehsil	10%	5%	49860	51326
Sarahan Forest Division	10%	5%	45812	47160
			Total	117535

* As per 17th Indian Livestock Census (2003)

The animal population estimate as per Table 6.3 has been used in the estimation of animal water need. The census data is available on tehsil basis. The study reach covers the major parts of Rampur and Nichar tehsils, and an insignificant area of Nirmad Tehsil.

The average percentage composition of different livestocks (Table 6.3) has been applied on total population of 117535 (Table 6.4) to estimate population of different livestock (Table 6.5).

Table 6.5: Population of different animal types

Animal	% Distribution			Population in year 2008
	CAT Plan (2004-05)	WAPCOS (1999)	Average	
Cows	22.5	34.7	28.6	33615
Buffalo	Negligible	0.71	0.4	470
Sheep	50	42.45	46.2	54301
Goat	24.2	20	22.1	25975
Horses and ponies	3.3	2.12	2.7	3173
Total	100	100	100	117535

6.2.2 Unit Water Requirement of Animals

The water consumption by animals varies significantly with type of breed, climate, food supply, pregnancy and lactation status. In villages of India, watering is done twice a day mostly in morning and evening after feeding of hay. Estimate of daily water requirement of different livestock given in various studies vary significantly as shown in Table 6.6.

Table 6.6: Daily water requirement of livestock (litre/day/livestock)

Source	Cow	Buffalo	Sheep	Goat	Horses, ponies and Donkeys	Swine	Poultry& Rabbits
Michael and Ojha (2001)	150-250	250-350	10-15	10-15	-	-	-
Noble Foundation (www.noble.org/ag)	40-85	-	2.25-6	1.5-10	30-55	9-20	0.06-0.1
Govt. of Canada (www.gov.bc.ca/wat)	65	-	5	5	60	7-17	0.32

In the study area, June is the hottest month and the mean daily temperature varies from 16.2 ^{0}C to 24.3 ^{0}C. On the other hand, it varies from 1.9 ^{0}C to 16.2 ^{0}C in

January, the coldest month of the year. Given the range of seasonal temperature variation, the variation in livestock water requirement is unlikely to be very high. Therefore, considering the climate of the area, the unit rates of water requirement are assumed as shown in Table 6.7.

Table 6.7: Water requirement of different animals during winter and summer

Animal	Winter (litre/day)	Summer (litre/day)
Buffalo	150	200
Cow	30	50
Sheep	2.5	5
Goat	2.5	5
Horses, ponies & donkey	30	50
Swine(pigs)& dogs	6	10
Poultry, turkeys, ducks & rabbit	0.1	0.4

6.2.3 Assessment of Animal Water Need

Animal water need is highly variable depending on type of breed, climate, food supply (pasture/dry fodder), pregnancy, lactation status, temperature. Animal population and daily water requirement have been discussed earlier. Estimate of animal water need is given below in Table 6.8:

Table 6.8: Annual water need of animal population in study area

Cattle	Cow	Buffalo	Sheep	Goat	Ponies
Population	33271	465	53745	25709	3141
Winter water need (lpd)	30	150	2.5	2.5	30
Summer water need (lpd)	50	200	5	5	50
Average water need (lpd)	40	175	3.75	3.75	40
Annual water requirement (m^3)	485757	29702	73563	35189	45859
				Total	= 670070 m^3 = 0.67 MCM

6.2.4 Managing the Animal Water Need

Study of literature shows that one of the simplest ways of reducing animal water need is to provide sheds, trees, roofs or simple well-ventilated shelters to shield the stock from sun. Alternatively, green and succulent feed can go long way towards meeting the water requirements of livestock. The water in forage is clean, is replenished by its growth, and does not need to be piped from the storage. Sheep, for example, can feed on lush pasture for weeks on and end without needing much additional water. It follows that the grazing areas should be divided into camps (each having at least one perennial water source), which can be grazed rotationally to rest the vegetation periodically and allow it to regenerate. There may be large patches of grazing remaining underutilized for lack of sufficient watering points for stock. Considerable water savings (some times 30 to 50 % in case of sheep) can be made during water deficit situation by watering sheep every alternate day instead of daily and cattle every second, or even, third day provided they do not loose their weight excessively.

6.3 EVAPOTRANSPIRATIVE DEMAND OF VEGETATION

Evapotranspiration includes evaporation from land surface and transpiration from plant bodies. Vegetation shades the soil, reduces wind speed and gives off water vapour. These tend to reduce direct evaporation from soil or semicover. However, vigorous absorbtion of soil moisture by roots (and subsequent loss as transpiration) together with losses due to interception usually more than offset the effects of vegetation in retarding evaporation from soil. Aggregate leaf surface of vegetation may be 20 times greater than the area of soil surface it occupies. Further, plants can withdraw water from considerable depths whereas surface evaporation commonly affects only the upper 15 cm to 37 cm. Therefore, water losses are increased greatly by plant cover.

6.3.1 Evapotranspiration in the Study Area

Evaporation from the snow covered area is very small due to high albedo. Rainfall occurring over snow covered area is absorbed or infiltrated through snow pack whereas contribution of rainfall to basin annual runoff is reduced in accordance with evapotranspiration from snow free area.

In a study by Jain (2001), the pan evaporation and air temperature data at Bhakra (elevation 518 m) has been correlated. It was found that mean monthly maximum temperature provides best correlation with monthly pan evaporation (coefficient of determination = 0.84). Singh et al. (1995) studied relation between pan evaporation and different meteorological parameters such as maximum temperature, minimum temperature, wind speed, relative humidity and duration of sunshine hours. Highest correlation (0.85) was obtained for relation of pan evaporation with maximum air temperature. Jain (2001) has evolved the following relation to estimate pan evaporation (E_p):

$E_p = 11.63 * \exp (0.077 * T_{max})$

$T_{max} = T_{Rmax} - \delta (H - H_R)$

T_{max} : mean monthly maximum temperature (^{0}C) at elevation H (m)

δ : temperature lapse rate (0.6 ^{0}C/100m)

T_{Rmax} = mean monthly maximum temperature at Rampur

H_R = elevation at Rampur = 1066 m

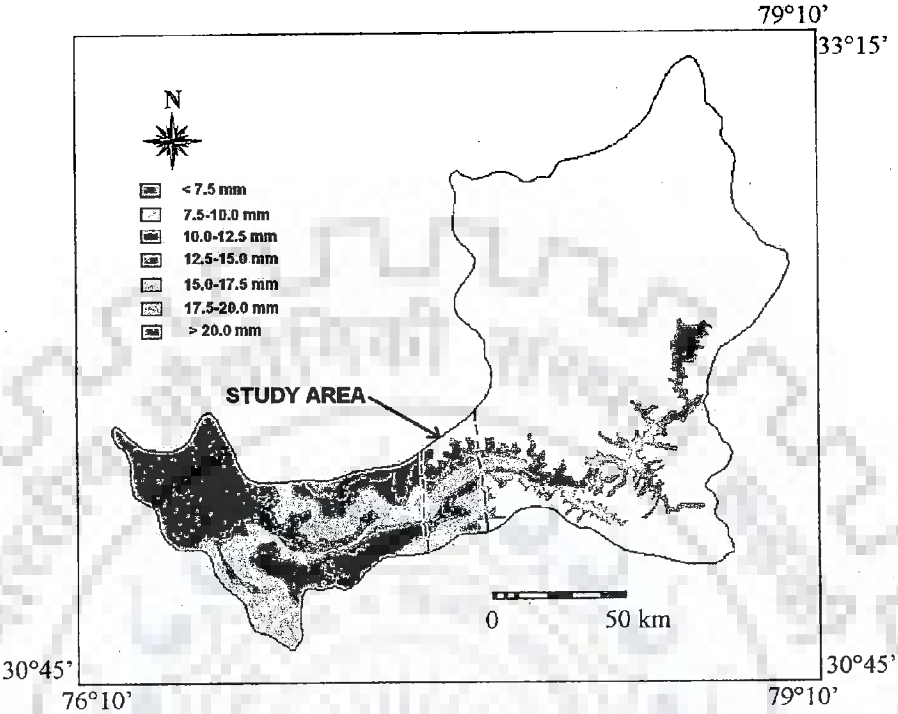
The above two equations can be used to provide pan evaporation estimate at mid elevation h of a snow free area.Monthly potential evapotranspiration ET is equal to k E_p. Average k value for US Weather Bureau pan is taken as 0.7. Jain (2001) used GIS approach to prepare maps of monthly evapotranspiration distribution in the study area for the March (Figure 6.1) and October (Figure 6.2). During March, snow covered area is expected to be maximum and during October it is expected to be least.

Actual evapotranspiration (AET) is less than potential evapotranspiration (PET). No study could be found on AET for Himalayan region. Therefore, a heuristic approach has been adopted. Satluj basin gets less rainfall and temperature is low during winter. Therefore, AET is expected to be low. During pre-monsoon period (April to June) temperature are high but rainfall is less hence PET is high but AET is not significant due to less rainfall. During monsoon period (July to September) rainfall provides sufficient moisture for evaporation from soil and temperature is also high therefore, AET is comparable to PET. The approximate values of AET/PET along with average rainfall at Rampur and Nichar are given in Table 6.9.

Areas and corresponding AET depth in March and October are used to estimate volume of water lost (Table 6.10). Water loss as evapotranspiration in March is 5.401 MCM and in October it is 8.035 MCM. Increase in water loss in October is mainly on account of larger snow free area.

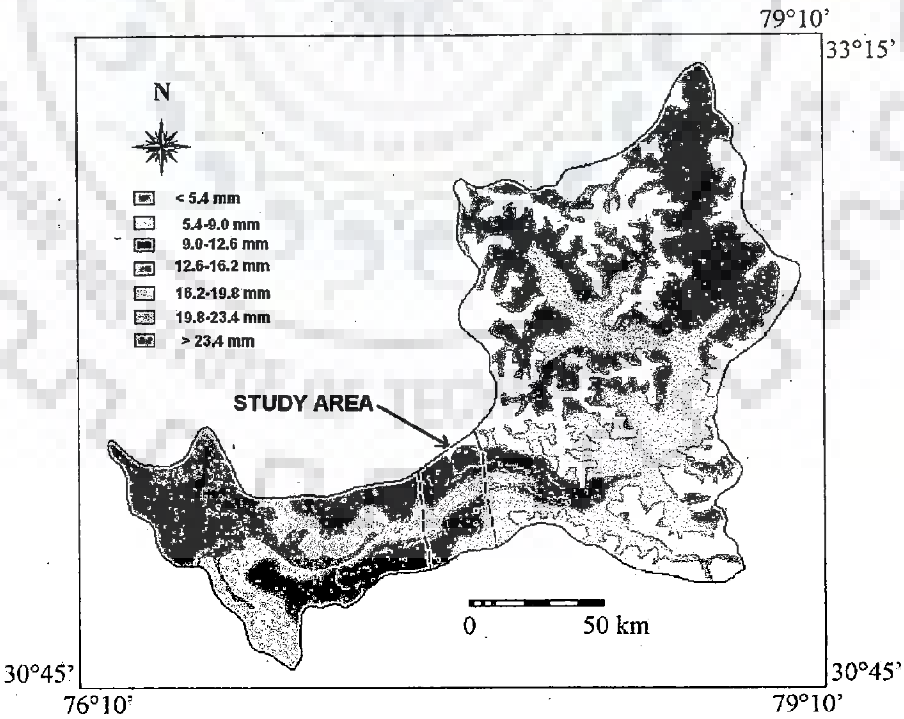
Table 6.9: Actual evapotranspiration as ratio of potential evapotranspiration

Month	AET/PET	No. of rainy days	Average rainfall at Rampur (mm)	Average rainfall at Nichar (mm)
Jan	0.2	4.6	59.65	29.51
Feb	0.2	4.6	79.21	48.85
Mar	0.15	5.1	88.56	106.50
Apr	0.2	4.9	46.71	76.99
May	0.15	7.2	57.43	84.86
Jun	0.25	4.7	73.87	65.86
Jul	0.85	12.3	184.84	126.92
Aug	0.9	11.1	151.51	128.64
Sep	0.65	6.6	82.39	79.68
Oct	0.25	2.8	25.67	32.51
Nov	0.25	1.1	15.70	15.33
Dec	0.25	2.1	28.61	18.83
Total/Average	0.4	67.1	894.13	814.47



Source: Jain (2001)

Figure 6.1: ET distribution during March



Source: Jain (2001)

Figure 6.2: ET distribution during October

Table 6.10: AET in the months of March and October

March				October			
AET (mm)	% Area	Area	AET (MCM)	AET (mm)	% Area	Area	AET (MCM)
0	45.285	392.286	0.000	0	14.024	121.482	0.000
3.8	5.374	46.551	0.177	7.2	34.902	302.34	2.177
8.8	13.408	116.146	1.022	10.8	27.057	234.385	2.531
11.3	15.768	136.594	1.544	14.4	13.425	116.294	1.675
13.8	8.741	75.717	1.045	18	10.593	91.763	1.652
16.3	11.425	98.968	1.613				
Total		866.264	5.401	Total		866.264	8.035

6.3.2 Annual Water Requirement of Vegetation

Average annual potential evapotranspiration = 363 mm

Actual evapotranspiration = 0.4 PET = 145.2 mm

Average annual rainfall = (av. rainfall at Rampur + av. rainfall at Nichar)/2

= (855.01 + 873.08)/2 = 864 mm

Interception loss = 0.2 * Annual rainfall = 172.8 mm

Total area of interim catchment of Satluj between Nathpa and Jhakri is 866 sq. km. Annual evapotranspirative need of vegetation in the study area is 64 MCM as computed in Table 6.11.

Table 6.11: Annual evapotranspirative need of vegetation in study area

Land use	% area*	Area (sq. km)	AET (mm)	Interception loss (mm)	ET loss (mm)	Volume (MCM)
dense forest (crown cover > 40%)	5.8	50.1	145.2	172.8	318.0	15.9
Open forest (crown cover 10-40%)	5.6	48.8	145.2	86.4	231.6	11.3
Degraded forest (crown cover < 10%)	8.6	74.8	145.2	0.0	145.2	10.9
Alpine pasture	2.4	20.9	145.2	172.8	318.0	6.6
Agriculture	3.2	27.8	145.2	0.0	145.2	4.0
Arboriculture	3.6	31.3	145.2	172.8	318.0	10.0
Water bodies	1.7	14.5	363.0	0.0	363.0	5.3
Snow and landslide	15.4	133.3	0.0	0.0	0.0	0.0
Settlement	10.7	92.5	0.0	0.0	0.0	0.0
Barren hill	49.8	431.5	0.0	0.0	0.0	0.0
		866.0				64.0

6.4 WATER REQUIREMENT OF HUMAN POPULATION

According to 2001 census report, rural population was 66373 in Rampur Tehsil and 26630 in Nichar Tehsil (total being 93003). An average growth rate of 15% per decade is taken for the area. Thus human population in the year 2008 in the study area is estimated to be 102768. Per capita water requirement is taken as 75 litre/day/person based on village level survey (Table 6.1) which is equivalent to 27.375 m^3/person/year.

Annual water requirement = 27.375 * 102768 = 2813283 m^3
= 2.813 MCM

6.5 TOTAL WATER REQUIREMENT

Total annual water need of vegetation, human beings and animal population in the study area is estimated to be 67.483 MCM. Evapotranspirative need of vegetation accounts for 94.839 % of total annual water need.

January and February happen to be the months of lowest flows during which flow contribution from tributaries and springs between Nathpa and Jhakri is in the range of 14.57 cumec (dry year) to 16.6 cumec (wet year). Annual water requirement of terrestrial ecosystem comes out to be 67.483 which is equivalent to 2.14 cumec. Hence, terrestrial water requirement can be easily met with the flows of tributaries of Satluj river.

6.6 IMPACT OF TUNNELING ON FLOWS OF STREAMS AND SPRINGS

6.6.1 Hill Streams as Source of Water Supply

Hill streams and springs are sources of water supply to human habitations, animals and for irrigation (Singh et al., 2002; Singh et al., 2003). There are 13 perennial streams, several non perennial streams and a large number of springs between Nathpa and Jhakri. On the left bank side of Satluj itself there are about 57 to 60 drainages and 50 to 70 cold water springs in the proximity of the NH-22 lying above head race tunnel. Hot water springs are also present at locations where deeper geothermal aquifers are tapped by tectonic dislocations such as faults, shear zones and joints.

Jhakri township of NJHEP has around 1000 houses. Water demand of this township is met from Sumej khad (60%) and through seepage of surge tank (40%). The seepage from surge tank is of the order of 20000 litres/day. It is taken to treatment plant by gravity (WAPCOS, 1999).

Annexure 6.1 and Annexure 6.2 provide discharge data of the springs and the human population/irrigation area covered. The Government sponsored 82 village water supply schemes are expected to provide 1.975 MCM of water per year to a population of 33236 and provide irrigation to 590.77 ha of land. The water supply schemes have not yet been implemented.

6.6.2 Impact of Tunnel Construction

During the construction of tunnel, heavy ground water inflows were encountered in 28 reaches (Table 6.12). The geological section (Kumar, 2002) of tunnel and overlying streams (Figure 6.3) shows that at some locations over burden is thin.

Table 6.12: Tunnel reaches encountering heavy ground water inflows

S. No.	Chainage (m)	Remarks	S. No.	Chainage (m)	Remarks
1.	1279-1356	Hot water dripping	15.	4750-4760	Warm water dripping, 50 lpm, shear zone
2.	1856-1860	Warm water, shear zone	16.	7530-7543	Warm water
3.	1962-1991	Hot water dripping	17.	7600-7608	Warm water dripping
4.	2155-2202	Hot water dripping	18.	7870-7886	Warm water dripping
5.	2387-2457	30-35^{0}C water temp.	19.	8253-8266	250 lpm
6.	3022-3037	Warm water	20.	8266-8268	Cavity formation
7.	3631-3678	50-52^{0}C water temp., 300 lpm	21.	12523-12531	Lukewarm water
8.	3696-3712	44^{0}C water temp.	22.	14646-14655	18-26^{0}C water temp.
9.	3712-3723	51^{0}C water temp.	23.	14655-14764	18-26^{0}C water temp.
10.	3751-3818	Hot water dripping	24.	17040-17070	55^{0}C water temp., 200 lpm
11.	4170-4178	Warm water dripping	25.	17837-17840	42^{0}C water temp.
12.	4178-4208	36^{0}C water temp.	26.	18531-18535	65^{0}C water temp., 125 lpm
13.	4278-4378	Warm water dripping	27.	18774-18777	57.4^{0}C water temp.
14.	4474-4478	Hot water dripping	28.	19200-19700	48.7^{0}C water temp. at Ch. 19559, 19576, 19586 m

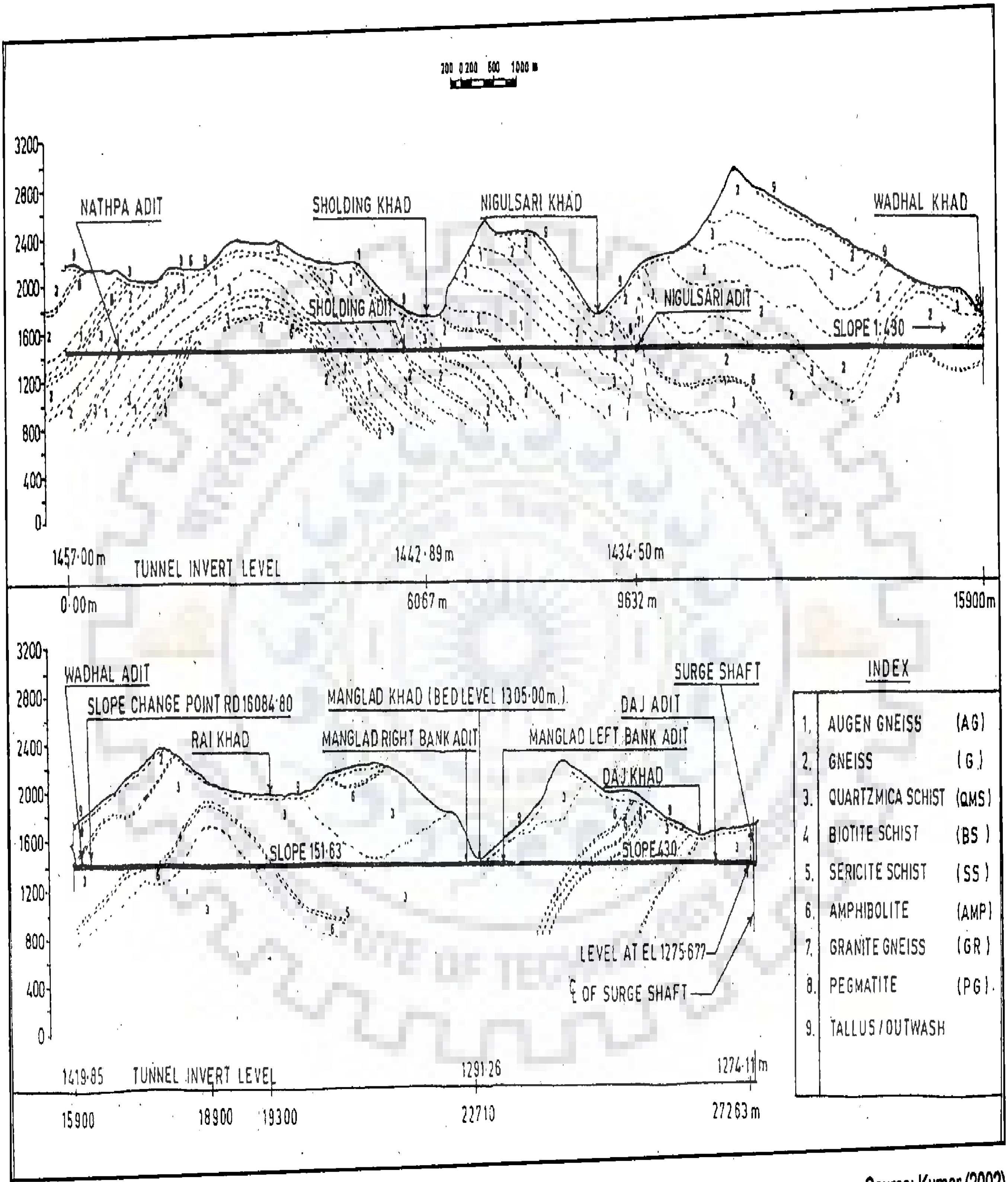
Source: Kumar (2002)

The extensive tunnelling operations in the area have had adverse effect on subsoil water regime and recharging capacity. Blasting and fracturing of the rock due to which ground water flow paths have changed and some streams have got hydraulically connected to the tunnel and below. Villagers have been complaining of non-availability of water in some of the springs and tributaries which were earlier a source of domestic and irrigation water for them. Field observations have confirmed that lean season flows of overlying tributaries have reduced. Some of the tributaries now remain dry for major part of lean season. Affected villages are Maghana, Majholi, Chandupur, Kartole, Khas Shah Jaluna, Rattanpur, Basara, Sanarsa and Jhakri.

Since tunnel in the entire reach is lined, seepage into tunnels from overlying streams and springs is not expected. Therefore water balance study of the tunnel through measurement of flow diverted in tunnel (Satluj and Sholding) and flow released in tail race after power generation needs to be carried out.

Spring sanctuary protection and development designed specifically for each spring in consideration of land use and characteristics of soil and rock should be an important component of Catchment Area Treatment (CAT) Plan.

Detailed study of water management of springs and hilly streams are given in Kumar and Rawat (1996), Palni et al. (2000), Negi et al. (1998), Juyal and Katiyar (1991) and Parekh et al. (2001).



Source: Kumar (2002)

Figure 6.3: Geological section and streams overlying tunnel alignment

6.7 SOIL MOISTURE MANAGEMENT

6.7.1 Muck Dumping Sites

The Nathpa Jhakri Hydroelectric Project is the largest underground hydroelectric project in the country. The under ground facilities are (i) an underground desilting complex, comprising four chambers, each 525 m long, 16.31 m wide and 27.5m deep (World's largest underground desilting chamber); (ii) a lined underground tunnel of 10.15 m dia and 27.39 km long, terminating in a 21.6 m/10.2 m dia and 301 m deep surge shaft; (iii) seven construction adits (iv) three circular pressure shafts, each of 4.9 m dia and 571 m to 622 m length, bifurcating near the power house to feed six generating units; (v) an underground power house with a cavern size of 222 m 20 m 49 m ; (vi) a 10.15 m dia and 982 m long Tail Race Tunnel and (vii) an underground transformer hall of size 196m X 18m X 27m.

Based on these dimensions of underground facilities, volume of underground space created for conveyance of water and for accommodating power generation facilities is 3.64 million cubic meter. However, volume of excavation and hence the muck disposed off is much higher than 3.64 MCM. The total quantity of muck generated is estimated to be in the order of 6003250 m^3 (Table 6.13). Total muck has been disposed at 10 dumping sites shown in Figure 6.4. The disposed muck on steep slopes of the valley usually has a very low moisture holding capacity. These sites will acquire materials and water from sites upslope. The water that flows to sites lower in the steep landscape by either surface runoff or subsurface lateral flow have profound influence on hydrologic regimes of the muck disposal sites.

Table 6.13: Details of muck disposal sites

Site	Jhakri I	Jhakri II	Koshgarh	Kotla	Dharali	Nigulsari	Plingi	Sakicharang	Punspa	Linge	Total
Capacity (1000 m^3)	1416.5		250.0	410.0	720.0	578.0	592.0	2015.0		21.7	6003.3

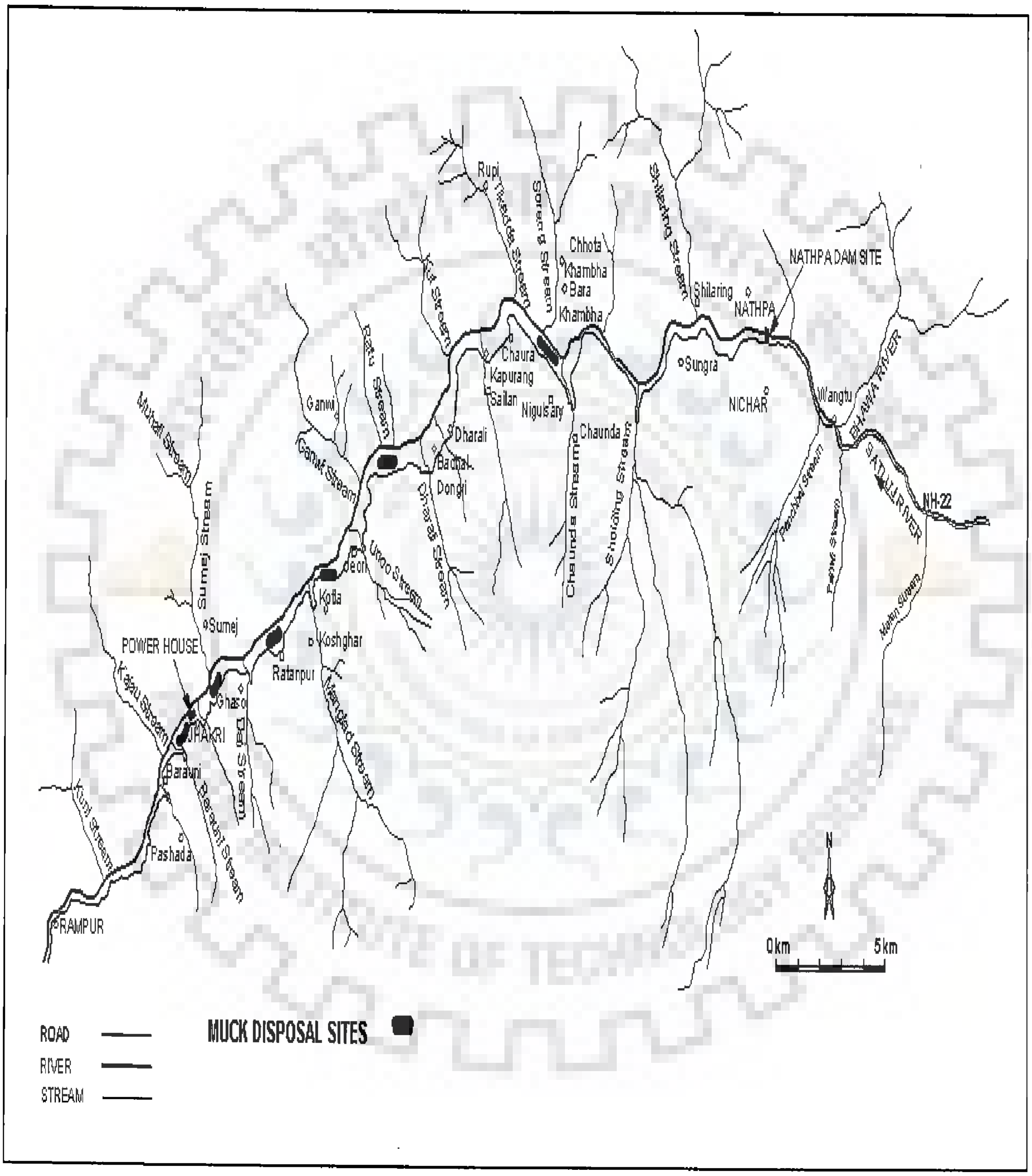


Figure 6.4: Muck disposal sites

6.7.2 Measures to Improve Moisture Retention Capacity

The following measures have been proposed by the project for restoration of dumping and quarry area:

- Utilization of 2.2 MCM muck for construction of roads, benches and play grounds
- Placement of the muck at natural angle of repose and protection of dumped material from sliding by providing wire crates at the toe
- Terracing of 1 m wide at 5 m vertical interval duly protected on hill side by edge walls
- Broad casting of grass seeds of local variety
- Plantation in the dumping area by providing imported soil mixed with farmyard manure

Field observations did not indicate any significant vegetation growth at the muck disposal sites indicating that the agronomic measures have not been successful (Plate 6.1). The agronomic measures such as broadcasting of grass seeds and plantation at the muck disposal sites could have been successful only if moisture retention capacity of the dumped material was adequate.

