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Irrigation Water Conveyance System: Digital Twin, Vegetation Dynamics in Irrigation Command Area

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Abstract

Gujarat, a western state of India, has an extensive irrigation conveyance infrastructure of about 26,295 km, more than 6000 km pipelines and 490 km of Recharge Canals. This paper attempts to narrate about the infrastructure of Water Resources Dept, Gujarat effort for creating digital twin of the irrigation infrastructure. The initiative for creation of a dedicated Geospatial Cell and extensive training of over 400 field officers on open-source GIS, satellite imagery, digital image processing, VEDAS and Bhuvan Geoportal etc. Nearly 24,000 km of canal and 5,500 km of pipelines geo database created, along with inline hydraulic structures, command areas, and recharge infrastructure. The geospatial layers were shared in interoperable formats and APIs integrated with key state and national platforms. A Web Map Service (WMS) developed to facilitate standard uniform interactive data usage enhancing transparency and user engagement. The system supports applications such as permission for crossings, monitoring of reservoir water storage, vegetation dynamics within irrigation command areas and seamless planning of deploying UAV surveys etc. This initiative has significantly enhanced geo-spatial data fidelity, accelerated decision-making and inter-departmental coordination. It proved a resilient digital backbone for the Irrigation Master Plan, enabled adaptive management strategies across administrative levels to bring equity and efficiency in water distribution.

1. Introduction

The management of irrigation infrastructure plays a vital role in agricultural productivity and sustainability, especially in arid and semi-arid regions like Gujarat. Traditionally, these networks have been managed through manual methods, often leading to inefficiencies in water distribution, delayed maintenance and lack of real-time data. Recognizing this challenge, the Government of Gujarat initiated a state-wide digital transformation of its irrigation infrastructure. The concept of digital twin - creating a digital replica of physical assets was adopted for the entire canal and pipeline network. Additionally, the facility of analyzing vegetation dynamics using satellite imagery provided valuable insights into crop health, command area utilization and water-use efficiency.

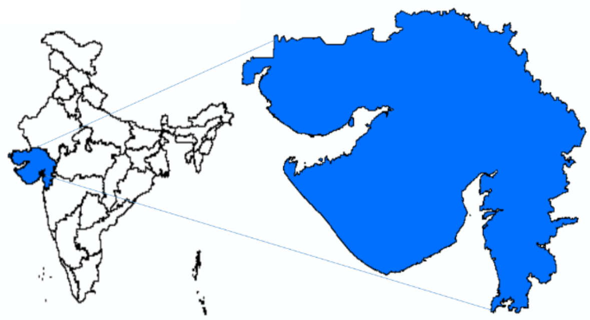

Figure 1 Gujarat is Westernmost State in India

2. Policy Framework and Institutional Setup

The Water Resources Department carried out several Remote Sensing and GIS activities however, the establishment of Geospatial Cell at the Central Flood Control Cell, Gandhinagar at State Water Data Centre, was a significant intervention in the year 2019. This initiative was supported by government resolutions and mandates and subsequently aligning with the National Geospatial policy of year 2022.

The 2022 policy facilitated access to satellite data, promoted open standards and empowered state departments to build GIS capabilities. The Geospatial Cell was equipped with modern tools and staffed with trained engineers and GIS specialists who coordinated with field divisions. Institutional capacity was enhanced systematically to ensure that data digitization, management and integration with national platforms became part of the regular workflow.

3. Digital Twin creation & Capacity building:

3.1 Initial Focus:

The initial focus was to create digital twin of Gujarat's irrigation water Conveyance system (belonging to Water Resources Dept. GoG) covering Reservoirs, Canals, Pipelines, Underground pipelines and other assets. This provided a live, updatable virtual model useful for line staff as well as top management.

Integration with satellite imagery enabled a foundation for building up robust applications towards sowing seeds for digital twin of Network operations and thinking for realistic dashboards.

Although in its early stages, Gujarat's digital twin initiative for irrigation infrastructure began yielding tangible benefits by fostering a deeper understanding of its applications and limitations, correlating performance issues, vulnerabilities, and facilitating proactive maintenance. The use of open source platforms such as QGIS, PostgreSQL/PostGIS and custom web map applications allowed WRD field engineers to monitor and interact with Water Conveyance network dynamically with a holistic view. Additionally, the field officers utilized popular open source mobile GIS apps to utilize the datasets made available, creating a bi-directional data flow amongst field officers and line staff.

