INTERIM REPORT
on
Vetting of Water Availability Studies and Climate Change Assessment for Kalpasar Project

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Submitted to:

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For:

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EXECUTIVE SUMMARY

The Kalpasar Project, also known as the Gulf of Khambhat Development Project, is a flagship multipurpose initiative of the Government of Gujarat aimed at creating a large freshwater coastal reservoir by constructing a dyke across the Gulf of Khambhat. The project is envisaged to meet long-term drinking water, irrigation, industrial, and other developmental requirements of Gujarat. Given the scale and strategic importance of the project, a reliable assessment of water availability is a critical prerequisite for project formulation and preparation of the Detailed Project Report (DPR).

Water availability studies for the Kalpasar Project were originally carried out by the Central Design Office (CDO), Water Resources Department, Government of Gujarat, with technical support from the National Institute of Hydrology (NIH) in 2014, based on long-term hydrological data from 1901 to 2006. Subsequently, the analysis was extended by CDO up to the year 2024. The present study, entrusted to NIH by the National Centre for Coastal Research (NCCR), Chennai, focuses on vetting the adopted methodologies, datasets, assumptions, and computations used in these assessments, along with evaluating the implications of climate change on future water availability.

The Kalpasar reservoir is proposed to receive inflows from multiple river systems draining into the Gulf of Khambhat, including the Sabarmati, Mahi, Dhadhar, rivers of the Saurashtra region, and the Narmada River downstream of the Sardar Sarovar Project (SSP). The study critically reviewed basin-wise hydrological analyses, rainfall–runoff relationships, reservoir operation simulations, and utilization adjustments adopted for estimating long-term flow series at different dependability levels (50%, 75%, and 90%). Observed discharge data from Central Water Commission gauge and discharge sites, and rainfall data from India Meteorological Department stations were used as the primary data sources. Standard procedures such as Thiessen polygon weighting, data consistency checks, gap filling, and development of rainfall–runoff relationships for monsoon and non-monsoon periods were applied.

For each contributing basin, water availability was estimated by accounting for existing and proposed upstream water resource developments, reservoir storage, regulated releases, and basin-wise consumptive uses. Reservoir simulation using standard linear operating policies was adopted to estimate spill series from major storage projects. Free catchment contributions downstream of reservoirs were assessed using rainfall–runoff relationships developed from observed data. The frequency analysis was performed using Weibull’s plotting position formula to estimate dependable flows relevant for planning and design.

The vetting exercise confirms that the overall methodological framework adopted by CDO is technically sound and consistent with accepted hydrological practices for large-scale water resource projects in India. NIH observations from earlier reviews, related to data presentation, use of observed flows, development of rainfall–runoff (r-R) relationships, and clarity in accounting for utilizations and free catchments, have largely been addressed in the revised and extended analyses. All the computations for different basins were checked and found correct. The basin-wise results indicate that the combined inflows from the contributing river systems provide substantial water availability to the proposed Kalpasar reservoir, with clearly quantified dependable flows at different reliability levels.

In addition, the preliminary analysis on trends was undertaken to examine trends and variability in rainfall and streamflow across the contributing basins. The analysis indicates no statistically significant long-term declining trend in basin-scale water availability, although increased interannual variability and changes in extremes are evident in some basins. These findings highlight the need for adopting adaptive and flexible reservoir operation strategies to ensure reliability under future climatic uncertainty.

Overall, the vetted water availability assessment provides a robust and scientifically defensible basis for evaluating the feasibility of the Kalpasar Project. The dependable flow estimates generated through this study can be used for sizing of storage, fixing project demands, assessing supply reliability, and supporting informed decision-making during DPR preparation, while incorporating suitable safeguards for climate resilience and future change in storage and water sharing.

CHAPTER 1
INTRODUCTION

1.1 Overview

Water availability is a key issue for sustainable development, environmental health, and human well-being. Freshwater is a limited resource, affected by natural renewal rates and competing demands from agriculture, industry, ecosystems, and households. Water availability is a fundamental prerequisite for project formulation across various sectors, as it directly determines a project's feasibility, operational continuity, long-term sustainability, and economic viability. Failing to assess water resources properly during the planning stages can lead to significant delays, financial losses, or project failure. Hejazi et al. (2014) pointed out that the limited supply of water and rising demand make water scarcity a growing global risk. One of the most influential studies on water availability is by Hoekstra *et al.* (2012), in which 405 major river basins around the world were analyzed and found that many regions experience severe water scarcity for at least one month each year. This situation threatens ecological health and social stability. The year-to-year variability highlights the need to assess water more frequently; looking at monthly and seasonal trends is essential for effective management.

1.2 Water Availability Assessment for Project Formulation

Water availability is one of the prerequisites for the preparation of the Detailed Project Report (DPR) of water resource projects. When preparing a DPR, water availability at the dam site is a critical input, as it determines key factors such as gross storage, dam height, command area, etc. When preparing a DPR, the specific assessment of water availability at the proposed dam site is a critical input that determines the following key factors:

1.2.1 Determination of live and gross storage capacity

The primary function of a dam is storage of water, and the required gross storage capacity is directly dictated by how much water is available over time and how much demand the project aims to satisfy. The amount of water required or available is used for the assessment of the following important aspects in the selection of gross storage:

- **Balancing Supply and Demand**: The historical hydrological data (streamflow records, rainfall patterns) can be used to simulate how a reservoir would fill and empty under various conditions (average year, drought year, wet year). This analysis helps define the minimum storage required to meet target demands consistently (known as dependable yield).

- **Sedimentation Allowance**: The gross storage capacity of a reservoir contains a dead storage zone to accumulate sediment (silt) over the project's lifespan (typically 50-100 years). This volume is calculated based on anticipated sediment yield data from the catchment area, ensuring the "live storage" capacity for water delivery remains functional.
- **Flood Control Storage**: If flood mitigation is a project objective, the water availability study helps define the temporary storage volume needed to absorb peak flows during extreme events, which adds to the gross capacity.

1.2.2 Finalization of dam height and design

The required gross storage capacity translates directly into the physical dimensions of the structure, primarily the dam height, which can be determined by the water availability and the following aspects:

- **Topographic Matching**: Once the volume is known, engineers use topographic surveys of the dam site and the upstream valley to determine the required water surface elevation (Full Reservoir Level or FRL) needed to achieve that volume. The dam height is then set relative to the riverbed or foundation level, plus a freeboard margin for safety.
- **Foundation and Stability**: The structural design and stability calculations in the DPR rely heavily on the maximum water pressure the dam will withstand (determined by height). Overestimating availability leads to an oversized, overly expensive dam; underestimating risks failing to meet project objectives with a structure that is too small.

1.2.3 Command area assessment and demand mitigation

The ultimate purpose of most water resource projects is to serve a specific command area or population. Water availability dictates the realistic scope of determining the following points:

- **Irrigable Area (Potential Command Area)**: The dependable yield of the reservoir determines the maximum area that can be reliably irrigated. The crop water requirements is matched against the available supply to propose a sustainable command area boundary. The larger command or other commitments from the dam than the water availability can lead to project failure and social conflict.

- **Reliability of Supply**: Water availability studies inform the level of service reliability the project can guarantee (e.g., 75% for irrigation, 90 to 95% for power generation, 99% for drinking water).

Long-term hydrometeorological data analysis is critical to reliable water resources planning and design, given its ability to reflect the entire spectrum of natural climate variability, including wet, dry, and extreme events that shorter records cannot represent. Analysis of extended datasets of rainfall, temperature, streamflow, and evapotranspiration enables the robust estimation of water availability in different dependability levels, flood and drought frequencies. If this long-term assessment is coupled with the assessment of climate change impacts, this opens up one's ability to identify trends, shifts in seasonality, changes in the intensity and frequency of extremes, which directly affect the inflow into reservoirs, irrigation potential, hydropower generation, and flood risks. In an integrated water resource project, such analysis will assure a climate-resilient design and operation, decrease uncertainty in future performance, and allow for adaptive management strategies aimed at ensuring water security, infrastructure safety, and socio-economic benefits in response to evolving climatic conditions. Furthermore, climate change adds pressure by increasing uncertainty and variability in precipitation, streamflow, and demand. Research, such as optimization under climate uncertainty, indicates that water allocation systems need to be resilient to such fluctuations to prevent future shortages or inequalities.

1.3 Objectives

The Kalpasar project, or the Gulf of Khambhat Development Project, is a dream project of the Government of India and Gujarat, which envisages building a 30 km dam across the Gulf of Khambhat in India for establishing a huge fresh water coastal reservoir for irrigation, drinking and industrial purposes. By isolating the Gulf of Khambhat, the Kalpasar Project aims to create a massive freshwater reservoir. This reservoir will provide drinking water, industrial water, irrigation water, tidal power generation, and a transportation link. In the formulation and preparation of the DPR, water availability is a key factor, since the project's viability depends on how much water can actually be stored. The water availability assessment for the Kalpasar project was initially done by the National Institute of Hydrology and Central Design Office (CDO), WRD, Govt of Gujarat in the year 2014. Further, the analysis was extended by CDO. The National Centre for Coastal Research (NCCR) entrusted the National Institute of Hydrology (NIH) with the **Vetting and Assessment of Climate Change on Water Availability for the Kalpasar Dyke Project**.

This consultancy project aims to examine the hydrological data, methods, assumptions, and analytical techniques used in previous reports. The purpose is to review, confirm, and verify the earlier assessments of water availability for the Kalpasar Project. According to the project scope, this study seeks to ensure that the estimates of river inflows, rainfall contributions, and Narmada water diversion potentials are sound and based on reliable long-term datasets. This foundation will help design the project's planned irrigation, drinking water, industrial supply, and reservoir operations based on solid science. It also aims to find out if the proposed reservoir can meet the multi-sector water demands outlined in the Kalpasar development plan, recalculate reliable flows when necessary, and assess the adequacy of the basin-wise data currently available, and under future climate change scenarios.

The key objectives of this study are as follows:

1. Vetting of the adopted methodology and calculations for the water availability and rainfall-runoff (r-R) relationships in the Kalpasar project.
2. Assessment of the impacts of climate change on the overall water availability of the Kalpasar project.

CHAPTER 2
STUDY AREA

2.1 Kalpasar Project

The Saurashtra peninsula and Central and South Gujarat surround the Gulf of Khambhat, the largest of the two gulfs in Gujarat. The Gulf of Khambhat area, which may eventually turn into the Khambhat reservoir, receives its water from multiple smaller river basins on the northeastern side of Saurashtra. It also gets water from major river basins in North and Central Gujarat, including the Sabarmati, Mahi, and Dhadhar rivers, as well as from the Narmada, which is the fifth largest river basin in the country. The river basins contributing flow to the Kalpasar Project are shown in **Figure 2.1**.

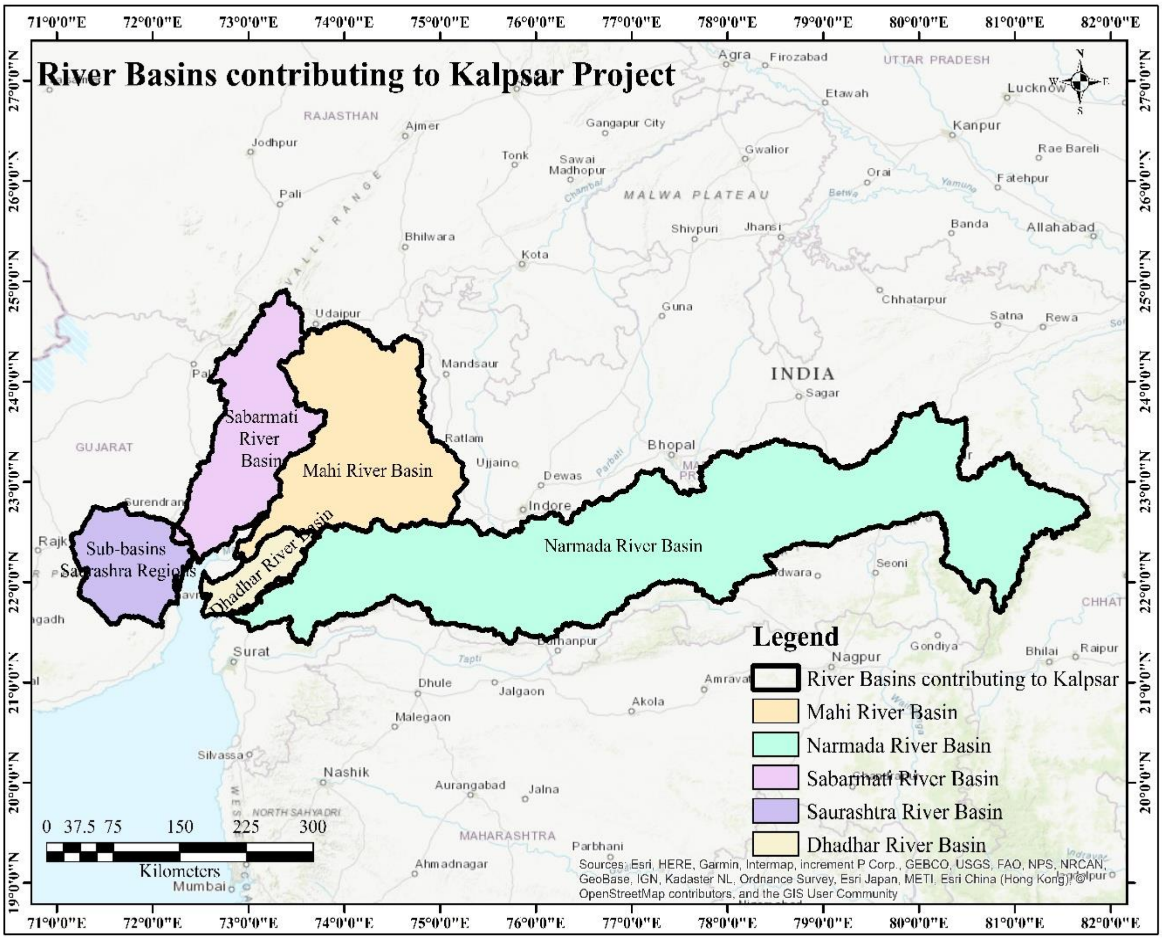
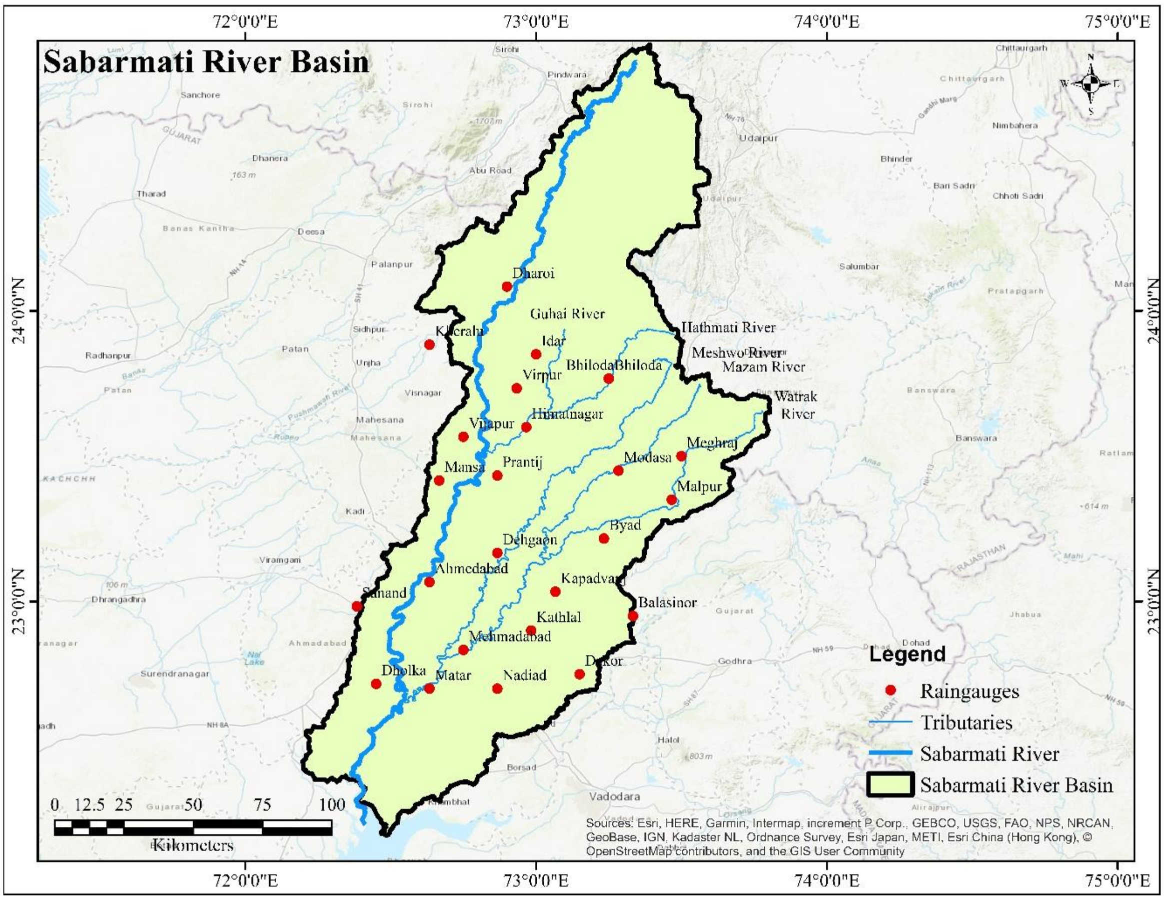


Figure 2.1: Kalpasar contributing river basins

A brief description of the various contributing river basins is given in the following headings.

2.1.1 Sabarmati river basin

One of the main rivers in western India, the Sabarmati River flows between latitudes 22°N to 25°N and longitudes 71°E to 73.5°E through the semi-arid states of Gujarat and Rajasthan (**Figure 2.2**). The river is 371 km long and covers a basin area of 21,674 sq km, with 17,550 sq km located in Gujarat. The average annual rainfall in the basin is about 780 mm, with more rain occurring in the upper levels. The area is home to 11.44 million people (2001), nearly half of whom live in cities. It also has 1,845 sq km of forest. The region has an irrigation potential of over 465,000 hectares and contains part of the highly industrialized Golden Corridor. Large-scale water resource development in the basin is supported by diversion projects and major water resource projects, including the Dharoi, Hathmati, Harnav, Guhai, Meshwa, Mazam, and Watrak dams.



Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), © OpenStreetMap contributors, and the GIS User Community

Figure 2.2: Sabarmati River Basin map

Hydrological estimates show that the basin's surface water yield dropped from 4654 MCM in 1949 to 1695 MCM in 1976. A follow-up analysis in 1996, done by sub-basin, estimated an average output of 3297.10 MCM and a reliable yield of 1539.18 MCM at a 75% level. From

June to September, the basin receives rainfall from the southwest monsoon, which is monitored by several hydrological stations, including six Central Water Commission sites and 105 rain gauges. Heavy irrigation has led to the overuse of groundwater resources, despite an annual recharge of 2,570 MCM. As a result, 23 out of 29 talukas are in critical stages of overdevelopment.

2.1.2 Mahi river basin

The Mahi River, a major west-flowing river that drains into the Gulf of Khambhat, originates at an elevation of about 500 m on the northern slopes of the Vindhyan range near Sardarpur in Madhya Pradesh. It flows for 583 km, with 167 km in Madhya Pradesh, 174 km in Rajasthan, and 242 km in Gujarat. Its basin, covering 34,842 sq km (6,695 sq km in Madhya Pradesh, 11,694 sq km in Gujarat, and 16,453 sq km in Rajasthan), lies between 72°15′–78°15′ E and 22°–22°15′ N. Bounded by the Aravalli Hills to the north, the Chambal basin to the east, the Vindhyas to the south, and the Gulf of Khambhat to the west (**Figure 2.3**). The basin extends about 330 km in length and 250 km in width. The upper basin features an undulating landscape with ridges and valleys, while the lower basin consists of flat, fertile alluvial plains.

