



A remote sensing approach to explore the available water spread for fisheries development in the reservoirs of Godavari River Basin, Telangana, India

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ABSTRACT

Reservoirs have tremendous fisheries potential amongst the inland water resources and aptly referred as 'sleeping giants', as the fish yield potential of these resources are yet to be tapped. Existing gaps in the availability of absolute information and data on the inland water resources hinder the applicability and implementation of various fisheries development programmes, which in turn impact inland fisheries production. The present study was carried out in the reservoirs viz., Sri Ram Sagar, Kaddam and Swarna from the Godavari Basin, covering the period 2016-2021, as a case study to demonstrate the use of remote sensed data in fisheries stock enhancement planning. The perennial and seasonal water spread area of the reservoirs under study, estimated through composite water maps prepared using Sentinel 2A data ranged between 8 to 19 and 4 to 29%, respectively. Further, the potential area for enclosure fish culture (both cage and pen culture) in these reservoirs were found to range between 14.89% (Sir Ram Sagar) to 48.54% (Kaddam). The field validated results revealed less than 0.1% of the perennial water spread area mapped in these reservoirs is under use for cage culture. This highlights under-utilisation of these reservoirs and demonstrates scope for developing enclosure fish culture or other culture-based fisheries for enhancing the fish production. The study also demonstrates the use of geospatial tools in development planning for expanding enclosure fish culture in the reservoirs and in turn enhancing fisheries production from the reservoirs in India.

Keywords: Composite water maps, Enclosure fish culture, Geospatial tools, Godavari River, NDWI, Reservoir, Sentinel 2A data, Water spread area

Introduction

Inland fishery resources are represented by rivers, canals, lakes, reservoirs, ponds and tanks, which provide various ecosystem services to humankind including food, water and livelihood. Reservoirs are man-made waterbodies created by impounding river water for multiple purposes including irrigation, energy generation, flood control and industrial water needs (Jhingran, 1988). These resources in India cover an area of 4.03 million ha (MHa) represented by 14,519 water bodies which are classified as small (<1000 ha), medium (1000 to 5000 ha) and large (>5000 ha) based on size (Srivastava, 1985; DoF, 2020). The small reservoirs (13,690 nos.) account for 44.07% of total reservoir area (1.77 MHa) while, medium and large reservoirs (829 nos.) contribute 55.92% (2.25 MHa) (DoF, 2020). Having been referred as 'sleeping giants', the reservoirs have tremendous fisheries potential both in culture and capture fish production amongst the inland water resources. However, due to the inadequate

knowledge on its ecology and productivity, the fish yield potential of these resources remain untapped and at present, the reservoirs are mostly contributing to the inland capture fisheries (Jhingran and Natarajan, 1978; Jhingran, 1988; Ramakrishnaiah and Das, 1998).

India contributed 9.7 million t to the world's inland fish production of which 1.7 million t is from capture fisheries and the remaining from culture fisheries systems (FAO, 2020). The culture fisheries production of reservoirs, wetlands and lakes are very meagre and most of the inland fish production mainly comes from carp-based pond culture systems. Culture fisheries in the reservoirs is emphasised by the Govt. of India as the said fishery will enhance the utilisation potential of these resources along with reducing the pressure on the land-based farms (NFDB, 2016). The studies carried out in the tropical Indian reservoirs showed that small, medium and large reservoirs have the production potential of 49.9, 12.3 and 11.4 kg ha⁻¹ yr⁻¹ respectively, against

500, 250 and 100 kg ha⁻¹ yr⁻¹ (Sarkar *et al.*, 2018; DoF, 2020). The major form of culture fisheries carried out in Indian reservoirs are cage and pen based, referred as enclosure culture (NFDB, 2016). Blue Revolution scheme of Govt. of India emphasised on exploring the unexploited potential of the Indian reservoirs through cage culture and about 13,982 cages/pens were installed during the years 2015-2020 (DoF, 2020). In the current scenario, the cages are installed based on the traditional knowledge on the water dynamics and variations of the water spread area of the reservoirs. The state of Telangana is relying on the spatial data of the Indian Space Research Organisation-National Remote Sensing Centre (ISRO-NRSC) to understand the annual water dynamics for the fingerling stocking in reservoirs since the development of Telangana State-specific Water Resources Information System *i.e.*, from 2017 (<https://bhuvan.nrsc.gov.in>; <https://fisheries.telangana.gov.in>). However, implicating spatial data for cage installations and culture practices may enhance the potential utilisation of the water resources. Cage culture is mostly practiced in the medium and large reservoirs of Telangana wherein 1,116 cages were sanctioned under Blue Revolution scheme (DoF, 2020).

Management of the dams and reservoirs in the developing countries is a challenging task due to the nature of services offered by them to various stakeholders, lack of proper documentation and consistent monitoring as the records of these resources have the least access for planning and research (Peng *et al.*, 2006; Gao *et al.*, 2012; Quang *et al.*, 2021). Remote sensing and Geographic Information System (GIS) are used for the assessment of the water resources by providing spatial and temporal data which are utilised in marking the dynamics of inland water bodies (Kapetsky, 1987; Avisse *et al.*, 2017; Ingole *et al.*, 2018; Sreekanth *et al.*, 2021) and fisheries management (Eder and Neely, 2013). Recently, Anand *et al.* (2019a and b) demonstrated the utility of geo-spatial tools in assessing the fishery potential of lentic waters based on spatio-temporal water spread.

The present study was piloted to explore the trends in potential water spread available for culture fisheries development in three different reservoirs *viz.*, Sri Ram Sagar, Kaddam and Swarna located in the Godavari River Basin in Telangana State, India. The specific objectives of the present study are to (i) assess the spatio-temporal water spread dynamics of different categories of reservoirs in Godavari Basin; (ii) estimate the potential area for the enclosure fish culture activities such as cage and pen and (iii) validate the mapping framework envisaged through field verification. The validated framework demonstrated in the present study helps to boost the ongoing Blue Revolution Mission in India by enabling the policymakers and fisheries managers in efficient planning and

implementation of culture fisheries in reservoirs through the provision of robust geo-spatial data.