Such effort laid the foundation for future smart irrigation management using remote sensing, geospatial analytics and spatial data infrastructure (SDI) and juxtaposition SCADA for operational digital twin.

3.2 Capacity Building

A major success factor was the systematic training of over 400 field officers in open-source GIS platforms, GNSS -based data collection and remote sensing techniques, BHUVAN portal, VEDAS and other national portals. Capacity building efforts were significantly scaled up and strategically intensified in the year 2020. Training modules included virtual sessions, physical workshops and use of actual field officers oriented geospatial exercises. The capacity building content initially covered the basics with focus on departmental needs and later the content evolved as per needs of the participants. This created a pool of resource personnel aware about geo spatial activities and their possible role to contribute across the state.

4. Geo-spatial database - Irrigation Conveyance Network

4.1 Methodology for Geospatial Data Creation:

The administrative hierarchical database was created first and thereafter the irrigation infrastructure (viz. Conveyance network, Reservoirs) database were coded to create standardized input templates and shared to field officers. Prior to creating geo spatial data, the meta data was collected through field offices in standard spreadsheet templates for the each geospatial layer. Figure 2 shows the methodology adapted. Virtual meetings with BHUVAN officers and NRSC officials clarified doubts and gave a direction for use of alternative open source geo spatial technologies to create geo spatial database.

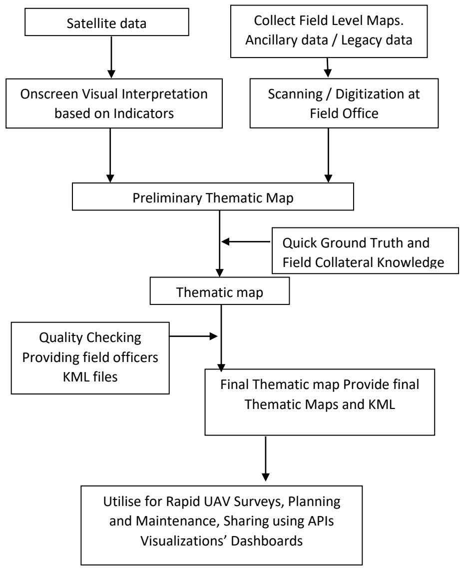

Figure 2 Administrative process for Digital Twin

Legacy maps and engineering drawings were compiled and geo-referenced to standard coordinate systems. GIS team created geo database with the full hierarchy of the canals - main canals, branch canals, distributaries, minors and sub minors along with hydraulic structures such as regulators, head-works, escapes, cross-drainage structures etc. using high resolution satellite imagery. Pipeline alignments were also captured and features containing metadata, under different administrative boundaries like Circle, Division, Sub-Division etc. Figure – 3 exhibits an example of part of the Irrigation Conveyance Network System with its corresponding satellite image. The effort realized a rich geo spatial database of 23,483 km of canal systems and 5,563 km of pipelines along with various structures using open-source GIS software.

5. Outputs and Visualization of Geospatial Data - Phases of development

5.1 Field Officers centric services :

The creation of local teams along vertical hierarchy from seniors officers to line staff led to timely creation of geo spatial data assets like inputs to digitize legacy maps and validation of ground data and its utilization maintaining WRD infrastructure. (Figure 4). Data sharing was streamlined through dissemination strategy, enabling both field-level operability and strategic oversight. For on-ground teams, outputs were provided in accessible formats such as KML files for geospatial visualization and PDF reports for offline reference and documentation. A centralized spatial database to support higher-level management.

Administrative units wise (Circle, Division, Subdivision) Maps were created in .pdf/.jpg formats and shared for verification in KML format. The field officers started consuming it on mobile devices and used as a referential information.

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This gradually built an ownership by field officers, and promoted usage for their own innovative usage in irrigation infrastructure management.

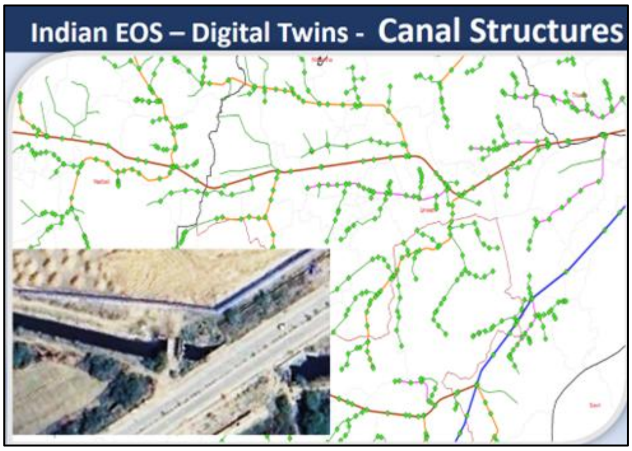

Figure 3 Canal Command Area and satellite image

Moreover, such maps were placed as online pdf documents with authorized access. The data is also available in VEDAS portal for visualization. Status of geo spatial dataset is Table – 1.