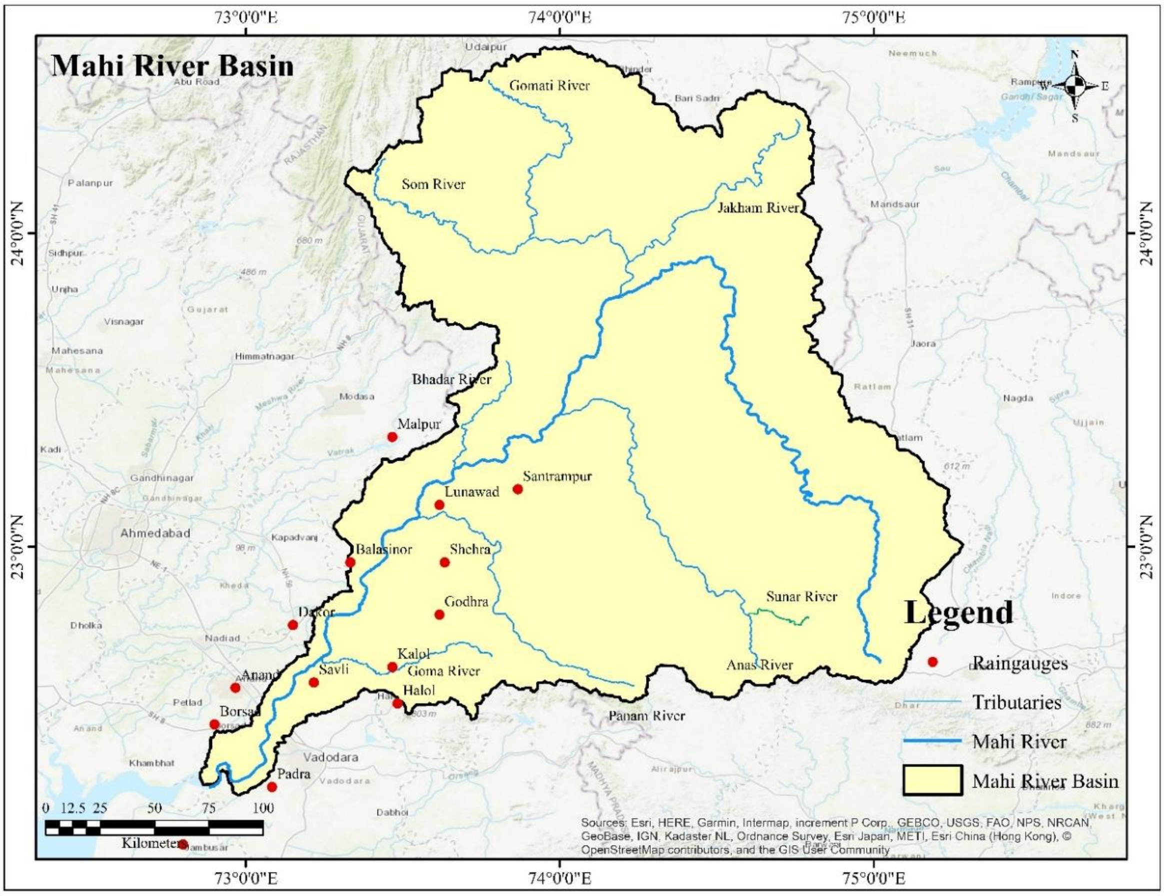


Figure 2.3: Mahi River Basin map

2.1.3 Dhadhar river basin

The Pavagadh Hills are the source of Gujarat's Dhadhar River, which flows westward for approximately 142 km through the districts of Vadodara and Bharuch before emptying into the Gulf of Khambhat. Along with smaller tributaries like the Jambuo and Surya rivers, its main tributaries are the Vishwamitri, which enters from the right bank near Pingalwada after 87 km, and the Deo, which rises near Umarvant in Halol taluka and runs 75 km southwest to meet the Dhadhar near Banalaya. The Dhadhar basin, which is fully within Gujarat and spans 4,201 sq km between 72° 30′ - 73°45′ E and 21°45′ - 22°45′ N (**Figure 2.4**), has a hot, dry summer, a temperate winter, and monsoon rains primarily from June to September. It is well-developed in terms of water resources, hosting several major and medium projects such as the Ajwa Tank, Pratap Pura, Uma Bhariara, Dhanora, Ghansarva, Haripura, Vadodara, and Deo dams, which contribute significantly to regional water management and irrigation.

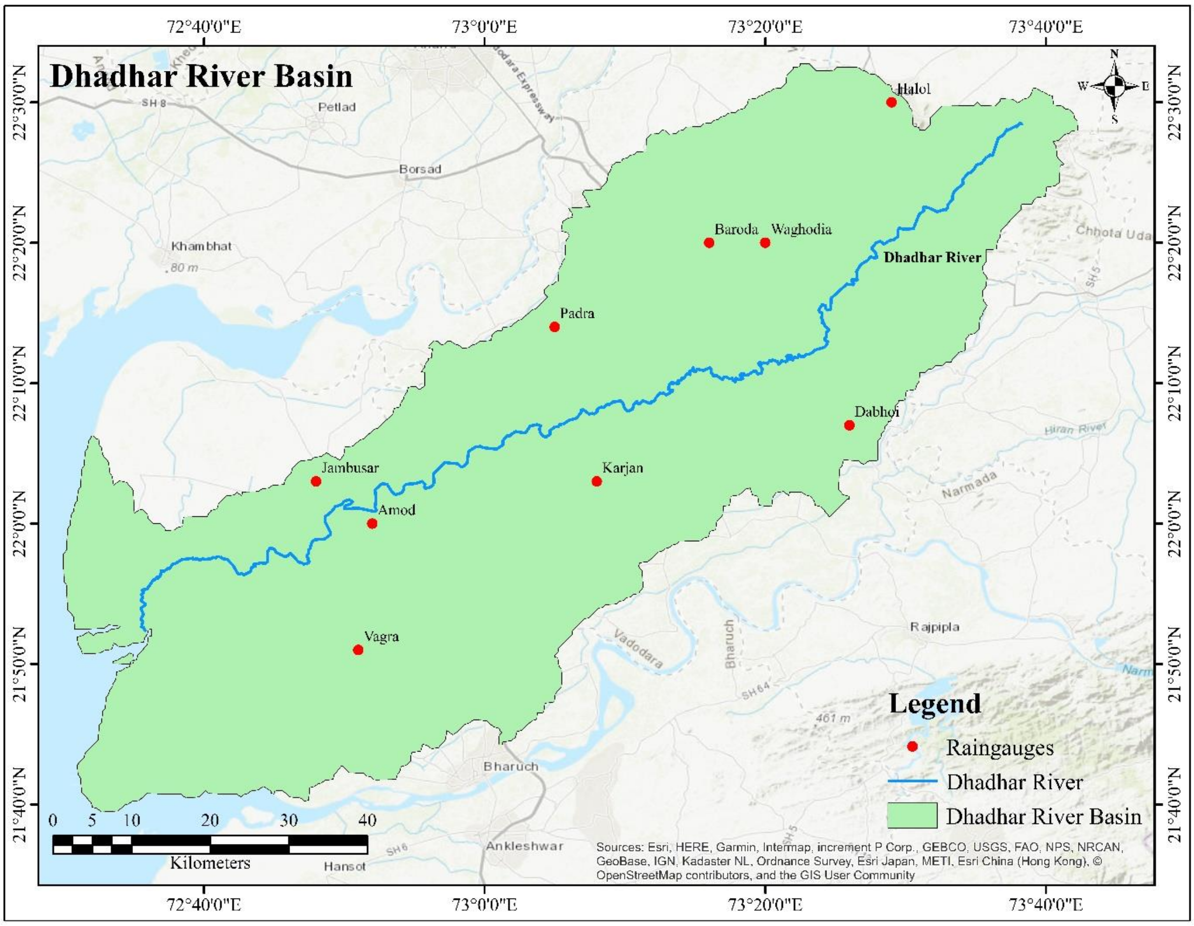


Figure 2.4: Dhadhar River Basin map

2.1.4 Basins of Saurashtra region

Originating from the central plateau and flowing in a radial pattern, the rivers on the northeastern side of the Saurashtra peninsula are typically short and empty into the Gulf of Khambhat. The area is made up of low hills that alternate with little alluvial basins. The average annual rainfall in the area is only 700 mm, which results in rivers that are largely dry and have shallow beds. While some of these rivers become minor creeks or merge into mangrove swamps at the coast, many lose their routes before they reach the sea. Wadhwan Bhogavo, Limbdi Bhogavo, Sukhbhadar, Kalubhar, Keri, Ghelo, and Utavali are the seven sub-basins that make up the Saurashtra Basin. The complete basin map is shown in **Figure 2.5**.

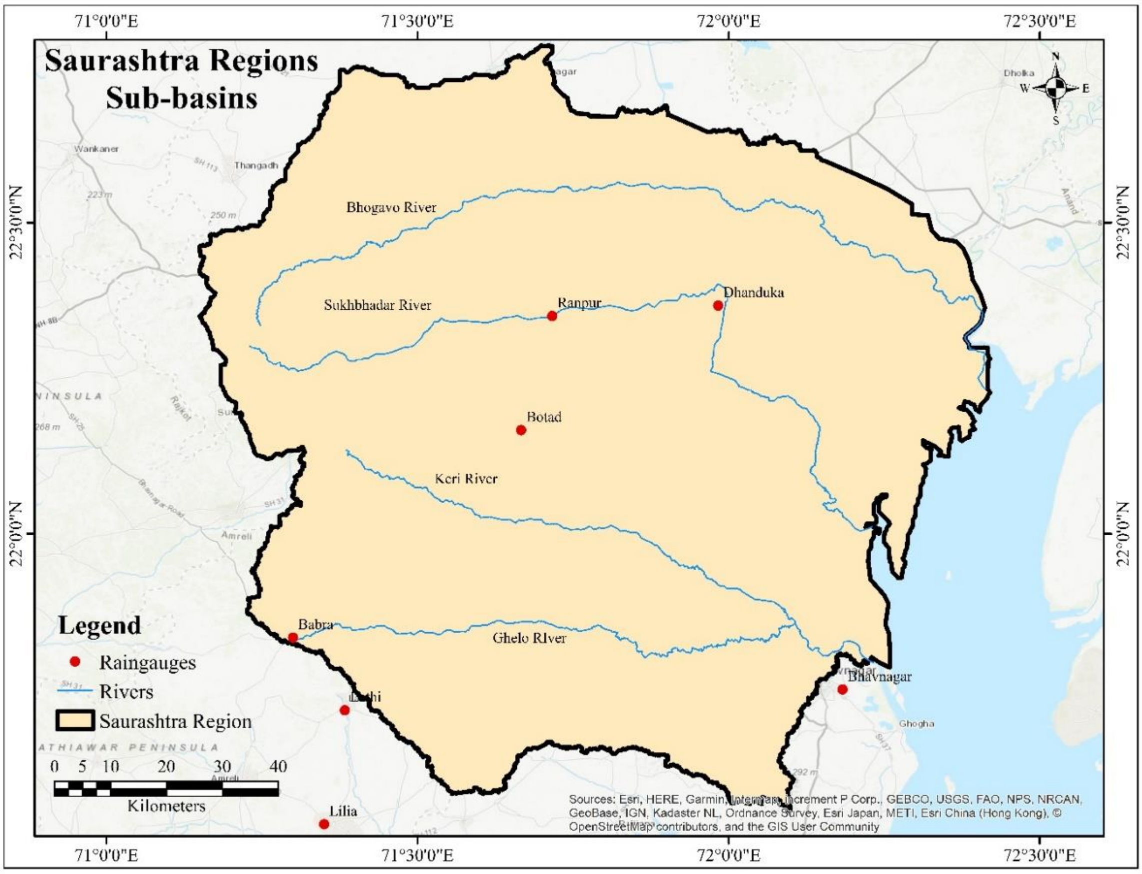


Figure 2.5: Saurashtra River Basin map

The size of the catchment and the degree of water resource development differ greatly among the sub-basins. Large portions of the catchments of Wadhwan Bhogavo (WB) (1569.5 sq km) and Limbdi Bhogavo (LB) (1942.5 sq km) are affected by several projects, including WB-I, WB-II, and WB-III, as well as LB-I, LB-II, and LB-III. The Sukhbhadar, Goma, and Dhari projects are in Sukhbhadar (2118.6 sq km). The Khambhada dam is located in Utavali (384 sq km), which has a free catchment area of 267.45 sq km. The Ghelo basin (614.4 sq km) has

101.3 sq km of free catchment beyond the Navagam Loliyana dam. The Keri basin (555.3 sq km) has 262.24 sq km of free catchment beyond the Sarangpur Gala and Bhimdad projects. The Kalubhar and Rangola projects are part of the Kalubhar basin (1493 sq km), which sends runoff to the Gulf of Khambhat from 905.31 sq km of net free catchment.

2.1.5 Narmada River Basin

The Narmada, the largest west-flowing river in the Indian Peninsula, starts at about 900 meters in elevation near Amarkantak in Madhya Pradesh's Maikhal Range. It flows for 1,312 km before reaching the Arabian Sea. Madhya Pradesh accounts for 1,077 kilometres of its total length, while Maharashtra and Gujarat cover 39 kilometres, Madhya Pradesh and Maharashtra together cover 35 km, and Gujarat contributes 161 km. Out of the 97,410 square kilometres that the river drains, 85,858 sq km are in Madhya Pradesh, 1,658 sq km are in Maharashtra, and 9,894 sq km are in Gujarat. The basin lies between latitudes 21°20′ and 23°45′ N and longitudes 72°32′ and 81°45′ E as shown in **Figure 2.6**.

The spill from the Sardar Sarovar Project (SSP) and the runoff from the free catchment area below SSP, which includes spills from the Karjan and Sukhi projects and runoff from sub-basins downstream, are the two components of the Narmada basin used to estimate the water availability at Bhadbhut village, downstream of Bharuch. The Sardar Sarovar Project is one of India's most important water resource development projects. It is a large interstate multipurpose project that involves Gujarat, Madhya Pradesh, Maharashtra, and Rajasthan. It is the largest and final dam on the Narmada.

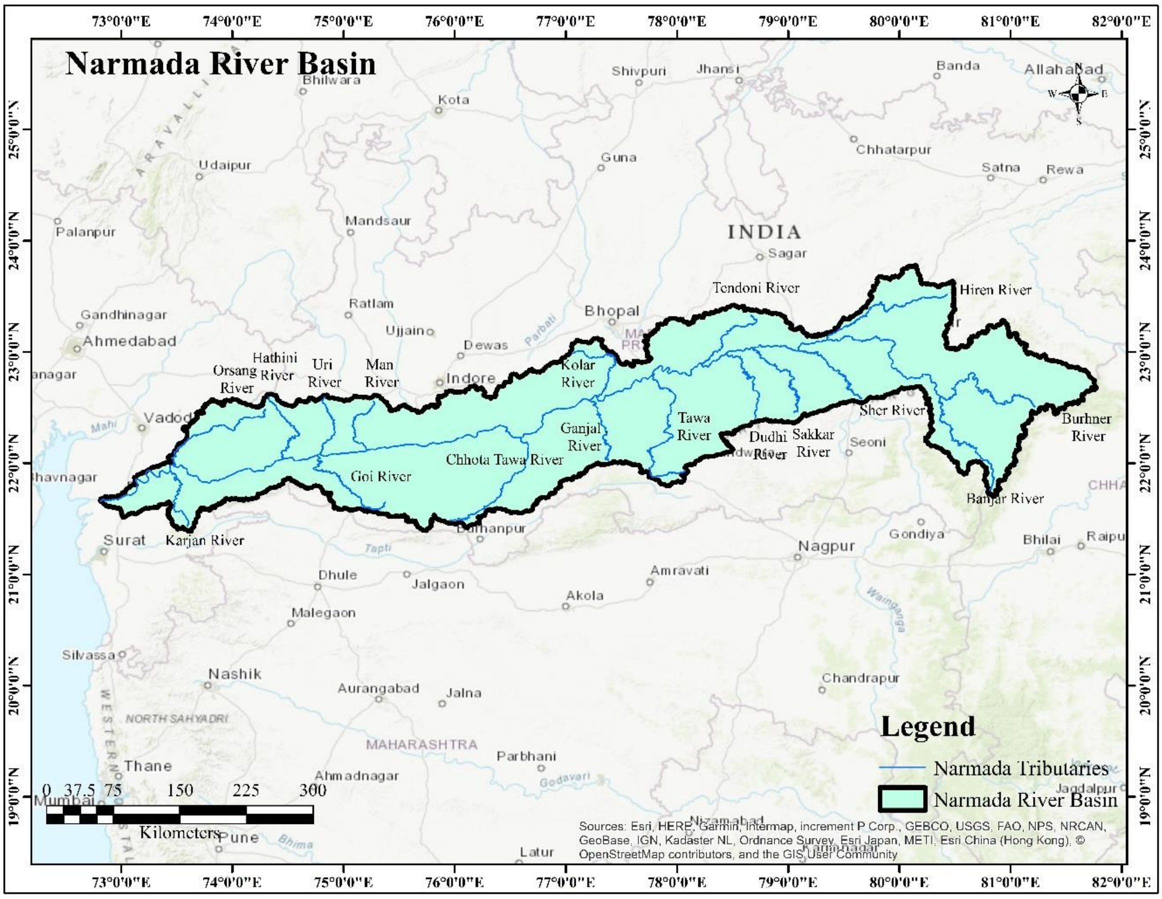


Figure 2.6: Narmada River Basin map

CHAPTER 3
METHODOLOGY & PREVIOUS ESTABLISHMENTS (2014)

3.1 Methodology Adopted by CDO and Incorporation of NIH Observations

This chapter details the earlier methodologies used by the Central Design Organization (CDO) and the National Institute of Hydrology (NIH) for assessing water availability for the Gulf of Khambhat Development Project (Kalpasar Project). The primary goal was to determine water availability at the outlet of various basins, considering factors like rainfall, water resource development, and utilization.

3.1.1 CDO's methodology for water availability

Flow Series Generation: The CDO generated long-term flow series (1901-2006) for contributing basins to determine water availability at specified dependability levels (50%, 75%, and 90%). The flow sequences for sub-basins were derived either by developing rainfall-runoff (r-R) relationships and extending runoff series or by using flow characteristics of adjacent sub-basins.

Sabarmati River Basin: The Sabarmati basin was divided into eleven sub-catchments. Inflow series were computed considering upstream utilizations, reservoir performance, and free catchment contributions. For instance, the Harnav Reservoir's inflow series for 1901-1917 was obtained by scaling Dharoi dam data, and later periods used reservoir performance data or flow data from other sites. Similar methods were applied to Dharoi, Guhai, Hathmati, Meshwo, Mazam, and Watrak dams, and other areas like Hathmati Weir, Wasna Barrage, Khari River, Raska Weir, Shedhi River, and various free catchments. The RIBASIM model was used to analyze utilizations and allocations within the Sabarmati basin.

Mahi River Basin: The Mahi basin's catchment area (34,842 sq. km) was divided into parts intercepted by Kadana, Bhadar, and Panam dams, and a free catchment area. Water availability was estimated from spills from these dams and runoff from the free catchment.