Moisture retention and transmission characteristics of soils at different locations along Nathpa-Jhakri reach have been analyzed as discussed in Chapter 4 (Section 4.4.2) and Annexure 4.5. The analysis shows that the available water holding capacity of the dumped material is less than 0.08 (vol./vol.) and organic matter content is negligible. Percent weight of coarse fraction in the dumped material is significantly high. Further, it is a common knowledge that segregation of particles of different sizes occurs during the dumping process.

A simple measure to modify soil texture (and hence dependent properties such as available water capacity) is to mix particles of appropriate size such as pulverised fuel ash; a waste product of coal burning electricity generating stations. Volcanic ash, fine coral sand and pulverised silica have also been used (Sharda and Juyal, 2006; Sastry et al., 1997; Shete, 1994). However, waste products may contain phytotoxic substance which may cause pollution of aquifers and water courses.

A more immediately practical method of increasing available water property of a soil is to incorporate in it large quantities of dead roots, peat or other organic material whose function is merely to act as a sponge.

Larger particles of greater than 2.0 mm are of importance in making the soil free from draining and thus highly and deeply leached. However, existing high percentage of coarse particles needs to be reduced to less than 15 % in agricultural lands. In addition, the percentage of organic matter and other size particles needs to be increased so that the top 2m depth contains soil texture of the type similar to that existing in the area. The analysis carried out in the previous sections can be used to design appropriate mix for placement.

6.8 CONCLUSIONS

Satluj river water is not a direct source of water for meeting community needs. It is not used for irrigation, cultural and religious activities in the study reach. Fishery is not commonly practised in Satluj river. Therefore reduced flows have insignificant impact on such uses of Satluj river water. However, Satluj river water provides habitat for aquatic flora and fauna. Impact of reduced flow on habitat is discussed in Chapter 5.

EWR of terrestrial ecosystem on annual basis is estimated to be 67.483 MCM. It consists of domestic water needs of human population (2.813 MCM), animal water need (0.67 MCM) and evapotranspirative demand of vegetation (64 MCM).

Evapotranspirative demand of agriculture and horticulture and water needs of human and animal population can be met by proper management of available water in tributaries and springs. Evapotranspirative demand of natural vegetation is to be met by soil moisture which depends on soil characteristics, topography and rainfall pattern. Analysis of 26 years concurrent rainfall data at Nichar and Rampur shows that rainfall in area is highly erratic in time and space and the study area is prone to meteorological drought. For the sustainable use of the scarce soil and water resources, proper knowledge of moisture retention and transmission characteristics is essential as the soils are shallow.

The extensive tunnelling and other underground excavations (6.0 MCM) in the area have had adverse effect on subsoil water regime and recharging capacity. Based on field observations it has been found that springs and streams have either dried up or lean season flow have reduced. This has had adverse impact on meeting human and animal water needs in the tributary catchments.

Natural vegetation at the muck disposal sites has been replaced by the dumped material. The analysis shows that the available water holding capacity of the dumped muck is less than 0.08 (vol./vol.) and organic matter content is negligible. Agronomic measures for vegetation growth at the muck disposal sites have not been successful. Measures to improve available water holding capacity are (i) to mix particles of appropriate size, (ii) to incorporate large quantities of dead roots, peat or other organic material, (iii) to reduce percentage of coarse particles to less than 15 % so that the top 2m depth contains soil texture of the type similar to that existing in the area.

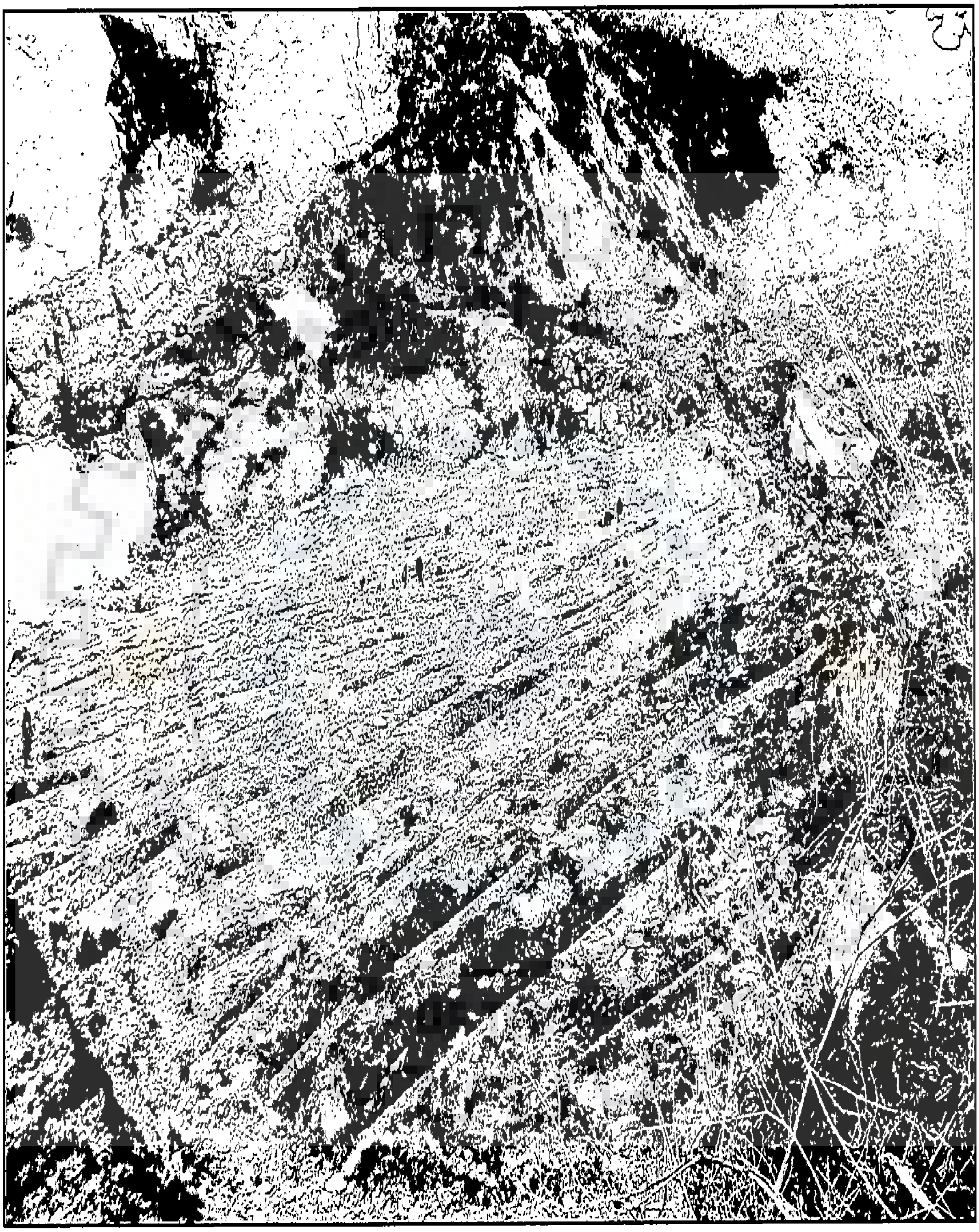


Plate 6.1: Scanty vegetation growth at muck disposal site

CHAPTER 7

ASSESSMENT AND MAPPING OF LOW FLOWS

Long-term hydrologic data (mainly stream flow) are the main input data in several EFA methods. Such data are usually not available for catchments in many parts of the world particularly in Himalayan mountainous region. Therefore, appropriate methods for assessment of flows in ungauged catchments are needed. Reliability of EFA depends on reliability of low flow assessment. Low flow regional regression models represent a relationship between low stream flow statistics and watershed characteristics. The watershed characteristics are used to describe the various processes that influence streamflow during low flow events. These processes need to be quantified in a way so as to be effectively represented within a regional regression model.

7.1 PREVIOUS STUDIES ON ASSESSMENT OF FLOWS IN SATLUJ BASIN

Feasibility reports of some of the hydroelectric projects in Satluj basin have been studied to understand and compare the procedures followed for assessment of flows in Himalayan catchments. Methods followed for assessment of flows in ungauged streams in Satluj basin are briefly reviewed below:

7.1.1 Rainfall and Catchment Area Proportion Based Study

The following methods were used for generation of flow series of river Satluj at Nathpa dam for the planning of Nathpa Jhakri Hydroelectric Project (NJPC, 1985).

Estimation of flow series from 1926 to 1963 of Satluj river at Nathpa

This method is based on discharge data at Bhakra (CA = 56875 sq. km) which is available since 1926.

Annual flow ratio = (Annual vol. of runoff in catchment area upto Nathpa)/(Annual vol. of runoff in catchment area upto Bhakra)

= (CA at Nathpa X Rainfall in catchment)/(CA at Bhakra X Rainfall in catchment)

= (49820 X 435)/(56875 X 485) = 0.79

Non-monsoon flow ratio = CA at Nathpa/CA at Bhakra = 49820/56875 = 0.876

Annual reduction factor being 0.79, reduction factor for monsoon period (June to September) thus was worked out as 0.618 since rainfall contribution during monsoon months from the intermediate catchment is significantly high. With these conversion factors, ten-daily flow series at Nathpa dam site were developed from 1926 to May 1963 for planning of NJHEP.

Estimation of flow series from 1963 to 1985 of Satluj river at Nathpa

Discharge observations are being carried out at Rampur (CA = 50880 sq. km) since June 1963. Catchment area at Nathpa is 49820 sq. km. Rainfall contribution towards annual runoff from the intermediate catchment between Nathpa dam site and Rampur (1060 sq. km) varies significantly as compared to rainfall contribution towards annual runoff from the catchment area upstream of Nathpa dam site. Keeping this in view, reduction factors based on rainfall volume were worked out as explained below:

$$\text{AnnualRatio} = \frac{\text{annual volume of rainfall in catchment upto Nathpa}}{\text{Annual volume of rainfall in catchment upto Rampur}} = \frac{49820 \times 435}{50880 \times 453} = 0.94$$

This represents the reduction factor on annual basis for deriving discharge series at Nathpa dam site from that of Rampur.

Annual runoff at Nathpa dam site = 0.94 X Annual runoff at Rampur

During non-monsoon period (October to May) precipitation pattern is almost uniform over entire catchment upto Rampur. Stream flow is mostly due to snow melt. Therefore, reduction factor is in proportion of catchment area, i.e.;

Non-monsoon flow ratio = CA at Nathpa/CA at Rampur = 49820/50880 = 0.98

Non-monsoon flow at Nathpa (October to May) = 0.98 X non-monsoon flow at Rampur

Annual reduction factor being 0.94, reduction factor for monsoon period (June to September) would work out as 0.86 as calculated below. Rainfall contribution during monsoon months from intermediate catchment is significantly high.

Monsoon flow at Nathpa = Annual flow at Nathpa – non-monsoon flow at Nathpa

= 0.94 X Annual (monsoon + non-monsoon) flow at Rampur – 0.98 X non-monsoon flow at Rampur

= 0.94 X (MRO + NMRO) – 0.98 X NMRO

Factor X $(\text{MRO})_{\text{Rampur}}$ = 0.94 MRO – 0.04 NMRO

$$\text{Factor} = \frac{\text{monsoon flow at Nathpa}}{\text{monsoon flow at Rampur}} = \frac{0.94\text{MRO} - 0.04\text{NMRO}}{\text{MRO}_{\text{Rampur}}}$$

$= 0.94 - 0.04 \times \text{NMRO}/\text{MRO}_{\text{Rampur}}$

≈ 0.86

With these conversion factors, ten daily flow series at Nathpa dam site have been developed from June 1963 to 1985.

7.1.2 Tributaries Discharge Correlation Studies

(i) Chaunda Stream: Chaunda Stream is a perennial stream. Its catchment area upto confluence with Satluj is 25 sq. km. Its catchment area upto discharge measurement site is 20 sq. km. Its catchment area includes about 4 sq. km above 4000 m which is permanently snow covered during most part of the year.

Daily discharge observations were carried out from 01.12.1996 to 31.05.1998. From this discharge data ten-daily discharge series have been prepared. Data of Chaunda Stream has been extended by correlation with discharge of Gaanvi Stream. Correlation is carried out by using ten-daily flow series (concurrent from Dec'96 to May'98). Extended data series (ten-daily) of Chaunda Stream from January 1976 to December 1996 has been prepared using Langbein's log deviation method.

(ii) Shilaring Stream: Altitude of catchment of Shilaring Stream ranges from 1400 m at confluence with Satluj to ±5000 m in glacier. Site for discharge measurement was chosen close to and on d/s of the proposed diversion structure. Stream was trained in the reach by pulling wire crates on both sides. Rectangular notch has been established at site. Daily discharge data is available for 01.11.2001 to 31.03.2003.

Max Q = 6.44 cumec on 21.08.02

Min Q = 840 lps on 25.01.02

Long-term ten-daily series for Shilaring Stream has been developed by correlation with observed discharge of Bhaba Stream (at Humta) for the period from January 1980 to December 2002.

7.1.3 Regional Flow Duration Model

Sailan Stream is a perennial spring/rain fed stream. The DPR describes Regional Flow Duration Model developed by Singh et al. (2001). For this purpose, available data of 13 catchments spread over entire Himachal Pradesh have been used. The catchment areas vary from 32.5 sq. km to 481.6 sq. km and covers rainfed catchments as well as catchments having snow covered area.

Long-term average flow, $Q_{mean} = C_1A^2 + C_2A$

C_1 and C_2 were determined by regression analysis.

$C_1 = -0.00008$

$C_2 = 0.0876$

Catchment area of Sailan Stream is 10 sq. km.

$Q_{mean} = -0.00008\ A^2 + 0.0876\ A$

Non-dimensional flow data seris (Q/Q_{mean}) is prepared combining data of all the 13 catchments. The non-dimensional data series is transformed to log series and power transformation series for the region W/W_{mean} for various levels of dependability are worked out.

Inverse Transformation is used to bring it in original domain. (Q/Q_{mean}) vs dependability curve for Himachal Pradesh is available in the report.

Probability (%)	Q/Q_{mean}	Q_{Sailan} (cumec)
25	1.1797	1.02
50	0.6609	0.57
60	0.5399	0.47
75	0.3917	0.34
80	0.3466	0.30
90	0.2544	0.22

7.1.4 Rainfall-Runoff Relationship

Rainfall-runoff relationship study was used for runoff estimation of Sailan stream.

Base flow, $Q_t = Q_0 \cdot e^{-kt}$

Q_t = baseflow at 't' in days (counted from 1st October)

Q_0 = baseflow at t = 0 (31st September)

k = -0.016 for 1997-98 series

Non-Monsoon base vs preceding monsoon rainfall:

It is assumed that total baseflow is proportional to the total rainfall in previous monsoon period;

Total baseflow = C X Monsoon rainfall

Baseflows of various months for the period 1963-75 and 1979-98 have been calculated.

Surface runoff during non-monsoon period (September to May):

Runoff due to rainfall = total runoff – baseflow

$\sum P$ vs $\sum R$ has been plotted.

Runoff (mm), $R = 0.2254\ P_{mm} - 13.394$

Monthly surface runoff contribution has been worked out for the non-monsoon period for the years from 1963-75 and 1979-98.

7.2 ESTIMATION OF TRIBUTARY DISCHARGES IN THE REACH

Several analysis such as Arihood and Glatfelter (1986), Vogel and Kroll (1992), Ries (1994) have considered drainage area as the important parameter in regional regression studies of low flows.

In the previous hydrological studies of Satluj basin, no attempt was made to consider differences in land use, rainfall, snow area coverage of different tributary catchments. The regional model proposed by Singh et al. (2001) also considers catchment area as the only influencing characteristic.

The proposed methodology is based on correlation between discharges of tributaries having similar catchment characteristics. Distinction has been made on the basis of (i) rainfed and snowfed catchments; (ii) periods with or without snowmelt contribution. Thus, tributaries have been grouped for correlation studies.

The Nathpa-Jhakri reach is only about 34 km in length with 866 sq. km interim catchment area. Long-term discharge data are not available for all the catchments except for Sholding and Gaanvi within Nathpa-Jhakri reach. The short-duration data for some catchments are available but not for concurrent period. However, long-term data for Bhaba and Baspa streams which are upstream of Nathpa dam. The reach can be considered to fall in one hydrometeorological region, which, by definition, covers relatively a large area (Singh, 1996; McCuen, 1989; Singh et al., 2001; Mishra and Singh, 2003; Bhunya et al., 2004; Bhunya et al., 2006).

Long-term discharge data of four tributaries (Sholding Stream, Gaanvi Stream, Bhaba Stream and Baspa river) of Satluj river upto Rampur is available The specific discharge (discharge per unit catchment area) duration curves for Sholding Stream, Gaanvi Stream, Bhaba Stream and Baspa river are compared in Figure 7.1. Figure shows that the specific discharge duration curves of Sholding Stream, Gaanvi Stream, Bhaba Stream and Baspa river are quite similar and hence it may be predicted that flow duration curves of other catchments may be generated using these curves. Hence, discharge data of these tributaries can be used for the estimation of discharges of other tributaries on catchment area basis. Further, tributaries in the study area are divided into three types:

(i) Left bank tributaries having snow melt contribution
(ii) Right bank tributaries having snow melt contribution
(iii) Tributaries having no snow melt contribution

Discharge per unit catchment area of Sholding and Gaanvi Streams and Sailan can be used to represent the discharge per unit area for other sub-catchments in the Nathpa-Jhakri reach. Based on the snow-melt contribution, the analysis is partitioned into two components, viz., December-February and before December and after February, as follows:

December-February

During this period, snow melt contribution can be taken to be negligible being it is the period of snowfall at sub-zero temperature. Thus, the rainfall-generated discharge per unit catchment area of Sholding and Gaanvi Streams holds for derivation of discharges occurring in the left and right bank tributaries, respectively.

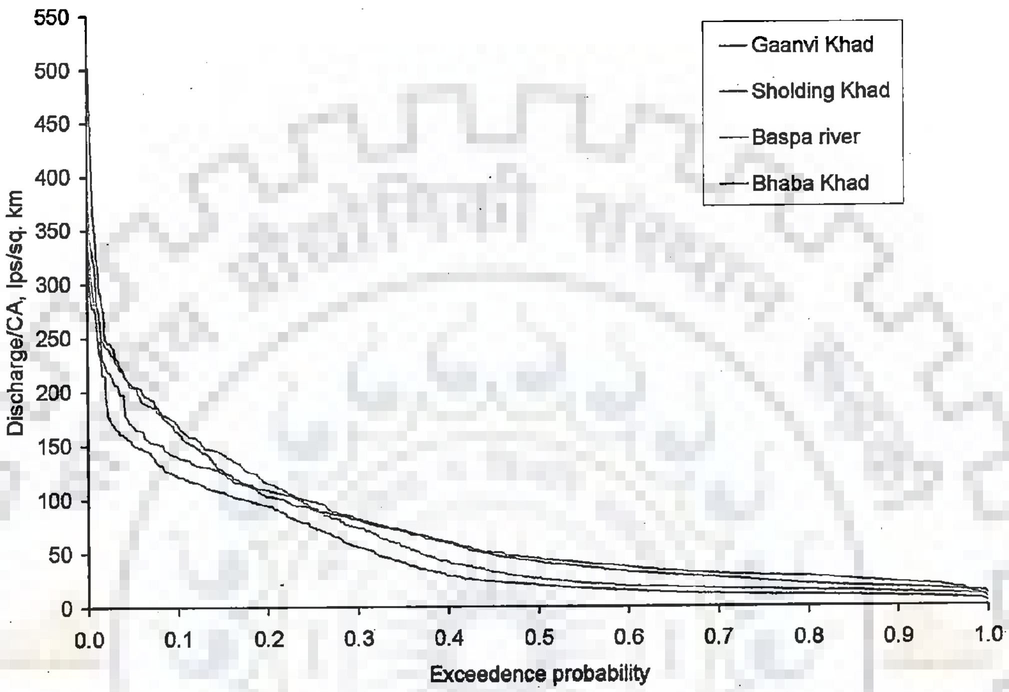


Figure 7.1: Specific discharge duration curves for Sholding Stream, Gaaanvi Stream, Bhaba Stream and Baspa river

October-November & March-June

During this period, since the snow-melt contribution is significant, the catchments were divided into two categories, (i) with negligible snow cover area and (ii) with significant snow cover area. For the first type of catchments, discharges were derived using discharge per unit catchment area of Sailan Stream, and for the second type, these were derived using those of Sholding and Gaanvi Streams, respectively, for left and right bank tributaries. The discharges of Sailan stream for the corresponding dry, normal and wet years are taken as derived discharges given in Detailed Project Report of Sailan Small Hydro Power Project.

7.3 SATLUJ RIVER FLOW D/S OF NATHPA AND SHOLDING CONFLUENCE

The average monthly flows of Satluj at Nathpa and Sholding Stream for the period 1970-1996 were used for estimation of time series downstream of Nathpa and Sholding Stream confluence during pre-project and post-project conditions. The discharges of other tributaries meeting Satluj between Nathpa and Sholding Stream confluence were worked out on discharge per unit catchment basis taking Sholding flows as reference. In the estimation, it was considered that if Satluj had discharges more than the tunnel capacity, no water was diverted from Sholding Stream into the tunnel and also that certain minimum flow is being released downstream of Nathpa dam. The Figure 7.2 depicts the line diagram showing all the terms used in this estimation. The procedure used is as follows:

Qnu = Discharge of Satluj river upstream of Nathpa

Qnd = Discharge of Satluj river downstream of Nathpa

Qndm = Minimum required release downstream of Nathpa

Qnt = Discharge of Satluj river going into tunnel

Qsu = Discharge of Sholding Stream upstream of tunnel intake

Qsd = Discharge of Sholding Stream downstream of tunnel intake

Qst = Discharge of Sholding Stream going into tunnel

Qss = Discharge of Satluj river downstream of Sholding confluence

Condition I:

If Qnu > 405 cumec + Qndm,

Qnt = 405 cumec

Qnd = Qnu – 405

Qst = 0

Qsd = Qsu

Condition II:

If Qnu ≤ 405 cumec + Qndm,

Qnd = Qndm

Qnt = Qnu – Qndm

Qst = lower of (405 – Qnt) and Qsu

Qsd = Qsu – Qst

Qss = Qnd + Qsd + Intermittent tributary discharge

Minimum required release d/s of Nathpa (Qndm) has been taken as 7 cumec based on environmental flow study.

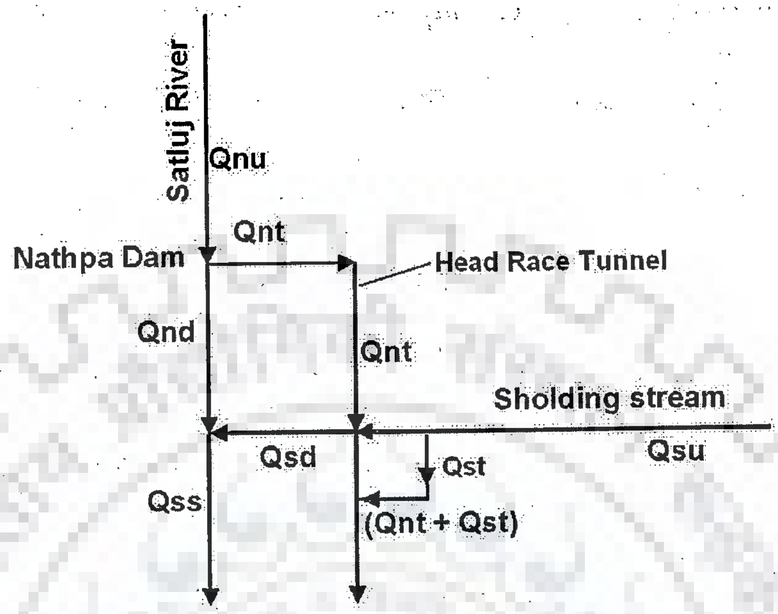


Figure 7.2: Line diagram showing flow diversion in head race tunnel of NJHEP

7.4 RIVER MAPPING

Mapping of a river reach can be defined as determination of river discharges at different locations in the river reach. This involves the following work:

(i) Delineation of tributary catchments

(ii) Estimation of catchment areas of tributaries and location of confluence with the river

(iii) Estimation of tributary discharges

Delineation of catchments, chainage of catchment outlets from Nathpa dam and catchment area have been worked out by ERDAS software package and planimeter using four scanned toposheets covering the study reach.

The river mapping has been done for the wet, dry and normal years by using long-term data. For this purpose Satluj river flow series from 1970 to 2001 was considered and years, in which total annual runoff corresponding to 90%, 50% and 10% exceedance probability occurred, were taken as dry, normal and wet years respectively. Thus, 1993, 1987 and 1983 were found out to be dry, normal and wet years respectively.

Subsequently, discharges of each catchment were computed and cumulated at different chainages. Discharges thus obtained at confluence of various tributaries are presented in Annexure 7.1 (wet year), Annexure 7.2 (normal year) and Annexure 7.3 (dry year). Annexure 7.4 corresponds to the year 2005-06 for observed discharges of Satluj river and its tributaries between Nathpa and Jhakri.

Observed discharge data (Annexures 4.6 and 4.7) and estimated discharges in Annexure 7.1 to Annexure 7.4) have been used to prepare Figure 7.3 to Figure 7.9.

Relative increase during dry year, wet year, normal year and the year 2005-06 are compared for each of the lean season month separately. Thus, Figure 7.3 shows Satluj river flow along its course during the month of October in dry, wet, normal years and in year 2005-06. Similarly, Figure 7.4 to Figure 7.9 show Satluj river flows in November, December, January, February, March and April respectively.