Sr no.	WRD Assets	Data type	Quantity digitized /Record counts
1	Canal	Line	23483 km
2	Pipeline/LI Schemes	Line	5563 km
3	Canal Structures	Point	61959 nos.
4	Pipeline structures	Point	9794 nos.
5	Tidal Regulator	Point	14 nos.
6	Bandhara	Point	75 nos.
7	Buildings	Point	4340 nos.
8	Irrigation Schemes (major, medium, minor)	Polygon	1101 nos.
9	Gujarat Rivers Basins	Polygon	38 nos.
10	185 River Basins	Polygon	185 nos.
11	Flood prone zones	Polygon	3923 villages
12	Command area Outer Boundary	Polygon	169 nos.
13	Command Area at Beat Outlet	Polygon	Work in progress

Table 1 Geospatial Dataset – WRD Gujarat

5.2 Phased Development of API-Enabled Geospatial Services:

The following Phases were implemented for the creation geospatial layers. Each phase progressively enhancing data interoperability and utilisation of Digital canal infrastructure and respective command areas as detailed in Table 2.

Figure 4 Legacy Command Area Maps geo spatial layer.

The field officers were conversant with the use of the Reservoir Data portal since 10 years. The Irrigation Conveyance Network was made available online on this Reservoir Data Portal with authorized access shown in Figure 5. The online visualization and access were enabled using the open-source Leaflet library. This enhancement allowed users to interactively explore the conveyance network with improved accessibility and spatial accuracy.

Phase	Key Steps	Activities
1. Preparation	Data Collection, Maps/Meta data - Administrative units and Line staff	Gathered Legacy maps & documents
2. Scanning	Map Scanning, enhancements	High-resolution scanning and processing
3. Geo referencing	Control Points, Transformations	Coordinate system, Reference points
4. Digitization	Layer Creation, Feature Tracing Topology	Create vector layers
5. Attributes	Database Design, and populating	Create Feature data, attribute tables
6.Quality Control	Accuracy Check, Error Fixing	Corrections / Validated against sources
7. Analysis	Data Integration	Merged datasets, use of spatial analytical tools, VEDAS , BHUVAN like tools
8. Outputs	Data Export, KML, online services and APIs	Digital maps

Table 2 Phases of the project

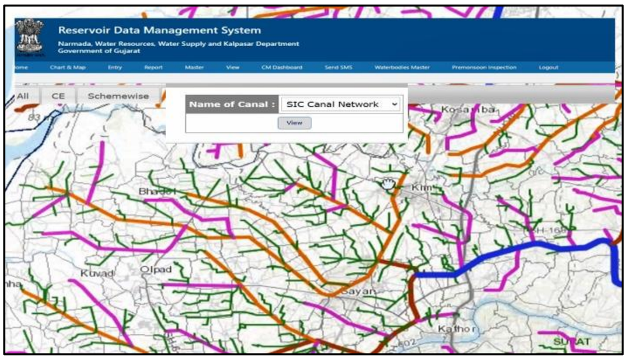

Figure 5 Circle wise Conveyance infrastructure placed online

6. Digital Twin : Utilisation Maintenance, Augmentation & New Infrastructure

6.1 UAV Survey Mission plan - Sujalam Sufalam Canal

The SSY canal was constructed around late 1990s. The unlined canal of 332 Kilometres Length having 2000 cusecs discharge, traversing through seven districts and having Major structures on 21 Rivers , 2 National Highways, 27 State Highways, 7 Railway crossings, 600 other structures, benefitting 70000 ha and water recharge to 1,20,000 hectare area, drinking water supply to 679 villages and 8 town shown in Figure 6 . It was essential to be updated w.r.t. status of the system. The digital twin effort involved creating the shape files and utilizing it for UAV Survey recorded the status of the Canal using Photo Videos tagged with important place markers. This proved a quick maintenance needs assessment tool for field engineers.