Dhadhar Basin: River Basin: The Dhadhar basin has a gross catchment area of 4201 sq. km. Monthly rainfall-runoff correlations were established to derive yield series, considering existing and future water utilizations.

Saurashtra Region Sub-basins: The CDO adopted a methodology for estimating water availability in various sub-basins in the Saurashtra region, including Wadhwan Bhogavo, Limbdi Bhogavo, Sukhbhadar, Utavali, Keri, Ghelo, and Kalubhar, using raingauge station data and rainfall-runoff correlations.

Narmada Basin: Water availability from the Narmada River was estimated by considering spills from the Sardar Sarovar Project (SSP) and runoff from free catchments below the SSP.

3.1.2 NIH observations on CDO reports

NIH recommended including hydro-meteorological networks, sub-basin layouts, Thiessen polygon maps, line diagrams, and tables detailing rainfall and discharge stations with data availability. They also advised incorporating details of hydraulic structures and present/projected demands. Improvements in data presentation and rectification of grammatical errors were also suggested.

Sabarmati River Basin: NIH suggested using rainfall data from various stations to develop rainfall-runoff relationships rather than solely relying on proportionate reduction/enhancement of inflow series from nearby sub-basins. They also recommended using observed flow data from Gauge & Discharge (G&D) sites directly.

Mahi River Basin: NIH requested details on the r-R relationship developed for the Wanakbori weir and suggested developing an r-R relationship for the Khanpur site.

Dhadhar River Basin: Observations included clarifying the use of gross vs. free catchment area in calculations and incorporating storage data from other projects for rainfall-runoff relationship development.

Saurashtra Region: NIH suggested considering data from 1901 onwards for Saurashtra rivers, similar to other basins, and checking for spills from terminal dams.

Narmada River Basin: NIH recommended using r-R relationships derived from the Sukhi project catchment for downstream sub-catchments and developing monthly r-R relationships for Karjan and Sukhi dam sites.

Further Discussions (July 2011): Subsequent discussions led to agreements on using CDO's catchment boundaries, CDO supplying utilization data, incorporating details of water resource projects, and addressing previous comments. It was also emphasised to use CWC G&D and IMD rainfall data, check data reliability, and develop monthly r-R relationships for various basins and sub-basins.

3.1.3 Analysis of water availability from different river basins contributing to Kalpasar project

The detailed analysis of water availability from various river basins contributing to the Kalpasar Project, incorporating NIH's observations are discussed here. Regarding the data processing, the water availability reports were finalized by NIH using CDO-supplied data. GIS analysis was performed using ILWIS GIS for river basin maps, sub-basin boundaries, and Thiessen weights of rainfall stations. For hydrological data management software like SWDES and HYMOS were used for processing and validating hydrological data. In the missing rainfall data gaps, the data were filled using the normal-ratio method. The double mass curves were plotted for consistency checks. Virgin flows were estimated from discharge observations at G&D sites and plotted against average rainfall.

3.1.3.1 Water availability analysis for the Sabarmati basin

The basin of the Sabarmati River is encompassed by the Aravalli hills, the Mahi basin, the Gulf of Cambay, and minor streams as its boundaries. It has a catchment area of 21,674 sq km, out of which 17,550 sq km lies in Gujarat and 4,124 sq km in Rajasthan. In the study, eleven sub-basins of the basin were delineated, out of which six were intercepted by storage reservoirs, namely, Dharoi, Guhai, Hathmati, Meshwo, Mazam, and Watrak, and four sites of G&D, namely, Gandhinagar, Ratanpur, Kheda, and Vautha and the remaining is the free catchment upto sea as shown in **Figure 3.1**. The project report aimed to find the availability of water to the Kalpasar Project at 50%, 75%, and 90% dependability. The average monthly rainfall from 1901 to 2003 was computed. The spill from six reservoirs was analyzed, and a rainfall-runoff (r-R) relationship was developed for monsoon months using observed flow data. Rainfall data from 29 IMD stations and flow data from three G&D sites were used. Thiessen polygon weights, spatial correlation, and distance matrices were developed to fill gaps in data and ensure homogeneity. The estimate of spill from Dharoi, Guhai, Hathmati, Meshwo, Mazam, and Watrak dams was computed by using reservoir performance data and the r-R relationship. For the free catchment, runoff was estimated by using the r-R relationship considering upstream spills and planned utilizations. In the study of CDO and NIH, the spill from different reservoirs in the Sabarmati basin was computed using reservoir operation considering standard linear operation policy and weighted rainfall from IMD data, while for the remaining free catchment upto sea, the spill from these dams and weighted rainfall of the corresponding catchment were used.

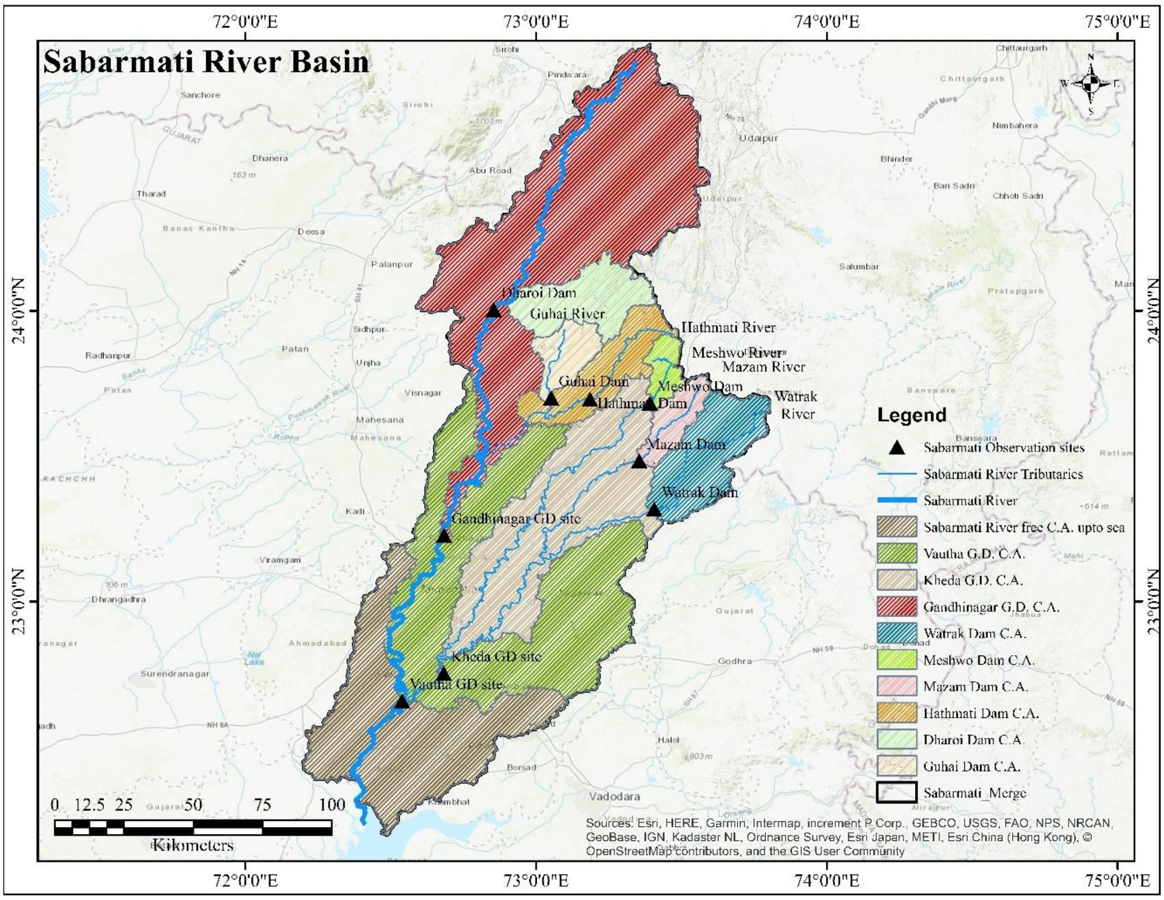


Figure 3.1: Observation site location and division of the Sabarmati river basin as per water availability analysis

The computation of the spill series from different dams by the CDO is described below:

(i) **Dharoi dam:** The Dharoi reservoir has a total catchment area of 5,540 sq km, with 3,217 sq km designated for the project. It also receives upstream influences from the Harnav dam and weir. The runoff data from 1890 to 1979 were collected from the CWC report, while the yield from 1980 to 2003 was computed from adjusted reservoir performance records. To evaluate the impact of the Harnav system, the reservoir operation analysis from 1901 to 2004 was conducted using a standard linear operating policy. The net monthly inflow series for Dharoi, covering the years 1901 to 2003, was used in the reservoir working table to simulate storage and spill conditions.

(ii) **Guhai dam:** The Guhai dam catchment covers 422.20 sq km, and the weighted mean rainfall (WMR) series has been derived using rainfall data from IMD stations. Inflow data for the monsoon months (June–September) from 1991 to 2003 were used to develop monthly rainfall–runoff (R–R) relationships for the Guhai sub-basin (SB-2).

These relationships were then applied to the average monsoon rainfall for 1901–2003 to generate long-term flow values. Using the resulting net monthly inflow series, a reservoir simulation was performed through the reservoir working table (RWT) to obtain the spill series from Guhai dam.

The developed r – R relationships for the Guhai sub-basin (SB – 2) by the CDO are given below:

$$R_{June} = 0.3704 * r_{June} - 33.744 \tag{3.1}$$

$$R_{July} = 0.2419 * r_{July} - 36.46 \tag{3.2}$$

$$R_{Aug} = 0.0549 * r_{July} + 0.3147 * r_{Aug} - 40.2564 \tag{3.3}$$

$$R_{Sept} = 0.1957 * r_{Aug} + 0.1202 * r_{Sept} - 20.7953 \tag{3.4}$$

Where,

R_{June}, R_{July}, R_{Aug}, R_{sept}: runoff in June, July, August and September, respectively

r_{June}, r_{July}, r_{Aug}, r_{sept}: Rainfall in June, July, August and September, respectively

(iii) **Hathmati dam:** The Hathmati dam has a catchment area of 595 sq km. The WMR series was developed using rainfall data from IMD stations. Inflow data for the monsoon months from June to September between 1991 and 2003 helped derive monthly rainfall-runoff (r-R) relationships for the Hathmati sub-basin (SB-3). These equations were applied to the average monsoon rainfall from 1901 to 2003 to convert rainfall into flow. The resulting net monthly inflow series was then used in a reservoir working table (RWT) simulation to calculate storage and spill behaviour.

The r – R relationships for the Hathmati sub-basin (SB – 3) developed by the CDO are presented below:

$$R_{June} = 0.1375 * r_{June} - 9.3519 \tag{3.5}$$

$$R_{July} = 0.3815 * r_{July} - 111.27 \tag{3.6}$$

$$R_{Aug} = 0.0268 * r_{July} + 0.2389 * r_{Aug} - 34.5383 \tag{3.7}$$

$$R_{Sept} = 0.0236 * r_{Aug} + 0.1821 * r_{Sept} - 3.4441 \tag{3.8}$$

(iv) **Meshwo dam:** The Meshwo dam has a catchment area of 259 sq. km, and its WMR series has been developed using IMD rainfall data. Inflow data for the monsoon months (June–September) from 1991 to 2003 were used to formulate monthly rainfall–runoff

(R–R) relationships for the Meshwo sub-basin (SB-4). These equations were applied to the average monsoon rainfall for 1901–2003 to convert rainfall into corresponding flow values. The resulting net monthly inflow series was used in reservoir working table (RWT) simulations to determine storage and spill behaviour.

The developed r – R relationships for the Meshwo sub-basin (SB – 4) are presented below:

$$R_{June} = 0.2484 * r_{June} - 14.089 \tag{3.9}$$

$$R_{July} = 0.3953 * r_{July} - 91.753 \tag{3.10}$$

$$R_{Aug} = 0.0750 * r_{July} + 0.4543 * r_{Aug} - 50.6986 \tag{3.11}$$

$$R_{Sept} = 0.4062 * r_{Aug} + 0.3244 * r_{Sept} - 58.2706 \tag{3.12}$$

(v) **Mazam dam:** The Mazam dam has a total catchment area of 407.80 sq km, of which 134.70 sq km lies in Rajasthan, while the project design considered a catchment area of 255.12 sq. km. The WMR series for the basin was developed using IMD rainfall data, and inflow data for June–September from 1991–2003 to derive monthly rainfall–runoff (r–R) relationships for the Mazam sub-basin (SB-5). These relationships were applied to the average monsoon rainfall for 1901–2003 to convert rainfall into flow. The resulting net monthly inflow series was then used in reservoir working table (RWT) simulations to estimate storage and spill behaviour.

The developed r – R relationships for the Mazam sub-basin (SB – 5) are:

$$R_{June} = 0.118 * r_{June} - 3.668 \tag{3.13}$$

$$R_{July} = 0.3496 * r_{June} + 0.7566 * r_{July} - 263.3433 \tag{3.14}$$

$$R_{Aug} = 0.0333 * r_{July} + 0.5131 * r_{Aug} - 70.4811 \tag{3.15}$$

$$R_{Sept} = 0.0966 * r_{Aug} + 0.2947 * r_{Sept} - 19.4847 \tag{3.16}$$

(vi) **Watrak dam:** The Watrak dam has a total catchment area of 1114 sq. km, with 337 sq. km lying in Rajasthan, while the project design accounts for 777 sq. km. The WMR series for the basin was developed using rainfall data from IMD stations, and inflow data for June–September from 1995–2003 was used to formulate monthly rainfall–runoff (r–R) relationships for the Watrak sub-basin (SB-6). These relationships were applied to the average monsoon rainfall for 1901–2003 to convert rainfall into corresponding flow values. The resulting net monthly inflow series was used in reservoir working table (RWT) simulations to estimate storage and spill behaviour.

The developed r – R relationships for the Watrak sub-basin are as follows:

$$R_{June} = 0.2329 * r_{June} - 14.136 \tag{3.17}$$

$$R_{July} = 0.6040 * r_{June} + 0.0912 * r_{July} - 41.6158 \tag{3.18}$$

$$R_{Aug} = 0.7734 * r_{Aug} - 89.0064 \tag{3.19}$$

$$R_{Sept} = 0.0343 * r_{Aug} + 0.1120 * r_{Sept} - 5.7006 \tag{3.20}$$

Estimation of runoff in the Sabarmati basin up to the sea: In the Sabarmati basin, four gauge and discharge stations, including Gandhinagar, Ratanpur, Kheda, and Vautha, monitor flows downstream of the six storage dams. Using observed flow data from the first three stations, along with upstream utilizations and spills from storage projects, virgin flows were estimated. Monthly average rainfall over the free catchments was determined using rainfall records from surrounding stations. Rainfall–runoff (r–R) relationships for monsoon months were then developed to convert long-term rainfall data into runoff. By adding spills from upstream reservoirs and subtracting planned future basin utilizations, the net flow series at each gauging site was obtained.

Computation of flow series from different G & D sites and ungauged catchments in the Sabarmati basin downstream of these dams is presented below:

(i) Estimation of flow series at Gandhinagar G & D site: The Gandhinagar G & D site has a free catchment area of 2160.75 sq. km located downstream of the Dharoi, Guhai, and Hathmati dams, with flow data available for 1980–1999. The weighted rainfall for this catchment (SB-7) was computed using IMD station data, and virgin flows were estimated by adjusting observed flows for upstream spills, regulated releases, and existing utilizations. Monthly virgin flows and monthly weighted rainfall were then used to develop rainfall–runoff (r–R) relationships for the monsoon months. These relationships were applied to long-term rainfall (1901–2003) to generate monthly flow values, which were further adjusted by subtracting planned utilizations and adding 90% of upstream spill flows (Considering 10% transit losses).

The developed r – R relationships for the Gandhinagar sub-basin (SB – 7) are:

$$R_{June} = 0.2483 * r_{June} - 13.152 \quad (3.21)$$

$$R_{July} = 0.1375 * r_{July} - 10.65 \quad (3.22)$$

$$R_{Aug} = 0.246 * r_{Aug} - 17.19 \quad (3.23)$$

$$R_{Sept} = 0.748 * r_{Sept} - 39.035 \quad (3.24)$$

(ii) Estimation of flow series at Ratanpur G & D site: The flow series at Ratanpur G & D site was estimated by first compiling observed flow records and computing the weighted rainfall (WR) using Thiessen Weights for IMD stations available in its free catchment. The virgin flows were derived by adjusting observed flows for upstream spills, regulated releases, and existing utilizations within the free catchment. The monthly virgin flows and corresponding monthly rainfall were used to develop rainfall–runoff (r–R) relationships for the monsoon months (June–September). These r–R equations were applied to long-term rainfall (1901–2003) to generate the net monthly inflow series, which were then adjusted by adding upstream spills and subtracting planned utilizations.

The developed r – R relationships for Ratanpur sub-basin (SB – 8) are:

$$R_{June} = 0.217 * r_{June} - 20.28 \quad (3.25)$$

$$R_{July} = -0.2345 * r_{June} + 0.0978 * r_{July} - 30.5694 \quad (3.26)$$

$$R_{Aug} = 0.1445 * r_{July} + 0.5800 * r_{Aug} - 96.1658 \quad (3.27)$$

$$R_{Sept} = -0.0499 * r_{Aug} + 0.2731 * r_{Sept} - 9.7709 \quad (3.28)$$

(iii) Estimation of flow series at Kheda G & D site: The Kheda G & D site has a free catchment area of 4969.54 sq. km downstream of the Meshwo dam and Ratanpur G & D site, with CWC flow records available for 1991–2008. The weighted rainfall for this catchment (SB-9) was computed using IMD data, and virgin flows were estimated by adjusting observed flows through deducting 90% of Meshwo dam spills and full flows from Ratanpur, while adding existing utilizations. Monthly virgin flows and rainfall were used to develop r–R relationships for July–September, and due to negligible June flows, the June r–R relation from Gandhinagar was adopted. These relationships were applied to long-term rainfall (1901–2003) to generate monthly flow values, which were further adjusted by subtracting planned utilizations and adding 90% of computed spills from the Meshwo dam.

The developed r – R relationships for Kheda sub-basin (SB – 9) are given below:

$$R_{July} = 0.0594 * r_{June} + 0.0348 * r_{July} - 11.2977 \quad (3.26)$$

$$R_{Aug} = 0.0597 * r_{July} + 0.2270 * r_{Aug} - 46.5594 \quad (3.27)$$

$$R_{Sept} = 0.0205 * r_{Aug} + 0.1306 * r_{Sept} - 7.8052 \quad (3.28)$$

(iv) **Estimation of flow series at Vautha G & D site**: The Vautha G & D site has a free catchment area of 1910.98 sq. km located downstream of the Gandhinagar and Kheda gauging sites, but no flow data were available for analysis. Therefore, the rainfall–runoff (r–R) relationships developed for the nearby Kheda sub-basin were adopted, and Weighted Mean Rainfall for the Vautha catchment (SB-10) was computed using IMD data. These r–R relations were applied to long-term rainfall (1901–2003) to derive monthly flow values for the free catchment. Net flows at Vautha were then estimated by subtracting planned utilizations of the Wasna Fatewari system from Gandhinagar flows and adding flow contributions from the Vautha free catchment and the Kheda G & D site.

(v) **Estimation of flow series from Sabarmati basin up to Sea:** The free catchment area of the Sabarmati basin from the Vautha G&D site to the sea covers 1852.19 sq. km. Since flow data are not available for this region, the r–R (rainfall–runoff) relationships developed for the Kheda catchment have been applied to this sub-basin as well. The Weighted Mean Rainfall for the downstream sub-basin (SB–11) has been estimated using data from IMD stations. Based on the adopted monthly r–R relationships, the average rainfall for the period 1901–2003 has been converted into corresponding flow values. To derive the net flow series for the Sabarmati basin up to the sea, the computed net flow at the Vautha G&D site has been combined with the monthly flow generated from the downstream free catchment (obtained through r–R relationships).