Materials and methods

Study area and period

Telangana State lies between 15°55'N to 19°55'N and 77°10'E to 81°50'E in peninsular India. Two rivers *viz.*, Godavari and Krishna drain in the state with a total of 82 reservoirs covering 0.21 MHa area (DoF, 2020). The Godavari Basin receives an average annual rainfall of 1097 mm which ranges from 755 to 1531 mm. The average annual minimum and maximum temperatures recorded in the basin were 20.53 and 32.85°C, respectively (MoWR, 2014). In the present study, three reservoirs *viz.*, Sri Ram Sagar (large), Kaddam (medium) and Swarna (medium) were selected from the Godavari Basin (Fig. 1), located in South Deccan Plateau region of Telangana (<http://www.bhoomigeoportal-nbsslup.in>). These reservoirs are fed by independent rivers *viz.*, Godavari, Kaddam and Swarna as detailed in Table 1. The boundaries of the reservoirs under study were delineated through manual digitisation using the study area colour composite generated through Sentinel-2 image of the post-monsoon season *i.e.*, 14 November 2020.

The spatio-temporal water spread dynamics of the selected reservoirs were assessed during the period 2016-21. In the present study, the maximum and least available water spread of a particular year was spatially assessed by considering the post-monsoon and pre-monsoon season, respectively (Anand *et al.*, 2019a). The datasets of the post-monsoon months (Oct-Dec) and pre-monsoon months (Jan-May) of reservoirs for the study period were obtained and processed to arrive at estimations on the available water spread areas during 8 and 11 months period, respectively. Based on the annual composite maps (2016-2021), February was considered for 8 months culture and May was considered for 11 months culture.

Data acquisition

The Multi-Spectral Instrument of Sentinel provides high spatial resolution satellite data, *i.e.*, Sentinel 2A MSI level 1C which are ortho-corrected imageries with Top of Atmosphere (ToA) reflectance (ESA, 2015; Avisse *et al.*, 2017), which were accessed and downloaded from the Copernicus Open Access Hub of the European Space Agency (<https://scihub.copernicus.eu/dhus/#/home>). The spatial resolution of the 4 bands considered in the present study *i.e.*, Red, Green, Blue and NIR (Near Infra-Red) is 10 m. Resourcesat-2 Liss-III images were acquired from the Bhuvan (<https://bhuvan.nrsc.gov.in>), Indian Geo-platform of ISRO, for the year 2016 due to the non-availability Sentinel 2A data for the section of study

Table 1. Details of the selected reservoirs from Godavari Basin for the study (source: CWC, 2016)

| Particulars | Sri Ram Sagar | Kaddam | Swarna |
|--------------------------------|--|--------------------------------|--------------------------------|
| Location | Nizamabad (18°58'8"N; 78°20'19"E) | Nirmal (19°6'33"N; 78°47'24"E) | Nirmal (19°14'9"N; 78°12'15"E) |
| River | Godavari | Kaddam | Swarna |
| Year of completion | 1977 | 1958 | 1978 |
| Length of dam (m) | 15600 | 2290 | 3204 |
| Height of dam (m) | 43 | 31 | 24 |
| Full Reservoir Level (FRL) (m) | 332.54 | 213.30 | 360.58 |
| Water spread area at FRL (ha) | 45082 | 2625 | 1035 |
| Type of reservoir | Large (>5000 ha) | Medium (1000-5000 ha) | Medium |
| Purpose | Irrigation, Hydroelectric and Navigation | Irrigation | Irrigation |

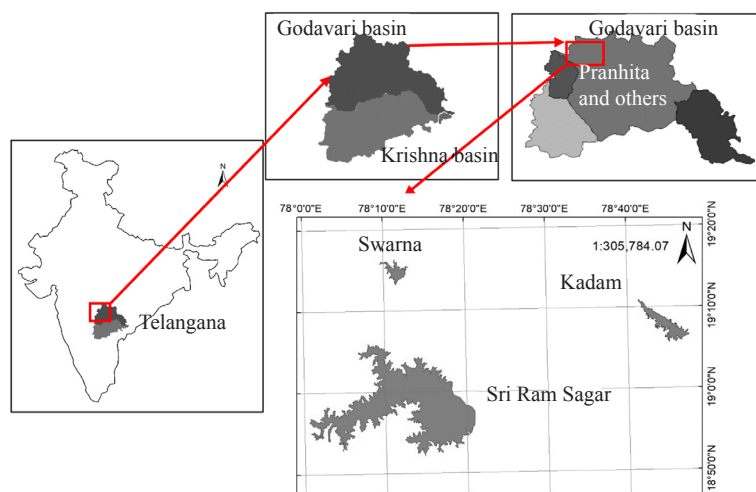


Fig. 1. Selected reservoirs in the Godavari River Basin of Telangana State, India

area. A total of 24 cloud-free images were obtained, visualised and processed for the three reservoirs using ERDAS IMAGINE-2015 and ArcGIS-10.8 software. The details of the satellite imagery used in the present study are given in Table 2.

Image processing and water body extraction

The water pixels of the study area were extracted using the water map generated by applying Normalised Difference Water Index (NDWI). This index is widely used for the delineation of the surface water bodies employing Sentinel imagery in diverse aquatic ecosystems (McFeeters 1996; Ouma and Tateishi, 2006; Lu *et al.*,

2017; Deng *et al.*, 2020; Phankamolsil and Kositsakulchai 2020) including reservoirs Anand *et al.* (2019a; b). This index uses NIR and green bands, as it is strongly absorbed by the water (McFeeters, 1996). The NDWI is generated using the Eq. 1:

$$NDWI = \frac{(Green-NIR)}{(Green+NIR)} \dots\dots\dots Eq. 1$$

where Green and NIR are the digital number (DN) values of the respective bands of the imagery. The NDWI values range from -1 to +1, water features have positive values while terrestrial features exhibit negative values (McFeeters, 1996).

Table 2. Details of the spatial datasets pertaining to the reservoirs acquired for pre- and post- monsoon seasons during 2016-2021

| Satellite | Product type | Date of acquisition | |
|--|--------------|--|--|
| | | Pre-monsoon season | Post-monsoon season |
| Sri Ram Sagar and Swarna Reservoirs | | | |
| Sentinel 2A | MSIL1C | 22-05-2016, 7-5-2017, 12-5-2018, 17-5-2019, 21-5-2020, 26-5-2021 | 16-02-2017, 21-2-2018, 16-2-2019, 21-2-2020, 25-2-2021 |
| Resourcesat-2 | L3 | - | 11-02-2016 |
| Kaddam Reservoir | | | |
| Sentinel 2A | MSIL1C | 09-05-2016, 14-05-2017, 29-05-2018, 24-05-2019, 28-05-2020, 13-05-2021 | 09-02-2016, 03-02-2017, 28-02-2018, 13-02-2019, 18-02-2020, 22-02-2021 |

The NDWI image was geo-linked with the respective false colour composite image in the adjacent views and the water pixel values were inquired and identified to ascertain the absolute identification of the water spread area. The threshold values for the water pixels were fixed for each NDWI image and features were reclassified into water and non-water pixels by performing conditional analysis by the toolmaker in ERDAS IMAGINE. The reclassified NDWI raster images were processed and converted to the vector polygon shape files. These polygon files were clipped with the delineated reservoir boundary shape file in the GIS platform.