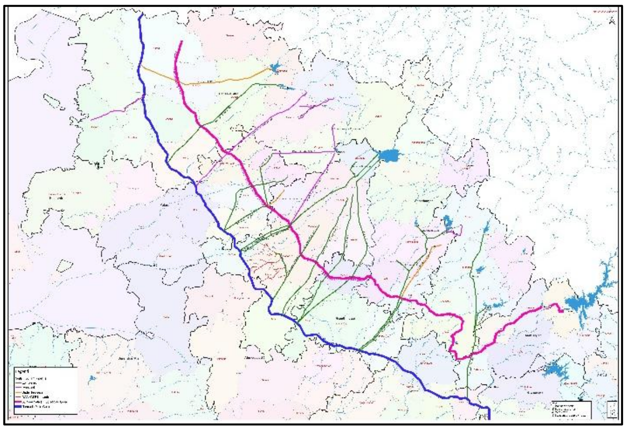

Figure 6 Sujalam Sufalam Canal geo data used for UAV mission planning.

6.2 Replenishing Village Ponds with Sujalam Sufalam Pipe infrastructure

The planning for connecting village ponds was carried in alignment finalization for feeders to the village ponds in water scarce regions of North Gujarat fulfilling the policy criterion for proximity, size, and beneficiary area and population illustrated in Figure 7. More than 1000 water bodies are connected through pipelines.

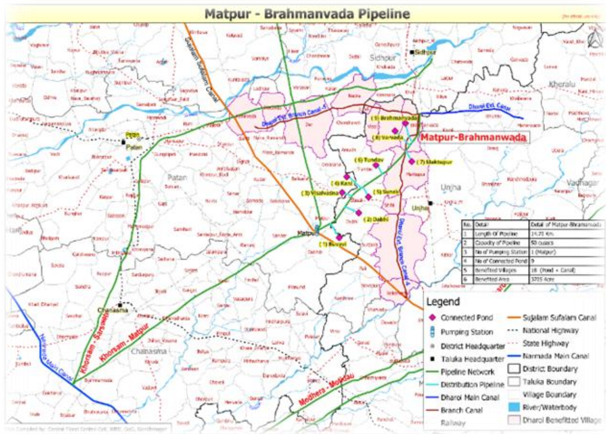

Figure 7 Feeding Villages ponds through Bulk Pipeline

6.3 UAV Survey Mission plan –New bulk Pipeline Kachchh Region

The Kachchh region bulk Pipelines, more than 1300 Kms including main and laterals, alignment finalization and approval pre requisites had to be fulfilled. The initial alignment was corrected on high resolution satellite imagery and later on the Shape files were utilized for a UAV based photo video survey for fine tuning the final alignment of the bulk water supply pipelines for the Northern link, Southern link and High level canal and their laterals shown in Figure 8.

Figure 8 Utilising the Shape files for UAV flight path to finalise Alignment of Bulk Water Supply pipelines

7. Vegetation Dynamics and Irrigation Monitoring

7.1 Various use cases - Vegetation dynamics in canal command area using VEDAS Geo-Portal

Monitoring vegetation dynamics within the irrigation command area is essential for understanding water distribution efficiency, crop health, and land use change. Using NDVI (Normalized Difference Vegetation Index) derived from Sentinel-2 and other Satellite imagery, vegetation status was assessed periodically across the command areas using VEDAS. This analysis helped to identify under-irrigated zones, changes in cropping patterns etc. This provided valuable insights to engineers to improve equitable water distribution and promote water-use efficiency. VEDAS

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portal has a potential use for better planning and decision making for identifying area of maintenance and long operational characterisation of canal commands.

7.2 State Level Vegetation Dynamics around new and old Irrigation Infrastructure

Using VEDAS long term trend in vegetation change was made possible. The 24 year period aggregated change in NDVI revealed (Figure 9) that the overall vegetation had increased which indirectly points to improvement in water availability, improved agricultural practices and social forestry.