The estimated dependable flows at different hydraulic structures from the Sabarmati river basin to the Kalpasar project are presented in **Table 3.1**.

Table 3. 1: Dependable flows (MCM) computed at different locations in the Sabarmati river basin

Annual flows from the Sabarmati river basin MCM)	**Flows (MCM) corresponding to different dependability**			
	50%	**75%**	**90%**	**Average**
Flows from Dharoi dam	0.00	0.00	0.00	177.36
Flows from Guhai dam	0.00	0.00	0.00	8.45

Flows from Hathmati dam	0.00	0.00	0.00	0.31
Flows from the Meshwo dam	0.00	0.00	0.00	10.25
Flows from the Mazam dam	0.27	0.00	0.00	15.22
Flows from the Watrak dam	7.41	0.00	0.00	48.82
Flows at Gandhinagar G & D site	268.06	110.87	56.02	437.34
Flows at Ratanpur G & D site	234.05	81.32	38.85	282.65
Flows at Kheda G & D site	448.99	202.02	55.50	564.16
Flows at Vautha G & D site	741.09	285.48	68.83	956.26
Flows from the Sabarmati basin up to the Sea	823.49	340.64	74.59	1047.77

3.1.3.2 Water availability analysis for the Mahi basin

Originating from the Vindhyanchal range, the Mahi River flows a distance of 583 km and merges into the Arabian Sea as shown in **Figure 3.2**. The total catchment area is 34,842 sq. km, extending into Rajasthan, Gujarat, and Madhya Pradesh. Water for the Kalpasar Project originates from spills of Kadana, Bhadar, and Panam dams, and runoff from the free catchment area below these dams. Rainfall data from 22 IMD stations were used, and discharge data from the Khanpur gauging site (1980-2005) were utilized. Thiessen polygon weights, spatial correlation, and data gap-filling methods were adopted. Spill series from Kadana, Bhadar, and Panam dams were estimated through simulation analysis of reservoir operations. The runoff from the free catchment was estimated using rainfall-runoff relationships developed at Khanpur. Gross runoff was computed by combining runoff from sub-basins and spills, and then net runoff was derived by subtracting planned utilizations. Dependable yields were estimated for 50%, 75%, and 90% reliability. Estimated dependable flows from the Mahi river basin to the Kalpasar Project are discussed in the report, along with spills from individual dams and gross flow from the free catchment. In the study of CDO and NIH, the spill from different reservoirs in the Sabarmati basin was computed using reservoir operation considering standard linear operation policy and weighted rainfall from IMD data, while for the remaining free catchment upto sea, the spill from these dams and weighted rainfall of the corresponding catchment were used.

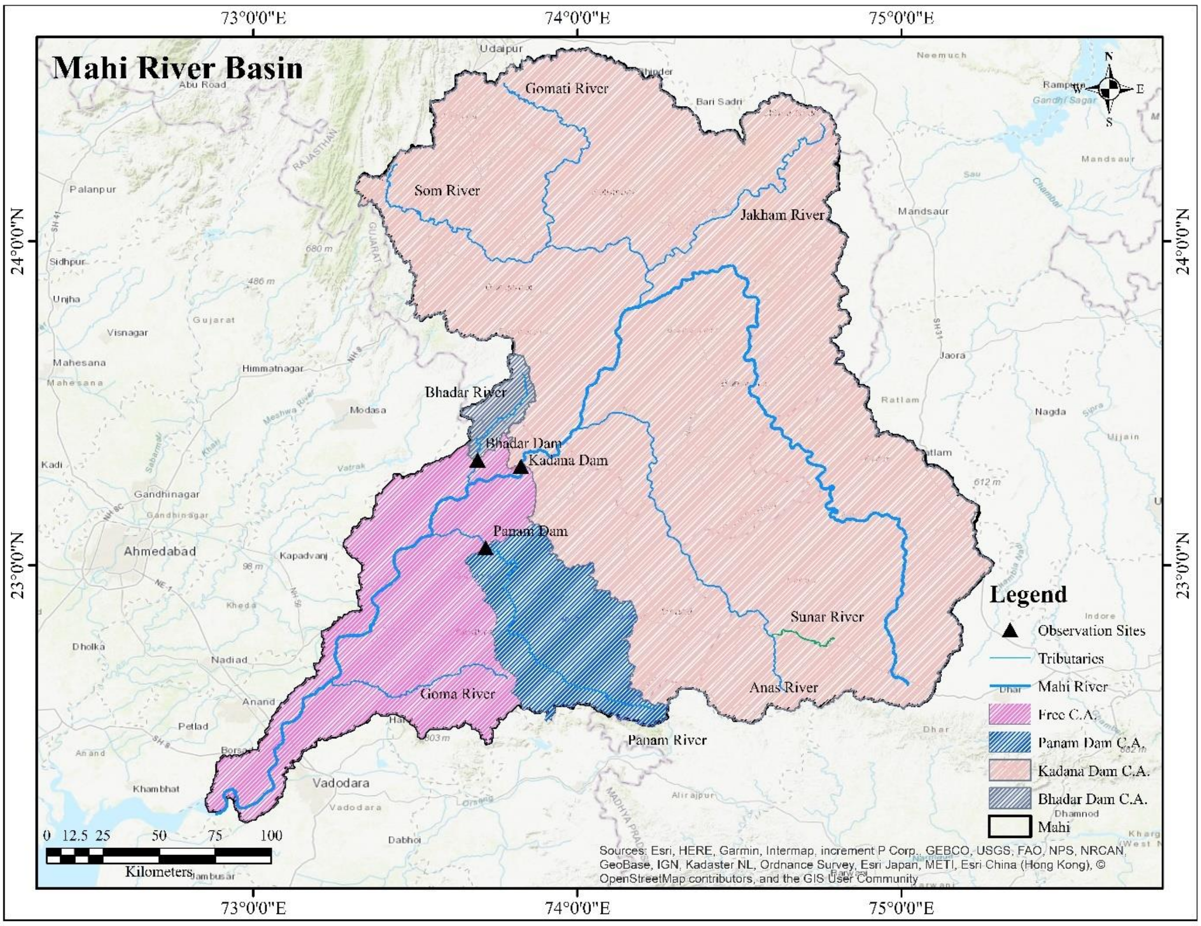


Figure 3.2: Observation site location and division of Mahi basin as per water availability analysis

The spill series from different dams was estimated as described below:

(i) **Kadana dam:** The yield series (gross and net) at Kadana dam has been compiled from previous studies, and a monthly yield series for 1901–2006 was finalized without considering most upstream utilizations. Since only the MBSP interception in Rajasthan was included, the remaining planned utilizations for 1901–1950, 1951–1982, and 1983–2006 were estimated separately and deducted to obtain the net monthly inflow series. This net inflow series was then used for reservoir simulation for the period 1901–2005. The simulation incorporated the demands of Kadana, Wanakbori, and the Sujlam Suflam Spreading Canal following a standard linear operation policy. Monthly and annual spill series were generated.

(ii) **Bhadar dam:** The gross catchment area of Bhadar dam is 407 sq. km (Rajasthan – 296 sq. km, Gujarat – 111 sq. km), while the present study considers a net catchment area of 141 sq. km. Observed flows for 1986–2006 for the full catchment were available, and the net yield series for 141 sq. km was derived on a pro-rata basis. Monthly yield series for 1901–1985 were compiled from previous studies, and the final net monthly yield series for 1901–2005 was used for reservoir simulation, incorporating the EAC table, normal monthly evaporation, and water demands, including future proposals. Reservoir operation followed a standard linear operating policy to generate monthly and annual spill series.

(iii) **Panam dam:** The gross catchment area of Panam dam is 2312 sq. km, with 2290 sq. km in Gujarat. Observed flow data for 1977–2006 are available and considered as the net yield series for this period. Monthly yield series for 1901–1976 were compiled from previous studies, and the final net monthly yield series for 1901–2005 was prepared. This series was used for reservoir simulation, incorporating the EAC table, normal monthly evaporation, and water demands, including proposed future requirements. Reservoir operation followed a standard linear operating policy to generate monthly and annual spill series.

(iv) **Estimation of runoff from free catchment:** The free catchment of the Mahi River basin below the Kadana, Panam, and Bhadar dams covers 6,603.2 sq km. To estimate water availability for the Kalpasar Project, rainfall-runoff relationships were developed at the Khanpur CWC gauging site for different monsoon months using data from 1980 to 2005. These relationships helped convert rainfall into runoff using long-term rainfall records. Then, planned uses within the free catchment were subtracted from the total yield. The net flow series that resulted shows the available water from the free catchment.

(v) **Estimation of actual spill from three dams:** Monthly flow data at Khanpur (1980–2005) were influenced by spills from Kadana, Bhadar, and Panam dams. Probable spills from these reservoirs were computed using reservoir working tables from operational analyses for June 1980–May 2006, with observed dam flows as input. For Bhadar and Panam, only existing demands were considered, while for Kadana, only independent demands of Kadana and Wanakbori were included, excluding SSSC releases. Assuming 5% transit loss, 95% of the monthly spill volumes from the three dams were deducted from observed flows at Khanpur. Additionally, 100 cusecs release from Wanakbori weir for Vadodara’s domestic use was subtracted. The resulting net flow series was used to compute the non-monsoon flow, which averages 35.81% of the monsoon flow, along with average monthly contributions for different non-monsoon months.

(vi) Development of r – R relations at Khanpur: To estimate long-term flow series from the free catchment below the Kadana, Bhadar, and Panam dams to the sea, the rainfall-runoff (r–R) relationships were developed for the monsoon months at Khanpur from 1980 to 2005. The Weighted Rainfall (WR) for sub-basins SB–1, which extends up to Khanpur, and SB–2, which goes from Khanpur to the sea, were computed using Thiessen Weights of IMD stations. The monthly net flows at Khanpur were converted to millimetres using the catchment area of 4,380.2 sq. km. The plots of rainfall versus net flow were developed for June to October to derive r–R relationships, including bi-variate correlations for July to October. Finally, the developed r–R equations were used to generate monsoon flows. Then, these flows were converted to million cubic meters (MCM) using the catchment areas (SB–1: 4,380.2 sq. km; SB–2: 2,223 sq. km). The non-monsoon flows were estimated by using average monthly percentages, finding that the total non-monsoon flow as 35.81% of the monsoon flow.

The following r – R relationships have been finalized and used in the analysis:

$$R_{June} = 0.1312 * r_{June} - 0.9548 \tag{3.29}$$

$$R_{July} = 0.2748 * r_{July} - 38.562 \tag{3.30}$$

$$R_{Aug} = 0.2165 * r_{Aug} - 9.0323 \tag{3.31}$$

$$R_{Sept} = 0.3134 * r_{Sept} - 0.4637 \tag{3.32}$$

$$R_{Oct} = 0.2105 * r_{Sept} + 0.2933 * r_{Oct} - 4.5730 \tag{3.33}$$

(vii) Estimation of net runoff series: The gross runoff series for the Mahi basin is computed by combining the runoff from SB–1 and SB–2 with the spill series from Kadana, Panam, and Bhadar dams. The net runoff series is obtained by subtracting planned utilizations in the free catchment from the gross runoff. The total annual gross utilization (GU) by existing, ongoing, and proposed projects in the basin is estimated at 365.2 MCM. Monthly reduction factors are calculated as the ratio of annual GU to annual flow. The net monthly runoff is then computed using the formula:

$$Net\ monthly\ runoff\ =\ (1\ -\ monthly\ reduction\ factor)\ \times\ gross\ monthly\ runoff.$$

(viii) Estimation of dependable yield: for the estimation of water availability at different dependability levels, the monthly net flow series from the Mahi basin is aggregated to an annual time step. The probability of exceedance of the long-term annual net flow series is computed to determine 50%, 75%, and 90% reliable flows into the Kalpasar project. The annual net runoff series is arranged in descending order, and ranks were assigned in ascending order. Probability of exceedance (P_i) for each annual flow is calculated using Weibull's formula. This approach provides the dependable flows required for planning and management of the Kalpasar project.

The estimated dependable flows from the Mahi river basin to the Kalpasar project are presented in **Table 3.2** as follows:

Table 3.2: Dependable flows (MCM) at different locations in the Mahi river basin

Annual flows from Mahi River basin (MCM)	Annual net flows (MCM) corresponding to different dependability			
	50%	**75%**	**90%**	**Average**
Spill (MCM) from Kadana dam	614.75	0.00	0.00	2110.51
Spill (MCM) from Panam dam	0.00	0.00	0.00	291.28
Spill (MCM) from Bhadar dam	0.00	0.00	0.00	13.90
Gross flow (MCM) from free catchment	1701.91	989.60	562.33	1669.81
Annual net flow (MCM) from Mahi basin	2237.22	671.11	244.69	3721.54

3.1.3.3 Water availability analysis for Dhadhar basin

Dhadhar River is a west-flowing river in Gujarat with a total catchment area of 4316 sq. km. It is divided into two sub-basins, with a CWC gauging site at Pingalwada as shown in **Figure 3.3**. The study aims to determine water availability at 50%, 75%, and 90% dependability. Virgin flows at Pingalwada were computed, and the rainfall-runoff relationship during monsoon months (June-September) was established. Rainfall data from 12 stations and daily discharge data from Pingalwada (1989-2006) were utilized in the study. Hydrological software HYMOS has been used for data processing, gap-filling, and homogeneity tests. Rainfall-runoff relationships were used for extending the flow series from 1901 to 2006. Virgin flow was computed by adding inflows and subtracting spills from upstream projects. Net runoff was derived by subtracting planned utilization from gross runoff. Dependable yields were computed for various reliability levels. The estimated dependable flows from the Dhadhar river basin to the Kalpasar Project are incorporated in the report.

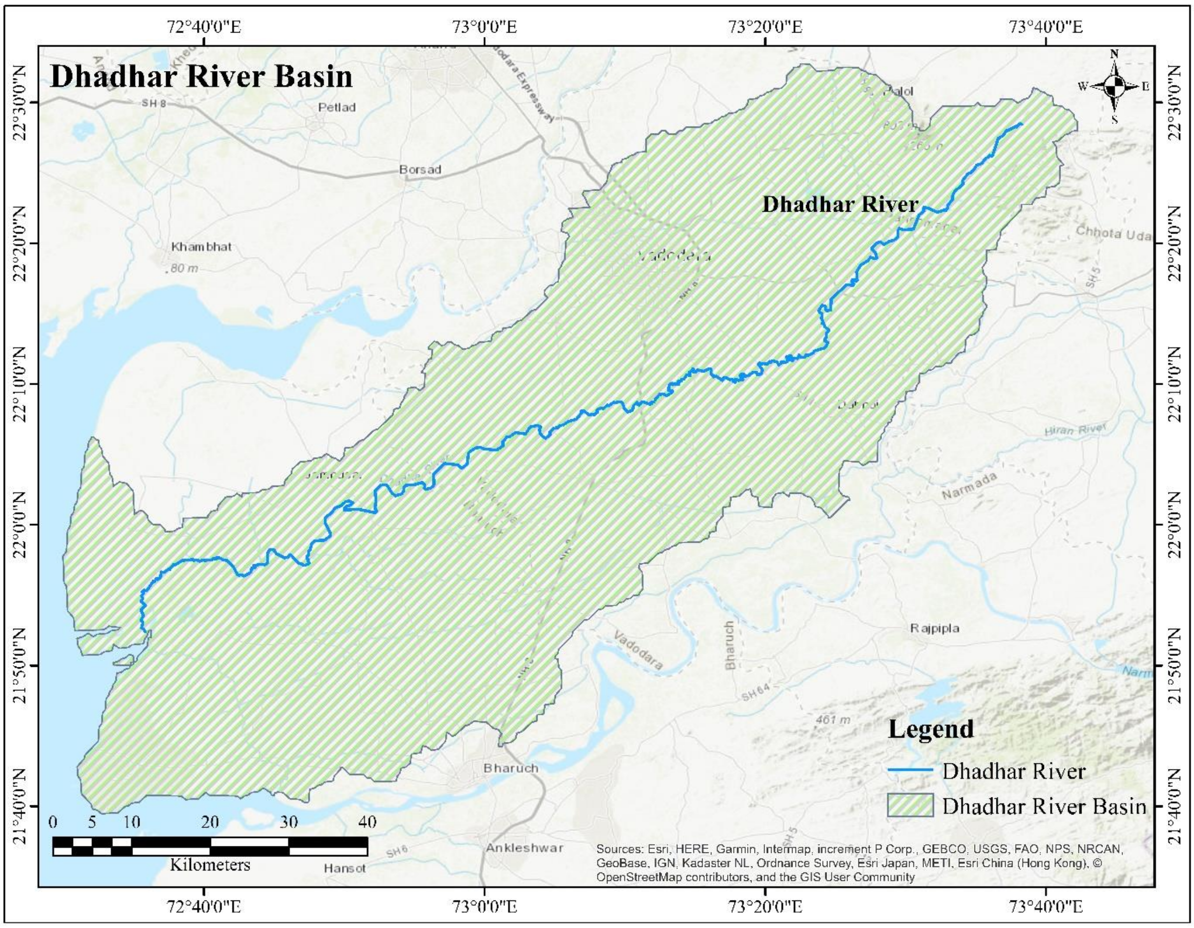


Figure 3.3: Observation site location and division of Dhadhar Basin as per water availability analysis

Since flow data at Pingalwada are available only from 1989, rainfall–runoff (r–R) relationships were developed for monsoon months to extend the flow series using long-term rainfall data (1901–2006). Virgin flows for 1993–2006 were computed by adjusting observed flows for inflows and spills from Deo reservoir and Ajwa/Partappura projects. Using weighted mean rainfall for the Pingalwada catchment (SB–1) and computed virgin flows, monthly r–R relationships were derived, including bi-variate correlations for July–September, and converted to mm using a catchment area of 2470 sq. km. These relationships were applied to hindcast flows for two sub-basins (SB–1 and SB–2), with monsoon flows converted to MCM (SB–1: 2470 sq. km, SB–2: 1846 sq. km). Non-monsoon flows were estimated using average monthly percentages (5.3941% of monsoon flow), and the gross runoff series for the Dhadhar basin was obtained by summing flows from SB–1 and SB–2.

The following r – R relationships have been derived and used in the analysis:

$$R_{June} = 0.2076 * r_{June} - 21.935 \tag{3.34}$$

$$R_{July} = 0.3287 * r_{July} - 59.213 \tag{3.35}$$

$$R_{Aug} = 0.5413 * r_{Aug} - 64.165 \tag{3.36}$$

$$R_{Sept} = 0.3904 * r_{Sept} - 76155 \tag{3.37}$$

The net runoff series from the Dhadhar basin is obtained by subtracting planned utilizations from the gross runoff series. The total annual gross utilization (GU) by existing, ongoing, and proposed projects in the basin is estimated at 206.01 MCM. Monthly reduction factors, calculated as the ratio of annual GU to annual flow, are applied to account for these utilizations. Net monthly runoff is then computed using the formula:

$$Net\ monthly\ runoff = (1 - monthly\ reduction\ factor) \times gross\ monthly\ runoff \tag{3.38}$$

This method provides the net flow series required for water availability assessment.