Assessment of seasonal water spread dynamics

The seasonal water spread area dynamics of Sri Ram Sagar, Kaddam and Swarna reservoirs were assessed for the pre-monsoon and post-monsoon seasons for the study period (2016-2021) based on the reclassified NDWI maps by utilising the frequency tools of the ArcGIS.

The season-wise composite map of the reservoirs were prepared to understand the dynamics of spatio-temporal water presence (Sun *et al.*, 2012; Borro *et al.*, 2014; Das and Pal, 2017; Mondal and Pal, 2018; Pal and Talukdar, 2018; Anand *et al.*, 2019a, b) using the Water Presence Frequency method (Borro *et al.*, 2014) as given below (Eq. 2):

$$WPF_j = \frac{\sum_{i=1}^n I_j}{n} \times 100 \dots\dots\dots \text{Eq. 2}$$

where WPF_j = Water Presence Frequency of j^{th} pixels in a time period; I_j = j^{th} pixel having water in the selected NDWI images; n =Number of images.

The WPF value of pixels range from 0 to 100% which indicates 'no water presence' to 'consistent water presence' throughout the study period. The reservoirs were demarcated into 7 classes based on the WPF value (%) of the composite map: No-water (0), very low (>0 - <16.6), low (>16.6 - <33.3), medium (>33.3 - <50), high (>50 - <66.6) and very high (>66.6 - <83.3) and perennial area (100). The classification of water body based on its water presence assist in monitoring the trend in water spread area of the reservoirs.

Estimation of potential water spread area (WSA) available for enclosure fish culture

Perennial water spread area (11 months)

The perennial water spread of the reservoirs, where the water is available all through the year was obtained from the pre-monsoon WPF composite map, *i.e.*, pixels with 100% water frequency during 2016 to 2021. This analysis of the pre-monsoon period WSA provides the

extent of water available in May *i.e.*, for at least 11 months (including the monsoon, post and pre-monsoon months) (Anand *et al.*, 2019b). The spatial information on perennial WSA is a vital necessity in planning and implementing enclosure fish culture practices in the reservoirs (Anand *et al.*, 2019a; Sugunan, 2019).

Seasonal water spread area (8 months)

The seasonal WSA of the selected reservoirs were obtained from the post-monsoon WPF composite maps, *i.e.*, pixels with 100% water frequency indicating the consistent water presence up to February *i.e.*, a duration of at least 8 months period available for enclosure fish culture in the reservoirs was estimated.

Estimation of the cage culture potential area

This study aimed at estimation of the potential WSA available for the cage culture practice with a detailed outlook on the perennial and seasonal water spread in Sri Ram Sagar, Kaddam and Swarna reservoirs. The maximum possible number of batteries of cages that can be installed in the available water spread area for cage culture in a reservoir is estimated as shown in Eq. (3):

$$\text{No. of batteries that can be installed} = \frac{\text{Potential water spread area available in the reservoirs for cage culture}}{\text{Area of 6 cages } i.e., \text{ a standard unit}} \dots\dots \text{Eq. 2}$$

Validation

The large and medium reservoirs selected in the present study *viz.*, Sri Ram Sagar and Kaddam already have cages installed by the Department of Fisheries, Govt. of Telangana. The potential cage culture area mapped through the demonstrated framework were validated with the available scenes of these reservoirs with the cages installed from Google Earth platform (accessed on 07 October 2021). The boundaries of those cages were delineated and overlaid on the seasonal composite map prepared in the present study to validate the mapping results of this approach.

Results and discussion

Temporal water spread dynamics of the selected reservoirs (2016-2021)

The seasonal water spread area (WSA) of three selected reservoirs during the study period (2016-21) were higher during the post-monsoon season while low value was observed during the pre-monsoon season. The reservoirs were expected to spread to the maximum water extent during the monsoon season and accordingly the post-monsoon water spread area of the reservoirs will be high which facilitates the recruitment of the fish in the reservoir (Patrick, 2016). Further, the WSA gets decreased

in a phased manner as per the utility of the water in the reservoir. The reservoirs under the study are meant for irrigational purpose and Sri Ram Sagar Reservoir is a multi-purpose project that offers both irrigational and hydro-electricity services (MoWR, 2014). The mean WSA of Sri Ram Sagar was reported to be 7585 ha (<25%) in pre-monsoon and 16075 ha (<50%) in the post-monsoon season for the study period *i.e.*, 2016-2021. The Kaddam and Swarna are irrigation projects and water from these reservoirs is mostly drawn out for irrigation of the command area. The culturable command area (CCA) of the reservoirs ranged from 0.02 million ha for Kaddam to 0.58 million ha for Sri Ram Sagar (CWC, 2016) and the reservoirs recorded >45% of average WSA in the post-monsoon during the study period (Table 3). The variations in the average WSA of the selected reservoirs indicated their multiple utilities, which determined the available WSA of the reservoir during different seasons.