The figures show that contributions to lean season flow of Satluj river are mainly from Shilaring stream, Sorang stream, Kut stream, Gaanvi stream, Manglad stream and Sumej stream. The tributary contributions to Satluj river flow start decreasing after monsoon season continuing from October to January and start increasing due to snow melt. There is not much difference in January flows during dry, wet and normal years. Flow contribution from October upto January is mainly from ground water which gets nearly depleted by end of January. Beyond January, flow contribution is mainly from snow melt and winter rain.

Satluj river reach from Nathpa and before confluence of Sorang Stream (about 10.8 km) is a critical reach in the context of environmental flow. Within this reach, contribution is mainly from Shilaring and Chaunda streams. Flow in this reach is leanest in January, February months and similar in dry, wet, normal years and the year of monitored flow data i.e. 2005-06.

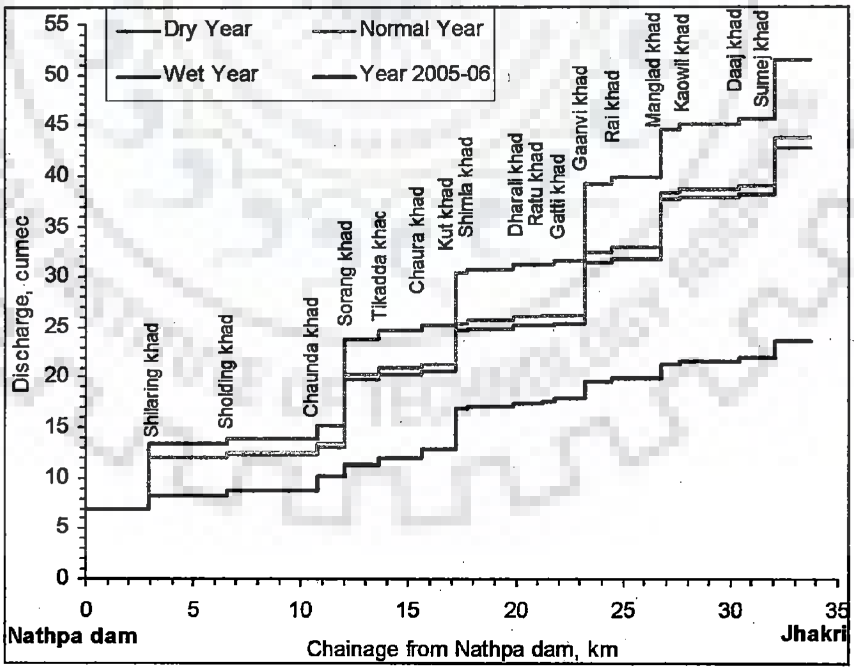


Figure 7.3: Discharges of Satluj river at confluence of tributaries for the month of October

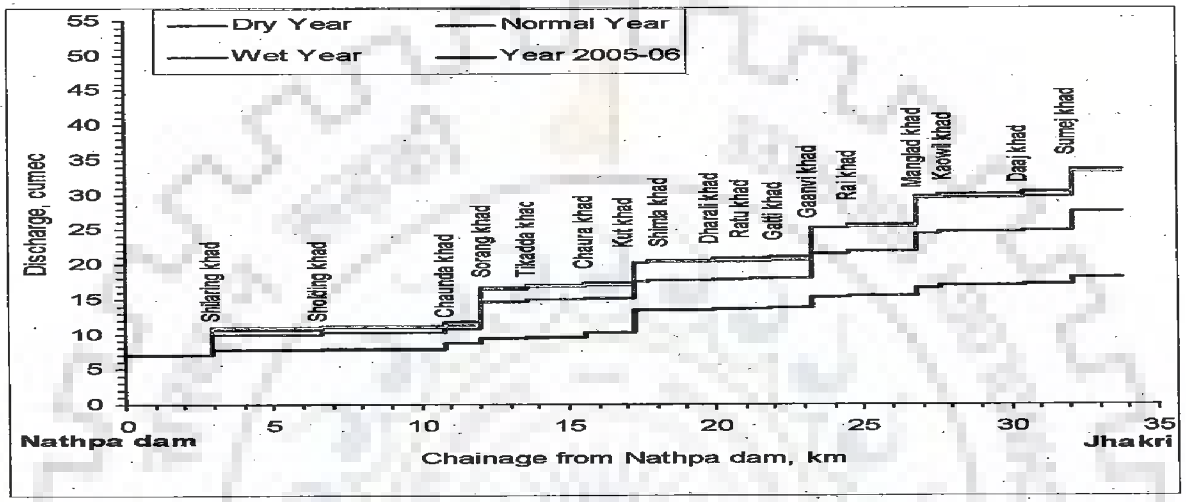


Figure 7.4: Discharges of Satluj river at confluence of tributaries for the month of November

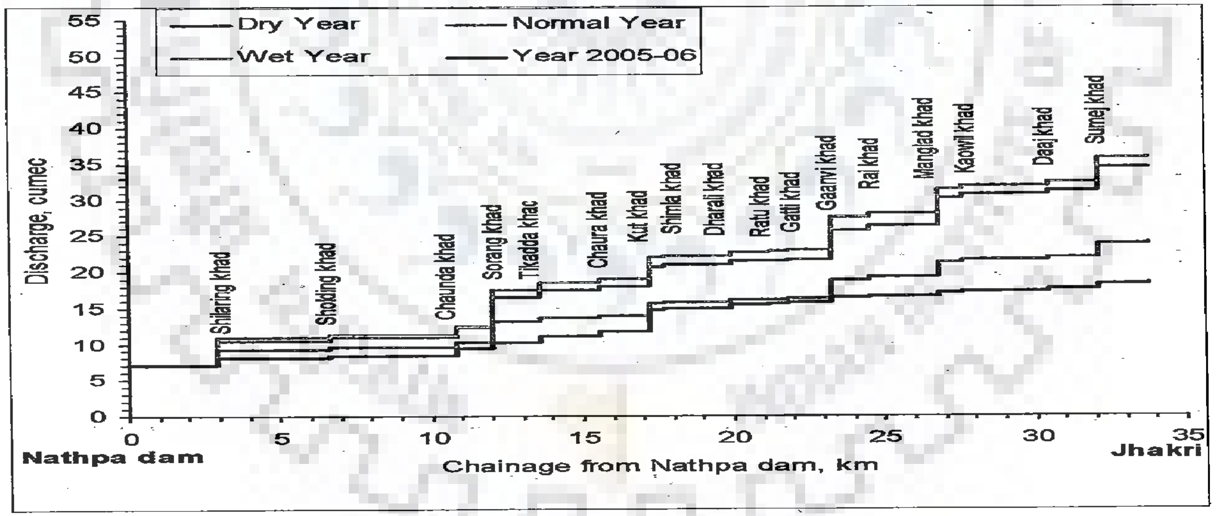


Figure 7.5: Discharges of Satluj river at confluence of tributaries for the month of December

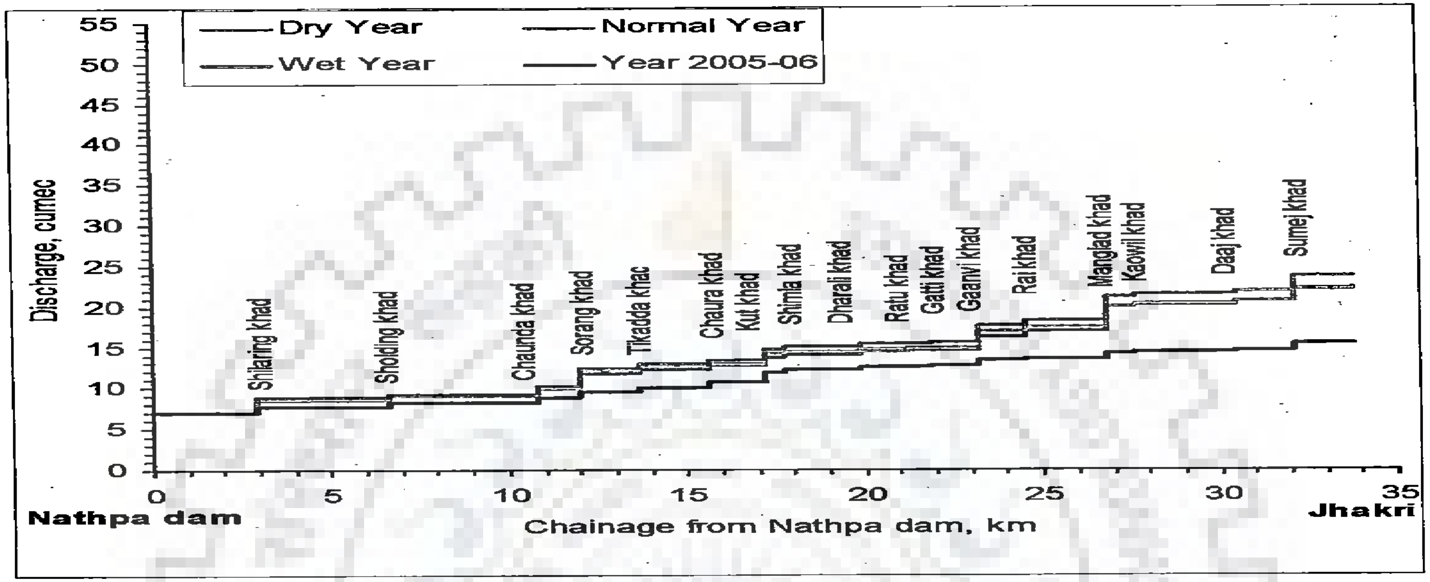


Figure 7.6: Discharges of Satluj river at confluence of tributaries for the month of January

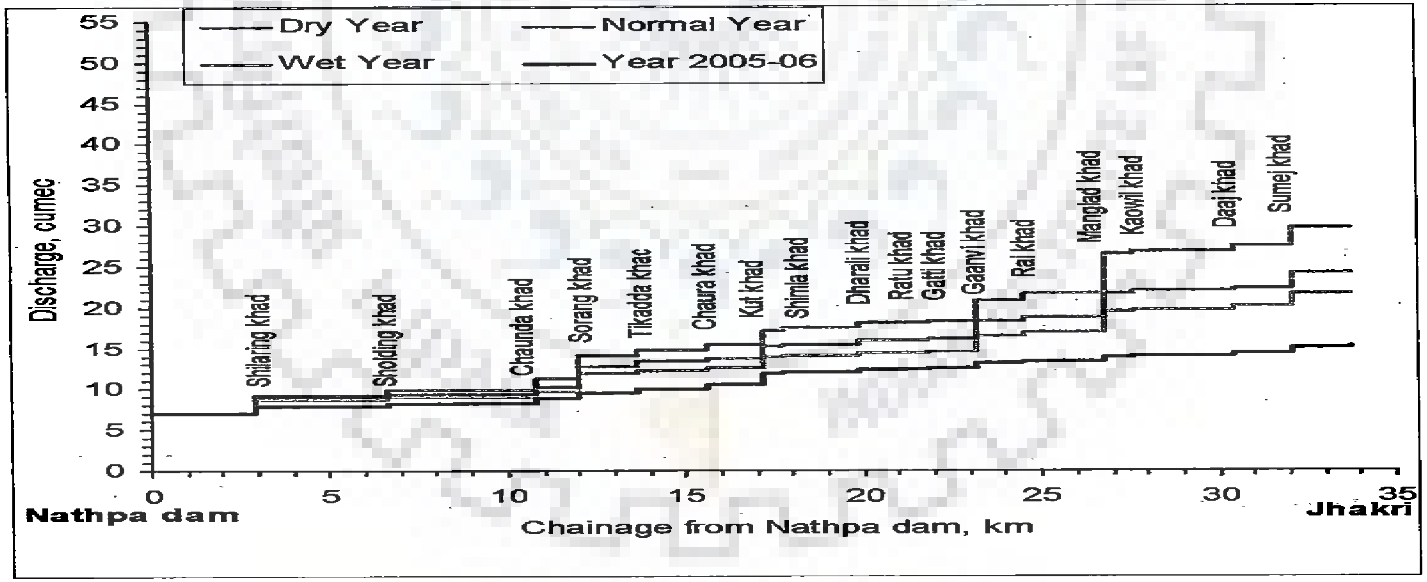


Figure 7.7: Discharges of Satluj river at confluence of tributaries for the month of February

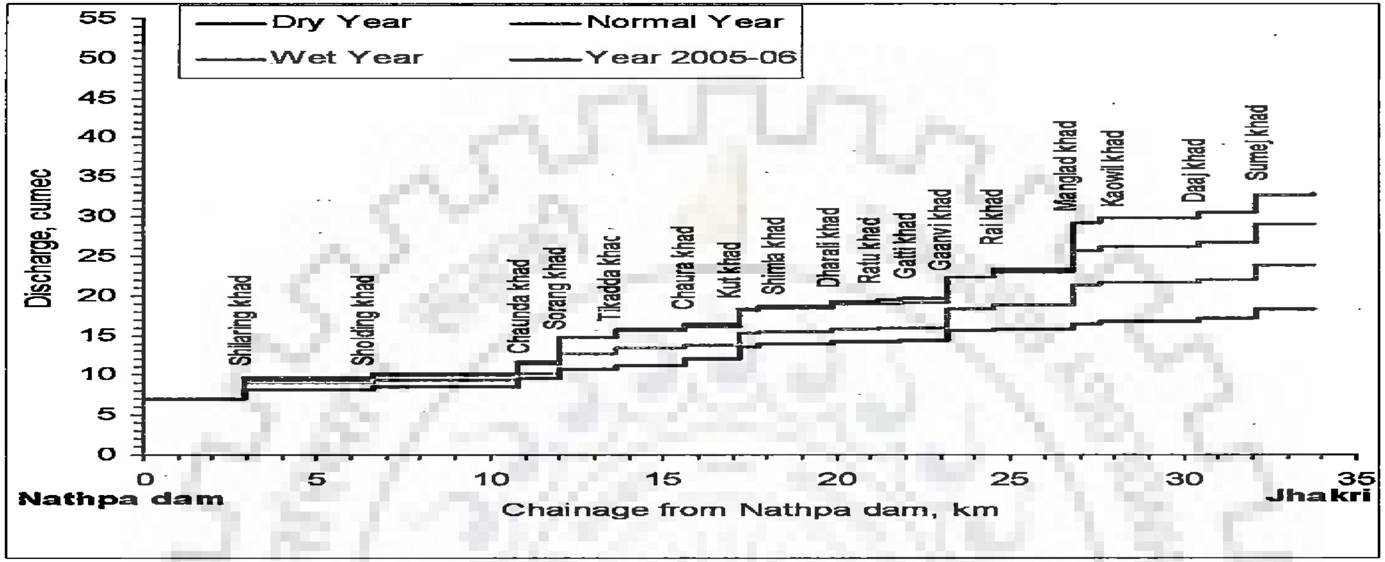


Figure 7.8: Discharges of Satluj river at confluence of tributaries for the month of March

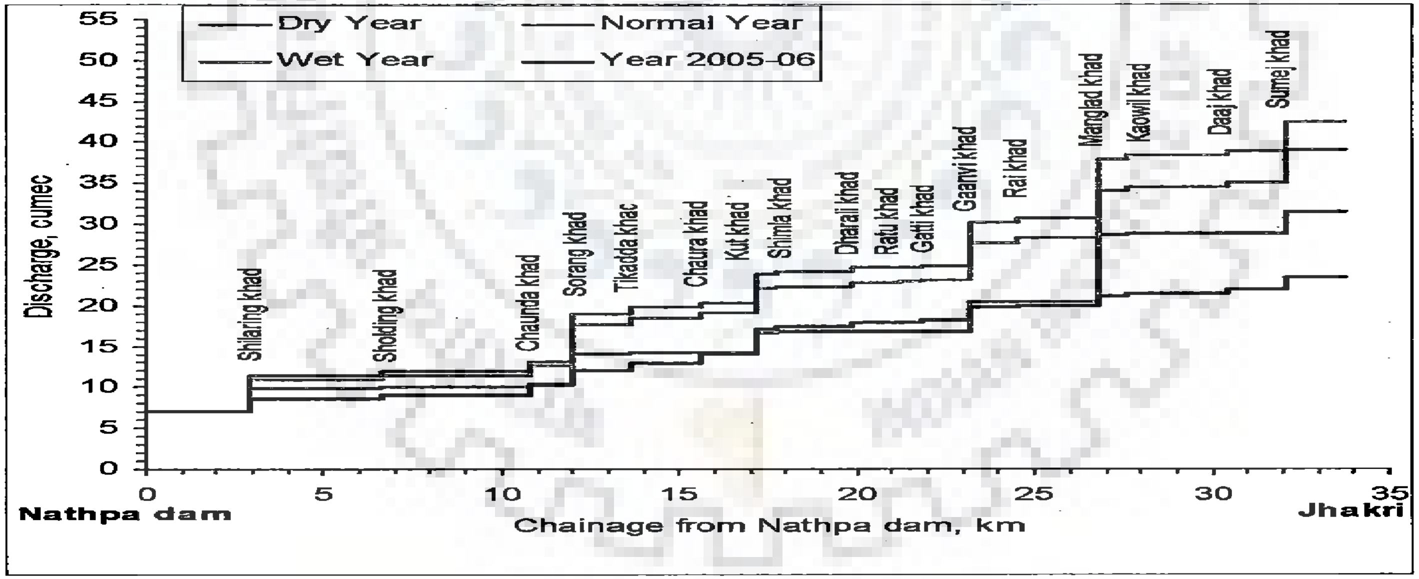


Figure 7.9: Discharges of Satluj river at confluence of tributaries for the month of April

7.5 LOW FLOW CHARACTERISATION OF SATLUJ RIVER FOR PRE AND POST PROJECT CONDITIONS

Low flow regime of a river can be analysed in a variety of ways dependent on the type of data initially available and the type of output information required. Consequently there exist a variety of low flow measures and indices. The term 'low flow measure' used here, refers to the different methods that have been developed for analysing, often in graphical form, the low flow regime of a river. The term 'low flow index' is used predominantly to define particular values obtained from any low flow measure.

7.5.1 Flow Duration Curve

A flow duration curve (FDC) is one of the most informative methods of displaying the complete range of river discharges from low flows to flood events. It is a relationship between any given discharge value and the percentage of time that this discharge is equalled or exceeded, or in other words, the relationship between magnitude and frequency of stream flows discharges.

The flow for the construction of FDC may be expressed in actual flow units, as percentage/ratio of MAR, MDF or some other index flow, or divided by the catchment area. Such normalisation facilitates the comparison between different catchments, since the differences in FDCs caused by the differences in catchment area or MAR. Consequently, the effects of other factors on the shape of FDCs (aridity, geology and anthropogenic factors) may be inspected. Here, the flows are divided by catchment area for the comparison.

FDC may be constructed using different time resolutions of stream flow data: annual, monthly, m-day or daily. In the present case, ten daily flows are available, hence these are used for the derivation of FDC.

A FDC is constructed by reassembling the flow time series values in decreasing order of magnitude.

m = order of event

N = total number of events

Probability, $P = m/(N+1)$

The flow duration curves for Satluj river (d/s of Nathpa and Sholding confluence) during pre-project and post-project conditions of NJHEP and at Rampur during pre-project and post-project conditions of RHEP are shown in Figure 7.10 and Figure 7.11.

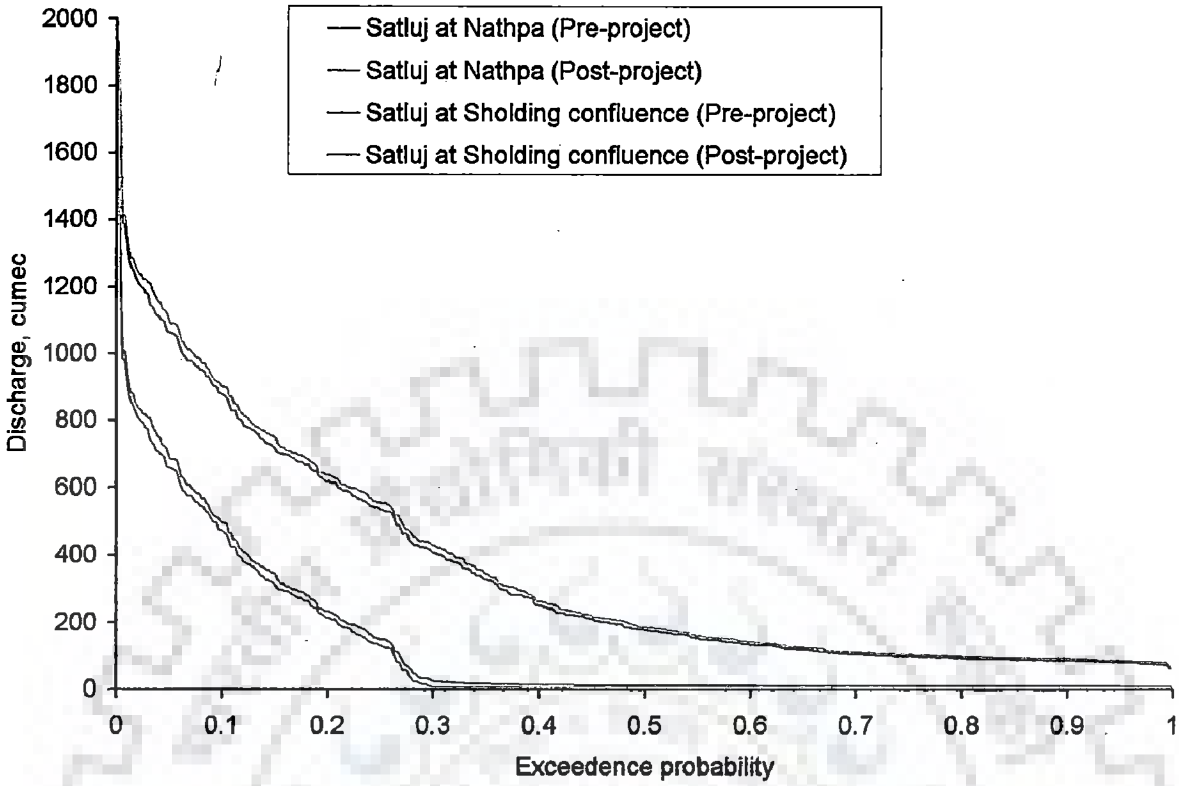


Figure 7.10: Flow duration curves for Satluj river (d/s of Nathpa and Sholding confluence during pre and post-NJHEP conditions)

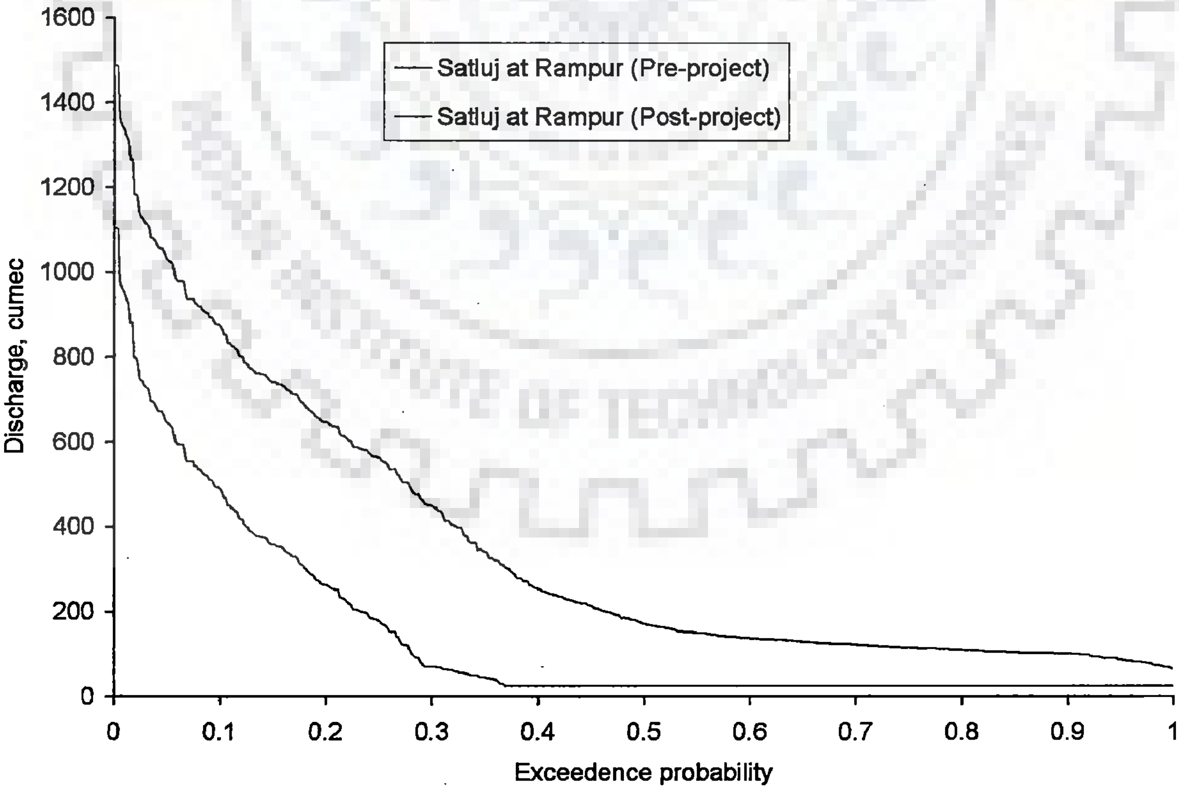


Figure 7.11: Flow duration curves for Satluj river (at Rampur) during pre and post-RHEP conditions

7.5.2 Low Flow Domain

The arbitrary 'upper bound' to low flow hydrology may be given by the Mean Annual Runoff (MAR), which is a mean value of the available flow time series of annual flow totals. Dividing MAR by the number of seconds in a year gives the long-term Mean Daily Flow (MDF).

The lowest recorded ten daily discharge may be referred to as Absolute Minimum Flow (AMF). The information content of this index varies with the length of record and depends upon the measuring limits of streamflow gauges. The values of low flow indices for the tributary catchments and for Satluj river during pre and post-project conditions of NJHEP and RHEP are given in Table 7.1 to Table 7.3, respectively,

Q20	=	discharge corresponding to 20% exceedance probability
Q50	=	discharge corresponding to 50% exceedance probability
Q90	=	discharge corresponding to 90% exceedance probability
Q20/Q90	=	measure of stream flow variability
Q50/Q90	=	measure of variability of low flow discharge
Q90/Q50	=	index representing proportion of flow originating from ground water storage

7.5.3 Low Flow Frequency Analysis

A low flow frequency curve (LFFC) shows the proportion of years when a flow is exceeded or equivalently the average interval in years (return period or recurrence interval) that the river falls below a given discharge. LFFC is constructed on the basis of a series of annual flow minima (daily or monthly minimum discharges or flow volumes), which are extracted from the available original continuous series (one value from every year of record. Some of the indices obtained from LFFC are as follows.

Table 7.1 shows that variability of low flow discharges (Q50/Q90) is almost same for Gaanvi, Sholding, Baspa and Bhaba streams placing confidence in consistency and reliability of data. Q20/Q90 is a measure of stream flow variability. Flows of Bhaba and Baspa are highly variable. Values of Q20/Q90 parameter for Bhaba and Baspa are significantly higher than (almost twice of) the values for Sholding and Gaanvi. The ratio Q90/Q50 is interpreted as an index representing proportion of stream flow originating from ground water storage excluding the effects of catchment area. Secondly, the values of Q50/Q90 or Q90/Q50 of those catchments lying on a particular side of the Sutluj river are quite close to each other, indicating a similar hydrologic character. For example, Gaanvi and Bhaba catchments which are on the right side indicate Q90/Q50 values as 0.49 and 0.48, respectively. Similarly, Sholding and Baspa catchments which are on the left side indicate values as 0.41 and 0.44, respectively. Significant difference between the values for right and left catchments indicate different normalized baseflow contributions from these catchments and it might be attributed to the amount of precipitation varying with the location of these catchments, whether in forward or leeward zones (Singh and Singh, 2001).