The estimated dependable flows from Dhadhar river basin to Kalpasar project are presented in **Table 3.3** as follows:

Table 3.3: Dependable flows (MCM) from Dhadhar river basin

Annual flows from Dhadhar basin (MCM)	**Annual net flows (MCM) corresponding to different dependability**			
	50%	**75%**	**90%**	**Average**
Annual net flow (MCM)	648.42	280.51	0.00	662.65

3.1.3.4 Water availability analysis for the Narmada basin

Availability of water at the Bhadbhut site for 50%, 75%, and 90% dependabilities, considering outflows from the Sardar Sarovar Project (SSP) as per the Narmada Water Dispute Tribunal Award, was computed. For this, the catchment area downstream of SSP was divided into four sub-basins: SB-1, SB-2, SB-3, and SB-4, as shown in **Figure 3.4**. The rainfall data of IMD for 1901-2006 from 23 rain gauges were analyzed by Thiessen Polygons, and the data was validated for consistency and gap-filled using HYMOS software. Thereafter, discharge data for Sukhi and Karjan catchments were generated using rainfall-runoff relationships. Runoff from free catchments downstream of SSP was analyzed along with spills from SSP. Rainfall-runoff relationships for Sukhi and Karjan dams were developed for monsoon months. Superimposition of computed spill series from Sukhi and Karjan dams and net runoff series from free catchments yielded Net dependable flows at Bhadbhut. The dependable flows at different sites in the Narmada River basin below SSP are summarized, outlining annual yield at Bhadbhut under various SSP spill options and dependabilities.

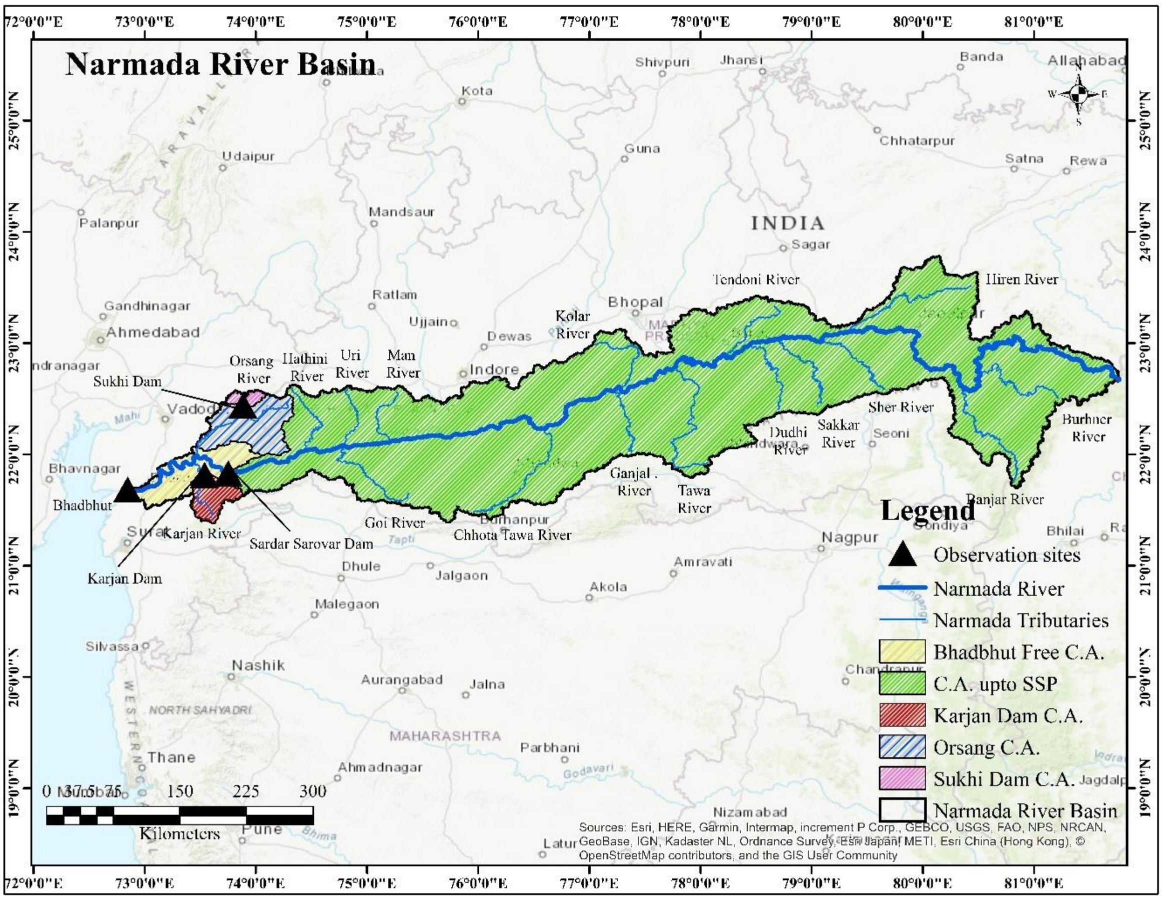


Figure 3.4: Observation site location and division of Narmada Basin as per water availability analysis

The free catchment downstream of the Sardar Sarovar Dam (SSD) is divided into four sub-basins. Water availability at Bhadbhut is calculated by developing rainfall-runoff (r-R) relationships. The r-R relationship from Sukhi Dam applies to Sub-basins 1 and 2, while the relationship from Karjan Dam is used for Sub-basins 3 and 4. Using rainfall data and dam-spill records from 1990 to 2004, we estimate monsoon season runoff from June to September. We generate non-monsoon flows using monthly flow ratios. Reservoir operation uses standard linear operating policies to determine releases, meet priority-based demand, and calculate spill quantities. The spill series and historical runoff series were arranged in descending order to determine dependable flows at 50%, 75%, and 90% levels.

For each sub-basin, we apply long-term rainfall to the corresponding r-R relationship to compute monsoon runoff. The non-monsoon flows were obtained with average monthly ratios. After applying reduction factors for gross use, we generate net monthly flows and prepare probability curves. For Sub-basin 4, we make an additional deduction of 4 MCM to account for future water supply plans before deriving dependable flows. The total net flows at Bhadbhut from the free catchment come from combining the computed spill series from the Sukhi and Karjan dams, net runoff from Sub-basin 2 of the Orsang basin, and net runoff from Sub-basin 4 of the Narmada basin. We then order these combined flows to determine 50%, 75%, and 90% dependabilities.

According to the Narmada Water Dispute Tribunal (NWDT) Award, we further evaluate water availability at Bhadbhut under four operational options. These options combine different spill percentages from SSP and releases from RBPH for Stage-II and Stage-III developments. The study assumes that monsoon flows at SSP are sufficient and that RBPH releases remain available after fulfilling environmental flow needs. We prepare ten-daily calculations for SSP releases separately for Stage-II and Stage-III. We integrate these with free-catchment flows to obtain total flows at Bhadbhut. We arrange the combined flow series for each option in descending order to determine dependable annual flows at 50%, 75%, and 90% reliability. This information is vital for assessing water availability for the Bhadbhut project.

The dependable flows at different sites in the Narmada River basin below SSP are summarized in **Table 3.4** below:

Table 3.4: Annual yield (MCM) from the Narmada basin at Bhadbhut for different dependability

Annual yield at Bhdbhut (MCM)	**Annual net flows (MCM) corresponding to different dependability**			
	50%	**75%**	**90%**	**Average**
Spill from Sukhi dam (SB - 1)	0.00	0.00	0.00	24.49
Orsang sub-basin (SB - 2)	871.76	558.25	176.68	924.11
Spill from Karjan dam (SB - 3)	0.00	0.00	0.00	137.38
Flow from free catchment below SSP (SB - 4)	1536.53	1092.57	591.70	1581.20

Flow from SSP releases assuming 100% SSP spill availability at Bhadbhut under Stage – II development (Option - 1)	8229.30	4602.25	2064.85	11333.39
Flow from SSP releases assuming 33.9% SSP spill availability at Bhadbhut under Stage – II development (Option - 2)	8136.79	4602.24	2064.85	8707.91
Flow from SSP releases assuming 100% SSP spill availability at Bhadbhut under Stage – III development (Option - 3)	3659.74	133.71	0.00	6388.83
Flow from SSP releases assuming 33.9% SSP spill availability at Bhadbhut under Stage - III development (Option - 4)	3312.52	133.71	0.00	4327.13
Total yield at Bhadbhut as per Option – 1	10377.73	6738.44	3843.12	14000.58
Total yield at Bhadbhut as per Option – 2	10077.73	6738.44	3843.12	11375.09
Total yield at Bhadbhut as per Option – 3	5683.24	3149.15	1678.13	9056.02
Total yield at Bhadbhut as per Option – 4	5438.65	3149.15	1678.13	6994.32

3.1.3.5 Water availability analysis for Saurashtra basins

River basins falling on the north-eastern part of the Saurashtra peninsula drain into the Gulf of Khambhat and are made up of seven sub-basins: Wadhwan Bhogavo, Limbdi Bhogavo, Sukhbhadar, Utavali, Keri, Ghelo, and Kalubhar, as shown in **Figure 3.5**. The study aimed at arriving at water availability at 50%, 75%, and 90% dependabilities. Gross annual flow series from 1901 to 2006 were computed based on the rainfall data of 10 IMD stations and the existing r-R relationships. Monthly rainfall data of 10 raingauge stations were used. Software HYMOS was used for data processing, and weights by Thiessen polygon were applied. Data gaps were filled up and homogeneity tests performed. Average monthly rainfall was computed from 1901 to 2006 and the r-R relationship used to convert rainfall depth to flow depth for monsoon months. For other months, runoff was considered as nil, except in Sukhbhadar. The gross annual flow series was used to estimate the net annual runoff series by deducting present and future utilizations, taking regeneration into account. Dependable yields for various reliabilities were then computed. Tables give estimated dependable flows from various Saurashtra sub-basins to the Kalpasar Project both without and with regeneration. This analysis gives detailed insight into the water resources that are beneficial to the Kalpasar Project, proposing methodologies adopted for estimation and specific observations that the NIH has made to refine these studies. Results of the final dependable flows from each major river basin and Saurashtra to the proposed Kalpasar reservoir are arrived at with a consideration of various levels of reliability and direct rainfall contributions.

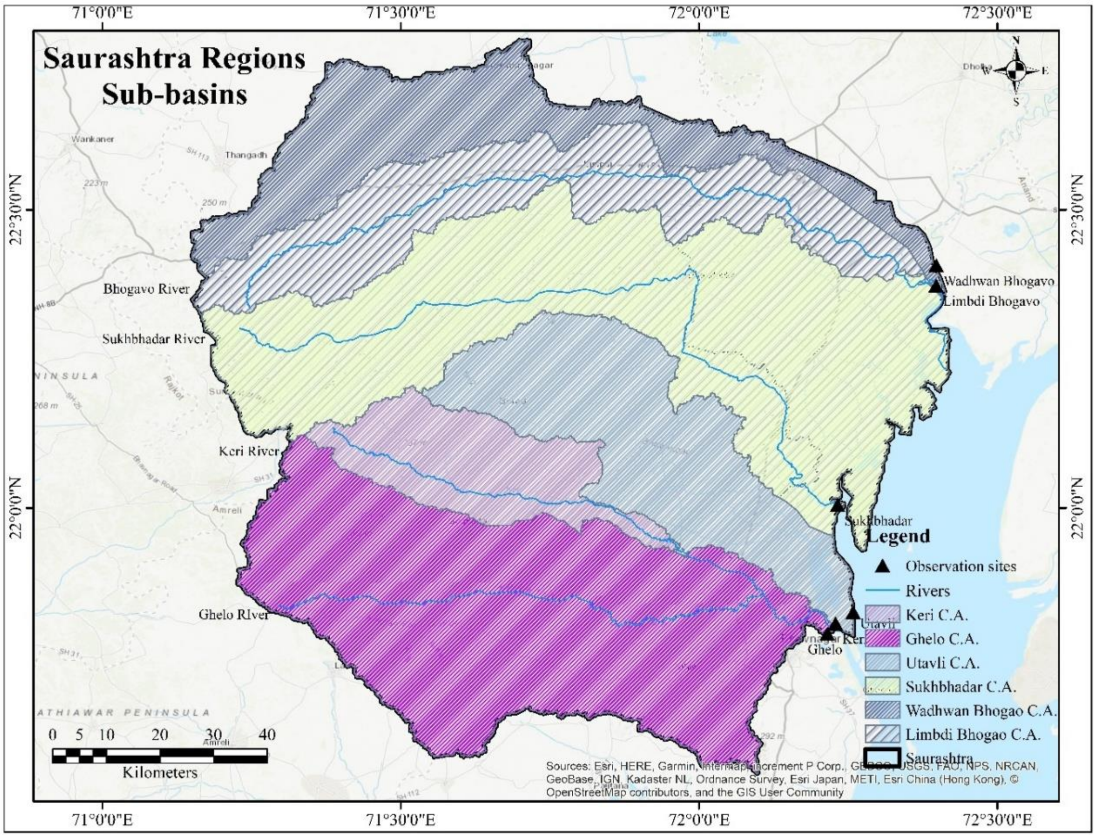


Figure 3.5: Observation site location and division of Saurashtra Basin as per water availability analysis

Using corrected rainfall data and Thiessen weights, monthly rainfall series from 1901 to 2006 were developed for all sub-basins and converted into runoff using the established r–R relationships. Gross annual flows were adjusted by deducting current and anticipated future utilizations while adding regeneration at 10%. Since detailed future development data were unavailable, the net flow series was reduced by 30% to account for planned utilizations, with regeneration again considered. Finally, the dependable water availability at 50%, 75%, and 90% dependability was computed by arranging the long-term net annual flows in descending order and applying Weibull’s formula to calculate the probability of exceedance.

Assuming all sub-basins to drain into the Kalpasar project as per the new alignment (L-3), the inflows to the Kalpasar project from the Saurashtra region for different probability levels are given in **Table 3.5**.

Table 3.5: Dependable flows (MCM) from the Saurashtra region to the Kalpasar project

Annual net flows (MCM) from Saurashtra region to Kalpasar project	**Annual net flows (MCM) corresponding to different dependability**			
	50%	**75%**	**90%**	**Average**
Annual net flow (MCM) (without regeneration)	649.49	424.40	173.34	654.60
Annual net flow (MCM) (without regeneration)	696.74	461.98	197.55	701.41

Using the database from the CDO, NIH Roorkee has finished water availability reports for the river basins that feed into the Kalpasar reservoir. This was done based on discussions with CDO representatives and the Kalpasar Department. River basin maps helped with GIS analysis in the ILWIS GIS environment. Thiessen polygon weights for rainfall stations and sub-basin boundaries were calculated. SWDES and HYMOS were used to process and validate hydrological data. The normal-ratio method, backed by spatial correlation and distance matrices to find stations with similar characteristics, filled in the gaps in rainfall data caused by differences in station establishment years. Double mass curve plots were also created using these stations.

CHAPTER 4
EXTENDED ANALYSIS (2024), VETTING & DISCUSSIONS

4.1 Vetting of the Analysis & Observations

A vetting or verification is an independent review of a water availability analysis to confirm that data, methods, assumptions, and conclusions are valid and appropriate for use in making decisions. This should not be confused with repeating the original analysis; rather, it will provide a framework to ask questions such as: what data was used? how was the information processed or the method applied? can the findings be validated or reproduced? and did the conclusions follow the evidence provided? An appropriate vetting process will identify vulnerabilities and provide an unambiguous statement of recommendations, so that governmental regulators, community planners, and project management groups can rely on the analysis results or modify the analysis results before implementing the findings.

Essentially, the vetting process can determine whether the information is appropriate, and whether the modelling methods used to analyze the data are appropriate. As part of the vetting process, it has been ensured that the hydrologic and groundwater models, as well as any empirical methods, are appropriate for the watershed scale, climate regime, and the amount of data that was available to them. It is also verified that the metadata and provenance of all hydrological, meteorological, groundwater, and geographical data sources and assess how the data gaps are handled or made adjustments during the vetting process. Finally, this vetting process examined the sensitivity tests performed, the results of calibration and validation of the models, and whether the calculations relied on a single deterministic forecast, or if they considered multiple robust scenarios i.e., dry or wet years, expected growth in water demand, and climate change trajectories.

Additionally, the vetting confirms demand-side accounting by confirming requirements, estimates, permitting, and other related requirements based on domestic, agricultural, industrial, and environmental applications, verifying that future population and land-use changes have been estimated and validating that the reported estimates relate to actual permitting, regulatory, and environmental-flow requirements. An equally important component of vetting is the assessment of risk and uncertainty. This report contains uncertainties that are beyond the control.

This vetting process gives a clear deliverable product in terms of a technical report and identifies (1) critical results, (2) significant gaps in data/methods, (3) prioritised risks, (4) any required revisions, additional research or monitoring. It also includes recommendations for adaptive management and clear acceptance criteria, and should provide opportunities for repeatable verifications. The credibility and confidence of stakeholders are enhanced through peer review and by the input of an independent panel of experts.

The assessment is based on the best available hydro-meteorological data and standard analytical methods. It is, however, inherent to uncertainties that exist due to the data limitations, natural climate variability, potential impacts of climate change, evolving land use conditions, and model assumptions. The Future changes in upstream abstractions, reservoir operations, and policy decisions are beyond the control of the present vetting and may influence actual project performance. Therefore, the results should be considered indicative estimates, and periodic review and adaptive management are recommended.

To review and document the procedure adopted by the Central Design Office (CDO), Government of Gujarat, for the assessment of water availability for the Kalpsar Project, a detailed technical interaction was undertaken covering the historical period from 1901 to 2006 and its subsequent extension up to the year 2024. In this context, two formal meetings were held between officers of the Kalpsar Department and CDO, Gujarat, and scientists from the National Institute of Hydrology (NIH), Bhopal, on Oct 13 and 14, 2025, at Ahmedabad. The proceedings of these meetings are enclosed as Annexure-I.

During the meetings, the CDO officials presented the complete methodology adopted for estimating basin-wise water availability, including the data sources used, assumptions made, and analytical procedures followed. They also explained the modifications incorporated in the methodology based on the recommendations provided by NIH in its earlier technical report. Particular emphasis was placed on the approach adopted for extending the historical hydrological series beyond 2007 up to 2024.

The discussions focused on the continued application of the previously developed empirical and regression-based equations for extending the yield series. The validity and applicability of these equations were critically examined in light of data availability, basin characteristics, and prevailing hydrological practices. It was informed that for the period from 2007 to 2024, there have been no significant changes in basin hydrology, land use pattern, water utilisation, or upstream regulation that would materially alter the runoff generation processes. Moreover, the preparation of a detailed reservoir water balance for the extended period was found to be constrained by the non-availability of consistent and reliable data on withdrawals, return flows, and operational details.

Considering these limitations and the need for methodological consistency, it was agreed that the use of the earlier established regression relationships for yield extension is technically justified. The approach benefits from a long and robust hydrological record spanning nearly 124 years, which provides adequate representation of inter-annual and long-term variability in water availability across the contributing basins. Overall, the methodology adopted by CDO for the computation and extension of water availability was found to be broadly appropriate and in line with accepted engineering practice under the given data constraints.

Central Design Organization performed an extended analysis using the available data for the period of 2019-2024. The rainfall-runoff relationship earlier developed in the CDO finalized by NIH was used to extend the runoff series. Water availability was calculated using the same R-r relationships and weighted rainfall for the respective basin. All the computations were checked for consistency and appropriateness for all the basins delivering water to the Kalpsar reservoir and found in accordance with earlier reports.

The analysis performed by CDO for the period from 1901 to 2024, presented in **Table 4.1** provided the estimated annual water flows in MCM for the Kalpasar Project at various dependability levels of 50%, 75%, and 90% as per the 2025 assessment using extended flow series data from 1901-2024. Dependability essentially defines the reliability of water availability. For instance, 50% dependability essentially characterizes median conditions, while 90% dependability reflects highly conservative, drought-like conditions. In the development scenario sans Narmada, also known as “Kalpasar Project without Narmada,” the annual flows drop drastically with increasing dependability, from 6042.92 MCM at 50% to as low as 1602 MCM at 90%-which indicated very high flow uncertainty or high inter-annual variability in the absence of any external support.