Year-wise seasonal analysis revealed that, the highest WSA (16951 ha) in Sri Ram Sagar Reservoir was in the pre-monsoon season in 2020, followed by 6464 ha in 2017 and 5969 ha in 2019. The seasonal variations in the spatial water spread dynamics of the three reservoirs are depicted in Fig. 2a, b, c. The receding water spread area was observed from 2016 to 2017 and an increase in the WSA of the reservoirs was recorded from 2018 to 2020 in the pre-monsoon season. The same was evident from the studies conducted in parts of the Godavari River Basin also (Anand *et al.*, 2019a). The Kaddam and Swarna reservoirs recorded >30% available water spread area in the pre-monsoon season (2016-20) which is comparatively higher than the value recorded in Sri Ram Sagar Reservoir (22.53%). This may be attributed to the purpose of the use of reservoir, elevation and culturable command area (CWC, 2014). Hence, it can be inferred that the intensive water utility must be a valid reason for the less water spread in Sri Ram Sagar (multi-purpose) during the pre-monsoon season. Further, the elevation of Sri Ram Sagar and Swarna reservoirs are reported to be greater than the Kaddam Reservoir which is one of the reasons for wide variations in the seasonal water spread, as the Godavari basin slopes towards the east and gravity has a

Table 3. Seasonal water spread areas in three selected reservoirs in Godavari Basin during 2016-2021

| Reservoir | Season | Water spread area (ha) | | |
|---------------|--------------|------------------------|---------|---------|
| | | Mean | SD | SEM |
| Sri Ram Sagar | Pre-monsoon | 7585.25 | 4846.28 | 2423.14 |
| | Post-monsoon | 16075.57 | 7558.97 | 3779.48 |
| Kaddam | Pre-monsoon | 815.36 | 79.35 | 39.67 |
| | Post-monsoon | 1271.59 | 327.53 | 163.77 |
| Swarna | Pre-monsoon | 346.09 | 126.73 | 63.37 |
| | Post-monsoon | 644.25 | 217.47 | 108.73 |

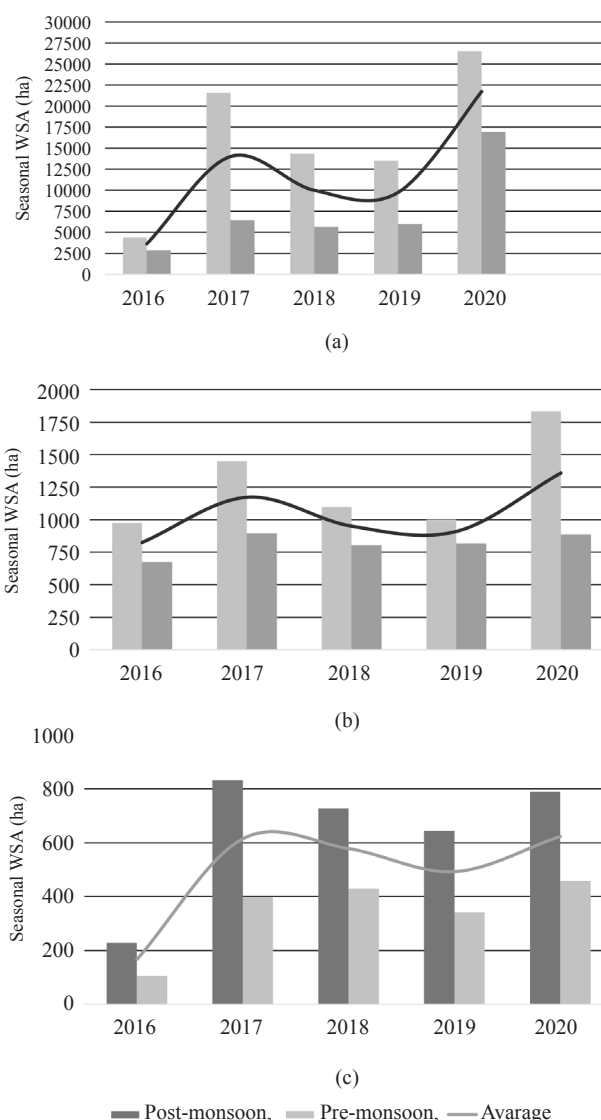


Fig. 2. Temporal change in water spread area of (a) Sri Ram Sagar; (b) Kaddam and (c) Swarna Reservoir during pre- and post-monsoon seasons of the study period 2016-2020

major role on the reservoir storage capacity (CWC, 2014). Knowledge on the suitability and availability of the water spread area for fish culture in the reservoirs gives a wide scope for effective planning for using the water resources for fish production, particularly to enclosure fish culture using cages and pens.

Spatio-temporal variations in the water spread frequency (2016-2021)

Pre-monsoon season (2016-21)

Monitoring of surface water dynamics of the reservoirs through remote sensing is very effective as it monitors the earth surface on regular intervals (Shrestha *et al.*, 2016; Huang *et al.*, 2018; Kulmatov *et al.*, 2021; Taloor *et al.*,

2021) which in turn helps in planning the culture-based fisheries (Wijenayake *et al.*, 2014; Anand *et al.*, 2019a). The no-water zone is the 0% Water Presence Frequency (WPF) and the study revealed that it contributes >50% of the total WSA of the selected reservoirs during the pre-monsoon season (Fig. 3). A contemporary study by Anand *et al.* (2019a) in Nizam Sagar and Pocharam reservoirs in Godavari Basin reported the extent of no-water zones up to 40% and attributed to the variations in the dynamics, water geographical setting, inflow and purpose of the reservoirs (CWC, 2014).

The perennial water spread reported in Sri Ram Sagar, Kaddam and Swarna reservoirs during the pre-monsoon season was 3604, 433 and 91 ha, respectively (Table 4). The variations of the water spread areas with 50% WPF from the post-monsoon to pre-monsoon period for Sri Ram Sagar and Kaddam reservoirs were >15%. However, the observed variations in the study period with 100% WPF from the post-monsoon to pre-monsoon season of the Kaddam and Swarna reservoirs were recorded as 26 and 14%, respectively and this might be due to the

irrigational uses. It was only 2.8% in case of Sri Ram Sagar Reservoir and the less variation in the perennial area may be attributed to the depth of this reservoir (Borro *et al.*, 2014).

Post-monsoon season (2016-21)

The present study observed >75% of reservoir area with varying degrees of water occurrence frequency in all three reservoirs during the post-monsoon season. This may be attributed to the seasonal rainfall and the consequent river inflow (Suleiman and Ifabiyi, 2015; Das and Pal, 2017; Mondal and Pal, 2018; Anand *et al.*, 2019a). Further, the high percent contribution of perennial area *i.e.*, pixels with 100% WPF to total water spread was reported in Kaddam (44.98%; 1031 ha) followed by Swarna (23.65%; 2478 ha) and Sri Ram Sagar (13.53%; 4554 ha) (Fig. 3). This available water spread area with very high WPF in the reservoir is the potential area for the long-term fish culture practices including cage and pen culture. Understanding the