Table 7.2 and Table 7.3 show that changes in Q20/Q90 from pre to post project conditions are more prominent for NJHEP than for RHEP. It is also noted that flow variability decreases towards downstream of Nathpa dam. The ratio Q90/Q50 represents proportion of stream flow originating from ground water storage. Increase in this value shows that proportion of ground water contribution to flow have increased after project implementation. This is due to the fact that main contribution to flow during lean season is from tributary catchments.

MAM10: The average of annual series of minimum 10-day average flows is known as Dry Weather Flow or Mean Annual 10-day Minimum Flow (MAM10).

10Q10 = 10-day minimum flow corresponding to 10 year return period

10Q2 = 10-day minimum flow corresponding to 2 year return period

Table 7.1: Low flow indices of Sholding stream, Gaaanvi stream, Bhaba stream and Baspa river

Indices	Sholding Stream	Gaanvi Stream	Bhaba Stream	Baspa river
MAR, MCM	244.19	181.69	547.35	1450.68
MDF, m^3/s	7.74	5.76	17.36	46.00
AMF, m^3/s	1.21	0.67	2.06	3.70
Q20/Q90	5.95	4.98	9.05	10.51
Q50/Q90	2.42	2.05	2.07	2.26
Q90/Q50	0.41	0.49	0.48	0.44
MAM10	1.72	1.77	3.35	8.04
10Q2	1.69	1.80	3.66	8.23
10Q10	2.11	2.42	3.96	11.00

Table 7.2: Low flow indices of Satluj river at Nathpa and at Sholding confluence during pre and post-NJHEP conditions

Indices	Satluj d/s of Nathpa		Satluj d/s of Sholding confluence	
	Pre-project	Post-project	Pre-project	Post-project
MAR, MCM	10800.00	3740.00	11300.00	4080.00
MDF, m^3/s	343.88	118.68	357.07	129.38
AMF, m^3/s	62.00	7.00	67.31	7.99
Q20/Q90	18.395	165.077	17.795	128.151
Q50/Q90	2.058	1.000	2.024	1.263
Q90/Q50	0.486	1.000	0.494	0.792
MAM10	80.14	7.00	85.22	9.42
10Q2	83.50	7.00	88.15	9.44
10Q10	91.33	7.00	96.86	10.24

Table 7.3: Low flow indices of Satluj river at Rampur during pre and post-RHEP conditions

Indices	Pre-project	Post-project
MAR, MCM	11074.40	4438.87
MDF, m^3/s	349.23	139.69
AMF, m^3/s	65	25
Q20/Q90	6.46	10.48
Q50/Q90	1.70	1.08
Q90/Q50	0.59	0.93
MAM10	88.84	25
10Q2	105	25
10Q10	93.5	25

7.6 CONCLUSIONS

The SDDCs of Gaanvi and Sholding are almost same particularly in the low flow range. Therefore, these SDDCs are considered as representative of SDDC for other tributaries between Nathpa and Jhakri. The ratio Q90/Q50 is interpreted as an index representing proportion of stream flow originating from ground water storage excluding the effects of catchment area. The values of Q90/Q50 of catchments lying on a particular side of the Satluj river are found to be close to each other, indicating a similar hydrologic character.

Contributions to lean season flow of Satluj river are mainly from Shilaring stream, Sorang stream, Kut stream, Gaanvi stream, Manglad stream and Sumej stream. The tributary contributions to Satluj river flow start decreasing after monsoon season continuing from October to January and start increasing due to snow melt.

There is not much difference in January flows during dry, wet and normal years. Flow contribution from October upto January is mainly from ground water which gets nearly depleted by end of January. Beyond January, flow contribution is mainly from snow melt and winter rain.

Satluj river reach from Nathpa and before confluence of Sorang stream (about 10.8 km) is a critical reach in the context of environmental flow. Flow in this reach is leanest in January, February months and similar in dry, wet, normal years and the year of monitored flow data i.e. 2005-06.

CHAPTER – 8
ASSESSMENT OF ENVIRONMENTAL FLOWS

Environmental flows are the water that is left in a river eco-system or released into it for the specific purpose of managing the condition of that ecosystem. The status of EF research in India may be characterized as being in its infancy because of very limited knowledge base (NCIWRDP, 1999). Environmental flow in India has usually been understood as a flow, which is to be released downstream from the dams as a riparian right of downstream users without considering river ecology and river morphology. Such releases have often been minimal implying maximum abstraction. Overall, there has been limited appreciation of the nature of rivers and catchments as ecosystems. Central Water Commission (CWC), the apex water sector body of Government of India, has made the following recommendations on environmental flows for Himalayan Rivers (CWC, 2007):

- Minimum flow to be not less than 2.5% of 75% dependable annual flow expressed in cubic meters per second and one flushing flow during monsoon with a peak not less than 250% of 75% dependable annual flow expressed in cubic meters per second.

CWC guidelines are based on opinions of water resource experts in India. This approach suffers for the same drawbacks of behavioural psychology as the Expert Panel Assessment method (Swales and Harris, 1995) and Scientific Panel Assessment method (Thoms et al, 1996). Cooksey (1996) provides a critique of such methods (Section2.6 in chapter 2).

Based on the analysis carried out in previous chapters, environmental flow assessment in the Satluj river reach influenced by the hydropower projects is discussed in this chapter. This EFA is in addition to the environmental water requirement of terrestrial ecosystem which have been analysed in Chapter 6.

8.1 LOOKUP TABLE METHOD

Low flow characteristics of tributaries and Satluj river between Nathpa and Jhakri have been analyzed in Chapter 7. Following parameters (Table 8.1) are taken for assessment of low flow requirements using lookup table methods recommended by various agencies (Section 2.4.1, Chapter 2 and Section 3.3.5, Chapter 3).

Table 8.1: Low flow characteristics of Satluj river

	Nathpa dam	D/S of Sholding confluence
Long term absolute min flow (m^3/s)	62	67.31
95% dependable flow (m^3/s)	80	84.66
75% dependable flow (m^3/s)	99	105.08
Mean annual flow (m^3/s)	342.17	365.30

Table 8.2 shows computation of environmental flow requirement in Satluj river d/s of Nathpa and d/s of Sholding confluence according to various practices. As discussed in Chapter 5, the Satluj river reach between Nathpa and Jhakri has low biological productivity. Fishery is not practiced in the reach.

It is seen from Table 8.2 that environmental flow requirement is lowest as per DH1 (2006) study. Flow required as per HPSEP&PCB guideline and as per practice in France are similar. Required flow as per criteria in UK and USA are comparatively high. On the other hand EFR as per CWC criteria is quite low. Criteria specified by HPSEP&PCB appears to be reasonable considering, economic status of the state and the country and the demand for power generation and needs of the ecosystem in the study area.

Table 8.2: Minimum flow requirement in Satluj river

Agency/Country Practice(Reference)	Minimum flow requirement criteria	Min. flow requirement d/s Nathpa dam (cumec)	Minimum flow requirement d/s of Sholding stream confluence (cumec)
France (Souchon and Keith, 2001)	0.025 x mean flow for existing scheme	0.025 x 342.17 = 8.55	0.025 x 365.3 = 9.13
U.K. (Barker and Kirmond, 1998)	Flow equaled or exceeded 95% of time (Q_{95})	80	84.66
USA (Montana method) (Tennant, 1976)	10% of mean flow for poor quality habitat of fish	0.1x 342.17 = 34.2	0.1 x 365.3 = 36.5
UK (Env. Agency, 2002)	0.7 x Q_{95} for least sensitive ecosystem	0.7 x 80 = 56	0.7 x 84.66 = 59.262
DHI study of Rampur HEP (DHI, 2006)	Flow velocity 0.6 to 1.2 m/s	5	Not specified
HP State Env. Protection and Pollution Control Board	15% of the observed min. flow in the lean season	0.15 x 62 = 9.3	0.15 x 67.31 = 10.1
CWC Guideline (CWC, 2007)	2.5% of 75% dependable annual flow	0.025 x 99 = 2.475	0.025 x 105.08 = 2.627

The Environment Agency of England and Wales is responsible for ensuring that the needs of water users are met whilst safeguarding the environment (Env. Agency, 2002). It has specified percentages of natural Q_{95} flow that can be abstracted for different environmental weighting bands.

Physical Characterization: Rivers with steep gradients score 5 since small reduction in flow result in relatively large reduction in wetted perimeter. River reaches that are narrow and deep are less sensitive to flow reduction and score 1. Physical character is determined by comparing the river with photographs of typical river reaches in each class. Sensitivity score for Satluj river is worked out as below:

	Score for Satluj river				
	1	2	3	4	5
Physical character	1				
Fisheries	1				
Macrophytes	1				
Macro invertebrates	1				

Sensitivity = (ΣScore)/4 = 1

The sensitivity score is taken as 1 for Satluj river reach in consideration of its physical character, low biological productivity and absence of fishery and less sensitivity of macrophytes and invertebrates to reduced flows in post project condition. Therefore, not more than 30% of Q_{95} should be abstracted i.e. downstream release should be at least 70% of Q_{95} as per lookup table specified by Env. Agency 2002 .

Sensitivity	Env. Weighting band	% of Q_{95} that can be abstracted
Most sensitive av. Score 5	A	0.5%
	B	5 – 10%
	C	10 – 15%
	D	15 – 25%
Least sensitive average score 1	E	25 – 30%
	Others	Special treatment

8.2 ENVIRONMENTAL MANAGEMENT CLASS BASED FDC APPROACH

Smakhtin and Anputhas (2006) have reviewed various hydrology based environmental flow assessment methodologies and their applicability in Indian context. Based on the study, they suggested a flow duration curve based approach which links environmental flow requirement with environmental management classes (Section 2.4.2 in Chapter 2).

FDC for the Satluj river at Nathpa dam site is prepared corresponding to the 17 fixed percentage points: 0.01, 0.1, 1, 5, 10, 20, 30, 40, 50, 60, 70, 80, 90, 95, 99, 99.9 and 99.99 percent. Six EMCs described in Table 2.4 (Chapter 2) have been used as scenarios of aquatic ecosystem condition. The default FDCs representing a summary of EF for each EMC were determined by the lateral shift of the original reference FDC – to the left, along the probability axis. FDCs thus obtained are presented in Figure 8.1 and the values of environmental water requirement and environmental flow are given in Table 8.3. The environmental flow for EMC 'A' is almost equal to the EF as per practice followed in UK (Environmental Agency, 2002). EF for EMC 'F' is equal to the EF as per practice followed in USA (Tenant, 1976).

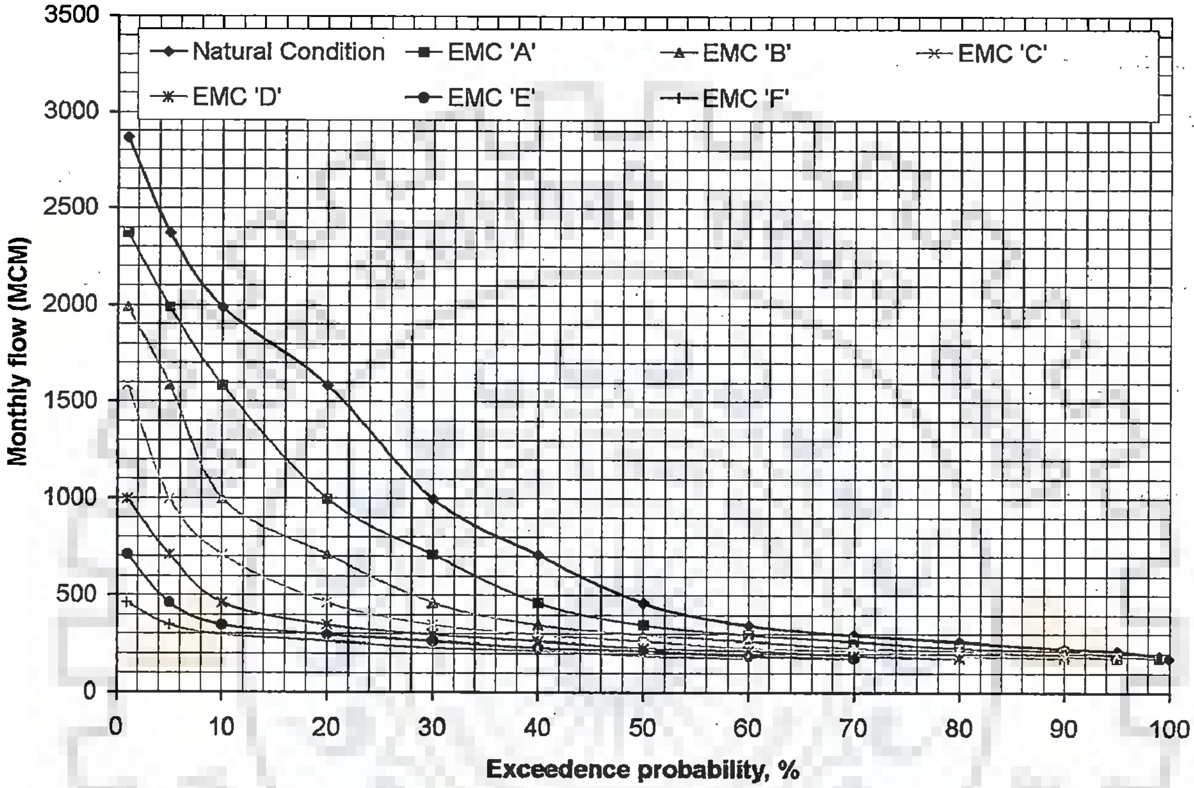


Figure 8.1: FDCs for different Environmental Management Classes by lateral shift

8.3 HYDRAULIC HABITAT ANALYSIS

In the hydraulic rating method, relationship between wetted perimeter as a function of discharge is graphically depicted. Break points in slope of curve indicate maximum available habitat for least amount of water until next break point (Gippel and Stewardson, 1998). Gippel and Stewardson (1998) have highlighted the problems of trying to identify thresholds (critical discharges below which wetted perimeter declines rapidly) that can be used to define minimum environmental flows. In the present study, variation in top width/depth ratio with discharge has been analysed.

For the purpose of maintaining habitat of aquatic flora and fauna, it is necessary to assess depth of flow, flow velocity and submergence of river bed in terms of top width of flow section for various flow conditions. As concluded from river mapping (Section 7.3, Chapter 7) initial reach of 10.8 km (downstream of confluence of Chaunda stream with Satluj) is taken as critical reach for hydraulic habitat analysis. Four sections have been chosen for this analysis as discussed later in Section 8.3.1.

8.3.1 River Bed Profile

Satluj river bed downstream of Nathpa dam up to first 6.815 km was surveyed. The river bed and banks are largely rocky and the flow is negligible immediately downstream of Nathpa dam but increases along the reach downstream. River bed profile (transverse cross-sections of the Satluj river bed) at four locations in initial 10.8 km reach d/s of Nathpa dam have been measured. Longitudinal section of the considered reach has also been prepared.

Plan of river bed

Figure 8.2 is a photographic view of Satluj river bed between Nathpa dam and 6.815 km downstream of it as seen during May' 2005. The plan view of river bed has been constructed from a large number of photographs taken in sequence at 17 locations. Bed width of river varies significantly in the range of 25m to 70m. Average bed width in the reach is 51.575m. Seepage flow from Nathpa dam is not visible due to rocky nature of the bed. River bed width is not uniform. Further the bed comprises of large and small size boulders. Flow appears to be confined.

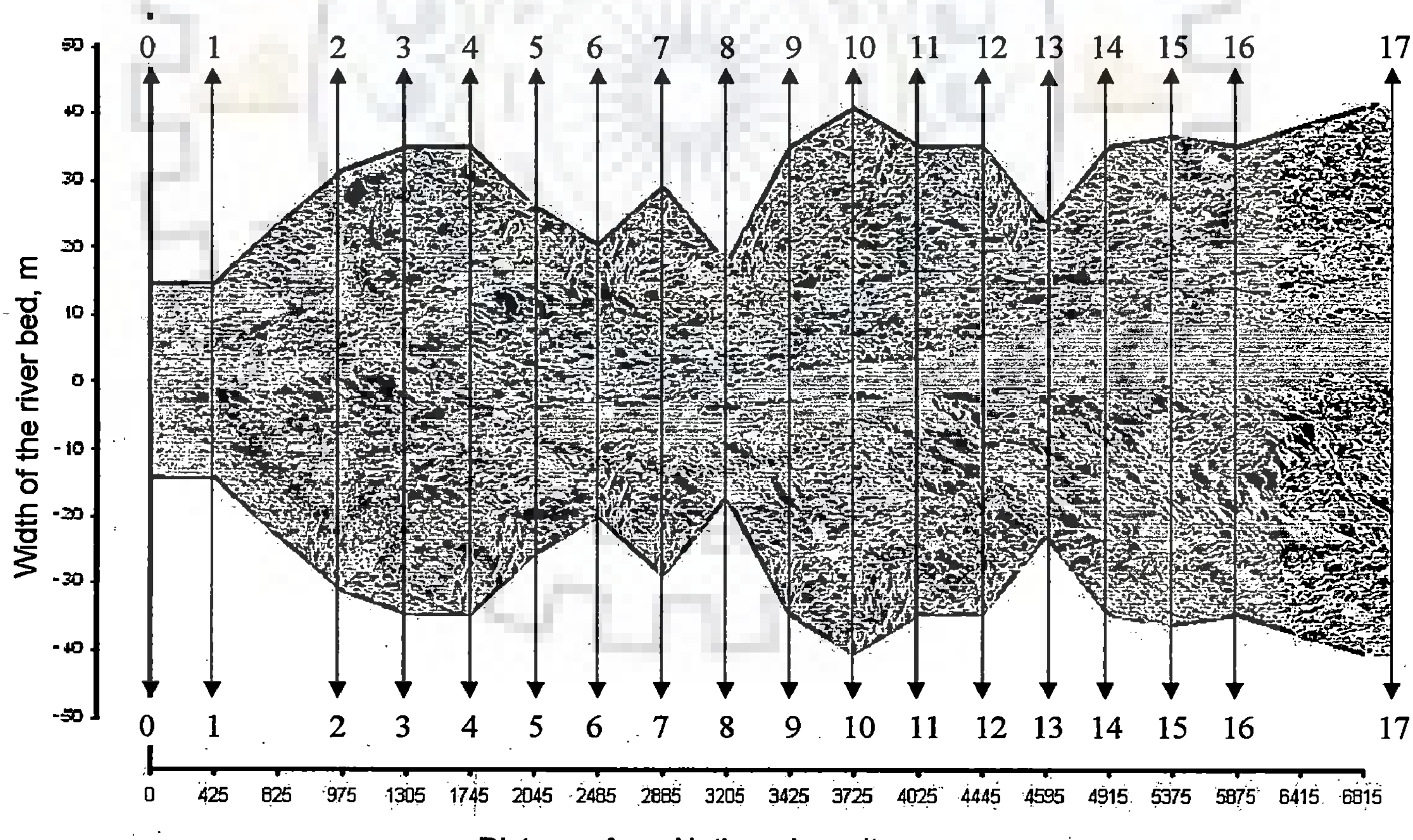


Figure 8.2: Satluj river bed plan from Nathpa dam to Sholding stream confluence

Longitudinal section between Nathpa and Jhakri

Figure 8.3 shows elevation of river bed upto 40 km distance from Nathpa dam.

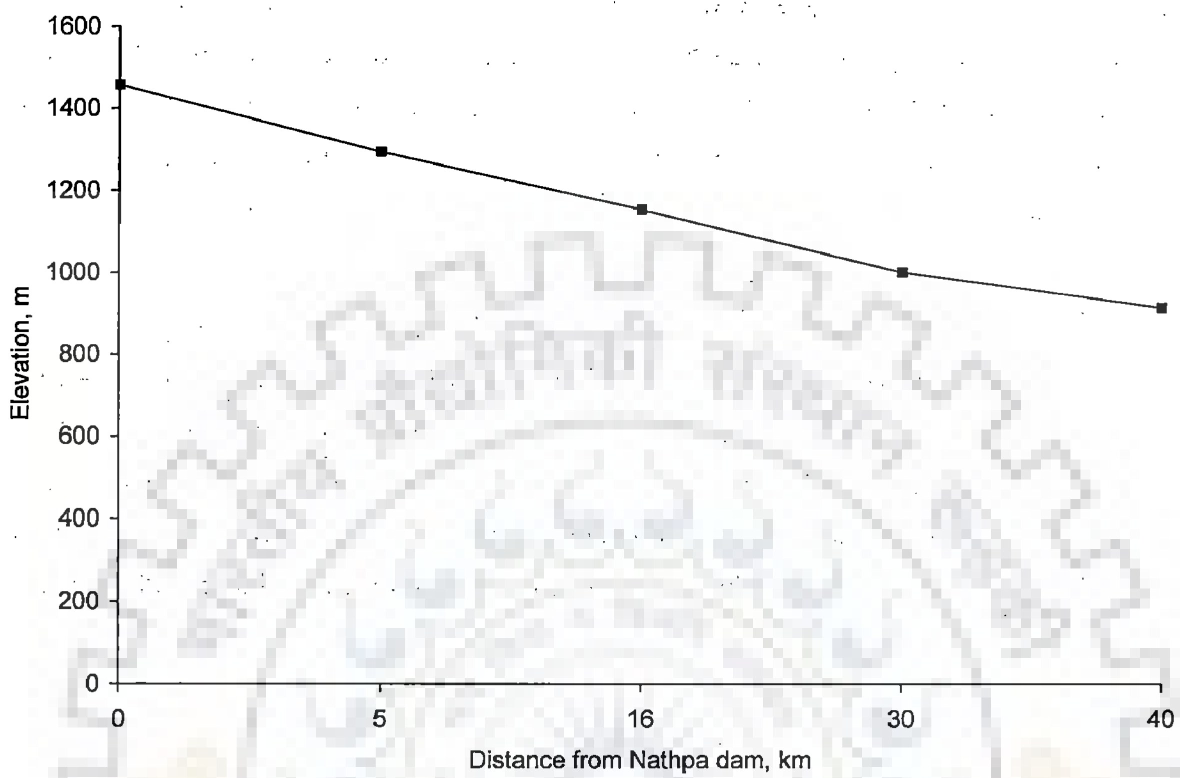


Figure 8.3: Longitudinal section of Satluj river between Nathpa and Rampur

River bed profile

Figure 8.7 to Figure 8.10 show transverse profile of Satluj river bed at following locations.

Site No.	Chainage from Nathpa dam	Locations d/s of Nathpa dam	Bed width	Figure
1.	100 m	Just d/s of Nathpa dam	40 m	8.4
2.	1.7 km	After confluence of three tributaries near Nathpa dam	41 m	8.5
3.	3.5 km	After confluence of Shilaring stream	60 m	8.6
4.	10.8 km	After confluence of Chaunda stream	60 m	8.7

8.3.2 Width, Depth and Ratio of Width to Depth for Required Discharge and Velocity

At each of the four sections flow area and related top width of flow and depth of flow (in deepest section) have been worked out. Variation in top width (W), depth in deepest section (D) and ratio of W/D with change in flow area are depicted in Figure 8.4 to Figure 8.6 at these four locations.

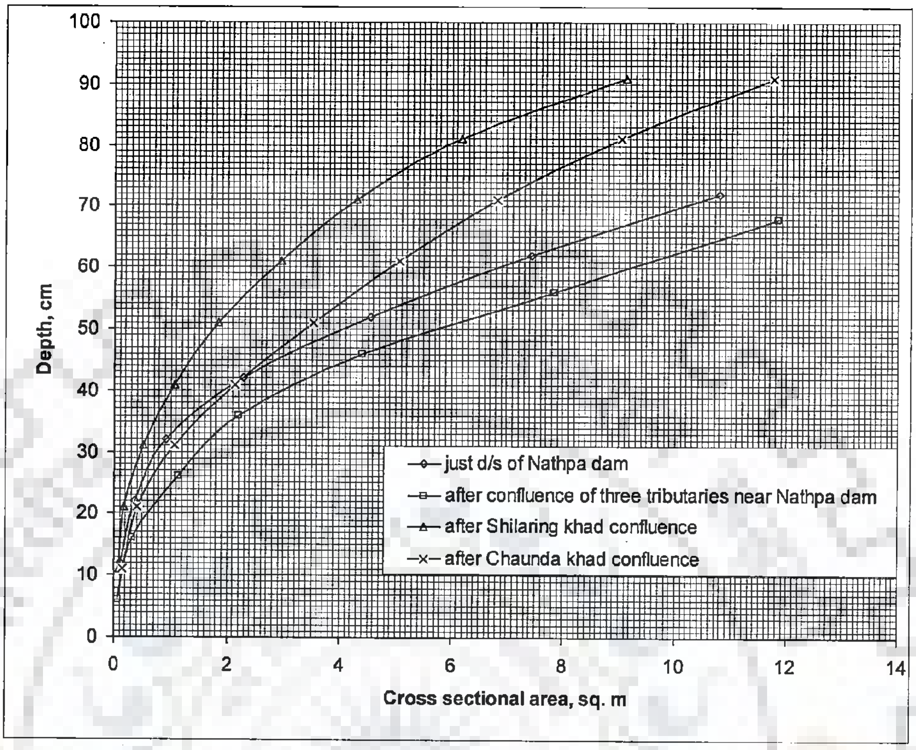


Figure 8.4: Relationship between cross sectional area and depth

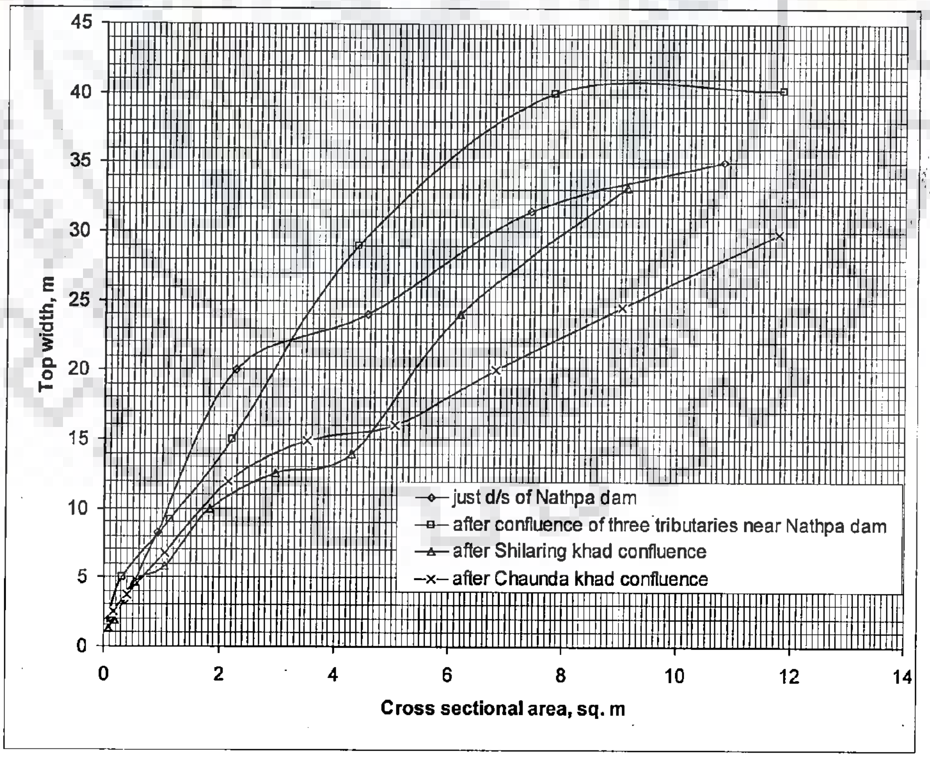


Figure 8.5: Relationship between cross sectional area and top width

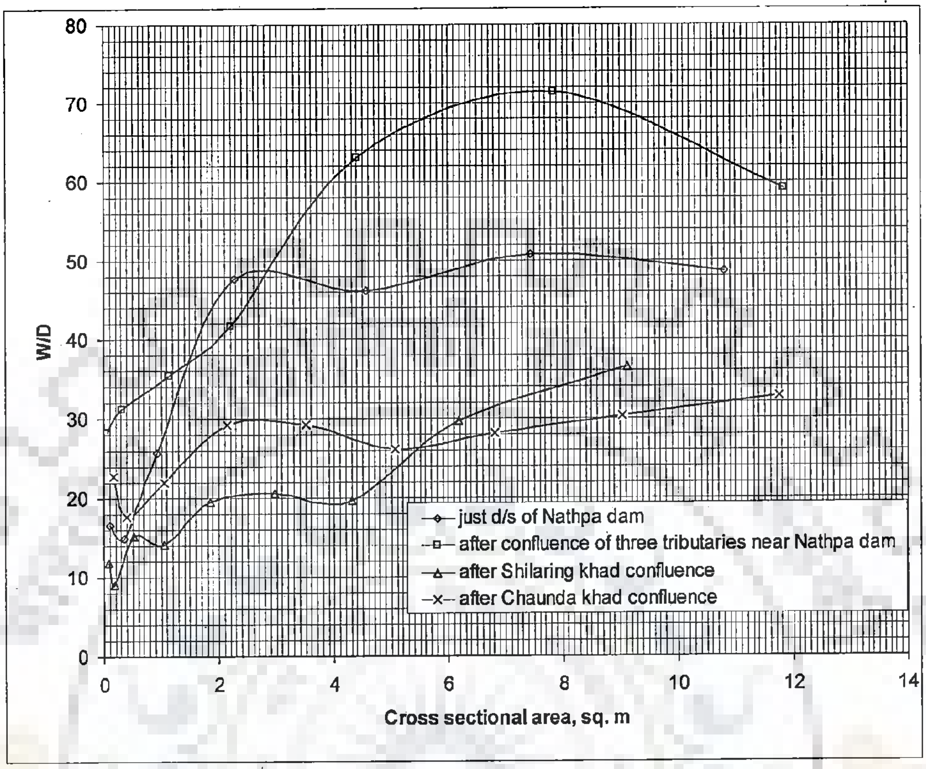


Figure 8.6: Relationship between cross sectional area and W/D ratio

8.3.3 Assessment of Environmental Flows

For the habitat of aquatic life, parameters such as width/depth ratio of flow, bed submergence and velocity of flow are important. For silt flushing, velocity of flow is as important as the discharge. Same discharge on different river bed profiles may produce different habitat conditions due to non-uniformity and irregularity in river bed.