Table 4.1: Annual flows (MCM) to Kalpasar Project corresponding to different dependability: 2025 Report (1901-2024)

Annual flows (MCM) to Kalpasar Project corresponding to different dependability	**Flows (MCM) corresponding to different dependability**		
	50%	**75%**	**90%**

Kalpasar Project without Narmada	6042.92	2990.54	1602
Kalpasar Project, including Bhadbhut, excluding SSP spill	9435.56	5273.31	2903.25
Kalpasar Project, including Bhadbhut and SSP spill	10376.97	5438.73	3179.17

With Bhadbhut included, the flow availability increases significantly. The scenario "Including Bhadbhut but excluding SSP spill" increases dependable flows to 9435.56 MCM (50%), 5273.31 MCM (75%), and 2903.25 MCM (90%), demonstrating the regulating influence of Bhadbhut on water availability for Kalpsar reservoir. Maximum flow availability can be observed in "Including Bhadbhut and SSP Spill," where dependable flows increase further to 10376.97 MCM (50%), 5438.73 MCM (75%), and 3179.17 MCM (90%). This indicates the crucial role that SSP spill contribution and Bhadbhut structure would play in enhancing the water security and dependability for Kalpasar, particularly at high dependability conditions (dry year), which is important from the perspective of long-term planning of its water resources.

The dependable yield assessment for the Kalpsar project from the long-term period 1901-2024 depicts large variability in water availability under various infrastructure scenarios. For instance, under the base scenario (the Kalpasar Project without Narmada), the 50% dependable yield was computed as 6042.92 MCM, which declined to 2990.54 MCM at 75% and 1602 MCM at 90% dependability. But, inclusion of the Bhadbhut structure imparts marked improvement in flow reliability; dependable flows rise to 9435.56 MCM at 50%, to 5273.31 MCM at 75%, and to 2903.25 MCM at 90%, showing the regulating and storage benefits introduced by upstream control. The maximum improvement of dependable flows is from the inclusion of both Bhadbhut and SSP spill contribution, yielding 10376.97 MCM at 50%, 5438.73 MCM at 75%, and 3179.17 MCM at 90% dependability. This showed the necessity of the SSP spill for supplementary supply during average and dry years.

These findings confirm that infrastructure integration substantially reduces hydrological risk and enhances supply stability from a water resources management point of view, under high dependability requirements. The relatively smaller gap between 75% and 90% dependable flows in the integrated scenario suggests improved system robustness during drought years. For planning assured municipal and industrial water supply, the 90% level has often been adopted as a design standard. Furthermore, the analysis points to the inadequacy of local basin runoff alone to meet future demands with climate uncertainty. The results stress that the Kalpasar–Bhadbhut–SSP system has its regional water security significantly enhanced and would assist the socio-economic development in a sustainable manner under normal and adverse hydrological conditions.

4.1.1 Annual dependable flow estimates using recent data

Dependable annual flow estimation is essential for hydrologic design, reservoir planning, irrigation scheduling, and flood/drought assessment. The reliability of such estimates heavily relies on the period length and representativeness of the streamflow records available. Long-term flow records, which generally span 50 to 100 years or more, capture in their entirety the full range of hydrological variability, including rare extreme floods, multi-decadal droughts, natural fluctuations in monsoon strength, and historical pre-development flow regimes. Because dependable flows, such as 50%, 75%, and 95% dependability, require a sufficiently large sample size, long-term datasets produce more statistically stable and less biased estimates. They provide the broad climatological context necessary for designing long-life water resource infrastructure that must perform reliably under a wide range of possible hydrological conditions.

In contrast, the recent 30–35 years of data are representative of the contemporary behaviour of the river system under present-day climatic and anthropogenic influences. Since many basins now exhibit modified seasonality, more extreme rainfall events, and reduced baseflow conditions, reliance solely on long-term records could overestimate water availability. Recent datasets therefore provide a more realistic and conservative estimate of dependable flows for operational planning and water allocation decisions, as well as short- to medium-term management strategies. They become particularly useful for assessing how catchment behaviour has changed in response to human interventions and shifting climate patterns.

Merging long-term with recent data provides a scientifically sound basis for dependable flow assessment. Long-term series establish the historical baseline and statistical stability, while the recent 35-year records outline the contemporary status of flow and emerging trends. A comparative study of both allows the identification of hydrological shifts, the assessment of changes in water availability, and the refinement of dependable flow estimates accordingly. This integrated approach, therefore, ensures that water resources planning, design, and management remain both historically informed and in step with current and future hydrological realities. The analysis for 35 years is presented in **Table 4.2** to provide insights into the recent past and present annual flows and their dependability in the respective basins.

Table 4.2: Comparison of dependable flows to the Kalpasar Project for the overall period (1901-2024) and the recent 35-year period (1990-2024)

Annual flows from various River Basins to the Kalpasar Project corresponding to different dependability	**Flows corresponding to different dependability (MCM)**					
	50%		**75%**		**90%**	
	Overall	**35-yrs**	**Overall**	**35-yrs**	**Overall**	**35-yrs**
Mahi	1559	906.94	677.27	517.22	249.41	29.04
Sabarmati	823.49	781.80	344.88	319.38	97.09	277.78
Dhadhar Saurashtra	653.85	668.19	308.13	406.90	0	0
Saurashtra	728.4	882.15	461.68	718.71	253.78	508.24
Narmada (Bhadbhut)	3274.56	4029.77	2092.43	2550.36	999.08	1604.53
Narmada (Bhadbhut + SSP Spill)	3503	4833.08	2154	3398.92	1148	1891.53
Kalpasar Reservoir	1102.15	1044	839.28	790.27	622.63	691

The recent 35-year annual flows comparison with long-term annual flows with different dependability shows an overall decline in Kalpasar reservoir yields from the value of 1102.15 MCM to 1044 MCM (50% dependability) and 839.28 MCM to 790.27 MCM (75% dependability). This means about 58.15 MCM reduction or 5.27% negative change in 50% dependable yield and 49.01 MCM or 5.83% negative change in 75% dependable yield under current hydrological and land-use conditions. However, a positive change in annual flows from 622.63 to 691 MCM (90% dependability) is observed for the Kalpasar project. The annual flows with 90% dependability tend to increase by 10% for the recent 35-year period. This suggests the improved low-flow reliability for the project. The basin-wise changes in the yield pattern in the recent period (1991-2024) from a long-term yield (1901-2024) are presented in the next sections.

4.1.1.1 Mahi River Basin

The Mahi River depicted a substantial reduction in dependable flows when comparing long-term records with recent 35-year data across all dependability levels. At 50% dependability, the long-term average flow of 1559 MCM reduces sharply to 906.94 MCM, indicating a significant decline in median annual water availability. This reduction becomes more pronounced at 75% dependability, where flows decrease from 677.27 MCM to 517.22 MCM, suggesting increased variability and reduced reliability of moderate flows. At 90% dependability, the contrast is extreme, with long-term flows of 249.41 MCM dropping to only 29.04 MCM in recent decades. This indicates that assured low flows have almost vanished, possibly due to upstream abstractions, land-use changes, and altered rainfall patterns. Overall, the Mahi basin exhibits high sensitivity to climatic and anthropogenic changes, raising concerns for dependable water supply planning.

4.1.1.2 Sabarmati River Basin

The Sabarmati River showed a moderate but consistent decline in flows from long-term to recent 35-year data, especially at higher dependability levels. At 50% dependability, the flow reduces slightly from 823.49 MCM to 781.80 MCM, suggesting that median flows are relatively stable but under stress. At 75% dependability, flows decrease from 344.88 MCM to 319.38 MCM, indicating reduced reliability during moderately dry years. Interestingly, at 90% dependability, the recent 35-year flow (277.78 MCM) is higher than the long-term value (97.09 MCM). This may reflect regulated releases, improved baseflow contributions, or altered reservoir operations in recent decades. Overall, the Sabarmati basin shows mixed hydrological behaviour, with reduced median flows but improved low-flow availability, likely influenced by infrastructure and basin management interventions.

4.1.1.3 Dhadar (Saurashtra region)

The Dhadar River basin exhibited relatively stable behaviour at 50% dependability, where recent 35-year flows (668.19 MCM) are slightly higher than long-term flows (653.85 MCM). This suggests no major decline in median annual runoff. However, at 75% dependability, the increase from 308.13 MCM to 406.90 MCM indicates improved availability in moderately dry years, possibly due to changes in rainfall patterns or watershed responses. At 90% dependability, both long-term and recent flows are zero, reflecting the ephemeral nature of the basin. This confirms that the Dhadar basin lacks assured low flows and remains highly rainfall dependent. The basin is therefore unsuitable for a dependable perennial water supply and is more appropriate for event-based or seasonal storage planning.

4.1.1.4 Saurashtra Basin

The Saurashtra basin depicted notable improvement in recent flows compared to long-term records across all dependability levels. At 50% dependability, flows increase significantly from

728.40 MCM to 882.15 MCM, indicating enhanced median runoff in recent decades. At 75% dependability, the increase from 461.68 MCM to 718.71 MCM is substantial, suggesting improved water availability even in relatively dry years. At 90% dependability, recent flows (508.24 MCM) are double the long-term value (253.78 MCM), indicating a strong improvement in dependable low flows. This behaviour may be attributed to climate variability, improved rainfall efficiency, groundwater–surface water interaction, or watershed development measures. Overall, the Saurashtra basin exhibits a positive hydrological shift in recent decades.

4.1.1.5 Narmada River (Bhadbhut location)

The Narmada River at Bhadbhut demonstrated a strong increasing trend in flows when comparing long-term and recent 35-year data. At 50% dependability, flows rise from 3274.56 MCM to 4029.77 MCM, indicating increased median water availability. At 75% dependability, flows increase from 2092.43 MCM to 2550.36 MCM, showing improved reliability during moderately dry years. At 90% dependability, the increase from 999.08 MCM to 1604.53 MCM is particularly significant, reflecting enhanced assured flows. This behaviour is likely influenced by regulated releases from upstream reservoirs (including SSP) and basin-scale water management. The Narmada thus remains a highly dependable and regulated river system, suitable for long-term water resource planning.

4.1.1.6 Narmada River (Bhadbhut + SSP spill contribution)

When SSP spill contributions are included, the Narmada system showed even stronger enhancement of flows across all dependability levels. At 50% dependability, flows increase markedly from 3503 MCM to 4833.08 MCM, reflecting the substantial impact of spill releases. At 75% dependability, flows rise from 2154 MCM to 3398.92 MCM, indicating increased reliability during drier years. At 90% dependability, flows increase from 1148 MCM to 1891.53 MCM, highlighting improved assured flows. This scenario represents a managed hydrological regime, where reservoir operations significantly augment downstream availability. The results clearly show that spillway contributions play a critical role in enhancing dependable flows for the Kalpasar project.

4.1.1.7 Kalpasar Reservoir

The Kalpasar Reservoir reflects a slight decline in recent median flows but improved low-flow dependability. At 50% dependability, flows reduce marginally from 1102.15 MCM to 1044 MCM, indicating a small decrease in the dependable inflow. At 75% dependability, the reduction from 839.28 MCM to 790.27 MCM suggests some stress in moderately dry years.

However, at 90% dependability, recent flows (691 MCM) are higher than long-term values (622.63 MCM), indicating improved assured storage availability. This pattern suggests that while overall inflows may be declining slightly, system regulation and basin integration improve reliability at higher dependability levels. The Kalpasar system thus benefits from inter-basin contributions and regulated inflows.

In summary, the assessment indicates a marked increase in streamflows from the Narmada River as well as from rivers of the Saurashtra region. At the Bhadbhut site on the Narmada River, including spills from the Sardar Sarovar Project (SSP), the analysis shows an increase in annual flows of 1330.08 MCM, 1244.92 MCM, and 743.53 MCM at 50%, 75%, and 90% dependability, respectively, over the most recent 35-year period.A comparison of the 35-year flow series with long-term historical records indicates that the deviation in annual flows is within 10% for 50% and 75% dependability levels. Accordingly, the rainfall–runoff (r–R) relationships developed from long-term datasets and applied for extending the analysis up to 2024 are considered technically appropriate, given the scale of the project and the prevailing regional hydro-meteorological characteristics. In this context, the water availability computations carried out by the Central Design Office (CDO), including the extension of records using established hydrological relationships, are found to be technically sound and appropriate.

In summary, the assessment indicated a marked increase in streamflows from the Narmada River as well as from rivers of the Saurashtra region. At the Bhadbhut site on the Narmada River, including spills from the Sardar Sarovar Project (SSP), the analysis showed an increase in annual flows of 1330.08 MCM, 1244.92 MCM, and 743.53 MCM at 50%, 75%, and 90% dependability, respectively, over the most recent 35-year period. A comparison of the recent 35-year flow series with long-term historical records indicated that the deviation in annual flows was within 10% for 50% and 75% dependability levels. Accordingly, the rainfall–runoff (r–R) relationships developed from long-term datasets and applied for extending the analysis up to 2024 were considered technically appropriate, given the scale of the project and the prevailing regional hydro-meteorological characteristics. In this context, the water availability computations carried out by the Central Design Office (CDO), including the extension of records using established hydrological relationships, were found to be technically sound and appropriate. The officials from the Gujarat Water Resources Department (WRD) and the Command Area Development Organisation (CDO) indicated that the project planning was based on 50% dependability, which was the standard adopted by WRD Gujarat for the Saurashtra region.

CHAPTER 5
CLIMATE CHANGE ANALYSIS

5.1 Overview

For the assessment of climate change signals, the 124-year runoff dataset has been divided into four separate time spans for analysis, allowing for the systematic assessment and comparison of long-term trends, consistency, and variability. The time spans selected for five different periods are given below:

First Period: from 1901 to 1930

Second Period: from 1931 to 1960

Third Period: from 1961 to 1994

Fourth Period: from 1994 to 2024

Complete Period: from 1901 to 2024

The change point was assessed using Pettitt's test, Buishand's range test, Von Neumann ratio test, and Standard normal homogeneity (SNH) test; while the trend was analysed using the Mann-Kendall test. The methodology and description of the different tests used in the analysis are presented below.

5.1.1 Pettitt's test

The Pettitt test is a non-parametric test used in climatological studies to detect abrupt changes in the mean of the distribution of the variable of interest. The Pettitt test uses a non-parametric statistic ($U_{t,N}$) in a series of length N ($1 \leq t < N$). It sums the signs of the differences between the observations before and after time, as given below:

$$U_{t,N} = \sum_{i=1}^{t} \sum_{j=t+1}^{N} sgn(x_i - x_j) \tag{5.1}$$

Where

N is the number of observations,

x_i, x_j are the i^{th} and j^{th} observation, and

$sgn\ (x_j - x_i)$ is the sign function, which can be defined as follows:

$$sign(x_j - x_i) = \begin{cases} 1 & if\ (x_j - x_i) > 0 \\ 0 & if\ (x_j - x_i) = 0 \\ -1 & if\ (x_j - x_i) < 0 \end{cases} \tag{5.2}$$

According to this test, the most likely change point may occur in a series where the absolute value of $U_{t,N}$ is at its maximum and can be represented as (K_T) using the following equation.

$$K_T = max\left|U_{t,N}\right| \tag{5.3}$$

The approximate significance probability (*p-value*) for a detected change point can be computed using the following equation for $p \leq 0.5$ (95% significance).

$$p \approx 2exp\left(\frac{6{K_T}^2}{T^3+T^2}\right) \tag{5.4}$$

If the computed value of the probability (*p-value*) is less than 0.05, the null hypothesis of no change point is rejected.

5.1.2 Standard normal homogeneity (SNH) test (Alexandersson, 1986)

The standard normal homogeneity (SNH) test used the construction of a ratio for two sections in a series defined by a breakpoint (Aguilar *et. al.*, 2003). The test statistic (T_k) for the SNH test is used to compare the mean of the first *k* observations with the mean of the remaining (*n-k*) observations in a series having *n* data points (Stepanek *et. al.*, 2009; Vezzoli *et al.*, 2012).

$$T_k = kZ_1^2 + (n-k)Z_2^2 \tag{5.8}$$

The constants Z_1 and Z_2 of equation 5.6 can be computed with the help of the following equations.

$$Z_1 = \frac{1}{k}\sum_{i=1}^{k}\frac{(x_i-\bar{x})}{\sigma x} \tag{5.9}$$

$$Z_2 = \frac{1}{n-k}\sum_{i=k+1}^{n}\frac{(x_i-\bar{x})}{\sigma x} \tag{5.10}$$

where, $\bar{x}$ and σx are the mean and standard deviation of the series. The year *k* can be considered as a change point and consist a break where the value of T_k attains the maximum value. To reject the null hypothesis, the test statistic should be greater than the p-value computed using 10000 monecarlo simulations.

5.1.3 Buishand's range test (Buishand, 1982)

The test statistics for Buishand's range test is adjusted partial sum (S_k), which is the cumulative deviation from the mean for k^{th} observation of a series $x_1, x_2, x_3 \ldots. x_k \ldots. x_n$ with mean ($\bar{x}$) can be computed using the following equation:

$$\mathrm{S_k} = \sum_{\mathrm{i=1}}^{\mathrm{k}}(\mathrm{x_i} - \bar{\mathrm{x}}) \tag{5.5}$$

A series may be homogeneous without any change point if $S_k \cong 0$ because in a random series, the deviation from the mean will be distributed on both sides of the mean of the series. The significance of the shift can be evaluated by computing rescales adjusted range (R) using the following equation.

$$R = \frac{\mathrm{Max}(S_k) - \mathrm{Min}(S_k)}{\bar{x}} \tag{5.6}$$

The computed value of $R/\sqrt{n}$ is compared with the computed p-value obtained by 10000 Monte Carlo simulations.

5.1.4 Von Neumann ratio test

The Von Neumann ratio test is closely related to the first-order serial correlation coefficient (WMO, 1966). The test has been described by Buishand (1982), Kang & Yusuf (2012) etc. The test statistics (N) for the Von Neumann ratio test for detection of a change point in a series of observations x_1, x_2, x_3 …..x_n can be described as:

$$N = \frac{\sum_{i=1}^{n-1}(x_i - x_{i-1})^2}{\sum_{i=1}^{n}(x_i - \bar{x})^2} \tag{5.7}$$

According to this test, if the sample or series is homogeneous, then the expected value E(N) = 2 under the null hypothesis with constant mean. When the sample has a break, then the value of N must be lower than 2; we can imply that the sample has a rapid variation in the mean.