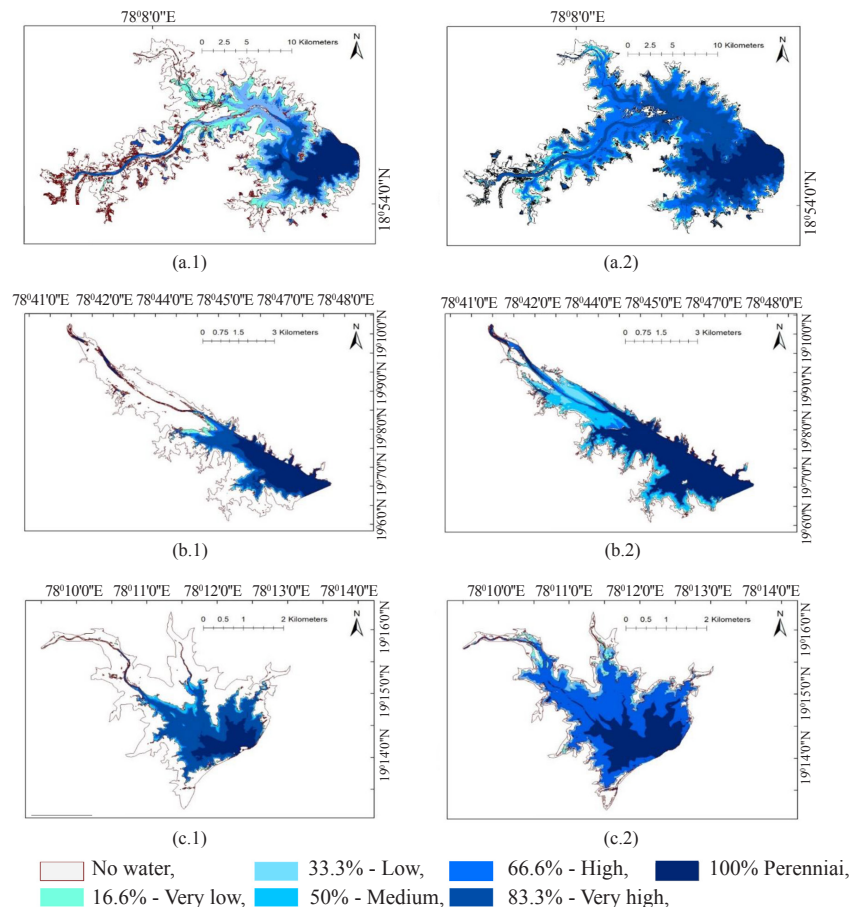


Fig. 3. Map showing the water presence frequency classes during pre-monsoon: (a.1) Sri Ram Sagar; (b.1) Kaddam; (c.1) Swarna and post-monsoon season: (a.2) Sri Ram Sagar; (b.2) Kaddam and (c.2) Swarna Reservoir

Table 4. Seasonal WSA of the three selected reservoirs in different WPF zones during 2016-2021

| Reservoir area (ha) | Season | Area (ha) under different water presence frequency zones | | | | | | | | | | | Total | | | | |
|--------------------------|--------------|--|-------|--------------|-------|----------------|------|-----------------|------|------------|------|---------------|-------|-------------|-------|----------|-------|
| | | No water zone (0.00) | | 0.1 - < 16.6 | | >16.6 - <33.33 | | >33.33 - <50.00 | | >50- <66.6 | | >66.6 - <83.3 | | >83.3 - 100 | | | |
| | | Area | % | Area | % | Area | % | Area | % | Area | % | Area | % | Area | % | Area | % |
| Sri Ram Sagar (33662.14) | Pre-monsoon | 17677.8 | 52.52 | 3976.8 | 11.81 | 4233.94 | 12.6 | 1196.68 | 3.55 | 534.941 | 1.59 | 2438.18 | 7.24 | 3603.8 | 10.71 | 15984.34 | 47.48 |
| | Post-monsoon | 7619.75 | 22.64 | 1820.21 | 5.407 | 1608.91 | 4.78 | 8177.85 | 24.3 | 1187.04 | 3.53 | 8694.21 | 25.8 | 4554.16 | 13.53 | 26042.38 | 77.36 |
| Kaddam (2292.02) | Pre-monsoon | 1406.49 | 61.36 | 54.70 | 2.387 | 26.71 | 1.17 | 33.32 | 1.45 | 78.94 | 3.44 | 259.20 | 11.3 | 432.65 | 18.88 | 885.5257 | 38.64 |
| | Post-monsoon | 442.54 | 19.31 | 67.84 | 2.96 | 168.39 | 7.35 | 395.06 | 17.2 | 130.62 | 5.7 | 56.50 | 2.47 | 1031.06 | 44.98 | 1849.476 | 80.69 |
| Swarna (1048.16) | Pre-monsoon | 619.27 | 59.08 | 16.13 | 1.54 | 7.91 | 0.75 | 44.21 | 4.22 | 28.92 | 2.76 | 240.32 | 22.93 | 91.41 | 8.72 | 428.8892 | 40.92 |
| | Post-monsoon | 237.62 | 22.67 | 46.08 | 4.40 | 68.98 | 6.58 | 14.31 | 1.36 | 10.53 | 1.01 | 422.79 | 40.34 | 247.86 | 23.65 | 810.5413 | 77.33 |

annual rainfall, water storage capacity and utility of the reservoirs and assessing the water occurrence frequency is essential for planning aquaculture activities (Abileah *et al.*, 2011; Kumar, 2013; Dauwalter *et al.*, 2017; Anand *et al.*, 2019a; b). Integration of the information acquired through remote sensing with ground-truthing and field studies may help in developing models for the given ecosystem and such models may be used for planning of the current and future utilisation of the resources (Gao *et al.*, 2015). The proportion of 'no-water' zone in the selected reservoirs during the post-monsoon season was recorded to be <25% of the total area.

Potential area for enclosure fish culture

Enclosure fish culture, cage culture in particular, is mostly allowed in reservoirs with water surface areas greater than 1,000 ha (medium and large) and average depths of 8-10 m (Sugunan, 2019; NFDB, 2020). The present study estimated that 48.54% of the total WSA in Kaddam has the potential for enclosure fish culture (both cage and pen culture), followed by 24.92% (261 ha) in Swarna and 14.89% (5013 ha) in Sri Ram Sagar Reservoir (Table 5 and 6).

As per the guidelines framed by the Govt. of India on a time-to-time basis, the policymakers and implementing agencies of all the states will frame, amend and update their policies in accordance with the scientific and traditional knowledge about the water resources so as to utilise the potential areas in an optimal and sustainable manner.