During the pre-project condition, a major part of river bed used to be in submerged condition. Similar bed submergence in lean season is not possible during the post-project condition. Analysis has been carried out to assess bed submergence at the four sections with different releases from Nathpa dam.

Releases from Nathpa dam in the range of 2 cumec to 10 cumec have been considered. A favourable velocity from various considerations (flushing, DO, aquatic life) is taken as 1.2 m/s (DHI, 2006). For a particular release from Nathpa dam, the resulting flow at various sections have been arrived at by addition of lowest flow contribution from the in-between tributaries as given in Annexure 7.3. The lowest flows correspond to January/February month which are 0.08 cumec, 1.51 cumec and 2.67 cumec before section 2, 3 and 4 respectively. Required flow area is given by the ratio of required discharge/required velocity. Then resulting D, W and W/D at various sections for various discharges and flow velocity of 1.2 m/s are read from Figure 8.4 to Figure 8.6. These are summarized in Table 8.3. Figure 8.7 to Figure 8.10 show the resulting discharge, depth and submerged bed width (as % of river bed width) at the four sections corresponding to various releases from Nathpa dam (2 cumec to 10 cumec).

It is seen that with release of 7 cumec the resulting flows at various sections (7, 7.08, 8.59 and 11.26 cumec) will cause bed submergence of 72.5%, 85.4%, 46.7% and 41.7% at Section 1, 2, 3 and 4 respectively in the month having lowest flow. This amount of bed submergence appears to be satisfactory in consideration of habitat requirement. Bed submergence will be higher in other months due to higher flows. It is therefore concluded that minimum release from Nathpa dam may be 7 cumec.

Table 8.3: Releases from Nathpa dam and resulting hydraulic parameters at various sections

		Releases from Nathpa dam (cumec)			
		2	**5**	**7**	**10**
Hydraulic Parameters at Section 1					
Chainage = 100 m	Discharge (cumec); Q	2	5	7	10
Total bed width (T) = 40 m	Cross sectional area (sq. m); A	1.7	4.2	6.3	8.3
	Depth (m); D	0.38	0.51	0.58	0.65
Elevation = 1450 m	Submerged bed width (m); W	16	23	29	33
	W as % of T (%)	**40**	**57.5**	**72.5**	**82.5**
	W/D	42.1	45.1	50.0	50.8
Hydraulic Parameters at Section 2					
Chainage = 1.7 km	Discharge (cumec); Q	2.08	5.08	7.08	10.08
Total bed width (T) = 41 m	Cross sectional area (sq. m); A	1.7	4.2	5.9	8.4
	Depth (m); D	0.38	0.48	0.54	0.62
Elevation = 1400 m	Submerged bed width (m); W	16	23	35	40
	W as % of T (%)	**39.0**	**56.1**	**85.4**	**97.6**
	W/D	42.1	47.9	64.8	64.5
Hydraulic Parameters at Section 3					
Chainage = 3.5 km	Discharge (cumec); Q	3.59	6.59	8.59	11.59
Total bed width (T) = 60 m	Cross sectional area (sq. m); A	3.0	5.5	7.2	9.7
	Depth (m); D	0.6	0.79	0.82	0.96
Elevation = 1300 m	Submerged bed width (m); W	12	21	28	35
	W as % of T (%)	**20.0**	**35.0**	**46.7**	**58.3**
	W/D	20.0	26.6	34.1	36.5
Hydraulic Parameters at Section 4					
Chainage = 10.8 km	Discharge (cumec); Q	6.26	9.26	11.26	14.26
Total bed width (T) = 60 m	Cross sectional area (sq. m); A	5.2	7.7	9.4	11.9
	Depth (m); D	0.61	0.78	0.81	0.85
Elevation = 1225	Submerged bed width (m); W	17	22	25	30
	W as % of T (%)	**28.3**	**36.7**	**41.7**	**50.0**
	W/D	27.9	28.2	30.9	35.3

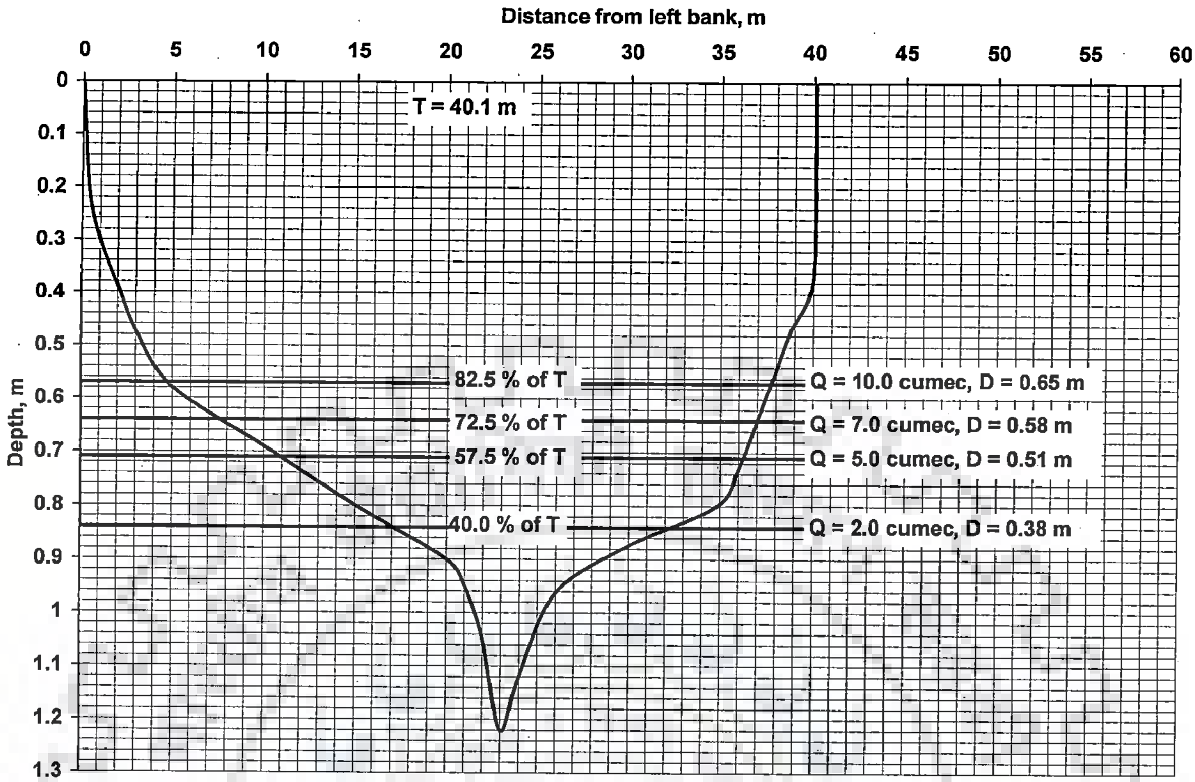


Figure 8.7: Hydraulic parameters at section 1

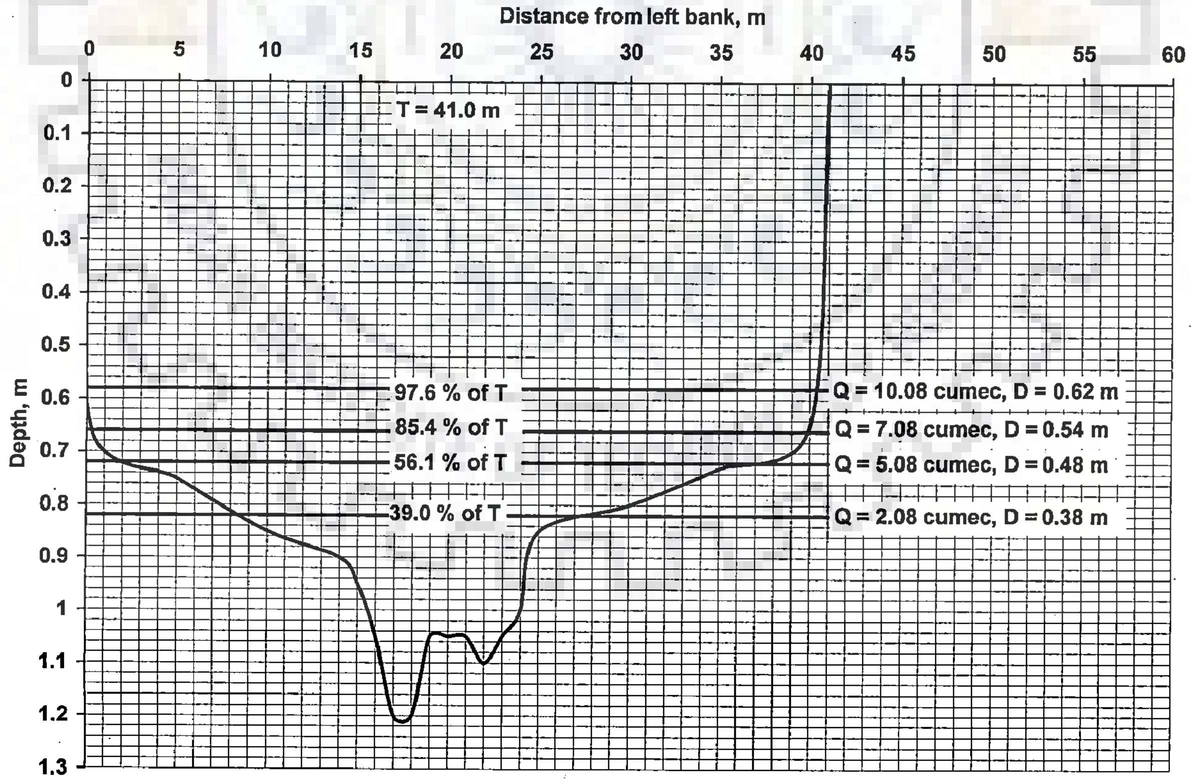


Figure 8.8: Hydraulic parameters at section 2

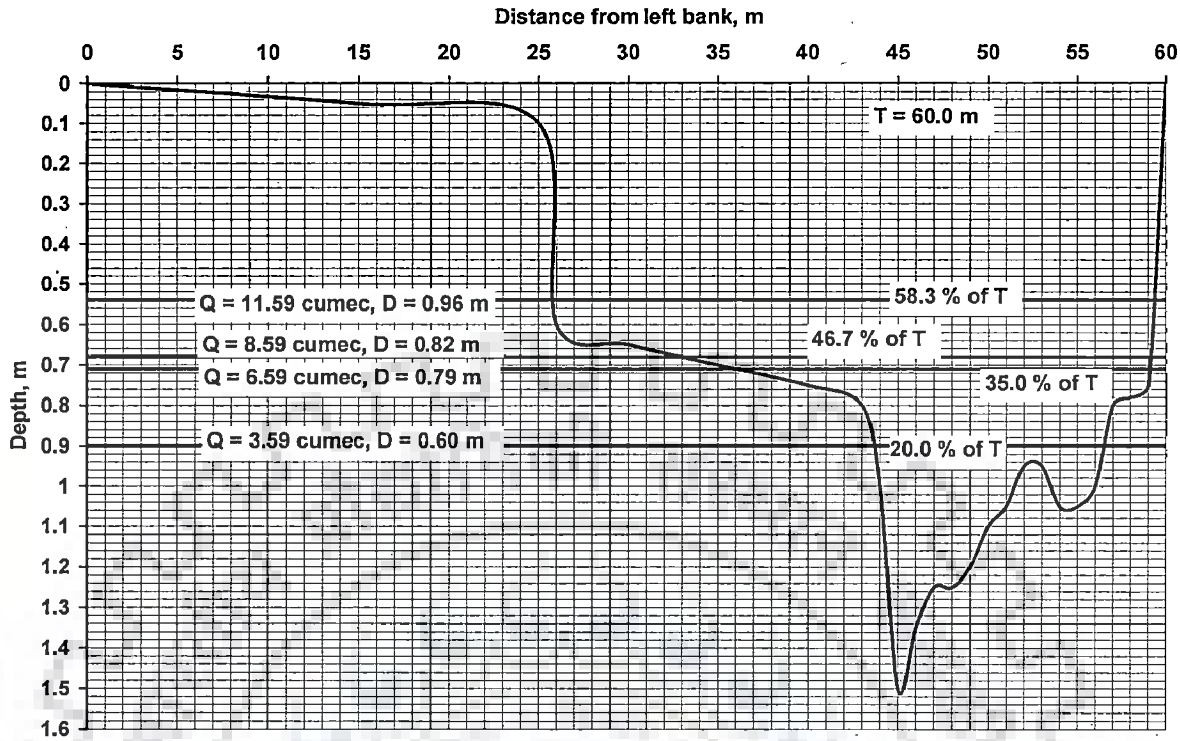


Figure 8.9: Hydraulic parameters at section 3

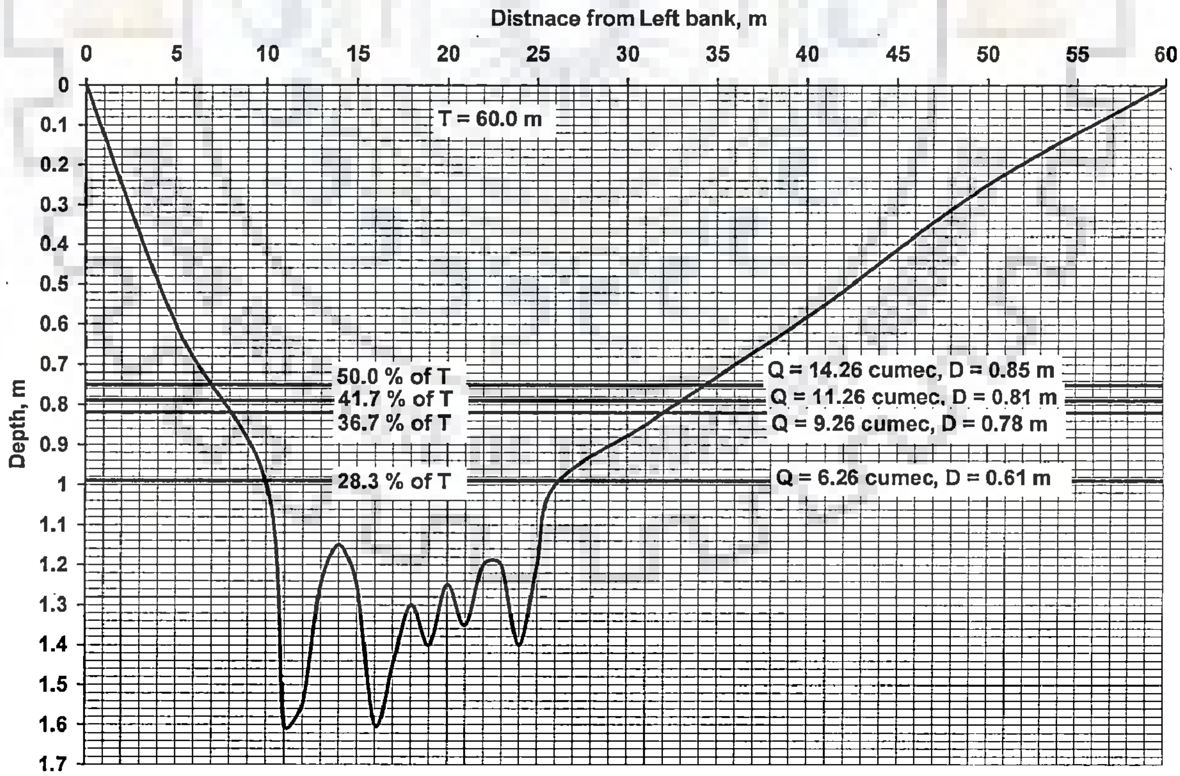


Figure 8.10: Hydraulic parameters at section 4

8.4 TRADEOFF BETWEEN ENVIRONMENTAL FLOW AND POWER GENERATION

Power generated at Jhakri Power House of NJHEP depends on discharge and head. Power function is defined as the power generated per unit of flow for a given head. Taking power plant efficiency as 0.89 and head of 425m as given in project report (NJPC, 1985), the power function is:

Power Function	=	9.81 X e X H kW/cumec
	=	9.81 X 0.89 X 425 kW/cumec
	=	3710.633 kW/cumec
	=	3.711 MW/cumec

Each unit of flow released d/s of Nathpa dam (as environmental flow requirement) instead of being utilized for power generation, will result in a loss of 3.711 MW. The power loss corresponding to environmental flow of 7 cumec is 26 MW.

Design discharge corresponding to 1500 MW design capacity is 405 cumec. The available 10-daily flow at Nathpa from 1985 to 2001 shows that flows at Nathpa dam are higher than 412 cumec (405 cumec design discharge + 7 cumec environmental flow) during May to August only. Therefore, loss in power generation due to environmental flow release downstream of Nathpa dam is likely to occur during September to April.

Hydropower has several socio-economic benefits for population in the vicinity of the project. A detailed study of tradeoff between power generation and its related socio-economic benefits on one hand and value of aquatic and terrestrial ecosystem components on the other hand is beyond the scope of this research.

8.5 CONCLUSIONS

1. The environmental flows have been assessed using various methods (i) lookup tables; (ii) hydrological method (FDC analysis) and (iii) by hydraulic habitat analysis.

(i) Lookup table approach: The different lookup methods suggest different values of environmental flows ranging from 2.475 cumec (CWC guidelines) to 80 cumec (practice followed in UK proposed by Barker and Kirmond (1998)).

(ii) FDC approach: The EF for EMC 'A' is almost equal to the EF as per practice followed in UK (Environmental Agency, 2002). EF for EMC 'F' is equal to the EF as per practice followed in USA (Tenant, 1976).

(iii) Hydraulic habitat analysis: EF is prescribed in terms of discharge (7 cumec), favourable velocity (1.2 m/s) and bed submergence greater than 41.7%.

2. Hydraulic habitat analysis is recommended for environmental flow assessment. Based on the analysis carried out in Chapter 8 (Section 8.3) and Chapter 5 (Section 5.7), the environmental flow may be prescribed as below:

(i). Release d/s of Nathpa dam should be at least 7 cumec. This release alongwith tributary inflows will cause submergence of 41.7% to 72.5% of bed width in the critical reach (10.8 km d/s of Nathpa dam) in the month having lowest flow. This amount of bed submergence is considered to be satisfactory in consideration of habitat requirement. Bed submergence will be higher in other months due to higher flows.

(ii) The velocity of 1.2 m/s should be maintained in consideration of silt flushing and maintenance of dissolved oxygen content and aquatic life.

(iii) Satluj WQI should be higher than 47 (for rainy season) and 55 (for lean season) based on CPCB criteria for outdoor bathing and Aquatic Life Turbidity Criteria

For further improvement in hydraulic habitat, flow should be managed as discussed below.

- Rapid flow decreases should be avoided because fish and macro-invertebrates may get trapped in off-channel habitats during rapid flow decreases.
- Flow should be allowed to gradually decline in winter season but not to the extent where river would recede to disconnected pools.
- Log weirs or wire gabions may be used to increase river bed submergence and create pool riffle habitat units at 200 m interval from Nathpa dam to Sholding confluence. These structures will normally get damaged/dislocated in monsoon season. Therefore, only temporary structures need to be provided every year after monsoon season and only in Nathpa-Sholding reach.
- Creation of pool riffle habitat units will also enhance aesthetic condition of river in the critical reach downstream of Nathpa dam.
- Adequate connections between pools and river flow reaches should be maintained wherever it is not possible to increase width/depth ratio of flow section.
- Net primary productivity of the riparian area is mainly influenced by physical site conditions, surrounding land use and composition of terrestrial flora rather than by river regulation. Annuals (grass and herbs) are observed at few locations along the river bank. Flow should be channelized along bank having riparian vegetation or width/depth ratio of the flow section should be increased.

3. Each unit of flow released d/s of Nathpa dam (as environmental flow requirement) instead of being utilized for power generation, will result in a loss of 3.711 MW. The power loss corresponding to environmental flow of 7 cumec is 26 MW.

Loss in power generation due to environmental flow release downstream of Nathpa dam is likely to occur during September to April. In this period flow at Nathpa dam is not sufficient to meet diversion requirement (405 cumec) for power generation of 1500 MW and environmental flow requirement (7 cumec) downstream of Nathpa dam.

Hydropower has several socio-economic benefits for population in the vicinity of the project. A detailed study of tradeoff between power generation and its related socio-economic benefits on one hand and value of aquatic and terrestrial ecosystem components on the other hand is beyond the scope of this research.

CHAPTER – 9
CONCLUSIONS

Efforts made by scientists in different parts of the world on EFA (methods, methodologies, approaches) vary in terms of available data and knowledge base particularly with regard to the biotic data and socio-economic relevance of EF. Some of these are subjective in nature. Further, impacts of application of these EFA methodologies in river reaches are not yet fully known.

Limited literature is available on Environmental Water Requirement (EWR) of terrestrial ecosystem. The EWR of terrestrial ecosystems are currently not explicitly considered (Smakhtin and Anputhas, 2006). Components of a hydropower project and the related impacts are spread over a river reach. Therefore, EWR is also important in addition to EFR as both are interlinked.

Present prediction and quantification of the biotic response to flow alteration can be done only with limited ability as long-term observations (over several years) on biological response are not available. Therefore, EFA methodologies requiring hydrologic and hydraulic data as input have been usually preferred by researchers and decision makers.

The research on EFA in India has recent origin. Though, ecology has been accorded a relatively lower (fourth) priority in National Water Policy document (2002), importance of water use for fresh water ecosystems has been emphasized in various national and state level documents in recent past. India differs from developed countries in addressing the problem of EFR due to several factors such as (i) direct use of river water by people for meeting social and religious needs (ii) importance of irrigation and hydropower in national economy (iii) prevalence of tropical monsoon hydrology and (iv) water being a State subject in the Constitution of India.

Several hydroelectric schemes in Satluj basin are in different stages of implementation. These schemes individually or in combination may have significant flow related impacts. Keeping in view the research gaps and objectives of the study, EFA study of Nathpa Jhakri Hydroelectric Project (NJHEP) and Rampur Hydroelectric Project (RHEP) has been carried out. The NJHEP is in operation stage and the diverted water (at Nathpa dam) is at present released back into Satluj after power generation at Jhakri. RHEP is under construction. The RHEP will make use of the water released in the tail race pool after power generation at Jhakri. Most of the project components are underground.

The conclusions drawn from study are arranged as below:

1. Flow related impacts on aquatic biodiversity
2. Water quality indexing and flow related impacts
3. Environmental Water Requirement of terrestrial ecosystem
4. River mapping and lean season flow characteristics
5. Assessment of environmental flows using various methods

9.1 FLOW RELATED IMPACTS ON AQUATIC BIODIVERSITY

Principles proposed by Bunn and Arthington (2002) form the basis for this assessment.

(i) Reduced flows immediately downstream of dam explains absence of hydropsyche.

(ii) Sudden increases in flow downstream of Nathpa dam may cause significant downstream drift of macroinvertebrates.

(iii) Hydrologic factors for fish being scanty in the study reach of river Satluj are (i) unstable flow regime (ii) continuous physiological stress due to loss of energy in maintaining their position in fast flowing waters (iii) frequent change in structure and consistency of river bed caused by high velocity of flow during floods.

(iv) The release of cooler water downstream of Jhakri power house can influence the spawning behaviour of fish and life history process of invertebrates in the downstream. After implementation of RHEP, cooler water downstream of Jhakri power house will be diverted into tunnel which may favour spawning of fish in Satluj reach upto Bael.

(v) Nathpa dam has transformed small length of the river Satluj into a pool habitat on upstream. Conversion of lotic to lentic habitat will result in the loss of fishes adapted to turbid riverine habitats. Creation of standing water body upstream of Nathpa dam is likely to favour introduced species. However, downstream of Nathpa dam long-term success of invading or introduced species is unlikely due to unstable flow regime.

9.2 WATER QUALITY INDEXING AND FLOW RELATED IMPACTS

In the present study, three indices have been used to assess water quality; namely NSF-WQI, CPCB-WQI and Satluj-WQI. NSF-WQI is based on 9 parameters, all of which may not be important with reference to bathing and river ecology. CPCB-WQI is an index suitable for assessing bathing water quality. It does not include turbidity. Therefore, a new index (Satluj-WQI) based on 5 parameters (DO, BOD, pH, Faecal coliform and turbidity) is proposed in the context of EFA as it considers turbidity also.

The Satluj WQI standard value has been calculated considering river bathing standards as per CPCB criteria and Aquatic Life Turbidity Criteria (for lean season and rainy season). Though, the Satluj WQI is higher than Satluj WQI standard at all the locations and also during rainy season and lean season, excessive turbidity due to silt flushing during the post-project condition will have adverse impact on the aquatic life. The lean season Satluj WQI at D/S of Rampur for the post-NJHEP and post-RHEP condition just meets the standard and therefore represents the critical condition.

9.3 ENVIRONMENTAL WATER REQUIREMENT OF TERRESTRIAL ECO SYSTEM

The annual evapotranspirative demand of vegetation is 64 MCM. It is based on classification of area under ten land uses in the tributary catchments and estimation of actual evapotranspiration under different land uses. The domestic water needs of human population (2.813 MCM), animal water need (0.67 MCM) are based on estimated population and daily water requirements for summer and winter seasons.

Analysis of 26 years concurrent rainfall data at Nichar and Rampur shows that the area is prone to meteorological drought. Improvement in soil moisture characteristics is essential as the soils are shallow and evapotranspirative demand of natural vegetation is high.

The extensive tunnelling and other underground excavations (6.0 MCM) in the area have had adverse effect on subsoil water regime and recharging capacity. Based on field observations it has been found that springs and streams have either dried up or lean season flow have reduced. This has had adverse impact on meeting human and animal water needs in the tributary catchments.