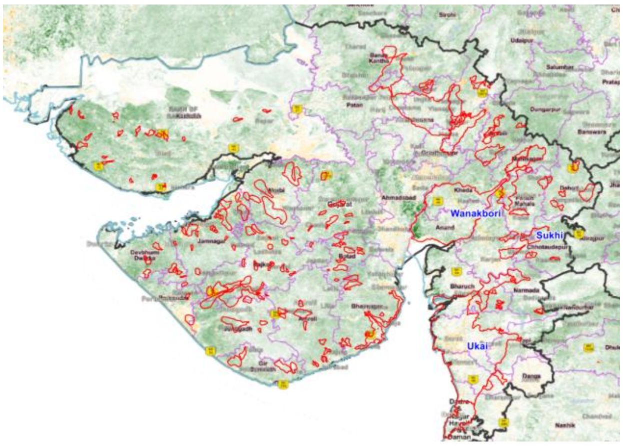

Figure 9 Vegetation trend 24 year duration 2001 till 2024 in Rabi Season, green color shows positive trend

At project level further analysis was done as an example for a Scheme in Kachcch region namely Jangadia Water Resources Scheme. Regression line (Figure 10) shows a positive slope for vegetation cover over a 24 years period using MODIS data in VEDAS. Such analytics can help field engineers to infer overall situation under the irrigation outlets

Figure 10 The positive slope of regression line indicating increase in vegetation cover at near tail end field Jangadia Scheme of Kachchh, Gujarat,

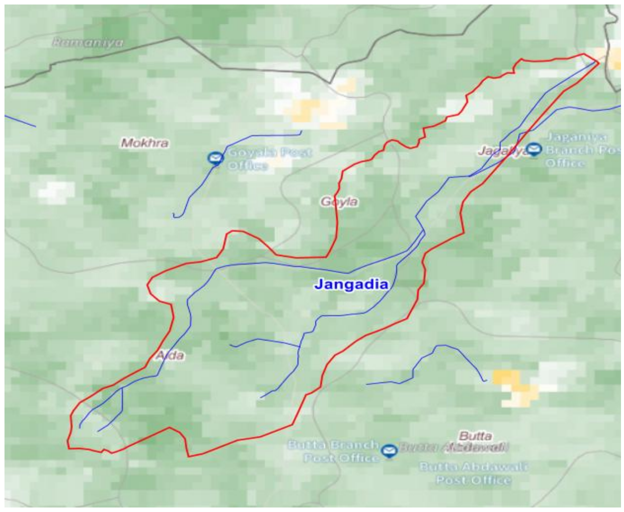

Figure 11 Rabi Season, Jangadia Water Resources Scheme in Kachchh, Gujarat, showing positive trend of vegetation over last 24 years Rabi 2001 to 2024

7.3 Head-to-Tail Inequity – Vegetation dynamics

The Canal and Command area geo dataset was useful in assessing the vegetation status across years in head and tail areas of the Command areas. To overcome these issues use of Geospatial Technology is a game changer for irrigation managers.

Mahi Irrigation Command of Central Gujarat observations were made using VEDAS. Figure-12 shows sparse vegetation at the tail end of the command in year-2001 whereas the improvements due to management and technical interventions show up significant improvement in year 2023 Figure-13 exhibits the increased Vegetation coverage at the tail command.

Figure 12 MRBC Command 9th Feb 2001 on VEDAS

Figure 13 MRBC Command 9 Feb 2023 on VEDAS

Vegetation Index Increased at Tail end of MRBC Command Area over Period of time of 22 years The trend is shown in Figure 14.

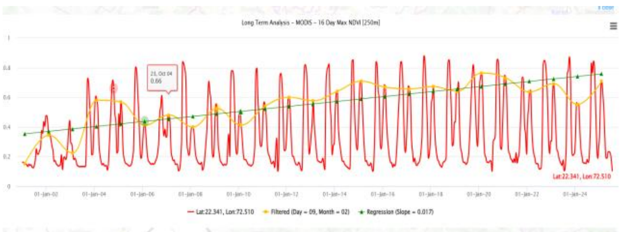

Figure 14 Increasing trend of Vegetation in MRBC Tail end

7.4 Vegetation dynamics in Arid Regions Command Area :

Rudramata Command Area Monitoring - Monthly Changes in Vegetation Dynamics are shown in Figure 15. Whereas, increase in Vegetation Index over Period of time (2012 to 2022) is shown in Figure 16. This is indicative of benefit to Castor or fodder crop yields from residual water, also Bajro, Summer groundnut, Jowar, Horticulture crop like Dates, Pomegranate etc

Figure 15 Rudramata Scheme, Kachchh region monthly changes - harvesting in a month during 5th Oct to 5th November 2023