In the context of the present study, it is to state that the Govt. of India has categorically indicated 7 classes of reservoirs with carrying capacities based on the WSA for installing cages. The reservoirs selected under the present study fall in the range of 1001-2000 ha (Swarna) with 500 cages, 2001-3000 ha (Kaddam) with 1000 cages and >10000 ha (Sri Ram Sagar) with 5000 cages (NFDB, 2016). Further, the Integrated Development programme for the large (>5000 ha), medium (1000-5000 ha) and small (<1000 ha) reservoirs under Blue Revolution scheme

Table 5. Estimated perennial and seasonal WSA in the three selected reservoirs in Godavari Basin based on WPF during 2016-2021

| Reservoir area (ha) | Category | WSA (ha) | |
|--------------------------|-----------|----------|--------------|
| | | Area | % Total area |
| Sri Ram Sagar (33662.14) | Perennial | 3609.78 | 10.72 |
| | Seasonal | 1403.27 | 4.17 |
| Kaddam (2292.02) | Perennial | 443.94 | 19.37 |
| | Seasonal | 668.71 | 29.18 |
| Swarna (1048.16) | Perennial | 93.43 | 8.91 |
| | Seasonal | 167.79 | 16.01 |

Table 6. Estimated potential area for enclosure fish culture in the selected reservoirs in Godavari Basin based on water presence during 2016-2021

| Reservoir area (ha) | Category of reservoir (Sugunan, 2019) | Estimated potential area for enclosure fish culture (ha) | | No. of cages possible in the potential area |
|--------------------------|---------------------------------------|--|---------------------------------------|---|
| | | Perennial availability for cage culture | Seasonal availability for pen culture | |
| Sri Ram Sagar (33662.14) | >10000 ha | 3609.78 | 1403.27 | 5000 |
| Kaddam (2292.02) | 2000-3000 ha | 443.94 | 668.71 | 1000 |
| Swarna (1048.16) | 1001-2000 ha | 93.43 | 167.79 | 500 |

was a holistic approach for the development of reservoir fisheries which includes cage culture during 2015-2019. The non-beneficiary oriented centrally sponsored scheme of the Pradhan Mantri Matsya Sampada Yojana (PMMSY) that is being implemented by the Govt. of India for the financial years from 2020-21 to 2024-25 is having an indicative scheme wherein financial assistance is proposed for the cages with floating working station in large and medium reservoirs, along with feed storage shed.

Pen culture is mostly supported towards fish seed rearing (NFDB, 2020) and fingerlings thus reared can be utilised for further stocking in the reservoirs. Mostly, the state fisheries department will carry out seed stocking in the reservoir during monsoon season wherein advanced fry is stocked in the reservoirs which may lead to less survival rates. Hence, rearing the advanced fry to fingerlings can be taken care in the seasonal WSA identified for pen culture. The 100% WPF zones ranging from 13-44% in the studied reservoirs serves as potential areas for fish seed rearing through pen culture. The knowledge on utilising the spatial data for planning and implementing the reservoir fisheries production and development-oriented schemes of the Govt. of India in collaboration with the state fisheries departments will enhance fisheries production from the inland lentic water bodies (Anand *et al.*, 2019b).

Potential area for cage culture

The perennial WSA mapped using the pre-monsoon composite map with 100% WPF is supposed to be suitable location for cage culture practices based on the availability of water for 11 months duration (Anand *et al.*, 2019b). The potential areas for cage culture was recorded as: 3610 ha for Sri Ram Sagar: 444 ha for Kaddam and 93 ha for Swarna, contributing 10.72, 19.37 and 8.91% to the total WSA of the reservoirs, respectively. The potential areas for cage culture in the studied reservoirs are in accordance to the integrity of the reservoir ecosystem *i.e.*, mostly restricted to the zones nearer to the dam structure and these installations have no interference to the interests of the licensed fishers fishing in the reservoirs. The potential area for cage culture estimated based on the frequency of water presence varies between 10-19% of the total area of the reservoirs, which provides ample scope to enhance

fisheries production through cage culture. However, the location for cage installation in the perennial areas need to be assessed with due consideration to various hydro-edaphic, biotic factors, primary productivity and sedimentation. Further, the factors like FRL, depth of the reservoir, water flow and speed during opening of gates and floods also impact the site selection for installation of cages.

The present study observed that <0.1% of the estimated area are being utilised in the Sri Ram Sagar and Kaddam reservoirs for cage culture as against their actual potential area for the same. The under-utilisation of the potential areas in the above said reservoirs may be due to lack of awareness by the local fishers on the Government schemes supporting the cage culture in reservoirs. As Govt. of India frames and issues guidelines on time to time basis, there is great need for promoting awareness programmes to the fishers for the development of reservoir fisheries through cage culture (DoF, 2020). Further, the administrative procedures involved in obtaining permissions from the state fisheries department and investment involved in cage culture practices along with the constraints in the inputs like fish seed, feeds and fuel were found to be the major reasons for the under-utilisation of the reservoir area for cage culture, as most of the fisher livelihoods are based on capture fishing practices. In the state of Telangana, the large reservoirs have open access and most of the fishers are depending on fishing through license issued by state fisheries department. Hence, capacity building on cage culture practices and supporting the infrastructure and inputs would encourage the fishers to take up cage culture in reservoirs that could influence both fish production and enhance fishers' livelihood.

Potential area for pen culture

The seasonal WSA (8 months) suitable for pen culture was recorded to be 4-29% of the total water spread. The seasonal WSA of Sri Ram Sagar (1403 ha) constitutes 4.17%, Kaddam (669 ha) 29.18% and Swarna (168 ha) about 16% (Table 5 and 6), which were estimated to be suitable for the pen culture. In the Indian scenario, the reservoirs are under state subject and entry 17 under list II of seventh schedule of Indian constitution that empowers the rights on the reservoir water resources to

the respective state administration and the fishing rights and any installations in these resources are under the control of the Department of Irrigation, Command Area Development in the state of Telangana. The utilisation of seasonal WSA would enhance the availability of quality fish seed for stocking in reservoirs and also offers good survival and yield.