Natural vegetation at the muck disposal sites has been destroyed by the dumped material. The analysis shows that the available water holding capacity of the dumped muck is less than 0.08 (vol./vol.) and organic matter content is negligible. Agronomic measures for vegetation growth at the muck disposal sites have not been successful. Measures to improve available water holding capacity are (i) to mix particles of appropriate size, (ii) to incorporate large quantities of dead roots, peat or other organic material, (iii) to reduce percentage of coarse particles to less than 15 % so that the top 2m depth contains soil texture of the type similar to that existing in the area.

9.4 RIVER MAPPING AND LEAN SEASON FLOW CHARACTERISTICS

As an improvement over the previous hydrological studies of Satluj basin, the methodology proposed in this study is based on correlation between discharges of tributaries having similar catchment characteristics. Distinction has been made on the basis of (i) rainfed and snowfed catchments; (ii) durations with and without snowmelt contribution.

Difference in the values of Q90/Q50 for tributaries on right bank (Gaanvi , Bhaba) and left bank (Sholding , Baspa) indicate different normalized baseflow contributions from these catchments and it might be attributed to the amount of precipitation varying with the location of these catchments, whether in forward or leeward zones (Singh and Singh, 2001).Therefore, tributaries in the study area are divided into (i) Left bank tributaries having snow melt contribution, (ii) Right bank tributaries having snow melt contribution and (iii) Tributaries having no snow melt contribution.

Estimated tributary discharges have been used in lean season flow mapping of Satluj river from Nathpa to Jhakri. Important conclusions of river mapping are:

(i) Contributions to lean season flow of Satluj river are mainly from Shilaring khad, Sorang khad, Kut khad, Gaanvi khad, Manglad khad and Sumej khad.

(ii) There is not much difference in January flows during dry, wet and normal years. Flow contribution from October upto January is mainly from ground water which gets nearly depleted by end of January. Beyond January, flow contribution is mainly from snow melt and winter rain.

(iii) Satluj river reach from Nathpa and before confluence of Sorang Khad (about 10.8 km) is a critical reach in the context of environmental flow. Flow in this reach is leanest in January, February months and similar in dry, wet, normal years and the year of monitored flow data i.e. 2005-06.

Low flow analysis of Satluj river at three locations i.e. (i) Nathpa, (ii) d/s of confluence of Sholding khad and (iii) Rampur have been carried out. Flow variability (represented by ratio Q20/Q90) from pre to post NJHEP condition is found to be more prominent compared to that of pre to post-RHEP condition. The ground water contribution to flow (represented by ratio Q90/Q50) have increased after implementation of NJHEP. This is due to the fact that main contribution to flow during lean season is from tributary catchments.

9.5 ASSESSMENT OF ENVIRONMENTAL FLOWS

The environmental flows have been assessed using three methods viz. (i) lookup tables, (ii) Environmental Management Class based FDC approach and (iii) hydraulic habitat analysis. The hydraulic habitat analysis is recommended for environmental flow assessment. The environmental flow may be prescribed as below:

(i) Release d/s of Nathpa dam should be at least 7 cumec. This release alongwith tributary inflows will cause submergence of 41.7% to 72.5% of bed width in the critical reach (10.8 km d/s of Nathpa dam) in the month having lowest flow. This amount of bed submergence is considered to be satisfactory in consideration of habitat requirement of aquatic life.
(ii) The velocity of 1.2 m/s should be maintained in consideration of silt flushing and maintenance of dissolved oxygen content and aquatic life.
(iii) Satluj WQI should be higher than 47 (for rainy season) and 55 (for lean season) based on CPCB criteria for outdoor bathing and Aquatic Life Turbidity Criteria

Each unit of flow released d/s of Nathpa dam (as environmental flow requirement) instead of being utilized for power generation, will result in a loss of 3.711 MW. The power loss corresponding to environmental flow of 7 cumec is 26 MW.

Loss in power generation due to environmental flow release downstream of Nathpa dam is likely to occur during September to April. In this period flow at Nathpa dam is not sufficient to meet diversion requirement (405 cumec) for power generation of 1500 MW and environmental flow requirement (7 cumec) downstream of Nathpa dam.

9.6 IMPORTANT RESEARCH CONTRIBUTION

i) The environmental flow assessment (EFA) practice in India has recent origin. This study contributes to limited literature on EFA in India and particularly to the Himalayan region wherein a large number of hydropower projects are being implemented.
ii) Flow requirements downstream of river valley projects in India are prescribed in terms of certain minimum flow or in terms of hydrological indices. This study is important as it attempts to incorporate hydrologic, hydraulic and ecological aspects in EFA and provides scientific basis for prescription of EF.
iii) Flow related impacts of a hydropower scheme are spread over a river reach and associated tributary catchments. Present study considers environmental water requirements of the tributary catchments also as these are distinct from environmental flow requirement in a river reach.
iv) As an improvement over the previous hydrological studies of Satluj basin, the methodology proposed in this study is based on correlation between discharges of tributaries having similar catchment characteristics. Distinction has been made on the basis of (i) rainfed and snowfed catchments; (ii) durations with and without snowmelt contribution.

v) Water quality index proposed by Central Pollution Control Board of India (CPCB-WQI) is an index suitable for assessing bathing water quality. It does not include turbidity which is an important consideration in environmental flow. A new index incorporating turbidity parameter (Satluj water quality index) has been proposed which is more appropriate in the context of environmental flow assessment. Water quality standard for EFA in terms of acceptable value of Satluj WQI has been prescribed.

9.7 SCOPE FOR FURTHER RESEARCH

As stated earlier, research on EFA in India is of recent origin. In the present study, several aspects of EFA as relevant to hydropower projects in Himalayan region have been dealt through case study of NJHEP on Satluj river. Direct water use of Satluj river water between Nathpa and Jhakri is almost negligible as the river flows through deep gorge. The EFA study needs to be carried out for other Himalayan rivers (such as tributaries of Ganga and Yamuna). These rivers are more influenced by anthropogenic activities and have great religious significance to vast population from all over the country. As is evident from coverage of various aspects, multidisciplinary study requiring expertise from various fields is needed for EFA. Field based studies of Himalayan rivers in the following areas are suggested for improving EFA methodology:

1. Pollution due to mass bathing in the rivers and flow requirements related to mass bathing
2. Hydraulic habitat requirements for existing species (particularly fish) in Himalayan rivers
3. Water quality assessment based on abundance of macroinvertebrates at different levels of pollution

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ANNEXURE 3.1: MINIMUM FLOW STUDIES IN INDIAN RIVERS

(A) Ganga and Yamuna river basins

Site	River	Minimum flow as % of		Non-monsoon flow as % of		Monsoon flow as % of		99%le Annual peak (cumec) as % of	
		Annual 75 %le	Annual mean	Annual 75 %le	Annual mean	Annual 75 %le	Annual mean	75 %le Annual dis-charge	Annual mean dis-charge
Rishikesh	Ganga	18.20	16.60	11.06	10.1	56.39	51.3	377	343
Tehri	Baghirathi	14.69	13.00	4.53	4.00	60.51	53.9	331	295
Rudrapayag	Alakananda	18.75	22.60	12.87	11.3	65.22	57.4	258	227
Tuni	Tons	24.22	24.40	15.00	12.2	51.02	41.4	231	187
Yaswantnagar	Giri	13.92	16.60	11.68	8.3	25.61	18.1	444	314

It may be seen that the minimum observed 10 daily flows with 99% exceedence expressed as a percentage of the 75% dependable Annual Flow varies from 13.92% to 24.22 % at various sites. Similarly the Annual peak flow expressed as a percentage of the 75% dependable Annual flow varies from 231% to 444%. These figures as well as the figures for Naugaon in the table below can be taken as for near virgin conditions.

(B) Krishna and Godavari river basins

Site	River	Minimum flow as % of		Non-monsoon flow as % of		Monsoon flow as % of		99%le Annual peak (cumec) as % of	
		Annual 75 %le	Annual mean	Annual 75 %le	Annual mean	Annual 75 %le	Annual mean	75 %le Annual flow	Annual mean flow
Sadalga	Dudhganga	0.00	0.00	0.00	0.00	53.21	37.35	1002	697
Huvinhedgi	Krishna	0.72	0.57	1.70	1.28	54.21	40.77	936	705
Yadgir	Bhima	0.00	0.00	0.46	0.34	40.68	30.52	747	562
K. Agraharam	Krishna	0.62	0.42	1.49	0.99	69.33	45.88	764	506
Pathagudem	Indravati	0.54	0.40	0.83	0.62	58.62	43.88	851	637
Tekra	Pranahita	0.56	0.36	1.29	0.83	50.36	32.21	706	452
Injaram	Sabari	4.60	3.50	4.42	3.36	52.05	39.52	652	494
Polavaram	Godavari	4.04	2.66	3.90	2.57	59.38	39.14	647	427

It may be seen that the minimum observed 10 daily flows with 99% excedence expressed as a percentage of the 75% dependable Annual Flow varies from zero to 4.8 % at various sites. Similarly the Annual peak flow expressed as a percentage of the 75% dependable Annual flow varies from 647% to 1002%.

(C) Southern tributaries of Yamuna river

Site	River	Min. Flow as % of		Non-monsoon flow as % of		Monsoon flow as % of		99%le annual peak (cumec) as % of	
		Annual 75%le	Annual mean	Annual 75%le	Annual mean	Annual 75%le	Annual mean	75%le annual discharge	Annual mean discharge
Naogaon	Yamuna	21.93	18.70	5.93	5.07	50.15	42.91	250	214
Kalanaur	Yamuna	2.10	1.02	1.09	0.53	24.60	11.93	685	332
Kalpi	Yamuna	7.62	5.98	5.69	4.48	52.17	41.05	122	96
Delhi	Yamuna	0.00	0.00	2.60	1.47	27.12	15.34	461	261
Mathura	Yamuna	1.12	0.50	3.67	1.63	22.27	9.88	339	150
Pratappur	Yamuna	6.77	4.78	4.13	2.92	44.61	31.53	583	412
Burhanpur Virgin Flow	Tapi	0.74	0.48	0.24	0.16	43.92	29.05	620	410

It may be seen that the minimum observed 10 daily flows with 99% excedence expressed as a percentage of the 75% dependable Annual Flow varies from zero to 21.93 % at various sites. Similarly the Annual peak flow expressed as a percentage of the 75% dependable Annual flow varies from 122% to 620%. However excepting Naugaon all other sites excepting Burhanpur on Tapi are affected by upstream diversions and hence cannot be taken as virgin sites. The Burhanpur site needs to be grouped with other peninsular rivers.

ANNEXURE 4.1

LIST OF REPORTS AND DOCUMENTS COLLECTED FROM VARIOUS AGENCIES

S. N.	Agency	Literature
1.	SJVNL, Shimla	NJHEP EIA Report NJHEP DPR (Hydrology part) HP Census 2001 (soft copy)
2.	NJHEP, Jhakri	Report on ER & R activities by SJVNL
3.	HPSEP&PCB	Report on water, soil and ambient air quality
3.	HPSEB, Shimla	Hydrology part of DPR of following hydroelectric projects: (i) Ganvi Stage II, (ii) Uhl Stage III, (iii) Kasang, (iv) Baspa Stage II, (v) Sanjay Vidyut Pariyojna (Bhaba)
5.	Himurja, Shimla	Hydrology part of DPR of following small hydropower projects: (i) Sailan, (ii) Panwi, (iii) Chaunda, (iv) Rakchad
6.	HP IPH, Rampur	1. Report on "Augmentation of sources WSS under I&PH section Gaura in Tehsil Rampur Distt. Shimla H.P. (effected due to c/o NJPC tunnel) 2. Report on water supply schemes in Nathpa-Jhakri reach
7.	NIH, Roorkee	Reports on: 1. Snow and glacier contribution in the Satluj river at Bhakra dam 2. Streamflow simulation of Satluj river using UBC watershed model 3. Temperature lapse rate study in Satluj catchment 4. Sediment yield estimation for lower Satluj basin
8.	HP Forest Deptt., Rampur	Brief details of Catchment Area Treatment (CAT) Plan
9.	Y. S. Parmar University, Nonni	Literature on flora of Himachal Pradesh
10.	G.B. Pant Intt. of Himalayan Env. & Dev., Kosi Katarmal (Almora), Mohal	Report on catchment area protection works and spring sanctuary development

ANNEXURE 4.2
AVAILABLE HYDROLOGICAL DATA NATHPA JHAKRI REACH

Hydrological data Nathpa Jhakri reach

S. N.	Location	Data
1	Satluj river at Nathpa Dam	Average ten daily discharge from 1926 to 2002 Daily discharge from 18/02/2000 to 31/04/2005 Daily silt content from 01/07/2003 to 31/03/2005 Hourly discharge from 01/01/2005 to 30/06/2006
2	Shilaring Khad	Daily discharge from 01/11/2001 to 31/03/2003
3	Sholding Khad	Average monthly discharge from 1970 to 1996 Average ten daily discharge from 1970 to 1984 Daily discharge from 01/01/2004 to 31/08/2005;
4	Chaunda Khad	Daily discharge from 01/12/1996 to 31/05/1998
5	Sorang Khad	Average ten daily discharge from 01/08/2001 to 28/02/2005
6	Chaura Khad	Daily discharge of Sailan Khad from 01/12/1996 to 21/09/1998
7	Kut Khad	Daily discharge from 01/02/2005 to 31/03/2005
8	Ganvi Khad	Average ten daily discharge from 01/01/1976 to 31/01/2005
9	Sumej Khad	Daily discharge from 01/12/2001 to 31/01/2002; 01/01/2003 to 31/03/2003; 01/08/2003 to 31/08/2003; 01/01/2004 to 29/02/2004
10	Satluj at TRT Outfall Jhakri	Daily discharge from 01/07/2003 to 31/07/2003; 01/09/2003 to 30/09/2003; 01/11/2003 to 31/12/2003; 01/03/2004 to 28/02/2005

*Sailan Khad is a tributary of Chaura Khad which meets Satluj in Nathpa – Jhakri reach

Hydrological data for catchments u/s of Nathpa

Khad/river	Data
Kasang Khad	Average ten daily discharge from 01/11/1996 to 31/08/1998
Baspa river	Average ten daily discharge at Sangla from 01/01/1965 to 30/09/1991
Bhaba Khad	Average ten daily discharge of Bhaba Khad at Humta from 01/01/1980 to 31/08/1998 Average ten daily discharge of Kangti Nallah/Shango Khad at Surchoo from 01/06/1986 to 31/05/2000
Panwi Khad	Daily discharge from 18/04/1996 to 28/02/1998

ANNEXURE 4.3: AVAILABLE METEOROLOGICAL DATA

Meteorological data for Nathpa-Jhakri reach

Jhakri	Daily temperature and rainfall at Jhakri for Nov to Dec 2001, June 2003, October 2003 01/11/2001 to 31/12/2001
Nichar	Daily rainfall at Nichhar (DFO Nichhar) from Jan 1995 to Dec 1996 and Jan 1998 to Sep 2005
	Monthly rainfall data (Nichhar Tehsil) from 1963 to 1998
	Monthly snowfall at Nichhar (DFO Nichhar) in mm from 1979 to 1996
Sumej Khad	Daily temperature at Sumej Khad from 01/01/2003 to 31/03/2003
Rampur	Daily rainfall at Rampur (Rampur Tehsil) in mm from 01/01/1996 to 27/08/1998
	Monthly rainfall at Rampur in mm from Jan 1975 to Dec 2004
	Max. and min. monthly temperature from 1977-1988 and 1992-2004

Meteorological data for catchments u/s of Nathpa

S. No.	Data
1.	Monthly and annual rainfall normals in mm at Kalpa, Purbani, Sangla and Kilba
2.	Average monthly rainfall in mm at Sangla, Purbani, Kalpa, Nichar, Khandrala, Pancha and Keylong

ANNEXURE 4.4

BROOKS AND COREY MODEL AND ITS APPLICATION

SOIL WATER RETENTION CHARACTERISTIC

Water retention characteristic of the soil describes the soil's ability to store and release water and is defined as the relationship between the soil water content (θ) and the soil suction or matric potential (h). Other terms that are synonymous with matric potential but may differ in signs or units are soil water suction, capillary potential, capillary pressure head, matric pressure head, tension and pressure potential. Matric potential is the measure of the energy status of water in soil. Since unsaturated soil water pressures are less than atmosphere, the capillary pressure and matric potential are negative numbers.

Brooks and Corey Model

The simplest method for estimating h(θ) is to use soil texture reference curves. Water retention curves for USDA soil textures are available in literature (Maidment, 1992). Also, soil water content and matric potential have a power function relationship. The model proposed by Brooks and Corey (1964) to describe this relationship is as follows:

Soil water retention $$\frac{\theta-\theta_r}{\phi-\theta_r}=\left(\frac{h_b}{h}\right)^{\lambda}$$

. . (1)

Where,

λ = pore size index = $f_1(C, \Phi, S)$
h_b = bubbling capillary pressure = $f_2(C, \Phi, S)$
θ_r = residual water content of soil = $f_3(C, \Phi, S)$
Φ = porosity (volume fraction)

Estimation of Φ

Soil porosity, $\Phi = 1 - BD/PD$ . . . (2)

Where,

BD = Soil bulk density (g/cc)
PD = Particle density (g/cc); normally assumed to be 2.65 g/cc

As bulk density increases, water retention and hydraulic conductivity near saturation decreases. Also water retention increases as the amount of soil organic matter increases.

(i) For material less than 2 mm,

$$BD = 1.51 + 0.0025 (S) - 0.0013 (S) (OM) - 0.0006 (C) (OM) - 0.0048 (C) (CEC)$$ . . . (3)

Where,

C = percent clay (5 % to 60 %)
S = percent sand (5 % to 70 %)
OM = % organic matter = 1.7 × % organic carbon
CEC = cation exchange capacity of clay; depends on % clay and ranges from 0.1 to 0.9

$$=\frac{\textit{cation exchange capacity of clay}}{\textit{percent clay}}$$

(ii) For material containing particles larger than 2 mm,

Corrected porosity, $\Phi_c = \Phi.CFC$ . . (4)

$$CFC = 1 - VCF/100 \quad \text{. . . (5)}$$

$$VCF = \frac{WCF}{2.65}\left[\frac{100}{(100 - WCF)BD} + 1\right] \quad \text{. . . (6)}$$

Where,

WCF = % weight of coarse fragments

BD = bulk density of soil fraction less than 2 mm; g/cc

Estimation of λ, h_b and θ_r

Brooks and Corey (1964) gave the following regression equations for the estimation of parameters in their model:

$$\lambda = \exp[-0.7842831 + 0.0177544 (S) - 1.062498 (\Phi) - 0.00005304 (S^2) - 0.00273493 (C^2) + 1.11134946 (\Phi^2) - 0.03088295 (S) (\Phi) + 0.00026587 (S^2) (\Phi^2) - 0.00610522 (C^2) (\Phi^2) - 0.00000235 (S^2) (C) + 0.00798746 (C^2) (\Phi) - 0.00674491 (\Phi^2) (C)] \quad \text{. . . (7)}$$

$$h_b = \exp[5.3396738 + 0.1845038(C) - 2.48394546(\Phi) - 0.00213853(C^2) - 0.04356349(S)(\Phi) - 0.61745089(C)(\Phi) + 0.00143598(S^2)(\Phi^2) - 0.00855375(C^2)(\Phi^2) - 0.00001282(S^2)(C) + 0.00895359(C^2)(\Phi) - 0.00072472(S^2)(\Phi) + 0.0000054(C^2)(\Phi) + 0.50028060(\Phi^2)(C)] \quad \text{. . . (8)}$$

$$\theta_r = 0.0182482 + 0.00087269(S) + 0.00513488(C) + 0.02939286(\Phi) - 0.00015395(C^2) - 0.0010827(S)(\Phi) - 0.00018233(C^2)(\Phi^2) + 0.00030703(C^2)(\Phi) - 0.0023584(\Phi^2)(C) \quad \text{. . . (9)}$$

HYDRAULIC CONDUCTIVITY

The hydraulic conductivity is a measure of the ability of the soil to transmit water and depends upon both the properties of the soil and the fluid. Total porosity, pore size distribution and pore continuity are the major soil characteristics affecting hydraulic conductivity.

Brooks and Corey Model

The hydraulic conductivity is a non-linear function of volumetric soil water content and varies with soil texture. Hydraulic conductivity prediction model proposed by Brooks and Corey (1964) is represented by the following equation:

$$\frac{k(\theta)}{k_s} = \left(\frac{\theta - \theta_r}{\phi - \theta_r}\right)^n \quad \text{. . . (10)}$$

Where,

k_s = saturated hydraulic conductivity, cm/h

$n = 3 + 2/\lambda$ . . . (11)

All other terms have the same denotation as for water retention equation (equation 2).

Ahuja et al. (1985) developed a technique for estimation of saturated hydraulic conductivity, which related saturated hydraulic conductivity to an effective porosity (Φ_e, total porosity obtained from soil bulk density minus the soil water content at -33 kPa matric potential) by the following generalised Kozeny-Carman equation:

$$k_s = B\phi_e^{\ n} \quad \text{. . . (12)}$$

where n can be set equal to 4 and B equals 1058 when k_s has the units of cm/h.

Coarse fragments (> 2.0 mm) in the soil in addition to their effect in reducing porosity also affect the saturated hydraulic conductivity of the soil. The saturated hydraulic conductivity of the soil matrix should be multiplied by the following correction for coarse fragments [2]:

$$\text{Coarse fragment correction} = 1 - \frac{\%\,\text{weight of coarse fragments}}{100} \quad \text{. . . (13)}$$

Table 1: Grain size analysis of soil samples

Sample	Location	% finer than size (mm)								
		2	1	0.85	0.6	0.425	0.3	0.15	0.075	0.063
T1	Satluj river bed, Nathpa dam	52.0	46.2	45.8	43.0	36.4	31.6	18.5	10.6	9.8
T2	Left bank of Satluj river, Linge village	75.7	72.9	71.5	68.3	61.9	51.0	39.5	23.9	15.9
T3	Left bank of Satluj river, Linge village	73.7	67.6	65.8	59.4	46.4	40.3	28.5	15.9	10.6
T4	Left bank of Satluj river, Linge village	73.4	65.7	63.1	57.2	45.5	39.2	26.7	11.7	7.1
T5	Sholding Khad, National highway	74.5	68.2	62.8	56.4	48.5	40.6	28.5	11.2	9.0
T6	Chaunda Khad, Nigulsari village	75.4	69.8	66.5	58.3	51.2	43.5	31.0	12.8	11.2
T7	Dharali Khad, Wadhal Dongri village	80.8	73.8	73.6	70.1	63.3	58.4	42.1	33.1	32.2
T8	Unoo Khad, Jeori town	83.4	77.5	77.2	74.8	68.7	63.3	44.4	33.8	32.2

Table 2: Physical and chemical properties of soil samples

Property		OM	S	C	WCF	CEC	BD	Water stable aggregates
Group	Sample	(%)	(%)	(%)	(%)	(meq/100g)	(g/cc)	(%)
1	T1	0.29	42.18	9.82	48.00	7.00	1.56	74.69
2	T2	0.38	59.75	15.90	24.35	10.16	1.58	52.80
	T3	0.51	63.07	10.60	26.33	10.39	1.57	63.00
	T4	0.29	66.34	7.10	26.56	10.00	1.60	64.30
	Average	0.39	63.05	11.20	25.75	10.19	1.58	60.03
3	T5	5.84	65.50	9.00	25.50	20.00	1.05	61.40
4	T6	0.32	64.20	11.20	24.60	10.05	1.59	60.00
5	T7	0.89	48.67	32.18	19.15	11.08	1.51	60.52
	T8	2.37	51.16	32.23	16.61	13.74	1.37	44.51
	Average	1.63	49.92	32.20	17.88	12.41	1.44	52.52

Table 3: Parameters of Brooks and Corey model

Group	Sample	Φ (vol./vol.)	Φc (vol./vol.)	λ	h_b (cm)	θ_r (vol./vol.)	n
1	T1	0.410	0.244	0.394	30.179	0.053	8.079
2	T2	0.405	0.336	0.357	13.884	0.080	8.603
	T3	0.407	0.331	0.404	13.817	0.065	7.956
	T4	0.396	0.322	0.440	14.517	0.054	7.547
	Average	0.402	0.330	0.400	14.072	0.066	8.035
3	T5	0.604	0.472	0.362	7.023	0.049	8.519
4	T6	0.399	0.331	0.402	13.485	0.068	7.979
5	T7	0.432	0.375	0.226	15.868	0.108	11.852
	T8	0.484	0.427	0.239	9.352	0.112	11.364
	Average	0.458	0.401	0.233	12.610	0.110	11.608

Table 4: Variation of available moisture holding capacity with soil physical and chemical properties

Group	WCF %	S %	C %	OM %	Porosity %	Bulk density g/cc	Available moisture holding capacity vol./vol.
1	48.00	42.18	9.82	0.29	0.24	1.56	0.080
2	25.75	63.05	11.20	0.39	0.33	1.58	0.091
3	25.50	65.50	9.00	5.84	0.47	1.05	0.116
4	24.60	64.20	11.20	0.32	0.33	1.59	0.089
5	17.88	49.92	32.20	1.63	0.40	1.44	0.102
	0.62	**0.49**	**0.20**	**0.92**	**0.99**	**0.91**	**Correlation coefficient**