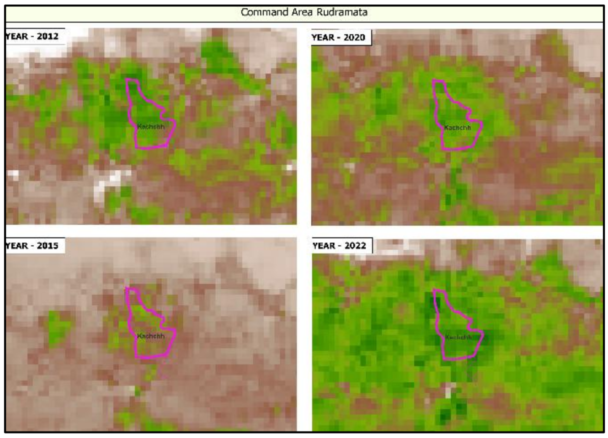

Figure 16 Rudramata, Kachchh region increase in Vegetation index from 2012 to 2022

7.5 Summer Irrigation in Arid Areas:

Observing summer Irrigation and its coverage helps irrigation managers. As an example, Figure 17 the Nara Command Area falling in arid Kachchh Region, Summer irrigation reveals the effectiveness of Water resources Scheme.

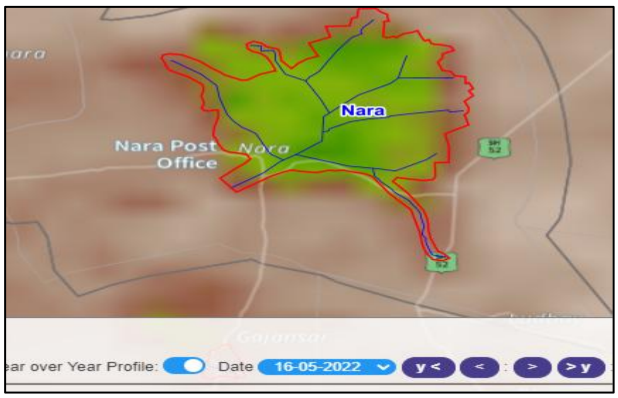

Figure 17 Summer Irrigation, Nara Scheme, Kachcchh Region

7.6 Cropping Intensity in Canal Commands :

The Command areas of all the major, medium and minor schemes of WRD Gujarat placed on VEDAS portal. This facilitates Visualising Cropping intensity in the canal commands. The cropping intensity was visualised in VEDAS.

Figure 18 shows Dantiwada Scheme mid reach of the Command with canal network, highlighting the cropping intensity during the three season, one year duration from 5 August 2024 to 5 August 2025. The analytical color visuals maps depicting Deep red colour as 100% of the time presence of vegetation (crop) whereas blue colour indicates 0% time presence of vegetation (crop) based on NDVI range of 0.25 to 1.0 based on MODIS satellite imagery (250m resolution).

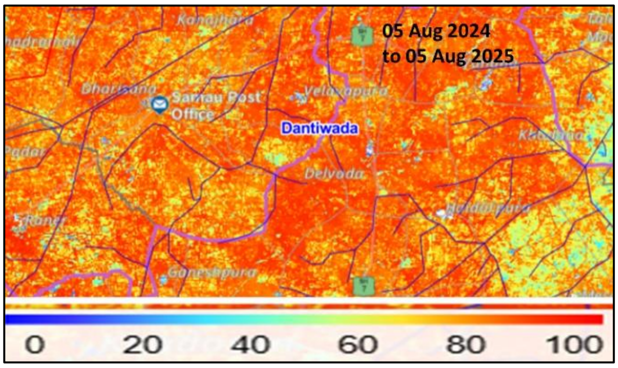

Figure 18 Cropping intensity in Dantiwada Scheme, North Gujarat

In contrast to Dantiwada, Uben Scheme of Saurashtra has lesser cropping intensity during the same duration 5 Aug 2024 to 5 August 2025. Figure 19 is the Uben Command area, its Canal network in mid reach of the Command.

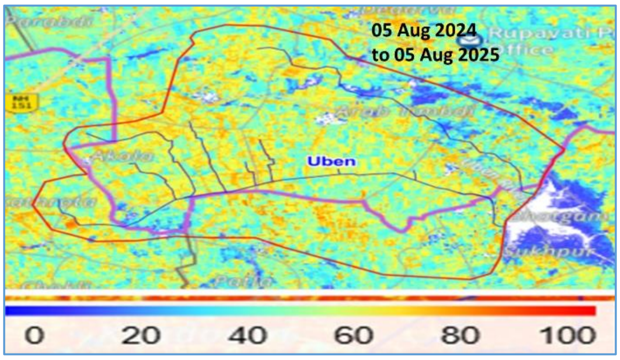

Figure 19 Cropping Intensity in mid command of Uben Scheme, Saurashtra Gujarat

Such cropping intensity analytics and visualisation provide the field engineer insights regarding likely cropping pattern and water availability and further insight in the cropping intensities along the Canal Commands from head to tail ends or respective jurisdictions. Contrast to Dantiwada, Uben Scheme of Saurashtra has lesser cropping intensity during the same duration 5 Aug 2024 to 5 August 2025. Figure 19 is the Uben Command area, its Canal network in mid reach of the Command.