Validation of mapping framework

Field visits conducted during the study period revealed that cage culture is being practised in the Kaddam (8 batteries) and Sri Ram Sagar reservoirs (5 batteries) as shown in Fig. 4a and b with 6 -10 cages in each battery with the cage dimension of 6 m x 4 m (length * breadth). The overlay of cage boundaries obtained from Google Earth on the water spread frequency map indicated that the cages are located within the presently mapped perennial WSA (Table 7; Fig. 4a, b). Through this, the present study

validated the framework developed by Anand *et al.* (2019a) for mapping the potential areas for enclosure fish culture in tropical reservoirs. Further, this study also validated the concept of locating the area suitable for permanent cages in the potential perennial waters of reservoirs under study. Presently, the cages are installed with the traditional knowledge of the water dynamics and technical support of the Irrigation Department of Telangana.

Status of cage culture in Sri Ram Sagar and Kaddam reservoirs

The Govt. of Telangana has earmarked 5% of the effective water spread area (EWSA) for research and development and 1% area for the promotion of cage culture. The Telangana State Fisheries Department has installed 72 demo cages and provided 510 cages to the fishermen cooperative societies and 160 cages to the private entrepreneurs under the Blue Revolution scheme

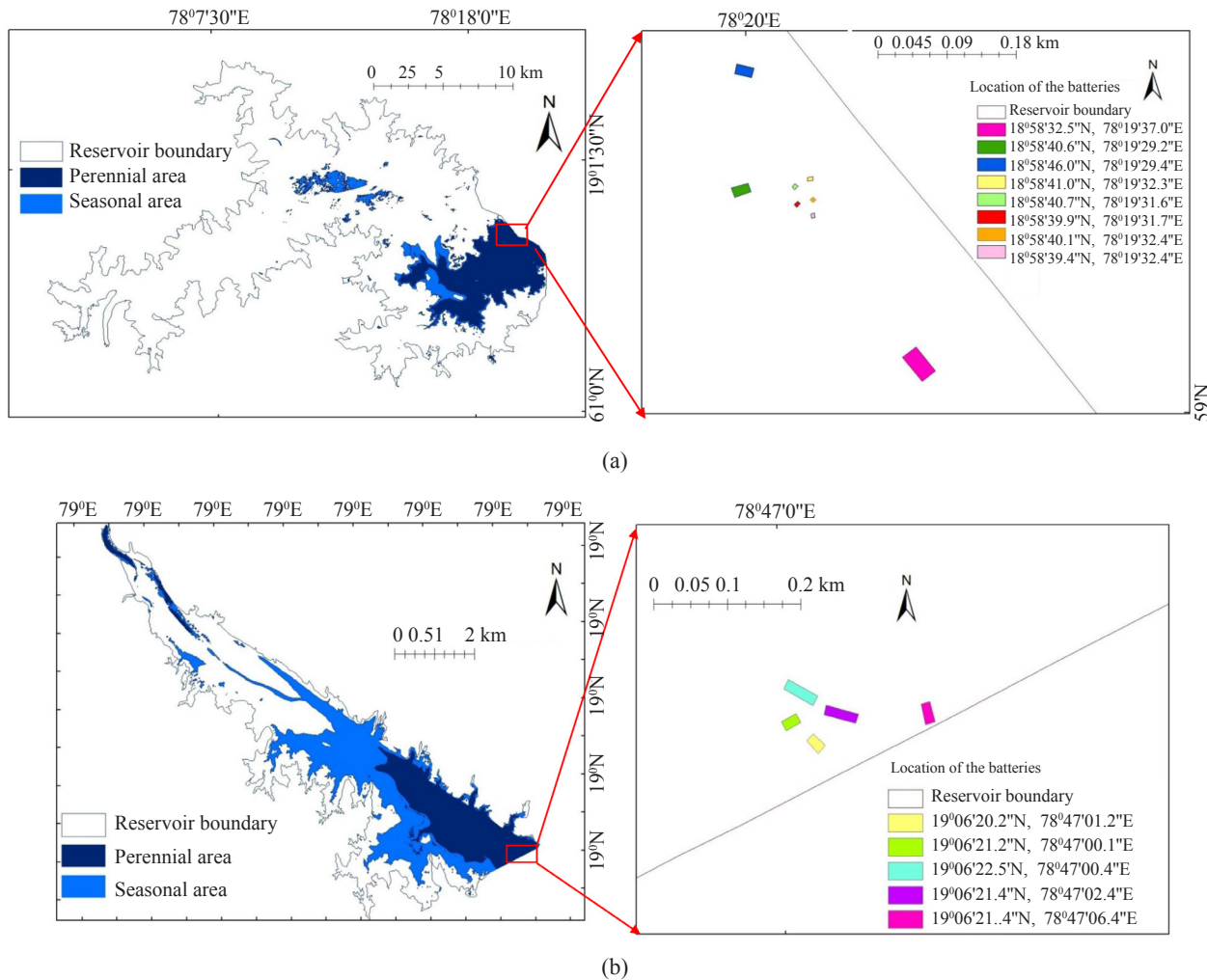


Fig. 4. Map of potential area for enclosure fish culture in (a) Sri Ram Sagar and (b) Kaddam reservoir, based on the frequency of water presence (2016-2021), depicting the installed cages in the perennial water area

Table 7. The estimated area of cages installed in Kaddam and Sri Ram Sagar reservoirs in Godavari Basin, through remote sensing

| Reservoir | Location of the cages | | No. of batteries | No. of cages | Area (ha) |
|---------------|-----------------------|---------------|------------------|--------------|-----------|
| | Latitude (N) | Longitude (E) | | | |
| Kaddam | 19°06'20.2" | 78°47'01.2" | 1 | 10 | 0.031 |
| | 19°06'21.2" | 78°47'00.1" | 1 | 10 | 0.030 |
| | 19°06'22.5" | 78°47'00.4" | 2 | 20 | 0.063 |
| | 19°06'21.4" | 78°47'02.4" | 2 | 20 | 0.059 |
| | 19°06'21.4" | 78°47'06.4" | 2 | 12 | 0.038 |
| Total | | | 8 | 72 | 0.220 |
| Sri Ram Sagar | 18°58'32.5" | 78°19'37.0" | 3 | 30 | 0.098 |
| | 18°58'40.6" | 78°19'29.2" | 1 | 10 | 0.030 |
| | 18°58'46.0" | 78°19'29.4" | 1 | 10 | 0.032 |
| | 18°58'41.0" | 78°19'32.3" | - | 1 | 0.004 |
| | 18°58'40.7" | 78°19'31.6" | - | 1 | 0.003 |
| | 18°58'39.9" | 78°19'31.7" | - | 1 | 0.004 |
| | 18°58'40.1" | 78°19'32.4" | - | 1 | 0.003 |
| | 18°58'39.4" | 78°19'32.4" | - | 1 | 0.003 |
| Total | | | 5 | 55 | 0.177 |

(<https://fisheries.telangana.gov.in>). In Kaddam Reservoir 72 cages were installed (0.22 ha) occupying only 0.049% of the total perennial area while in Sri Ram Sagar Reservoir 55 cages (0.17 ha) were installed (0.004% of the perennial WSA *i.e.*, 3609.78 ha) (Table 7).