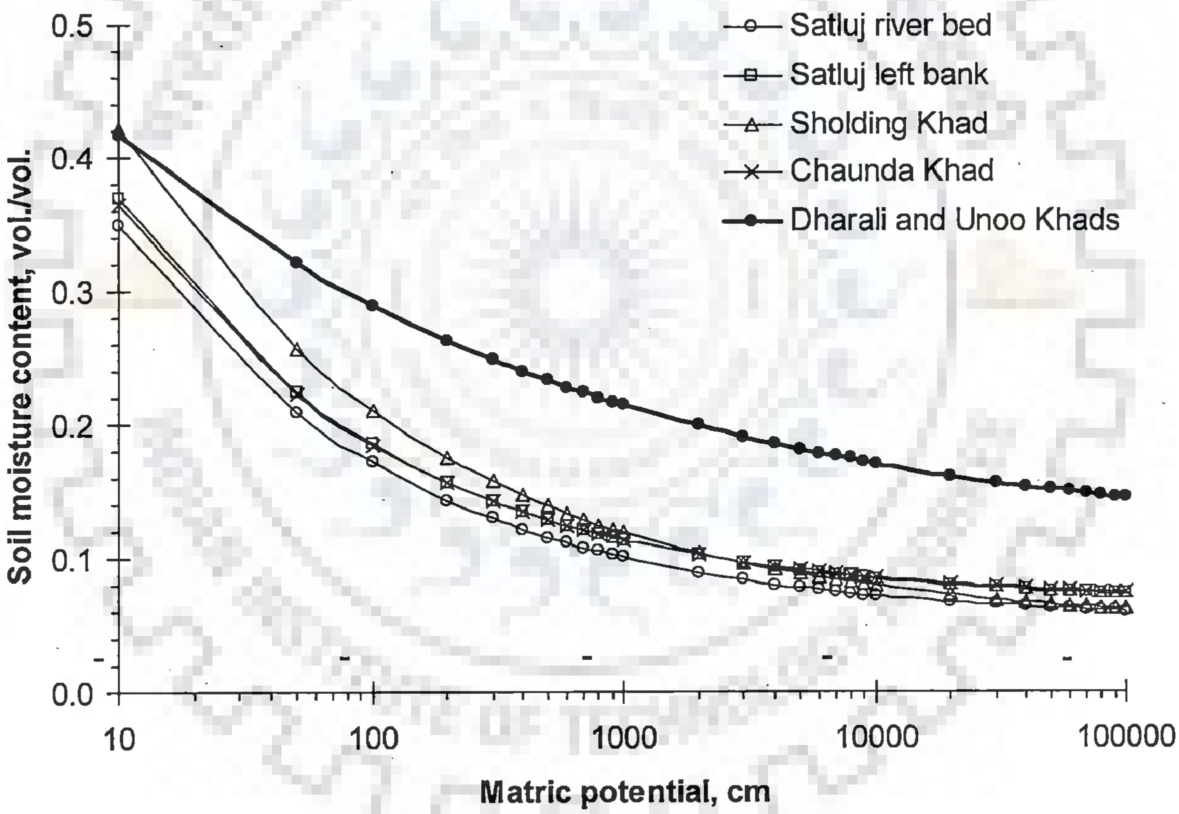

Figure 1: Soil moisture retention curves

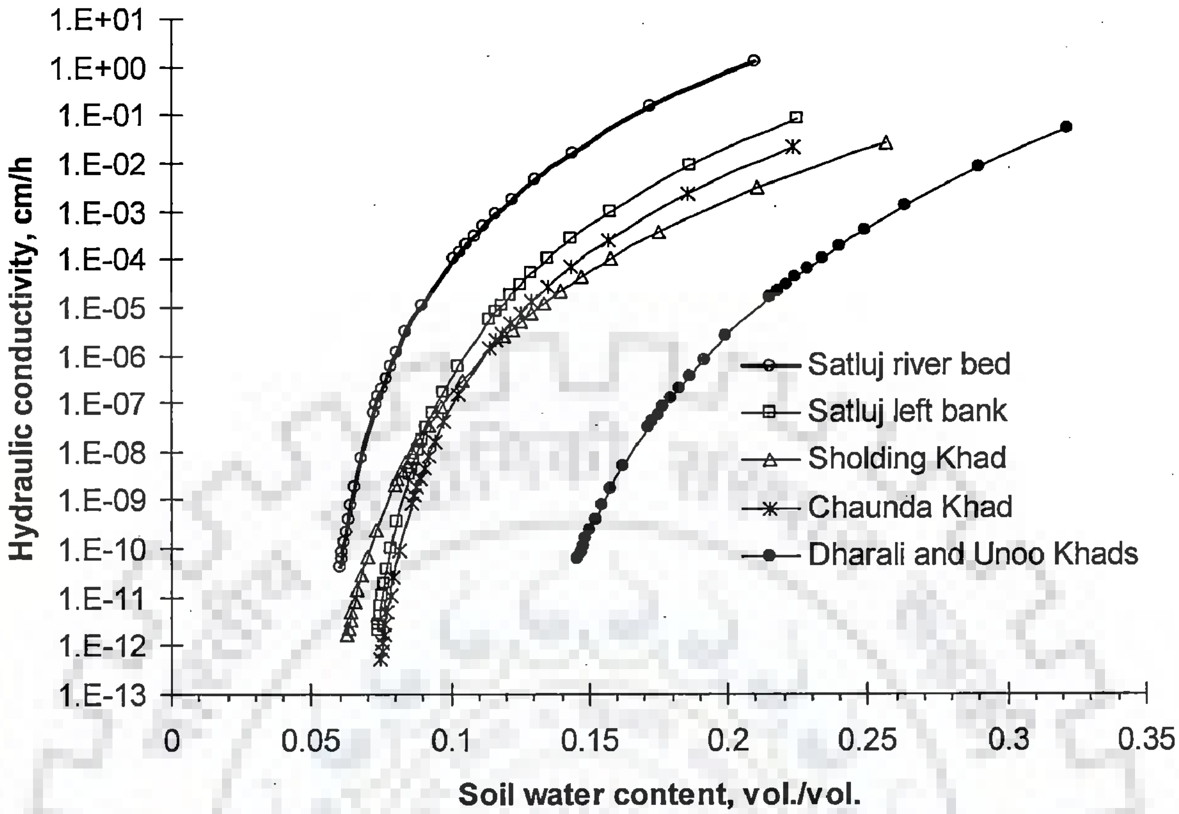

Figure 2: Hydraulic conductivity curves

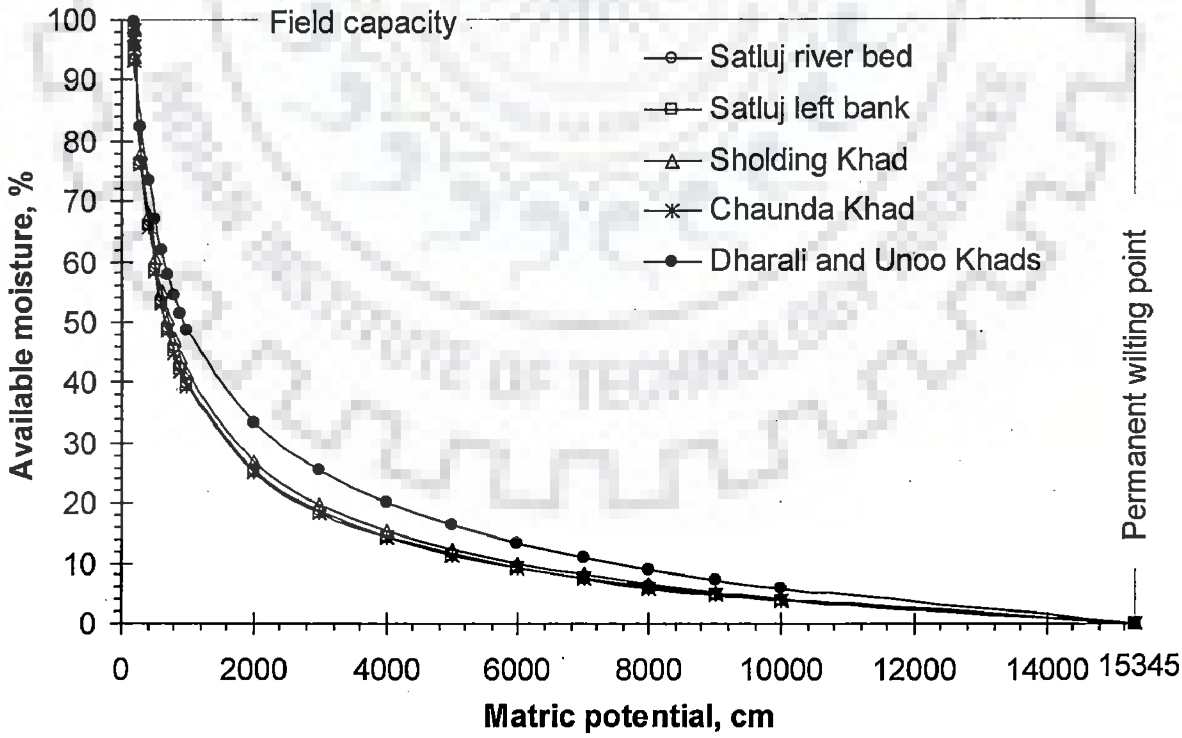

Figure 3: Available soil moisture characteristic curves

ANNEXURE 4.5
PROFORMA FOR VILLAGE LEVEL SURVEY

DATE: ______________

VILLAGE: ________________________ BLOCK: ____________________________

TEHSIL: _________________________ POPULATION: _______________________

ROAD CONNECTIVITY: ____

APPROACHABILITY UPTO SATLUJ: _____________________

DISTANCE FROM SATLUJ RIVER: _____________

NEAREST STREAM: ______________________ SPRING: ____________ WELL: ____

SEWAGE DRAIN: ________________________

NAME: ____ AGE: __________

FATHER'S NAME: _________________________________ EDUCATION: _________

PROFESSION MAIN: ___________________________ OTHER: __________________

FAMILY MEMBERS:

MALE: _____________ FEMALE: ______________ CHILDREN: ______________

DOMESTIC WATER USE

1. DAILY DOMESTIC NEED PER PERSON:
IN WINTER: ________________________ IN SUMMER: _________________________

2. SOURCE:
PUBLIC WATER SUPPLY: ______________ OWN ARRANGEMENT: ____________

3. WATER AVAILABILITY:
IN WINTER: ________________________ IN SUMMER: _________________________

4. WATER QUALITY:
IN WINTER: ________________________ IN SUMMER: _________________________

AGRICULTURAL WATER USE

CROP	CROP AREA				PRODUCTION				IRRIGATORY WATER DEMAND
	RAINFED		IRRIGATED		RAINFED		IRRIGATED		
	BEFORE	NOW	BEFORE	NOW	BEFORE	NOW	BEFORE	NOW	

CHANGE IN CROP TYPES OVER THE YEARS:
CHANGE IN CROP AREA OVER THE YEARS:
CHANGE IN DISCHARGE OF GROUND WATER, SPRING OR STREAMS:

WATER USE FOR IRRIGATION
SOURCE OF IRRIGATION: ____
WATER CONVEYANCE TO FIELD: ____
METHOD OF FIELD IRRIGATION: ____
NUMBER OF IRRIGATION: ___________

USE OF FERTILIZERS AND OTHER CHEMICALS:

FERTILIZER	QUANTITY		COST	
	NOW	5 YEARS BEFORE	NOW	5 YEARS BEFORE

ANIMAL NEED

ANIMAL	NUMBER	PURPOSE	WATER USE/DAY	BENEFIT PER YEAR
GOAT				
SHEEP				
COW				
BUFFALO				
HORSE				
ANY OTHER				

SOURCE OF WATER: ____________________

ADEQUACY: ____________

WHETHER SATLUJ WATER IS USED: YES ______ NO ______

FEED:

FODDER TYPE: ____________________

QUANTITY: ____________

HOW MUCH FODDER IS BROUGHT TO STALL: ____________________

LOCATION OF GRAZING LAND: ____________________

DISTANCE OF GRAZING LAND FROM SATLUJ RIVER: ____________________

WILD ANIMALS IN VICINITY OF VILLAGE:

FISHERIES

SOURCE OF AVAILABILITY:

SHOP __________ STREAM __________ SATLUJ RIVER __________

AVAILABILITY IN DIFFERENT SEASONS:

WINTER

SUMMER

MONSOON

CHANGE IN AVAILABILITY OVER THE YEARS:

METHOD OF CATCHING:

FISH AVAILABILITY IN SATLUJ RIVER:

TYPE	QUANTITY	SEASON

ANNEXURE 4.6

OBSERVED DISCHARGES OF TRIBUTARIES BETWEEN NATHPA AND JHAKRI FOR THE YEAR 2005-06

Tributary	Average ten daily discharge (cumec)																				
	October			November			December			January			February			March			April		
	I	II	III	I	II	III	I	II	III	I	II	III	I	II	III	I	II	III	I	II	III
Manglad	1.44	1.35	1.32	1.23	1.15	1.12	0.59	0.59	0.56	0.57	0.79	0.62	0.59	0.54	0.51	0.66	0.73	0.93	0.98	1.10	1.12
Chaura Khad	0.62	0.58	0.61	0.60	0.56	0.51	0.49	0.45	0.41	0.46	0.56	0.49	0.47	0.45	0.44	0.69	0.75	0.81	0.87	1.05	1.06
Chaunda Khad	1.01	0.87	0.91	0.79	0.76	0.72	0.44	0.46	0.39	0.41	0.47	0.44	0.42	0.41	0.35	0.59	0.67	0.68	0.74	0.96	0.98
Rupi Khad	1.74	1.46	1.37	1.40	1.15	0.98	0.64	0.54	0.53	0.52	0.71	0.53	0.55	0.52	0.54	0.74	0.77	0.82	0.88	1.11	1.15
Sholding Khad	1.93	1.84	1.56	1.27	1.16	0.98	0.70	0.64	0.54	0.76	0.69	0.59	0.67	0.61	0.51	1.02	0.93	0.79	1.39	1.27	1.07
Sumej Khad	1.66	1.56	1.32	1.08	1.03	1.00	0.63	0.56	0.54	0.68	0.65	0.64	0.59	0.58	0.77	0.90	0.89	1.18	1.23	1.21	1.60
Gaanvi Khad	1.92	1.67	1.56	1.53	1.60	1.12	0.75	0.67	0.66	0.68	0.69	0.58	0.67	0.63	0.83	1.02	0.97	1.27	1.39	1.32	1.72
Sorang Khad	1.58	1.21	0.96	0.75	0.72	0.44	0.77	0.71	0.67	0.74	0.70	0.60	0.66	0.61	1.00	1.01	0.94	1.53	1.37	1.28	2.08
Silaring Khad	0.91	1.19	1.09	0.69	0.60	0.45	0.76	0.68	0.62	0.61	0.58	0.55	0.58	0.53	0.68	0.90	0.81	1.04	1.22	1.10	1.41
Unoo Khad	0.29	0.30	0.33	0.24	0.25	0.28	0.13	0.14	0.15	0.16	0.22	0.16	0.15	0.15	0.12	0.16	0.20	0.22	0.25	0.30	0.29
Daaj Khad	0.23	0.21	0.19	0.19	0.17	0.15	0.11	0.09	0.09	0.11	0.15	0.13	0.12	0.11	0.11	0.21	0.22	0.23	0.24	0.31	0.31
Kaowil Khad	0.36	0.26	0.22	0.30	0.21	0.18	0.17	0.12	0.10	0.13	0.17	0.16	0.15	0.14	0.13	0.18	0.20	0.25	0.28	0.35	0.34
Gatti Khad	0.35	0.33	0.30	0.29	0.27	0.25	0.16	0.15	0.14	0.14	0.17	0.15	0.14	0.14	0.14	0.22	0.21	0.21	0.30	0.29	0.28

Note:

1. Discharge data for Sholding, Sumej, Gaanvi, Sorang and Shilaring during December'05 to April'06 are estimated values based on proportionate decrease in discharge of other khads
2. Discharge data for Unoo, Daaj, Kaowil and Gatti khads during October'05 to November'05 are estimated values based on proportionate decrease in discharge of other khads.

ANNEXURE 4.7

OBSERVED DISCHARGES OF TRIBUTARIES BETWEEN NATHPA AND JHAKRI FOR THE YEAR 2006-07

Tributary	Average ten daily discharge (cumec)								
	December			January			February		
	I	II	III	I	II	III	I	II	III
Manglad	0.90	0.89	0.81	0.89	0.87	0.86	0.89	0.78	1.11
Chaura Khad	0.77	0.73	0.66	0.85	0.78	0.78	0.82	0.74	0.94
Chaunda Khad	0.69	0.64	0.62	0.83	0.75	0.67	0.65	0.71	0.91
Rupi Khad	1.05	0.90	1.00	0.89	0.89	0.84	0.82	0.73	1.03
Sholding Khad	1.11	1.00	0.89	1.34	0.90	0.89	1.05	0.94	1.12
Sumej Khad	0.88	0.79	0.75	0.95	0.91	0.90	0.83	0.82	1.08
Gaanvi Khad	1.05	0.94	0.93	0.96	0.97	0.81	0.94	0.89	1.16
Sorang Khad	1.08	0.99	0.95	1.04	0.99	0.84	0.92	0.86	1.40
Silaring Khad	1.06	0.96	0.87	0.85	0.82	0.77	0.82	0.74	0.95
Unoo Khad	0.30	0.28	0.22	0.24	0.24	0.22	0.23	0.21	0.29
Daaj Khad	0.20	0.19	0.19	0.21	0.20	0.18	0.19	0.18	0.24
Kaowil Khad	0.20	0.18	0.17	0.19	0.18	0.17	0.18	0.17	0.23
Gatti Khad	0.21	0.18	0.16	0.18	0.17	0.16	0.16	0.15	0.21
Dharali Khad	0.19	0.16	0.16	0.17	0.17	0.16	0.16	0.15	0.21

Note: Discharge data for Unoo, Daaj, Kaowil, Gatti and Dharali khads January'07 to February'06 are estimated values based on proportionate decrease in discharge of other khads

ANNEXURE 4.8
ANNUAL AND SEASONAL RAINFALL (MM) AT NICHAR AND RAMPUR

	Nichar					Rampur				
Year	Winter	Pre-monsoon	Monsoon	Post-monsoon	Total	Winter	Pre-monsoon	Monsoon	Post-monsoon	Total
1979	93.60	212.00	188.80	68.50	562.90	433.90	319.00	214.50	33.17	1000.57
1980	138.40	259.80	442.90	23.40	864.50	224.40	180.20	1427.40	28.50	1860.50
1981	193.00	232.40	282.30	119.00	826.70	345.60	580.80	746.80	139.70	1812.90
1982	277.20	295.60	222.00	50.60	845.40	686.80	193.90	101.10	45.10	1026.90
1983	191.60	365.20	367.80	57.80	982.40	212.60	259.70	466.40	73.49	1012.19
1984	111.80	202.60	228.40	22.80	565.60	224.40	67.30	271.50	5.00	568.20
1985	78.00	208.60	510.20	147.20	944.00	178.90	123.50	397.90	112.90	813.20
1986	264.40	334.20	205.60	51.00	855.20	187.00	206.00	247.10	74.20	714.30
1987	162.00	526.00	185.80	65.00	938.80	151.40	117.00	96.00	64.80	429.20
1988	440.00	175.60	564.60	13.80	1194.00	373.00	127.00	644.30	0.00	1144.30
1989	212.40	174.40	355.80	76.20	818.80	196.80	66.80	343.00	53.00	659.60
1990	387.80	187.60	257.80	45.00	878.20	423.00	126.00	375.00	14.00	938.00
1991	220.00	261.80	203.20	1.00	686.00	243.60	96.10	164.70	0.00	504.40
1992	385.00	170.00	460.40	37.00	1052.40	297.75	107.90	462.60	12.50	880.75
1993	355.00	172.60	367.20	40.00	934.80	322.80	145.40	370.30	27.60	866.10
1994	169.20	387.00	535.00	2.00	1093.20	236.20	191.30	514.20	4.00	945.70
1995	173.80	202.00	413.40	41.60	830.80	224.50	64.80	504.20	11.70	805.20
1996	368.00	239.20	466.60	43.00	1116.80	291.40	155.00	342.50	35.80	824.70
1997	301.10	270.36	362.00	91.00	1024.46	100.50	239.40	412.10	18.70	770.70
1998	223.20	270.00	321.10	150.60	964.90	191.00	219.50	383.10	105.50	899.10
1999	71.20	106.40	264.00	25.80	467.40	125.80	113.40	359.40	1.00	599.60
2000	141.00	341.20	187.20	30.80	700.20	152.50	269.50	341.70	3.50	767.20
2001	243.80	247.60	326.90	23.00	841.30	164.90	157.70	184.30	26.00	532.90
2002	165.66	284.90	276.40	12.70	739.66	302.70	164.40	268.20	2.50	737.80
2003	215.22	225.40	387.80	37.80	866.22	238.80	120.00	467.40	8.00	834.20
2004	220.00	187.90	162.40	65.20	635.50	111.20	221.10	323.70	95.90	751.90
RN	223.17	251.55	328.68	51.61	855.01	255.44	178.18	401.13	38.33	873.08
0.75RN	167.38	188.66	246.51	38.71	641.25	191.58	133.64	300.85	28.75	654.81
n	8.00	7.00	8.00	11.00	4.00	9.00	11.00	8.00	15.00	5.00
n/N	30.77	26.92	30.77	42.31	15.38	34.62	42.31	30.77	57.69	19.23
Std. Dev.	100.32	86.87	118.36	39.29	178.28	125.33	105.17	258.22	39.97	331.98
CV	44.95	34.53	36.01	76.13	20.85	49.06	59.02	64.37	104.28	38.02
Correlation coefficient						0.346	0.170	0.511	0.830	0.225

R_N : average rainfall; n : number of years when rainfall is less than $0.75R_N$
Std. Dev : standard deviation; C_V : coefficient of variation

ANNEXURE 5.1
WATER QUALITY PARAMETERS DURING PRE-PROJECT CONDITION

Source	Location	Period	DO	BOD	pH	Faecal Coli	TDS	TSS	TS	Turbidity	Nitrate	Phosphate	Temperature
			mg/L	mg/L		MPN/100 mL	mg/L	mg/L	mg/L	JTU/NTU	mg/L	mg/L	^{0}C
HPPCB	Nathpa U/S	May, 2002	9.80	0.1	7.93	4	176		176	245	1.05	0.26	10.15
	Nathpa D/S	May, 2002	9.78	0.1	8.20	8	178		178	260	0.8	0.39	10.15
	Jhakri U/S	May, 2002	9.45	0.1	8.09	15	191		191	10.2	0.41	0.75	10.2
	Jhakri D/S	May, 2002	9.43	0.1	8.23	20	181		181	75	0.17	0.39	10.2
HPPCB	Nathpa U/S	July, 2002	8.50	0.1	8.22	38	189		189	560	0.94	0.26	13.7
	Nathpa D/S	July, 2002	8.00	0.1	8.23	40	161		161	640	0.98	0.68	13.75
	Jhakri U/S	July, 2002	8.20	0.2	8.32	45	161		161	560	0.6	0.22	13.8
	Jhakri D/S	July, 2002	8.50	0.2	8.24	70	172		172	520	0.46	0.4	13.8
HPPCB	Nathpa U/S	Sep-Oct, 2002	9.30	0.1	8.22	0	249		249	44	0.38	0.14	16
	Nathpa D/S	Sep-Oct, 2002	9.30	0.1	8.14	2	225		225.4	36.5	0.31	0.13	16
	Jhakri U/S	Sep-Oct, 2002	9.50	0.1	8.17	81	504		503.9	44	0.31	0.13	17
	Jhakri D/S	Sep-Oct, 2002	9.00	0.1	8.13	14	263		262.7	46	0.29	0.16	17
HPPCB	Nathpa U/S	Nov-Dec, 2002	9.20	0.1	8.33	4	246		246.2	14	0.38	0.6	10
	Nathpa D/S	Nov-Dec, 2002	9.15	0.1	8.80	16	237		236.5	13	0.37	0.61	10
	Jhakri U/S	Nov-Dec, 2002	9.13	0.2	8.27	18	197		196.6	22	0.61	0.23	11
	Jhakri D/S	Nov-Dec, 2002	9.20	0.2	8.25	32	236		236	25	0.36	0.21	11
HPPCB	Nathpa U/S	Feb, 2003	8.30	0.2	7.95	39	249		249	6	0.22	0.56	-
	Nathpa D/S	Feb, 2003	8.20	0.3	8.03	48	253		253	8.5	0.21	0.66	-
	Jhakri U/S	Feb, 2003	9.80	0.6	7.60	39	200		200	18	0.36	0.15	-
	Jhakri D/S	Feb, 2003	10.50	0.5	8.30	45	222		222	28	0.34	0.18	-
HPPCB	Nathpa U/S	Mar, 2003	8.50	0.1	8.20	-	254		254	72.8	0.5	1.59	12
	Nathpa D/S	Mar, 2003	8.70	0.2	8.17	-	258		258	104	0.53	1.86	12.5
	Jhakri U/S	Mar, 2003	9.50	0.3	7.93	-	207		207	68	0.64	1.9	12.9
	Jhakri D/S	Mar, 2003	10.00	0.7	10.00	-	250		250	2400	0.59	0.11	13
HPPCB	Nathpa U/S	Apr, 2003	9.20	0.1	8.24	-	245		245	76.8	0.57	3.76	13.5
	Nathpa D/S	Apr, 2003	9.00	0.2	8.17	-	317		317	73.8	0.42	0.14	14
	Jhakri U/S	Apr, 2003	6.90	0.1	8.13	-	332		332	79.2	2.23	1.15	13
	Jhakri D/S	Apr, 2003	6.50	0.1	8.24	-	123		123	27.6	0.91	1.69	16

ANNEXURE 5.2
WATER QUALITY PARAMETERS DURING POST-PROJECT CONDITION

Location	Period	DO	BOD	pH	Total Coliform
		mg/L	mg/L		MPN/100 mL
Wangtu Bridge	June, 2004	8.3	0.1	8.17	22
Rampur U/S	June, 2004	8.7	0.1	8.19	395
Rampur D/S	June, 2004	8.8	0.2	8.1	418
Wangtu Bridge	October, 2004	10.3	0.1	8.2	7
Rampur U/S	October, 2004	9.9	0.1	8	204
Rampur D/S	October, 2004	9.8	0.1	8.27	241
Wangtu Bridge	January, 2005	10.8	0.1	8.06	10
Rampur U/S	January, 2005	10	0.1	8.04	170
Rampur D/S	January, 2005	10.2	0.1	8.04	210
Wangtu Bridge	April, 2005	9.1	0.2	8.11	8
Rampur U/S	April, 2005	9.5	0.2	8.03	221
Rampur D/S	April, 2005	9.5	0.3	8.02	246
Wangtu Bridge	October, 2005	9.2	0.1	8.1	1
Rampur U/S	October, 2005	9.1	0.1	8.06	170
Rampur D/S	October, 2005	9.1	0.3	8.19	186
Wangtu Bridge	January, 2006	9.8	0.1	8.12	-
Rampur U/S	January, 2006	10.6	0.1	7.92	46
Rampur D/S	January, 2006	10.6	0.3	0.09	64
Wangtu Bridge	April, 2006	9.8	0.2	8.25	4
Rampur U/S	April, 2006	10	0.1	8.15	156
Rampur D/S	April, 2006	10	0.4	8.25	170
Wangtu Bridge	July, 2006	9.8	0.2	7.71	30
Rampur U/S	July, 2006	9.5	0.2	8.41	80
Rampur D/S	July, 2006	9.6	0.4	8.43	120
Wangtu Bridge	October, 2006	8.7	0.1	8.05	8
Rampur U/S	October, 2006	8.8	0.1	7.91	102
Rampur D/S	October, 2006	8.6	0.4	8.03	210
Wangtu Bridge	January, 2007	11.6	0.3	8.21	12
Rampur U/S	January, 2007	11.9	0.2	8.24	162
Rampur D/S	January, 2007	11.5	0.4	8.14	180

ANNEXURE 6.1
WATER SUPPLY SCHEMES IN THE STUDY AREA

S. No.	Name of scheme	Location of source	Type of source	Discharge (lpm)	Population covered		
					Persons	Student	Pilgrims
Rampur							
1	Prov. Jhakri Makrora	Nehla	Spring	75.96	747	244	
2	Prov. Dwarkapuri Phanoti	Kothia Salta	Spring	61.8	835	50	
3	Prov. Goura Kapti	Dugiriwani	Spring	68.4	429		
4	Kash Shah Jaleend	Kali Nala	Spring	69.96	867	42	
5	Prov. LOH Chandpur (Chodali)	Ranot Bawali	Spring	20	176		
6	Prov.Kartot	Jumkrali II	Spring	454	408		
7	Prov. WSS Rattanpur II	Rattanpur	Spring	15	42		
8	Pro. LOH Sanarsa	Sanarsa	Spring	15	191		
9	Prov. WSS Basra II and Sanarsa II	Basara II	Spring	10	121		
10	Prov. Sharan Rattanpur	Jumkrali II	Spring		929		
11	Prov. Koti	Duglu	Spring	15	84		
12	Prov. Gopalpur (Dobi)	Jumkrali II	Spring	40	200		
13	Prov. Gopalpur Shandhar	Juni Nala	Spring		575		
14	Prov. Rasaya Maghara	Maghara Nala	Spring	24	51		
15	LOH Kiari Majhewali	Kiari	Spring	5	21		
16	Prov. WSS Chhanu Bahali	Malku Bai	Spring	2.4	134		
17	Prov. PC Maghara Majholi Koshgarh	Chand Bala	Spring	54	1210		
18	Prov. WSS Dofda Shah Uchi	Gathuya	Spring	81.6	931		
19	Prov. Rama Jung Baiwa Ph I, II, III & IV	Bajwa I, Rama	Spring	136.2	605		
20	Prov. PC Garora	Sankari	Spring	20	146		
21	Prov. GWSS Mashnoo	Kahali Nala	Spring	36	532		
22	LWSS Karali Thana	Badnal	Spring	27.84	350		
23	LWSS Lalsa Pow Dawalsa	Gharat Gad	Spring	10.86	1333		
24	LWSS Jaguni	Charani	Spring	30	416		
25	LWSS Shrai Koti	Talai	Spring	35.4			200
26	Prov. WSS Sarahan Rawin	Rai Nala	Nallah	123	2000		
27	Prov. WSS Kalai Bonda	Kanchi Nala	Spring	130	3300		
28	Prov. WSS Manjgaon	Bishti Kuti	Spring	15	225		
29	Prov. WSS Pithvi Ph I, II & III	Chanach, Gharat, Kharga	Spring	27, 30, 6	575		
30	Prov. WSS Runpoo	Runpoo	Spring	7	200		
31	Prov. WSS Kinoo Ph I to VII	Lahawar, Kalai Dawar, Gartada, Bati, Soom, Rashi, Dharta	Spring/ Nallah	30, 8, 10, 23, 9, 7, 5	1130		
32	Prov. WSS Shahdhar	Damani Dabar	Spring	8	115		
33	Prov. WSS Dheu Ardi Ph I & II	Dehu, Basa	Spring	20, 12	288		
34	Prov. WSS Bathara	Bathara	Spring	28	350		
35	Prov. WSS Dwarch	Doba	Spring	15	90		
36	LOH Bonda	Rawin	Spring	5	45		
37	LOH Sarahan	Gadar	Spring	19	65		
38	LOH Kanchi & Jadanbai	Kanchi Nala	Spring	6	69		
39	LOH Rawin	Banli Bai	Spring	27	120		
40	LOH Manjgaon	Rai Bai	Spring	21	125		
41	Prov. GWSS Jangal Bashaldhar	Jadgi	Spring	7	30		

Annexure 6.1 continued ...