5.1.5 Mann-Kendal test

The Mann-Kendall test is a statistical test widely used for the analysis of trends in climatology and in hydrologic time series. There are two advantages of using this test. First, it is a non-parametric test and does not require the data to be normally distributed. Secondly, the test has low sensitivity to abrupt breaks due to inhomogeneous time series. According to this test, the null hypothesis H0 assumes that there is no trend (the data is independent and randomly ordered), and this is tested against the alternative hypothesis H1, which assumes that there is a trend. The Mann-Kendall test is a non-parametric test for identifying trends in time series data. This test assumes that there exists only one data value for a time period. When multiple data points exist for a single time period, the median value will be used. The initial value of the Mann-Kendall statistics S is assumed to be 0. If a data value from a later time period is higher than a data value from an earlier time period, S is increased by 1. On the other hand, if the data value from the later time period is lower than a data value sampled earlier, is decreased by 1. The net result of increments and decrements yields the final value of S. This method is more suitable for non-normally distributed and censored data, and is less influenced by the presence of outliers in the data [18]. Let $x_1, x_2, x_3, \ldots\ldots.$, x_n represent n data points, then the Mann-Kendall test statistic S is given by:

$$S = \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} sgn(x_j - x_i) \tag{5.11}$$

Where

N is the number of observations,

x_i, x_j are i^{th} and j^{th} observation, and

$sgn\ (x_j - x_i)$ is the sign function, which can be defined as follows:

$$sign(x_j - x_i) = \begin{cases} 1 \quad if\ (x_j - x_i) > 0 \\ 0 \quad if\ (x_j - x_i) = 0 \\ -1\ if\ (x_j - x_i) < 0 \end{cases} \tag{5.12}$$

Under the assumption that the data are independent and identically distributed, the variance Var(S) and expected value ($E[S]$) of the test statistic (S) can be defined as:

$$Var(S) = \frac{N(N-1)(2N+5) - \sum_{k=1}^{n} t_k(t_k-1)(2t_k+5)}{18} \tag{5.13}$$

$$E[S] = 0 \tag{5.14}$$

The Z-statistics can be computed as follows:

$$Z = \begin{cases} \frac{S-1}{\sigma} \quad if\ S > 0 \\ \quad 0 \quad if\ S = 0 \\ \frac{S-1}{\sigma}\ if\ (x_j - x_i) < 0 \end{cases} \tag{5.15}$$

Here, if the computed value of $|Z_{mk}| > Z\alpha/2$, then the null hypothesis of no trend is rejected at α level of significance in a two-sided test (i.e. the trend is significant). In this study, the null hypothesis was tested at 5% significance level. A positive value of Z indicates an increasing trend, and a negative value of Z_{mk} indicates a decreasing trend.

5.2 Results of change point analysis

The Pittet's test, Buishand's range test, Von Neumann ratio, and SNH test were used to compute a significant change point in the runoff series generated from different basins contributing to the Kalpsar project. The change point test was applied for five different periods of different time scales. The results are presented in the next section.

5.2.1 Sabarmati river basin

In the case of the Sabarmati River, the results have been categorised into four sub-periods: (1901-1930), (1931-1960), (1961-1994), and (1995-2024), and the entire period (1901-2024). The results of the Pettitt test, Buishand's range test, Von Neumann ratio, and SNH tests are presented in **Tables 5.1 to 5.4,** respectively.

Table 5.1: Results of the Pettitt test for different periods for the Sabarmati river basin

Time Window	**Results of Pettitt's test**		
	Test Statistic (K_T)	p-value	Result
1901-1930	67	0.562	p-value > 0.05. The null hypothesis cannot be rejected.
1931-1960	52	0.852	p-value > 0.05. The null hypothesis cannot be rejected.
1961-1994	102	0.302	p-value > 0.05. The null hypothesis cannot be rejected.
1995-2024	74	0.437	p-value > 0.05. The null hypothesis cannot be rejected.
1901-2024	537	0.684	p-value > 0.05. The null hypothesis cannot be rejected.

Table 5.2: Results of the SNH test for different periods for the Sabarmati river basin

Time Window	**Results of SNH test**		
	Test Statistic (T_K)	p-value	Result
1901-1930	3.126	0.556	p-value > 0.05. The null hypothesis cannot be rejected.
1931-1960	1.803	0.866	p-value > 0.05. The null hypothesis cannot be rejected.
1961-1994	5.665	0.222	p-value > 0.05. The null hypothesis cannot be rejected.
1995-2024	1.576	0.749	p-value > 0.05. The null hypothesis cannot be rejected.
1901-2024	4.40	0.356	p-value > 0.05. The null hypothesis cannot be rejected.

Table 5.3: Results of the Buishand's test for different periods for the Sabarmati river basin

Time Window	Results of Buishand's test		
	Test Statistic (R)	p-value	Result
1901-1930	3.671	0.635	p-value > 0.05. The null hypothesis cannot be rejected.
1931-1960	2.531	0.941	p-value > 0.05. The null hypothesis cannot be rejected.
1961-1994	5.471	0.246	p-value > 0.05. The null hypothesis cannot be rejected.
1995-2024	3.427	0.740	p-value > 0.05. The null hypothesis cannot be rejected.
1901-2024	8.486	0.476	p-value > 0.05. The null hypothesis cannot be rejected.

Table 5.4: Results of Von Neumann's test for different periods for the Sabarmati river basin

Time Window	Results of Von Neumann's test		
	Test Statistic (N)	p-value	Result
1901-1930	1.909	0.395	p-value > 0.05. The null hypothesis cannot be rejected.
1931-1960	2.075	0.582	p-value > 0.05. The null hypothesis cannot be rejected.
1961-1994	1.939	0.409	p-value > 0.05. The null hypothesis cannot be rejected.
1995-2024	2.044	0.185	p-value > 0.05. The null hypothesis cannot be rejected.
1901-2024	2.008	0.369	p-value > 0.05. The null hypothesis cannot be rejected.

From the analysis of the results, it can be concluded that there is no statistically significant change point found in the hydrological series of the Sabarmati basin for individual sub-periods and the complete periods from 1901 to 2024. In practical hydrological terms, it means that the data in the Sabarmati River series does not contain evident steps associated with large climatic and anthropogenic changes in the periods considered and is amenable to analysis for trends and variability in a manner not necessitating division by points of change.

5.2.2 Mahi river basin

Different change point tests have been applied for the Mahi river basin for four sub-periods (1901–1930, 1931–1960, 1961–1994, and 1995–2024) and for the complete period (1901–2024) and presented in **Tables 5.5 to 5.8**.

Table 5.5: Results of the Pettitt test for different periods for the Mahi river basin

Time Window	Results of Pettitt's test		
	Test Statistic (K_T)	p-value	Result
1901-1930	73	0.457	p-value > 0.05. The null hypothesis cannot be rejected.
1931-1960	52	0.820	p-value > 0.05. The null hypothesis cannot be rejected.
1961-1994	61	0.854	p-value > 0.05. The null hypothesis cannot be rejected.
1995-2024	66	0.584	p-value > 0.05. The null hypothesis cannot be rejected.
1901-2024	1422	0.003	p-value < 0.05. The null hypothesis can be rejected. The year of the change point is 1998.

Table 5.6: Results of the SNH test for different periods for the Mahi river basin

Time Window	Results of SNH test		
	Test Statistic (T_K)	p-value	Result
1901-1930	3.109	0.563	p-value > 0.05. The null hypothesis cannot be rejected.
1931-1960	2.127	0.784	p-value > 0.05. The null hypothesis cannot be rejected.
1961-1994	5.561	0.232	p-value > 0.05. The null hypothesis cannot be rejected.
1995-2024	15.658	0.011	p-value < 0.05. The null hypothesis can be rejected. The year of the change point is 1998
1901-2024	12.825	0.043	p-value < 0.05. The null hypothesis can be rejected. The year of the change point is 1998

Table 5.7: Results of the Buishand's test for different periods for the Mahi river basin

Table 5.7: Results of the Buishand's test for different periods for the Mahi river basin

Time Window	**Results of Buishand's test**		
	Test Statistic (*R*)	p-value	Result
1901-1930	4.812	0.310	p-value > 0.05. The null hypothesis cannot be rejected.
1931-1960	4.026	0.520	p-value > 0.05. The null hypothesis cannot be rejected.
1961-1994	3.163	0.852	p-value > 0.05. The null hypothesis cannot be rejected.
1995-2024	7.494	0.005	p-value < 0.05. The null hypothesis can be rejected. The year of the change point is 1998.
1901-2024	16.392	0.015	p-value < 0.05. The null hypothesis can be rejected. The year of the change point is 1997.

Table 5.8: Results of Von Neumann's test for different periods for the Mahi river basin

Time Window	**Results of Von Neumann's test**		
	Test Statistic (N)	p-value	Result
1901-1930	2.214	0.712	p-value > 0.05. The null hypothesis cannot be rejected.
1931-1960	2.117	0.612	p-value > 0.05. The null hypothesis cannot be rejected.
1961-1994	1.909	0.360	p-value > 0.05. The null hypothesis cannot be rejected.
1995-2024	0.948	0.008	p-value < 0.05. The null hypothesis can be rejected. The year of the change point is 1998.
1901-2024	1.879	0.239	p-value > 0.05. The null hypothesis cannot be rejected.

From the analysis, it has been found that no change point was detected in different individual sub-periods. From 1901 to 2024, all the tests confirmed that there is indeed a statistically significant change point after the year 1998, which is far below the standard level of significance, set at 0.05 (**Figure 5.1**).

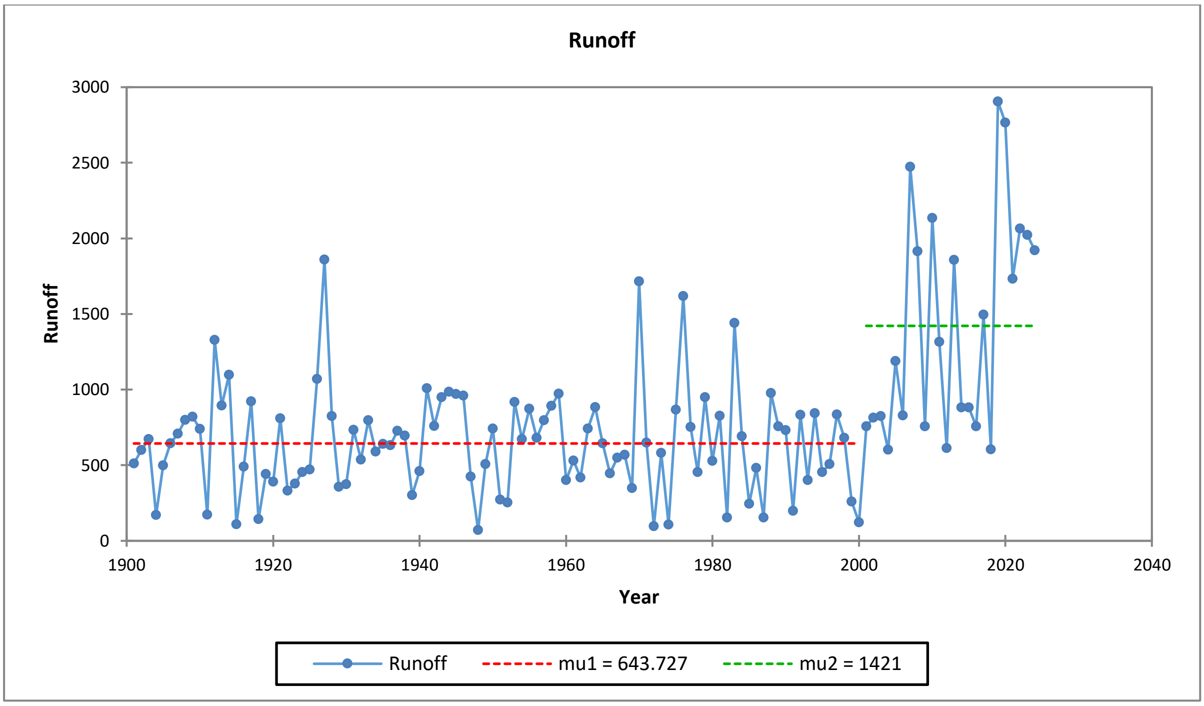


Figure 5.1: Change point in Mahi river basin

5.2.3 Dhadhar river basin

For the Dhadhar River basin, the results of the different tests applied on four sub-periods (1901-1930, 1931-1960, 1961-1994, and 1995-2024) and the whole period from 1901 to 2024 are presented in **Tables 5.9 to 5.12**.

Table 5.9: Results of the Pettitt test for different periods for the Dhadhar river basin

Time Window	**Results of Pettitt's test**		
	Test Statistic (K_T)	p-value	Result
1901-1930	47	0.894	p-value > 0.05. The null hypothesis cannot be rejected.
1931-1960	41	0.954	p-value > 0.05. The null hypothesis cannot be rejected.
1961-1994	66	0.786	p-value > 0.05. The null hypothesis cannot be rejected.
1995-2024	83	0.313	p-value > 0.05. The null hypothesis cannot be rejected.
1901-2024	454	0.846	p-value > 0.05. The null hypothesis cannot be rejected.

Table 5.10: Results of the SNH test for different periods for the Dhadhar river basin

Time Window	**Results of SNH test**		
	Test Statistic (T_K)	p-value	Result
1901-1930	2.587	0.686	p-value > 0.05. The null hypothesis cannot be rejected.
1931-1960	2.219	0.819	p-value > 0.05. The null hypothesis cannot be rejected.
1961-1994	1.581	0.942	p-value > 0.05. The null hypothesis cannot be rejected.
1995-2024	2.953	0.588	p-value > 0.05. The null hypothesis cannot be rejected.
1901-2024	2.399	0.874	p-value > 0.05. The null hypothesis cannot be rejected.

Table 5.11: Results of the Buishand's test for different periods for the Dhadhar river basin

Time Window	**Results of Buishand's test**		
	Test Statistic (R)	p-value	Result
1901-1930	3.340	0.734	p-value > 0.05. The null hypothesis cannot be rejected.
1931-1960	2.165	0.982	p-value > 0.05. The null hypothesis cannot be rejected.
1961-1994	3.482	0.754	p-value > 0.05. The null hypothesis cannot be rejected.
1995-2024	4.387	0.408	p-value > 0.05. The null hypothesis cannot be rejected.
1901-2024	6.948	0.762	p-value > 0.05. The null hypothesis cannot be rejected.

Table 5.12: Results of Von Neumann's test for different periods for the Dhadhar river basin

Time Window	**Results of Von Neumann's test**		
	Test Statistic (N)	p-value	Result
1901-1930	2.216	0.723	p-value > 0.05. The null hypothesis cannot be rejected.
1931-1960	2.161	0.666	p-value > 0.05. The null hypothesis cannot be rejected.

1961-1994	1.931	0.417	p-value > 0.05. The null hypothesis cannot be rejected.
1995-2024	1.281	0.021	p-value < 0.05. The null hypothesis can be rejected. The year of the change point is 1998.
1901-2024	1.929	0.353	p-value > 0.05. The null hypothesis cannot be rejected.

The analysis of different tests confirmed that there are no change points in different time scales in the Dhadhar river basin, and the runoff series is hydrologically homogeneous.

5.2.4 Sub-basins of Saurashtra Region

For the sub-basins of the Saurashtra region, different change point tests were conducted on four sub-periods (1901-1930, 1931-1960, 1961-1994, and 1995-2024) and the whole period from 1901 to 2024 (**Tables 5.13 to 5.16**).

Table 5.13: Results of the Pettitt test for different periods for the Saurashtra river basin

Time Window	**Results of Pettitt's test**		
	Test Statistic (K_T)	p-value	Result
1901-1930	70	0.514	p-value > 0.05. The null hypothesis cannot be rejected.
1931-1960	68	0.545	p-value > 0.05. The null hypothesis cannot be rejected.
1961-1994	64	0.807	p-value > 0.05. The null hypothesis cannot be rejected.
1995-2024	166	0.001	p-value < 0.05. The null hypothesis can be rejected. The year of the change point is 2004.
1901-2024	1608	0.000	p-value < 0.05. The null hypothesis can be rejected. The year of the change point is 2000.

Table 5.14: Results of the SNH test for different periods for the Saurashtra river basin

Time Window	**Results of SNH test**		
	Test Statistic (T_K)	p-value	Result

1901-1930	2.855	0.592	p-value > 0.05. The null hypothesis cannot be rejected.
1931-1960	1.967	0.842	p-value > 0.05. The null hypothesis cannot be rejected.
1961-1994	0.770	0.997	p-value > 0.05. The null hypothesis cannot be rejected.
1995-2024	12.984	0.002	p-value < 0.05. The null hypothesis can be rejected. The year of the change point is 2006.
1901-2024	49.437	0.0001	p-value < 0.05. The null hypothesis can be rejected. The year of the change point is 2018.

Table 5.15: Results of the Buishand's test for different periods for the Saurashtra river basin

Time Window	**Results of Buishand's test**		
	Test Statistic (R)	p-value	Result
1901-1930	3.508	0.690	p-value > 0.05. The null hypothesis cannot be rejected.
1931-1960	3.898	0.557	p-value > 0.05. The null hypothesis cannot be rejected.
1961-1994	2.366	0.980	p-value > 0.05. The null hypothesis cannot be rejected.
1995-2024	9.225	0.002	p-value < 0.05. The null hypothesis can be rejected. The year of the change point is 2006.
1901-2024	28.506	0.0001	p-value < 0.05. The null hypothesis can be rejected. The year of the change point is 2004.

Table 5. 16: Results of Von Neumann's test for different periods for the Saurashtra river basin

Time Window	**Results of Von Neumann's test**		
	Test Statistic (N)	p-value	Result
1901-1930	1.687	0.186	p-value > 0.05. The null hypothesis cannot be rejected.
1931-1960	1.405	0.05	p-value < 0.05. The null hypothesis can be rejected.
1961-1994	2.294	0.803	p-value > 0.05. The null hypothesis cannot be rejected.

1995-2024	9.225	0.014	p-value < 0.05. The null hypothesis can be rejected. The year of the change point is 2004.
1901-2024	1.13 7	0.0001	p-value < 0.05. The null hypothesis can be rejected. The year of the change point is 2004.

From the analysis, it can be concluded that the complete series from the year 1901 to 2024 depicted a significant change point after the year 2000 (**Figure 5.2**).

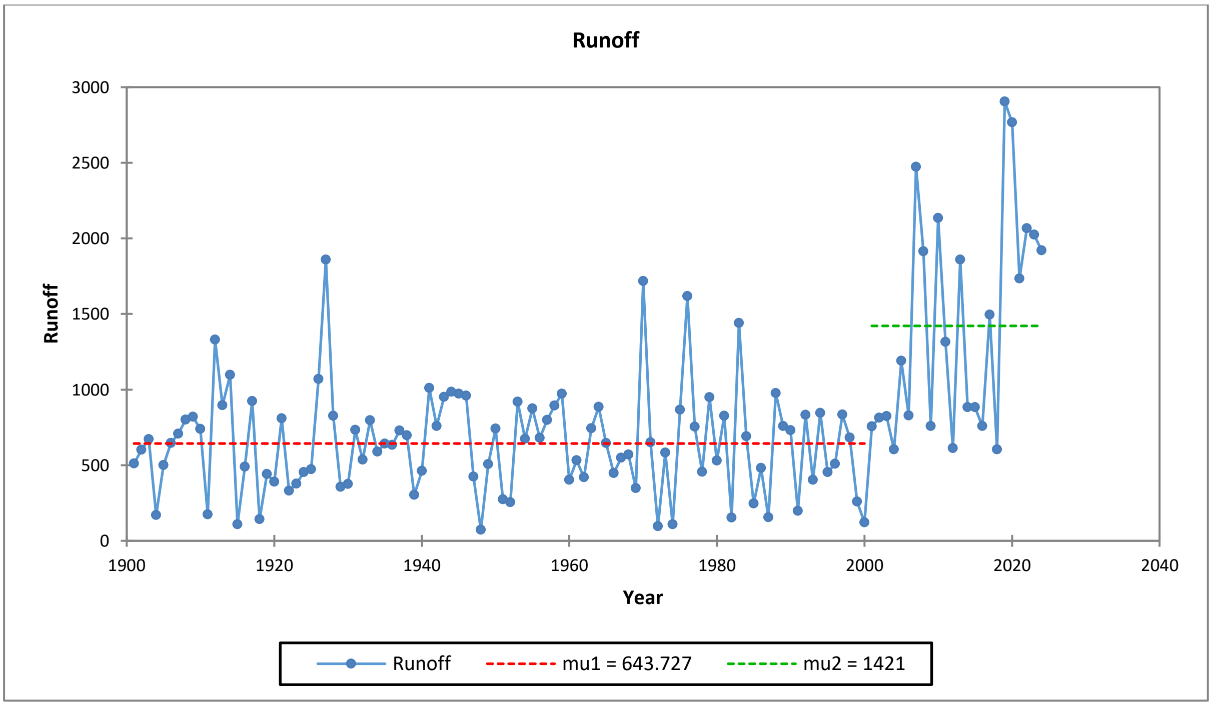


Figure 5.2: Change point in Saurashtra river basin

5.2.5 Narmada river basin

For the Narmada river basin, the result of the different tests on four sub-periods (1901-1930, 1931-1960, 1961-1994, and 1995-2024) and the whole period from 1901 to 2024 are presented in **Tables 5.17 to 5.20.**

Table 5.17: Results of the Pettitt test for different periods for the Narmada river basin

Time Window	**Results of Pettitt's test**		
	Test Statistic (K_T)	p-value	Result
1901-1930	77	0.399	p-value > 0.05. The null hypothesis cannot be rejected.