The cages were installed at a distance of 280 to 457 m and 1.27 to 1.8 km from the dam gates of Kaddam and Sri Ram Sagar, respectively to avoid the pressure on the cages due to the flood levels, wave action and wind currents (Bandyopadhyay *et al.*, 2012). However, seasonal WSAs have not been explored for the installation of temporary cages/pens for fingerling/seed rearing. It is evident from the present study that, there is potential area for enclosure culture of fish and this area may be used for rearing of fingerlings before carrying out stocking in the reservoirs. However, the state fisheries department implements the fingerling stocking in the reservoirs as per the guidelines of the state government in consonance with the Govt. of India.

Implications for enhancing reservoir fish production

The state fisheries department was implementing the stocking programme in the reservoirs with the traditional knowledge on the water dynamics of the resources wherein they adopted a method of calculating the fingerlings stocking based on the effective water spread area which is normally taken as 1/4th of the total WSA. Further, the Full Supply Level (FSL) and Dead Storage Level (DSL) were also being used to arrive on the average WSA for implementing various reservoir fisheries development plans by the state fisheries department during 2008-2014. Since 2017, stocking programme was carried out in consonance to water dynamics data from the

ISRO-NRSC. However, the lack of information on the actual perennial WSA available and the spatio-temporal variations of the WSA are affecting the planning and implementation of the various reservoir fisheries development schemes to enhance production (Anand *et al.*, 2019a). In parallel to the stocking of fingerlings, cage culture serves as an opportunity to sustainably utilise the resources to the optimum level (Karnatak and Kumar, 2014).

Fingerling stocking is the reservoir fisheries development scheme that is being implemented by the state and central governments in India for enhancing fisheries production (NFDB, 2017). However, quality fish seed in the fingerling stage, *i.e.*, 80-100 mm is a constraint being faced by the state fisheries departments/agencies that stock the fish seed in the reservoirs (Vass *et al.*, 2009; Anand *et al.*, 2019a; Kiran *et al.*, 2015; 2020). Erecting pens in suitable areas of reservoirs for fish seed rearing may serve as an effective economical alternative to the land-based nursery rearing of the fry to fingerling stage for stocking in the reservoirs and these pens may not impact the other utilities of the reservoirs (Murugesan *et al.*, 2005). As per the Govt. of India guidelines, unit cost of the fingerling is ₹3 for the beneficiary oriented centrally sponsored scheme on "Stocking of Fingerlings in Reservoir". In this scheme, the Govt. of India provides financial assistance against the unit cost of each fingerling (PMMSY, 2020). However, the unit cost fixed by the government is not in accordance with the market rate of the fingerling as it ranges with the weight of the fingerling. Hence, mostly the stocking agencies compromise with fry/early fingerling of 15-40 mm size for stocking in reservoirs due to which survival

rate of these fingerlings is affected. Installing pens in the seasonal waters for nursery rearing of these fry/early fingerlings may help to increase the survival rates after stocking. An overall survival rate of 78.6% was observed by the fingerlings reared in the pens installed in the Odathurai Reservoir of Tamil Nadu (Murugesan *et al.*, 2005) which shows the utilisation of seasonal WSA for pen based seed rearing thus increasing the survival rate and enabling fisheries production (Rajak *et al.*, 2016; Mane *et al.*, 2017). Installation of pens in the open water bodies like reservoirs needs prior permission from the respective state departments and the selected open water bodies should have adequate depth *i.e.*, at least 1-3 m for pen culture (Anand *et al.*, 2019a; PMMSY, 2020).

Govt. of India supports pen culture in small reservoirs on par with the medium and large reservoirs (PMMSY, 2020) and installation of pens does not require expertise and the raw materials are quite cheaper and easily available (Natarajan, 1976; Selvaraj and Murugesan, 1990). Reservoirs contribute through capture and culture-based capture fisheries wherein the fish seed are being stocked as fingerlings for further growth to marketable size and the same are being harvested (Sugunan, 2017; Anand *et al.*, 2019a). Usage of the seasonally available waters for the installation of pens by self-help groups (SHGs) and fishermen/women cooperatives or the state fisheries department for fish seed rearing activity may enhance the overall yield from the reservoirs.

The present study recorded two-dimensional observations wherein the extent of water spread of the reservoirs from the spatial data was determined. However, the lack of depth particulars was a constraint in this study as only length and width of the reservoirs were considered. Depth details of the perennial water area of the reservoir may not be really useful for the stock enhancement programmes. But the cage fish culture practices in the reservoirs require the depth details of the site to ascertain suitability for installations (Anand *et al.*, 2019a). The potential cage culture sites are located in perennial water areas, which naturally occur in deeper parts of the reservoir. In case of Kaddam Reservoir, the maximum depth was recorded to be at least 28.4 m wherein the mean depth is 8.9 m (Ramakrishniah and Das, 1998). The depth of greater than 8-15 m will generally allow good growth of the stocked fish. Though, depth details of the reservoirs play a vital role in planning and site selection for cage installation in the reservoirs, this constraint can still be overcome during the implementation phase through ground truthing.

Identifying the potential area for installing the enclosure systems for fish culture in the reservoirs using

remote sensing would aid in understanding the water dynamics and also in resource-use planning. From the study, it is understood that the seasonal and perennial water spread area of the reservoirs is not being utilised effectively for enclosure fish culture. A remote sensing based reservoir management plan depicting seasonal extent of reservoirs with their corresponding depths would aid in earmarking specific areas for grow-out and fish seed rearing using pens or temporary cages. Fish seed reared in the temporary cages can be utilised for seed stocking programmes and can also be transferred to grow-out permanent cages for further culture, thus ensuring continuity in cage fish culture. The data generated on the reservoir water dynamics through geo-spatial tools aid in effective planning for resource use and implementation of management plans by the policymakers and fisheries managers in India and also other countries in the region.

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