S. No.	Name of scheme	Location of source	Type of source	Discharge (lpm)	Population covered		
					Persons	Student	Pilgrims
Rampur							
42	Prov GWSS Badhal Dharali	Parla Badhal, Shimla khad, Dharali khad	Spring/ Nallah	25, 60, 90	1075		
43	Prov GWSS SBF Jeori	Jeori	Spring	18	35		
44	Prov GWSS Nawara	Dwarch	Spring	45	138		
45	Prov GWSS Jeori Tayal	Bathara	Spring	16	400		
46	Prov. GWSS Kuni	Kuni	Spring	13	230		
47	Prov GWSS Kotla	Bathara	Spring	40	244		
48	Prov GWSS Unoo	Dwarch	Spring	50	422		
49	LOH of C.V. Dharali	Nainee	Spring/ Nallah	30	50		
50	Prov. WSS Jeori Bazar	Jeori	Spring	30	538		
51	Prov. WSS PC Hab. Bathara	Bathara	Spring	28	35		
52	Prov. WSS Kotla	Kotla	Spring	20	45		
53	Prov. WSS Jeori, Kiar Dhankru	Damni, Dwarch	Spring	90, 105			
54	LOH GWSS Dharali Badhal	Dharali, Badhal	Spring	90, 35	97		
55	Prov. GWSS Koot	Koot, Kinfe	Spring	18, 29	184		
56	Prov. GWSS Kandri	Kandri	Spring	25	128		
57	Prov. GWSS Ganvi	Mohali	Spring	46	129	120	
58	LOH Kiao	Kiao	Spring	29	77		
59	LOH Koot	Ropni	Spring	10	32		
Nichar							
1	WSS Nichar in G.P. Nichar	Baro/Chhotekanda	Nallah	127	2178		
2	WSS Baro I in G. P. Nichar	Baro/Chhotekanda	Nallah	120	168		
3	WSS Baro II in G. P. Nichar	Baro/Chhotekanda	Nallah				
4	WSS Sungra	Baro Nal	Nallah	45.4	777		
5	WSS Kachey Kangosh	Darude I	Spring	12	497		
6	WSS Ponda Palingi	Dauruda II	Spring	28	144		
7	WSS Bari Vikasnagar	Nagasthi	Spring	26	544		
8	WSS Ventay	Ventey	Spring	12	105		
9	WSS Shakicharan	Shaki Charan	Spring	48	283		
10	WSS Granghe in G. P. Nichar	Baro	Nallah	59	589		
11	WSS Bara Khambha	Sorang	Nallah	35	310		
12	WSS Chhota Khambha	Dev Khang Nal	Nallah	40	409		
13	WSS Gharsoo	Chawva Nal	Nallah	85	410		
14	WSS Rockcharang Shalaring	Shalla	Spring	38.4	150		
15	WSS Nathpa	Kandhar Nal	Nallah	25	275		
16	WSS Kandhar	Gopanga	Spring	9.08	85		
17	WSS Nathpa Jhulla	Nichhi	Spring	22.2	121		
18	WSS Chhoura Thach	Thach Nal	Nallah	15	250		
19	WSS Nigulsari	Chaunda	Spring	40	320		
20	WSS Nanaspoh Trandha	Darving	Nallah	25	410		
21	WSS Roopi	Devdhaw	Spring	55	372		
22	WSS Chadding	Kasnanal	Spring	15	102		
23	WSS Tichhi Shilpi	Tichchi Nal	Spring	27	162		

ANNEXURE 6.2
IRRIGATION SCHEMES IN THE STUDY AREA

S. No.	Name of scheme	Location of source	Type of source	Discharge (cusec)	Area irrigated (ha)
Rampur					
1	FIS Dwarch Bathara Kuhl No. I & II	Dharali khad	Nallah		40
2	FIS Dwarch Bathara Kuhl No. IV	Rai Nallah	Nallah		115
3	FIS Dwarch Bathara Kuhl No. V	Unoo Nallah	Nallah		42
4	FIS Parla Badhal	Shimla khad	Nallah		19.20
5	FIS Bonda	Rai Nallah	Nallah		37
6	FIS Kandri				17
7	FIS Nainee in GP Sarahan	Dharali Khad	Nallah		32
8	C/O FIS Karan Kio in 15/20 Area	Kalo	Nallah	1.00	32.57
Nichar					
1	FIS Nichar	Chhote kanda	Nallah	6.50	121
2	FIS Barakhambha	Soran Nal	Khad	39.50	135

ANNEXURE 7.1
DISCHARGE OF SATLUJ RIVER FOR WET YEAR

S. No.			Chainage from Nathpa (km)	CA (sq. km)	Discharge up to corresponding chainage (cumec)								
					Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June
1	Nathpa Dam		0		7.00	7.00	7.00	7.00	7.00	7.00	7.00	69.33	264.33
2	Three tributaries near Nathpa	R	1.4	4.97	7.31	7.20	7.24	7.22	7.23	7.29	7.30	69.52	264.44
3	Shilaring Khad	R	2.9	90.02	13.36	9.98	9.24	8.83	8.99	9.70	11.40	77.40	272.50
4	Near Sungra	L	3.3	14.63	13.88	10.19	9.53	9.26	9.40	10.18	11.90	77.94	272.80
5	Sholding Khad	L	6.6	88.36	13.88	10.19	9.53	9.26	9.40	10.18	11.90	84.85	284.74
6	Near Gharsoo and Chhota Khambha	R	7.4	12.03	14.32	10.36	9.80	9.48	9.63	10.58	12.31	85.29	285.00
7	Near Taranda	L	8.7	3.87	14.45	10.41	9.88	9.59	9.74	10.71	12.44	85.43	285.08
8	Chaunda Khad	L	10.8	19.60	15.16	10.69	10.28	10.17	10.29	11.35	13.11	86.16	285.49
9	Sorang Khad	R	12	127.87	23.75	14.64	13.11	12.46	12.79	14.77	18.93	97.35	296.94
10	Near Chaura village	L	13.2	7.62	24.02	14.75	13.27	12.68	13.01	15.02	19.19	97.63	297.10
11	Tikadda Khad	R	13.6	16.94	24.63	14.99	13.64	12.99	13.34	15.58	19.77	98.26	297.45
12	Near Phagi	R	15.4	5.34	24.83	15.06	13.76	13.08	13.44	15.76	19.95	98.46	297.57
13	Chaura Khad	L	15.6	10.62	25.21	15.21	13.98	13.40	13.74	16.11	20.31	98.85	297.79
14	Kut Khad	R	17.2	76.24	30.33	17.57	15.67	14.76	15.23	18.14	23.79	105.52	304.61
15	Shimla Khad (Watoli Khad) etc.	L	17.7	9.20	30.66	17.70	15.86	15.03	15.49	18.45	24.10	105.86	304.81
16	Between Kut Khad and Ratu Khad	R	19.2	3.51	30.79	17.75	15.93	15.10	15.56	18.56	24.22	105.99	304.88
17	Dharali Khad	L	19.9	11.05	31.19	17.90	16.16	15.42	15.87	18.93	24.59	106.40	305.11
18	Ratu Khad	R	21.2	2.60	31.28	17.94	16.22	15.47	15.92	19.01	24.68	106.50	305.17
19	Gatti Khad	R	21.8	5.38	31.47	18.01	16.34	15.56	16.02	19.19	24.86	106.70	305.28
20	Ganvi Khad	R	23.2	114.97	39.20	21.57	18.89	17.63	18.27	22.26	30.10	116.76	315.57
21	Rai Khad/Unoo Khad	L	24.5	19.49	39.90	21.84	19.28	18.20	18.82	22.91	30.77	117.48	315.98
22	Manglad Khad	L	26.8	101.49	44.58	24.46	21.35	21.18	21.66	25.62	34.09	125.73	330.24
23	Kaowil Khad (opposite to Manglad Khad) etc.	R	27.6	14.15	45.09	24.66	21.66	21.44	21.94	26.09	34.57	126.26	330.54
24	Between Manglad Khad and Daaj Khad	L	28.6	5.74	45.30	24.74	21.78	21.61	22.10	26.27	34.76	126.47	330.66
25	Daaj Khad	L	30.4	9.25	45.63	24.87	21.97	21.88	22.36	26.58	35.08	126.81	330.85
26	Between Daaj and Jhakri	L	32	6.30	45.85	24.95	22.09	22.06	22.53	26.79	35.29	127.04	330.98
27	Sumej Khad	R	32.1	83.85	51.49	27.55	23.95	23.57	24.18	29.03	39.11	134.38	338.49
28	TRT Outfall Jhakri		33.7	866.26	51.53	27.57	23.98	23.59	24.20	29.07	39.15	134.43	338.52

R – Right Bank; L – Left Bank

ANNEXURE 7.2
DISCHARGE OF SATLUJ RIVER FOR NORMAL YEAR

S. No.			Chainage from Nathpa (km)	CA (sq. km)	Discharge up to corresponding chainage (cumec)								
					Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June
1	Nathpa Dam		0.0		7.00	7.00	7.00	7.00	7.00	7.00	7.00	7.00	236.56
2	Three tributaries near Nathpa	R	1.4	4.97	7.26	7.17	7.32	7.21	7.21	7.24	7.30	7.45	236.72
3	Shilaring Khad	R	2.9	90.02	12.06	10.94	10.85	8.75	8.64	9.06	10.87	14.03	244.76
4	Near Sungra	L	3.3	14.63	12.45	11.05	11.31	9.12	9.01	9.39	11.37	14.96	245.23
5	Sholding Khad	L	6.6	88.36	12.45	11.05	11.31	9.12	9.01	9.39	11.37	14.96	266.22
6	Near Gharsoo and Chhota Khambha	R	7.4	12.03	12.78	11.15	11.78	9.32	9.20	9.67	11.78	15.73	266.61
7	Near Taranda	L	8.7	3.87	12.88	11.18	11.90	9.42	9.30	9.76	11.91	15.98	266.73
8	Chaunda Khad	L	10.8	19.60	13.41	11.34	12.52	9.92	9.80	10.21	12.58	17.23	267.36
9	Sorang Khad	R	12.0	127.87	20.22	16.69	17.53	12.10	11.83	12.78	17.65	26.58	278.79
10	Near Chaura village	L	13.2	7.62	20.42	16.75	17.77	12.29	12.02	12.96	17.91	27.06	279.03
11	Tikadda Khad	R	13.6	16.94	20.88	16.88	18.43	12.58	12.29	13.35	18.49	28.15	279.57
12	Near Phagi	R	15.4	5.34	21.02	16.92	18.64	12.67	12.37	13.47	18.67	28.49	279.74
13	Chaura Khad	L	15.6	10.62	21.31	17.01	18.98	12.94	12.64	13.72	19.03	29.17	280.08
14	Kut Khad	R	17.2	76.24	25.37	20.20	21.97	14.24	13.85	15.25	22.06	34.74	286.90
15	Shimla Khad (Watoli Khad) etc.	L	17.7	9.20	25.62	20.27	22.26	14.48	14.09	15.46	22.37	35.33	287.19
16	Between Kut Khad and Ratu Khad	R	19.2	3.51	25.71	20.30	22.39	14.54	14.14	15.54	22.49	35.56	287.31
17	Dharali Khad	L	19.9	11.05	26.01	20.39	22.74	14.82	14.42	15.80	22.87	36.26	287.66
18	Ratu Khad	R	21.2	2.60	26.08	20.41	22.84	14.86	14.46	15.86	22.96	36.43	287.74
19	Gatti Khad	R	21.8	5.38	26.23	20.45	23.05	14.95	14.55	15.98	23.14	36.77	287.91
20	Ganvi Khad	R	23.2	114.97	32.35	25.26	27.56	16.91	16.37	18.30	27.70	45.17	298.19
21	Rai Khad/Unoo Khad	L	24.5	19.49	32.87	25.42	28.17	17.41	16.87	18.75	28.37	46.42	298.81
22	Manglad Khad	L	26.8	101.49	38.25	29.51	31.37	19.99	19.45	21.33	37.86	61.88	323.88
23	Kaowil Khad (opposite to Manglad Khad) etc.	R	27.6	14.15	38.63	29.63	31.93	20.23	19.68	21.66	38.34	62.79	324.33
24	Between Manglad Khad and Daaj Khad	L	28.6	5.74	38.78	29.67	32.11	20.38	19.82	21.79	38.54	63.16	324.51
25	Daaj Khad	L	30.4	9.25	39.03	29.75	32.40	20.61	20.06	22.00	38.85	63.75	324.81
26	Between Daaj and Jhakri	L	32.0	6.30	39.20	29.80	32.60	20.77	20.22	22.15	39.06	64.15	325.01
27	Sumej Khad	R	32.1	83.85	43.67	33.30	35.88	22.20	21.55	23.83	42.39	70.28	332.50
28	TRT Outfall Jhakri		33.7	866.26	43.70	33.31	35.93	22.22	21.57	23.86	42.43	70.35	332.54

R – Right Bank; L – Left Bank

ANNEXURE 7.3
DISCHARGES OF SATLUJ RIVER FOR DRY YEAR

S. No.			Chainage from Nathpa (km)	CA (sq. km)	Discharge up to corresponding chainage (cumec)								
					Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June
1	Nathpa Dam		0.0		7.00	7.00	7.00	7.00	7.00	7.00	7.00	7.00	89.50
2	Three tributaries near Nathpa	R	1.4	4.97	7.23	7.24	7.30	7.20	7.24	7.35	7.15	7.24	89.65
3	Shilaring Khad	R	2.9	90.02	11.98	10.61	10.36	8.56	9.18	9.45	9.95	11.61	96.40
4	Near Sungra	L	3.3	14.63	12.29	10.93	10.91	8.99	9.89	10.10	10.01	11.93	96.85
5	Sholding Khad	L	6.6	88.36	12.29	10.93	10.91	8.99	9.89	10.10	10.01	11.93	108.57
6	Near Gharsoo and Chhota Khambha	R	7.4	12.03	12.54	11.20	11.32	9.18	10.15	10.65	10.06	12.20	108.94
7	Near Taranda	L	8.7	3.87	12.62	11.28	11.47	9.29	10.33	10.82	10.08	12.28	109.06
8	Chaunda Khad	L	10.8	19.60	13.04	11.71	12.22	9.87	11.27	11.70	10.15	12.71	109.67
9	Sorang Khad	R	12.0	127.87	19.78	16.50	16.56	11.80	14.04	14.68	14.14	18.92	119.25
10	Near Chaura village	L	13.2	7.62	19.94	16.67	16.85	12.02	14.40	15.02	14.17	19.09	119.49
11	Tikadda Khad	R	13.6	16.94	20.30	17.05	17.43	12.28	14.77	15.78	14.24	19.46	120.01
12	Near Phagi	R	15.4	5.34	20.41	17.16	17.61	12.36	14.88	16.02	14.26	19.58	120.18
13	Chaura Khad	L	15.6	10.62	20.63	17.40	18.01	12.67	15.39	16.50	14.30	19.82	120.51
14	Kut Khad	R	17.2	76.24	24.65	20.25	20.60	13.82	17.04	18.27	16.67	23.52	126.22
15	Shimla Khad (Watoli Khad) etc.	L	17.7	9.20	24.85	20.45	20.95	14.09	17.48	18.69	16.71	23.72	126.51
16	Between Kut Khad and Ratu Khad	R	19.2	3.51	24.92	20.53	21.07	14.15	17.56	18.84	16.73	23.80	126.62
17	Dharali Khad	L	19.9	11.05	25.15	20.78	21.49	14.47	18.09	19.34	16.77	24.04	126.96
18	Ratu Khad	R	21.2	2.60	25.21	20.83	21.58	14.51	18.14	19.46	16.78	24.10	127.04
19	Gatti Khad	R	21.8	5.38	25.32	20.95	21.76	14.59	18.26	19.70	16.80	24.22	127.21
20	Ganvi Khad	R	23.2	114.97	31.39	25.26	25.67	16.33	20.75	22.37	20.38	29.80	135.82
21	Rai Khad/Unoo Khad	L	24.5	19.49	31.80	25.69	26.41	16.90	21.68	23.25	20.46	30.23	136.42
22	Manglad Khad	L	26.8	101.49	37.54	29.72	30.27	19.90	26.54	29.20	28.75	42.77	150.42
23	Kaowil Khad	R	27.6	14.15	37.84	30.03	30.75	20.11	26.85	29.83	28.80	43.08	150.86
24	Between Manglad Khad and Daaj Khad	L	28.6	5.74	37.96	30.16	30.97	20.28	27.12	30.09	28.83	43.20	151.04
25	Daaj Khad	L	30.4	9.25	38.15	30.36	31.32	20.56	27.56	30.51	28.86	43.41	151.32
26	Between Daaj and Jhakri	L	32.0	6.30	38.28	30.50	31.56	20.74	27.86	30.79	28.89	43.55	151.52
27	Sumej Khad	R	32.1	83.85	42.71	33.64	34.41	22.01	29.68	32.74	31.50	47.62	157.80
28	Jhakri		33.7	866.26	42.73	33.67	34.45	22.02	29.70	32.79	31.51	47.64	157.84

R – Right Bank; L – Left Bank

ANNEXURE 7.4
DISCHARGES OF SATLUJ RIVER FOR YEAR 2005-06

S. No.			Chainage from Nathpa (km)	CA (sq. km)	Discharge upto corresponding chainage (cumec)																				
					Oct			Nov			Dec			Jan			Feb			Mar			Apr		
					I	II	III	I	II	III	I	II	III	I	II	III	I	II	III	I	II	III	I	II	III
1	**Nathpa Dam**		**0.0**		7.00	7.00	7.00	7.00	7.00	7.00	7.00	7.00	7.00	7.00	7.00	7.00	7.00	7.00	7.00	7.00	7.00	7.00	7.00	7.00	7.00
2	Three tributaries near Nathpa	R	1.4	4.97	7.26	7.26	7.26	7.26	7.17	7.17	7.17	7.17	7.32	7.32	7.32	7.32	7.21	7.21	7.21	7.21	7.21	7.21	7.21	7.21	7.24
3	Shilaring Khad	R	2.9	90.02	8.17	8.45	8.35	8.33	7.86	7.77	7.62	7.75	8.08	8.01	7.94	8.01	7.82	7.80	7.76	7.79	7.79	7.74	7.89	7.80	8.14
4	Near Sungra	L	3.3	14.63	8.57	8.85	8.75	8.72	7.98	7.89	7.74	7.87	8.54	8.47	8.41	8.47	8.19	8.17	8.14	8.17	8.17	8.11	8.26	8.18	8.48
5	Sholding Khad	L	6.6	88.36	8.57	8.85	8.75	8.72	7.98	7.89	7.74	7.87	8.54	8.47	8.41	8.47	8.19	8.17	8.14	8.17	8.17	8.11	8.26	8.18	8.48
6	Near Gharsoo and Chhota Khambha	R	7.4	12.03	8.89	9.17	9.07	9.05	8.07	7.98	7.83	7.96	9.01	8.94	8.88	8.94	8.40	8.38	8.34	8.37	8.36	8.30	8.45	8.37	8.75
7	Near Taranda	L	8.7	3.87	9.00	9.28	9.18	9.15	8.10	8.01	7.86	7.99	9.13	9.06	9.00	9.07	8.50	8.47	8.44	8.47	8.45	8.40	8.55	8.47	8.84
8	Chaunda Khad	L	10.8	19.60	10.01	10.15	10.09	10.08	8.89	8.77	8.58	8.75	9.57	9.52	9.39	9.49	8.90	8.94	8.88	8.91	8.87	8.81	8.90	8.86	9.43
9	Sorang Khad	R	12.0	127.87	11.59	11.36	11.05	11.33	9.64	9.49	9.02	9.39	10.34	10.23	10.06	10.21	9.64	9.65	9.48	9.59	9.53	9.42	9.90	9.61	10.44
10	Near Chaura village	L	13.2	7.62	11.79	11.56	11.25	11.54	9.70	9.55	9.08	9.45	10.58	10.47	10.30	10.45	9.84	9.84	9.67	9.78	9.72	9.61	10.09	9.81	10.61
11	Tikadda Khad	R	13.6	16.94	12.25	12.02	11.71	11.99	9.84	9.69	9.22	9.58	11.24	11.13	10.97	11.11	10.13	10.13	9.96	10.07	9.99	9.88	10.36	10.08	11.00
12	Near Phagi	R	15.4	5.34	12.40	12.17	11.86	12.14	9.88	9.73	9.26	9.63	11.45	11.34	11.18	11.32	10.22	10.22	10.05	10.16	10.08	9.97	10.44	10.16	11.13
13	Chaura Khad	L	15.6	10.62	13.02	12.75	12.47	12.74	10.48	10.29	9.77	10.18	11.94	11.79	11.58	11.77	10.68	10.78	10.54	10.67	10.55	10.41	10.88	10.61	11.81
14	Kut Khad	R	17.2	76.24	17.07	16.80	16.52	16.80	13.67	13.48	12.96	13.37	14.92	14.78	14.57	14.76	11.98	12.08	11.84	11.97	11.76	11.62	12.09	11.82	13.35
15	Shimla Khad	L	17.7	9.20	17.32	17.05	16.77	17.05	13.75	13.56	13.04	13.45	15.21	15.07	14.86	15.05	12.21	12.32	12.07	12.20	11.99	11.85	12.32	12.06	13.56
16	Between Kut Khad and Ratu Khad	R	19.2	3.51	17.42	17.15	16.87	17.14	13.77	13.58	13.06	13.47	15.35	15.21	15.00	15.19	12.27	12.38	12.13	12.26	12.05	11.91	12.38	12.11	13.64
17	Dharali Khad	L	19.9	11.05	17.72	17.45	17.17	17.44	13.86	13.67	13.15	13.56	15.70	15.56	15.35	15.53	12.55	12.66	12.41	12.54	12.33	12.19	12.66	12.39	13.89
18	Ratu Khad	R	21.2	2.60	17.79	17.52	17.24	17.51	13.88	13.69	13.17	13.58	15.80	15.66	15.45	15.64	12.60	12.70	12.46	12.59	12.37	12.23	12.70	12.44	13.95
19	Gatti Khad	R	21.8	5.38	18.13	17.84	17.53	17.84	14.17	13.96	13.42	13.85	15.96	15.81	15.58	15.78	12.73	12.87	12.61	12.74	12.51	12.37	12.84	12.57	14.17
20	Ganvi Khad	R	23.2	114.97	20.05	19.51	19.09	19.55	15.70	15.56	14.54	15.27	16.71	16.48	16.25	16.48	13.42	13.56	13.18	13.39	13.18	13.00	13.66	13.28	15.20
21	Rai Khad/Unoo Khad	L	24.5	19.49	20.34	19.81	19.43	19.86	15.94	15.81	14.82	15.52	16.84	16.61	16.40	16.62	13.58	13.77	13.35	13.57	13.33	13.15	13.78	13.42	15.35
22	Manglad Khad	L	26.8	101.49	21.78	21.16	20.75	21.23	17.17	16.96	15.94	16.69	17.43	17.20	16.96	17.20	14.15	14.56	13.97	14.23	13.92	13.69	14.29	13.96	16.01
23	Kaowil Khad	R	27.6	14.15	22.15	21.42	20.97	21.51	17.47	17.17	16.12	16.92	17.60	17.32	17.07	17.33	14.28	14.73	14.12	14.38	14.06	13.83	14.42	14.11	16.20
24	Between Manglad Khad and Daaj Khad	L	28.6	5.74	22.30	21.57	21.13	21.67	17.52	17.22	16.17	16.97	17.78	17.50	17.25	17.51	14.43	14.88	14.27	14.52	14.21	13.98	14.57	14.25	16.33
25	Daaj Khad	L	30.4	9.25	22.53	21.78	21.31	21.88	17.71	17.39	16.32	17.14	17.89	17.59	17.33	17.60	14.54	15.03	14.40	14.65	14.33	14.09	14.68	14.37	16.54
26	Between Daaj and Jhakri	L	32.0	6.30	22.70	21.95	21.48	22.05	17.76	17.44	16.37	17.19	18.09	17.79	17.53	17.80	14.70	15.19	14.56	14.82	14.49	14.25	14.84	14.53	16.69
27	Sumej Khad	R	32.1	83.85	24.36	23.51	22.80	23.56	18.84	18.47	17.37	18.23	18.71	18.36	18.07	18.38	15.38	15.84	15.20	15.47	15.08	14.83	15.61	15.17	17.59
28	**Jhakri**		**33.7**	866.26	24.40	23.54	22.83	23.59	18.85	18.48	17.38	18.24	18.76	18.40	18.11	18.42	15.40	15.86	15.22	15.49	15.10	14.85	15.62	15.19	17.62

R – Right Bank; L – Left Bank

PUBLICATIONS FROM THE THESIS

1. Chaube, U. C., Mishra, S. K. and **Kumar, P.** 2007. Effect of flow diversion project on low flow characteristics - study of a Himalayan river. International Seminar on "River and Development" at Bali, Indonesia.
2. Chaube, U. C., Sharma, S., Sharma, P. and **Kumar, P.** 2008. Water quality assessment of river Satluj using benthic macroinvertebrates. Proceedings of the Scientific Conference "Rivers in the Hindu Kush-Himalaya – Ecology and Environmental Assessment", Kathmandu, Nepal.
3. **Kumar, P.,** Chaube, U. C. and Mishra, S. K. 2005. Model estimation of moisture retention and transmission characteristics of soils in mountainous Satluj valley, India. International Conference on "Recent Advances in Water Resources Development and Management", IIT Roorkee.
4. **Kumar, P.** , Chaube , U. C. and Mishra, S. K. 2006. Environmental aspects of tunnels and underground structures – a case study. National Seminar on "Environmental Audit of Hydroelectric Projects for Sustainable Development", Department of Zoology, Government Degree College, Vikasnagar, Dak-Pathar, Dehradun.
5. **Kumar, P.,** Chaube, U. C. and Mishra, S. K. 2006. Methodology for assessing environmental flows in Himalayan rivers – a case study of Nathpa-Jhakri Hydroelectric Project. National Seminar on "Environmental Audit of Hydroelectric Projects for Sustainable Development", Department of Zoology, Government Degree College, Vikasnagar, Dak-Pathar, Dehradun.
6. **Kumar, P.,** Chaube, U. C. and Mishra, S. K. 2007. Environmental flows for a hydropower project – a case study. International Conference "Hydro Sri Lanka" at Candy, Sri Lanka.
7. Sharma, S. K., **Kumar, P.,** Chaube, U. C., Mishra, S. K. and Sharma, P. 2006 Effect of Regulated Flow on Benthic Macroinvertebrates of the River Satlu International Conference on "The Majestic River Ganga: Health, Integrity a Management", Patna University, Patna, India. (Abstract)