7.7 Repair, Renovation and Restoration (RRR) Schemes : performance of 32 RRR Schemes

A total of 32 irrigation schemes across the Saurashtra region were selected for performance analysis under the Repair, Renovation, and Restoration (RRR) project. The study focused on evaluating the variation in vegetation cover within the respective command areas over a five-year period from 2018 to 2023, using satellite-based vegetation indices and geospatial analytics.

One illustrative example is the Raidy Irrigation Scheme, located in the Amreli district of Gujarat (refer to Figure 20). This scheme provides assured irrigation to nine villages—namely Nana Barman, Mota Barman, Chotra, Nageshri, Mithapur, Khalsa Kanthariya, Dudhala, and Jikadri—covering a command area of approximately 1,500 hectares.

Following the implementation of renovation and strengthening interventions, the Raidy Scheme recorded notable improvements in vegetation health and density, reflecting enhanced water availability and agricultural productivity observed over the past seven years, underscore the socio-economic impact and ecological benefits of targeted RRR investments in canal infrastructure and water conveyance systems.

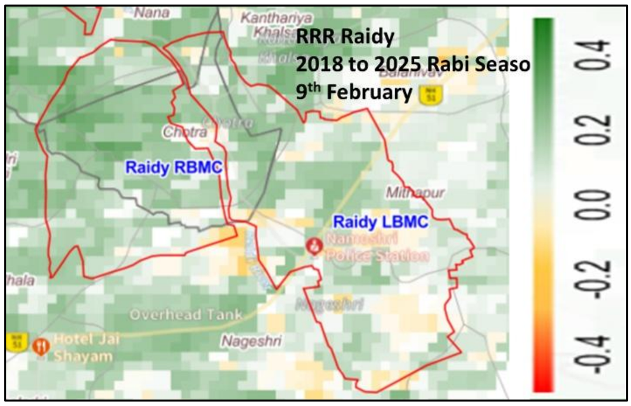

Figure 20 RRR Raidy Scheme : Change of vegetation status during 7 years Rabi Season

8. Conceptual Canal Operations Dashboard for MRBC Command :

Building upon the data sets a conceptual dashboard was developed for the Mahi Right Bank Canal (MRBC) Project (Figure 21). This initiative marks a strategic advancement toward real-time monitoring and decision support for canal operations.

The envisioned dashboard aims to serve as a digital twin of the MRBC system—integrating spatial data with operational logistics to simulate, monitor, and optimize water delivery across the command area. However, the creation of a true digital twin demands a comprehensive digitization of operational workflows. This conceptual framework sets the stage for data-driven canal management, enabling stakeholders to visualize system performance, anticipate bottlenecks, and enhance water use efficiency across the MRBC command.

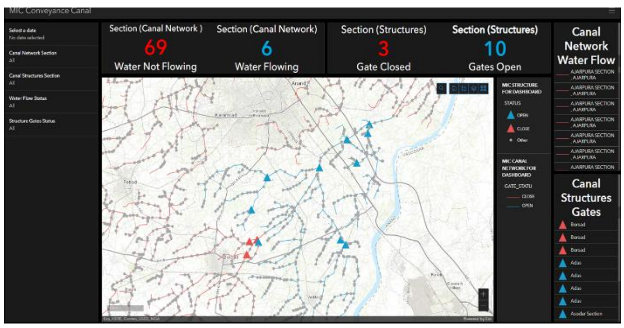

Figure 21 Conceptual Dashboard for Canal Operations MRBC Command

9. Water Conservation Master Plan (Short term Water Security) for Irrigation :

Water Conservation Master Plans were prepared for all the districts of Gujarat for the Jalshakti Abhiyan – a Central Govt initiative, a portion is shown in Figure 22.