1931-1960	77	0.397	p-value > 0.05. The null hypothesis cannot be rejected.
1961-1994	68	0.762	p-value > 0.05. The null hypothesis cannot be rejected.
1995-2024	158	0.002	p-value < 0.05. The null hypothesis can be rejected. The year of the change point is 2004.
1901-2024	1376	0.003	p-value < 0.05. The null hypothesis can be rejected. The year of the change point is 2004.

Table 5.18: Results of the SNH test for different periods for the Narmada river basin

Time Window	**Results of SNH test**		
	Test Statistic (T_K)	p-value	Result
1901-1930	1.935	0.852	p-value > 0.05. The null hypothesis cannot be rejected.
1931-1960	1.935	0.845	p-value > 0.05. The null hypothesis cannot be rejected.
1961-1994	5.042	0.253	p-value > 0.05. The null hypothesis cannot be rejected.
1995-2024	17.263	0.001	p-value < 0.05. The null hypothesis can be rejected. The year of the change point is 2018.
1901-2024	72.545	0.0001	p-value < 0.05. The null hypothesis can be rejected. The year of the change point is 2018.

Table 5.19: Results of the Buishand's test for different periods for the Narmada river basin

Time Window	**Results of Buishand's test**		
	Test Statistic (R)	p-value	Result
1901-1930	3.840	0.566	p-value > 0.05. The null hypothesis cannot be rejected.
1931-1960	3.840	0.572	p-value > 0.05. The null hypothesis cannot be rejected.
1961-1994	3.973	0.613	p-value > 0.05. The null hypothesis cannot be rejected.

1995-2024	9.258	0.001	p-value < 0.05. The null hypothesis can be rejected. The year of the change point is 2018.
1901-2024	24.204	0.0001	p-value < 0.05. The null hypothesis can be rejected. The year of the change point is 2004.

Table 5.20: Results of Von Neumann's test for different periods for the Narmada river basin

Time Window	**Results of Von Neumann's test**		
	Test Statistic (N)	p-value	Result
1901-1930	1.757	0.251	p-value > 0.05. The null hypothesis cannot be rejected.
1931-1960	1.757	0.249	p-value < 0.05. The null hypothesis can be rejected.
1961-1994	1.861	0.332	p-value > 0.05. The null hypothesis cannot be rejected.
1995-2024	1.228	0.024	p-value < 0.05. The null hypothesis can be rejected. The year of the change point is 2004.
1901-2024	1.110	0.000	p-value < 0.05. The null hypothesis can be rejected. The year of the change point is 2004.

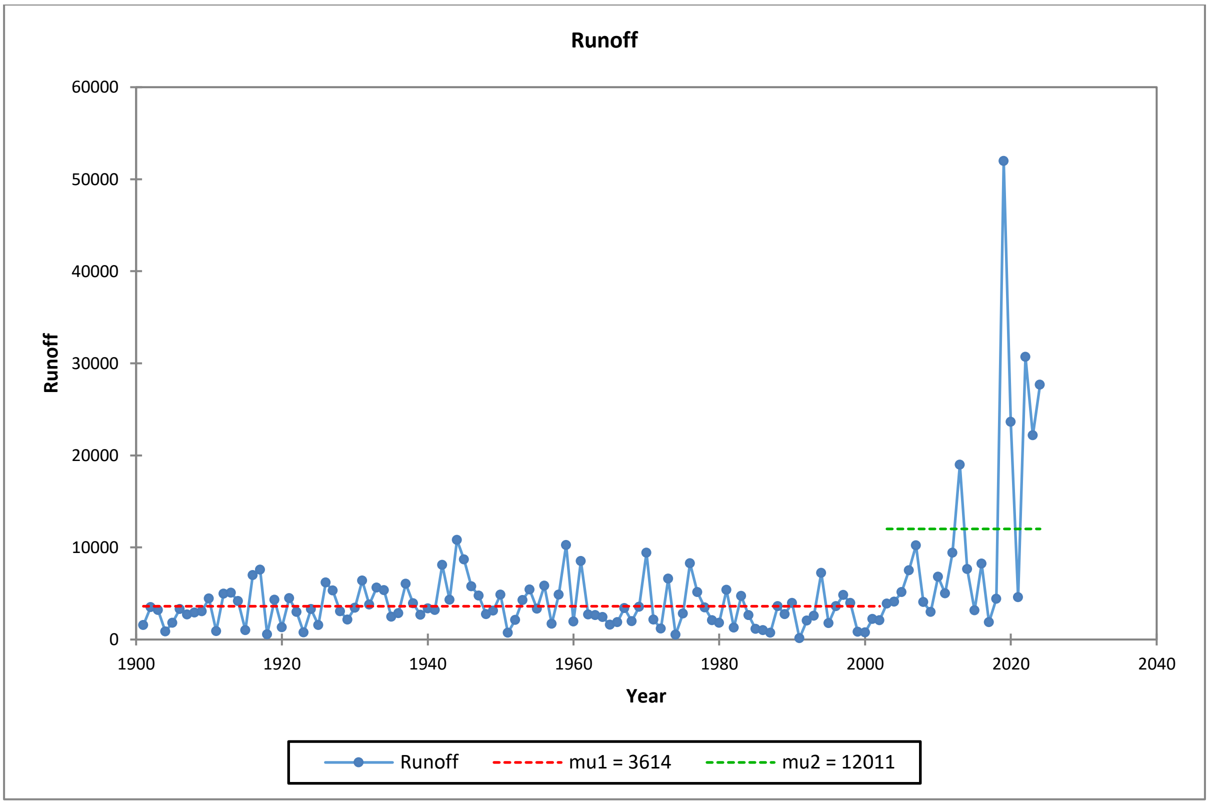


Figure 5.3: Change point in the Narmada river basin

5.3 Results of Trend Analysis

The results for the trend assessment for all river basins contributing to the Kalpsar project are explained below:

5.3.1 Trend test results for the Sabarmati river basin

The results of all tests are shown in **Table 5.21** for five different periods i.e. 1901-1930, 1931-1960, 1961-1994, 1995-2024, and 1901-2024.

Table 5.21: Results of tests for Sabarmati River Basin

Year	**Man-Kendall Test**				
	Tau	***S***	***P-value***	**Sen's Slope**	**Trend**
1901-1930	0.048	21	0.724	4.747	No
1931-1960	0.039	17	0.777	3.299	No
1961-1994	0.087	49	0.48	9.104	No
1995-2024	-0.076	-33	0.572	-4.468	No
1901-2024	-0.053	-407	0.381	-1.45	No

The analysis of the results of the Man-Kendall test for the sub-periods 1901–1930, 1931–1960, and 1961–1994, the Tau values are small and positive/negative, suggesting weak increasing tendencies, but the corresponding *Z* and *P-values* indicate that these trends are not statistically significant. The period 1995–2024 and 1901-2024 show a weak negative *Tau* and Sen's slope, implying a slight decreasing tendency; however, the relatively high P-value again confirms no significant trend during this period.

5.3.2 Trend test results for the Mahi river basin

The results of Man-Kendall's test on runoff series for the Mahi river basin were presented in **Table 5.22**.

Table 5.22: Results of tests for the Mahi River Basin

Year	**Man-Kendall Test**				
	Tau	***S***	***P-value***	**Sen Slope**	**Trend**
1901-1930	0.207	90	0.112	58.65	No
1931-1960	0.053	23	0.697	30.185	No
1961-1994	-0.016	-9	0.906	-4.145	No
1995-2024	-0.016	-7	0.916	-0.527	No
1901-2024	-0.093	-709	0.126	-6.295	

The analysis of the Man-Kendall test for the Mahi river basinfor the sub-period 1901–1930, a positive Tau (0.207) and a relatively large positive Sen's slope (58.65) suggest an increasing tendency; however, the P-value (0.112) exceeds the 0.05 significance level, indicating that this increase is not statistically significant. During 1931–1960, the Tau value is small and positive, again implying a weak increasing tendency, but the high P-value (0.697) confirmed the absence of a significant trend. The periods 1961–1994 and 1995–2024 showed very small negative *Tau* values with negative Sen's slopes, indicating slight decreasing tendencies, yet the very high P-values (>0.90) clearly indicate no significant trend in these intervals.

For the entire period (1901–2024), the negative Tau (−0.093) and negative Sen's slope (−6.295) indicate an overall decreasing tendency in the Mahi River basin time series. However, the corresponding Z value (−1.5291) and P-value (0.126) showed that this trend may not be statistically significant. Overall, the results indicate that the Mahi River basin does not exhibit any statistically significant monotonic trend in any sub-period or over the full study period, and the observed variations are likely due to natural inter-annual variability rather than long-term systematic change.

5.3.3 Dhadhar River Basin

The results of Man-Kendall test for different periods for the Dhadhar river basin are shown in **Table 5.23.**

Table 5.23: Results of tests for Dhadhar river basin

Year	**Man-Kendall Test**				
	Tau	***S***	***P-value***	**Sen Slope**	**Trend**
1901-1930	0.049	21	0.721	0.34	No
1931-1960	-0.002	-1	1.0	0	No
1961-1994	0.002	1	1.0	0	No
1995-2024	0.095	41	0.475	6.019	No
1901-2024	0.006	43	0.928	0	No

The analysis of Man-Kendall's test and Sen's slope for the sub-periods 1901–1930, 1931–1960, and 1961–1994, the values of Tau were very small (positive and negative), with corresponding Z values almost equal to zero, thereby leading to very high P-values (≥0.72), reflecting no statistically significant trend. The Sen's slope values over the periods WEre all very small, too, and reflect hardly any variation in the series. In the recent period 1995–2024, a fairly positive Tau (0095) and a positive Sen's slope (6.019) indicated a weak growing tendency. For the full period 1901-2024, the Tau value of 0.0049 and a high P-value of 0.721, confirmed that there is no monotonic trend in the long term. In summary, all the sub-periods and full study periods did not show any significant increasing or decreasing trends in the Dhadhar River basin.

5.3.4 Sub-basins of Saurashtra Region

Table 5.24 presents the results of the Mann–Kendall (MK) trend test applied to the hydrological time series of the Sub-basins of the Saurashtra region for different time periods.

Table 5.24: Results of tests for the Saurashtra river basin

Year	**Man-Kendall Test**				
	Tau	***S***	***P-value***	**Sen Slope**	**Trend**

1901-1930	0.007	3	0.972	0.38	No
1931-1960	0.053	23	0.692	2.483	No
1961-1994	0.041	23	0.746	2.366	No
1995-2024	0.465	202	0.00	50.449	Positive
1901-2024	0.211	1609	0.001	3.5	Positive

The results of the trend tests for the basins of Saurashtra for the early and mid-series period of 1901-1930, 1931-1960, and 1961-1994, indicated the small and positive Tau values, showing a tendency that is barely increasing. The Z-scores are low, and the P-values are much larger than 0.05 for all series. During the period from 1995-2024, with a large positive Tau value of 0.465 and a large Z-score of 3.5866 with a low P-value of approximately 0.0003, a statistically significant increasing trend is observed with a positive Sen’s slope value of 50.45, thus showing a strong rise of the series during the past few years. For the entire period (1901-2024), the positive Tau (0.211), high Z-value (3.473), and low P-value (.0005) support the significantly increasing pattern with the positive Sen's slope (3.50) corresponding to the average rate.

5.3.5 Narmada River Basin

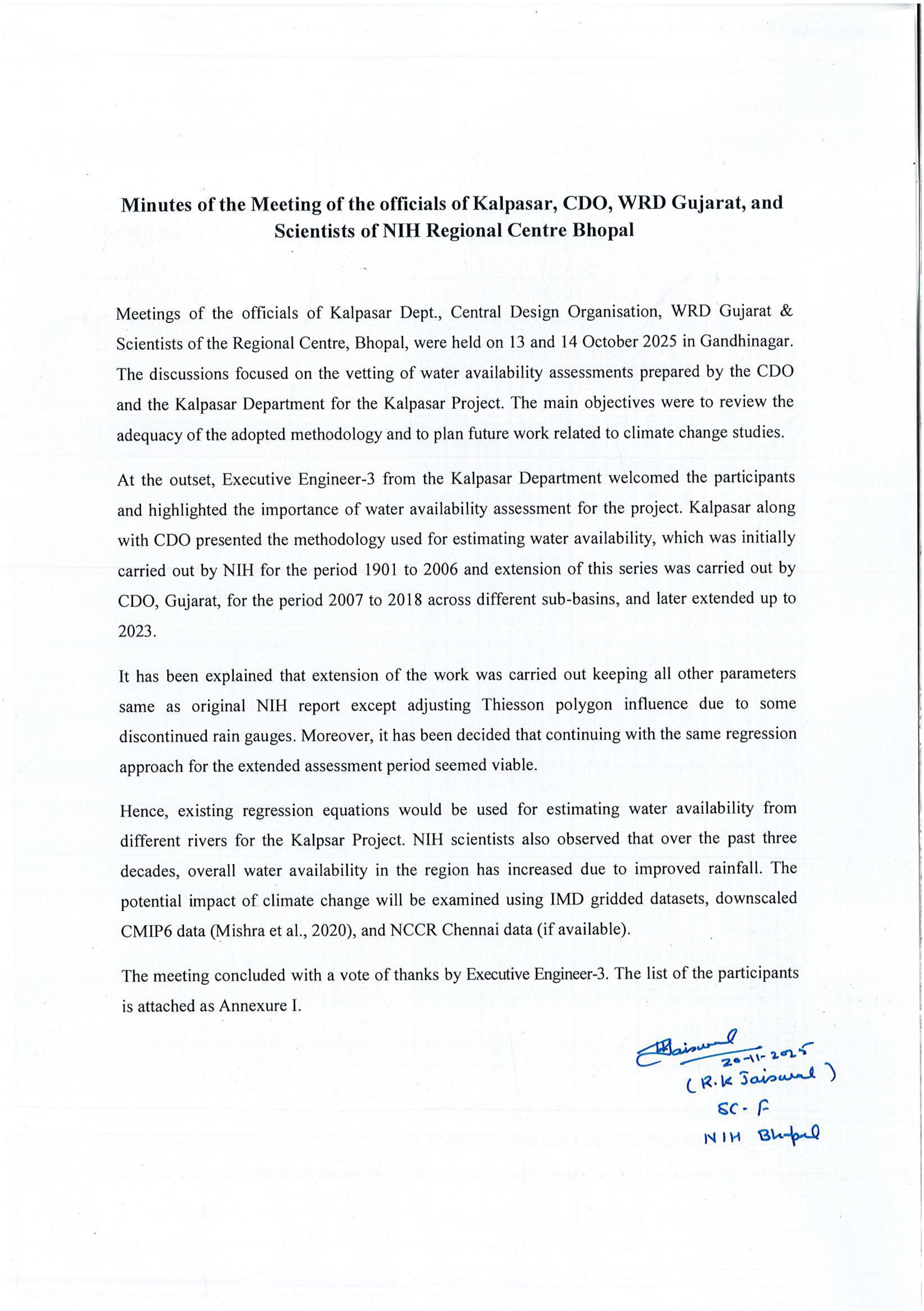
The results of the trend test for the Narmada river basin are presented in **Table 5.25**. The analysis suggested that for the early sub-periods (1901-1930), the positive Tau (0.122) and the Sen's slope of 33.0 indicated a weak increasing movement. The high P-value of 0.357 within the same periods shows that the trend may not be statistically insignificant. The negative Tau’s and the negative Sens' slope during the periods 1931-1960 and 1961-1994 with P-values greater than 0.40 show that the weak decreasing movements are statistically insignificant. Conversely, the strong positive Tau of 0.499 and the high S-value of 217 along with the P-value of 0.0001 during the last sub-periods of 1995-2024, showed that the statistically significant strong increasing movement with the large Sen's slope of 443.25 indicated a dramatic rise in the series during the last decades. For the complete period (1901-2024), Tau = 0.135, S = 1026, and P = 0.0268 revealed that there exists a statistically significant increasing trend in the Narmada river basin

Table 5.25: Results of tests for Narmada River Basin

Year	**Man-Kendall Test**				
	Tau	***S***	***P-value***	**Sen Slope**	**Trend**

1901-1930	0.122	53	0.357	33	No
1931-1960	-0.080	35	0.548	-34.529	No
1961-1994	-0.102	-57	0.410	-35.647	No
1995-2024	0.499	217	0.0001	443.25	Positive
1901-2024	0.135	1026	0.027	14.702	Positive

ANNEXURE-I: Minutes of Meetings during Oct 13-14, 2025



Minutes of the Meeting of the officials of Kalpasar, CDO, WRD Gujarat, and Scientists of NIH Regional Centre Bhopal

Meetings of the officials of Kalpasar Dept., Central Design Organisation, WRD Gujarat & Scientists of the Regional Centre, Bhopal, were held on 13 and 14 October 2025 in Gandhinagar. The discussions focused on the vetting of water availability assessments prepared by the CDO and the Kalpasar Department for the Kalpasar Project. The main objectives were to review the adequacy of the adopted methodology and to plan future work related to climate change studies.

At the outset, Executive Engineer-3 from the Kalpasar Department welcomed the participants and highlighted the importance of water availability assessment for the project. Kalpasar along with CDO presented the methodology used for estimating water availability, which was initially carried out by NIH for the period 1901 to 2006 and extension of this series was carried out by CDO, Gujarat, for the period 2007 to 2018 across different sub-basins, and later extended up to 2023.

It has been explained that extension of the work was carried out keeping all other parameters same as original NIH report except adjusting Thiesson polygon influence due to some discontinued rain gauges. Moreover, it has been decided that continuing with the same regression approach for the extended assessment period seemed viable.

Hence, existing regression equations would be used for estimating water availability from different rivers for the Kalpsar Project. NIH scientists also observed that over the past three decades, overall water availability in the region has increased due to improved rainfall. The potential impact of climate change will be examined using IMD gridded datasets, downscaled CMIP6 data (Mishra et al., 2020), and NCCR Chennai data (if available).

The meeting concluded with a vote of thanks by Executive Engineer-3. The list of the participants is attached as Annexure I.

Jaiswal
20-11-2025
(R.K Jaiswal)
SC-F
NIH Bhopal

PROJECT TEAM

NATIONAL INSTITUTE OF HYDROLOGY

Dr. Y. S. R. Rao	**Director**
Dr. R. K. Jaiswal	**Scientist F & PI**
Dr. Ravi Galkate	**Scientist G & Head CIHRC**
Er. Suryansh Mandloi	**Scientist B**
Er. Bhupendra Dhankar	**JRF**