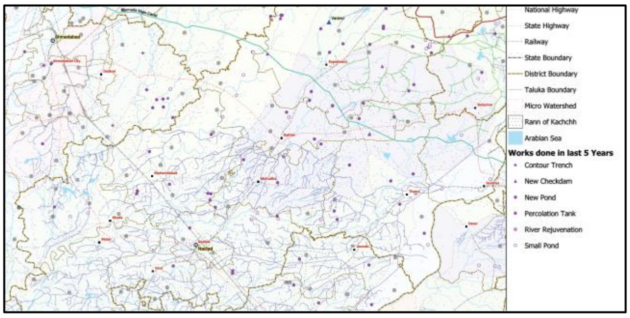

Figure 22 The Water Conservation Master Plans covering all districts of the Gujarat State

10. Irrigation Infrastructure and Disaster Management:

The Flood Prone Area Maps for all the basins of Gujarat are hosted online as .pdf format proved useful to local administration during emergencies.

The Basin Maps showing Flood prone area derived from historic flood data for entire Gujarat at village level was made available online to field officers. (Figure 23) These maps contain information about reservoirs, rivers, administrative boundaries, road networks, flood-prone areas, and basin boundaries, hydromet stations of both state and central government. Authorised access provided for 36 River Basin Maps and 6 interstate Basin online Maps.

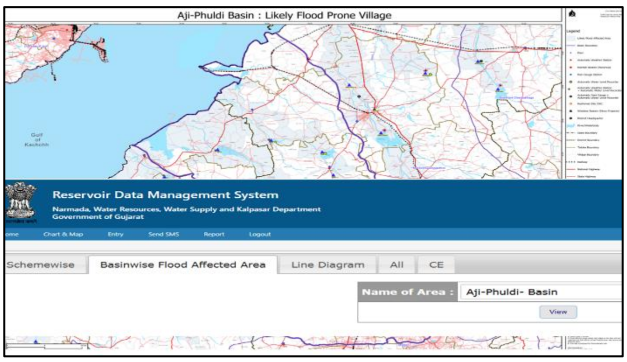

Figure 23 Flood Prone Area maps

Further, the maps of low lying areas are kept handy derived from high resolution Digital Elevation Models and super imposed with human settlement areas, satellite imagery, reservoirs. Such maps were used proved useful during the cyclone events Tauktae and Biparjoay Cyclones. (Figure 24).

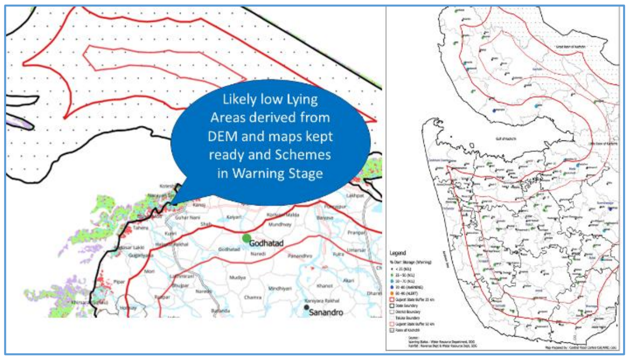

Figure 24 Quick Maps showing Low Lying Areas and Irrigation Infrastructure and settlement boundaries

11. Data Sharing and Stakeholder Engagement

A cornerstone of Gujarat's digital twin initiative was its robust approach to data integration and stakeholder empowerment. Through API-based interoperability, geospatial datasets were seamlessly disseminated to key national platforms. WRIS of NWIC, MoWR, VEDAS portal of SAC-ISRO and PM Gati Shakti of MeitY. The Web Map Service (WMS) supported dynamic visualization and decision support for infrastructure planning, reservoir storage monitoring, and permissions for crossings of Govt water conveyance infrastructure

12. Irrigation Master Plan and Future Roadmap

The digital twin initiative laid the foundation for a comprehensive Irrigation Master Plan. WRD is now leveraging 10 m CartoDEM, high-resolution satellite imagery and UAV surveys to support watershed delineation, planning of new irrigation infrastructure and modernization of existing infrastructure. The roadmap includes integration of various static and dynamic data sets, design and development of WEB GIS dashboard. The department also aims to link this system with crop advisory services and weather forecasting models for holistic irrigation water management.

13. Conclusion

The in-house digital transformation of Gujarat's Irrigation Water Conveyance System represents a paradigm shift in the management of large-scale water infrastructure. By integrating a digital twin framework with satellite-based vegetation monitoring and comprehensive capacity-building initiatives, the system has achieved remarkable improvements in planning precision, resource optimization, and stakeholder engagement. As the initiative continues to evolve, it stands poised to serve as a replicable model for leveraging geospatial technologies to enhance public infrastructure operations across diverse sectors and regions.

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