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Resource Evaluation and Site Selection for Microalgae Production in India

Anelia Milbrandt and Eric Jarvis

Technical Report
NREL/TP-6A2-48380
September 2010

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Abbreviations and Acronyms

CGWB	Central Groundwater Board
CO_2	carbon dioxide
CPCB	Central Pollution Control Board
FAO	Food and Agriculture Organization
GHG	greenhouse gas
GIS	Geographic Information Systems
MNRE	Ministry of New and Renewable Energy
MPNG	Ministry of Petroleum and Natural Gas
MRD	Ministry of Rural Development
MWR	Ministry of Water Resources
NRSA	National Remote Sensing Agency
PBRs	photobioreactors
R&D	research and development
STP	sewage treatment plant
TAGs	triacylglycerols
TDS	total dissolved solids
WSP	waste stabilization ponds

Units of Measure

bbl	barrel
cm	centimeter
ft^3	cubic feet
g	grams
ha	hectare
km	kilometer
km^3	cubic kilometer
kWh	kilowatt-hour
L	liter
m	meter
m^2	square meter
m^3	cubic meter
mg	milligram
Mha	million hectares
MJ	megajoule
mm	millimeter
Mmcf	million cubic feet
Mt	million tonnes
tonne (t)	metric ton

Executive Summary

India's growing demand for petroleum-based fuels associated with its growing economy and population presents challenges for the country's energy security given that it imports most of its crude oil from unstable regions in the world. This and other considerations, such as opportunities for rural development and job creation, have led to a search for alternative, domestically produced fuel sources. Biofuels derived from algal oil show considerable promise as a potential major contributor to the displacement of petroleum-based fuels, given its many advantages including high per unit land area productivity compared to terrestrial oilseed crops, utilization of low-quality water sources and marginal lands, and the production of both biofuels and valuable co-products.

The purpose of this study is to provide understanding of the resource potential in India for algae biofuels production and assist policymakers, investors, and industry developers in their future strategic decisions. To achieve this goal, the study integrates relevant resource data from various public and private institutions in India and uses state-of-the-art geographic information systems (GIS) technology to analyze the collected information and visualize the results.

The results of this study indicate that India has very favorable conditions to support algae farming for biofuels production: considerable sunshine, generally warm climate, sources of CO_2 and other nutrients, low-quality water, and marginal lands. Sustainable algae biofuels production implies that this technology would not put additional demand on freshwater supplies and use low-quality water such as brackish/saline groundwater, "co-produced water" associated with oil and natural gas extraction, agricultural drainage waters, and other wastewaters. Although information on the quantity of these water resources in India is not available, the intensity of activities associated with their production suggests that there is a vast potential in the country.

Sustainable algae production also implies that farming facilities would not be located on valuable fertile agricultural lands but on marginal lands (classified as wastelands in India). These lands include degraded cropland and pasture/grazing land, degraded forest, industrial/mining wastelands, and sandy/rocky/bare areas. It is estimated that the extent of these lands in the country is about 55.27 Mha, or approximately 18% of the total land area. If India dedicates only 10% (5.5 Mha) of its wasteland to algae production, it could yield between 22–55 Mt of algal oil, which would displace 45%–100% of current diesel consumption. The production of this amount of algae would consume about 169–423 Mt of CO_2, which would offset 26%–67% of the current emissions.

The study illustrates options for siting two algae production facility types: *co-located facilities*, which produce algal biomass as a consequence of another process, and *dedicated facilities*, with the main purpose of algae production. Co-located facilities are those operating in conjunction with wastewater treatment where algae are produced as a byproduct of the wastewater treatment process. Using the wastewater effluent as pond medium provides a cost-effective solution to water, land, and nutrients considerations because the wastewater treatment function would cover nearly all costs. Domestic and industrial wastewater treatment facilities were considered in the analysis as potential sites for co-locating algae farms. This opportunity exists in most states of India.

The site-suitability analysis for dedicated algae farms was centered on the stationary industrial CO_2 sources given key advantages of co-locating algae production with these facilities: supplying carbon for enhanced algal growth with low/no transportation costs and a means for capturing CO_2 before it is released to the atmosphere, thus providing potential carbon credits for utilities. The study considered stationary CO_2 sources in areas where these facilities coincide with other inputs necessary for algae growth or conditions that meet the engineering, economic, environmental, and social requirements for this technology. The results of this analysis indicate that suitable locations for dedicated algae farms are in the western and southern parts of the country and along coastal areas.

India is a large country with diverse landscape and resources. Therefore, future work could focus on a state or even smaller geographic area to provide a more detailed examination of the resource potential for algae production and pinpoint the most suitable locations. The authors believe that the information provided in this study will serve as a base for further analysis of the algae biofuels potential in India and assist policymakers and industry developers in their strategic decisions.

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Introduction

India's growing demand for petroleum-based fuels associated with its growing economy and population presents challenges for the country's energy security given that it imports most of its crude oil from unstable regions in the world. This and other considerations, such as opportunities for rural development and job creation, have led to a search for alternative, domestically produced fuel sources. Biomass-derived fuels, namely biodiesel and ethanol, are considered by the Indian government as one option to substitute petroleum-based products—diesel and gasoline, respectively. To promote the production and use of these fuels, the government announced a Biofuels Policy in December 2009 that calls for the blending of at least 20% biofuels with diesel and gasoline by 2017 (MNRE 2009).

India is essentially a diesel-driven economy. Diesel consumption in 2008–2009 was 52 million tonnes (Mt)—about 40% of the total petroleum products consumed—against gasoline consumption of 11 Mt (MPNG 2009), and it grows by about 6%–8% annually. Diesel is widely used in all sectors—transportation, agriculture, power generation, and industry—but it is mainly consumed in road and rail transport (more than 50% of total diesel use). Biomass-based diesel substitutes include: *biodiesel*, typically produced by chemically reacting lipids (vegetable and waste oils such as animal fat and used cooking oil) with an alcohol; *green diesel*, produced either from hydroprocessing lipids or indirect liquefaction of any biomass feedstock[1]; and *unmodified vegetable and waste oils*, which may be used directly, without conversion, in diesel engines. Feedstock for these fuels considered in India (except green diesel produced from indirect liquefaction, which could use any source of biomass) includes non-edible vegetable oils such as those from Jatropha (*Jatropha curcas*) and Karanj (*Pongamia pinnata*) and waste oils. In addition, biofuels derived from algal oil show considerable promise as potential major contributors to the displacement of petroleum-based fuels, given the many advantages including high per unit land area productivity compared to terrestrial oilseed crops, utilization of low-quality water sources (brackish, saline, and wastewater) and marginal lands, and the production of both biofuels and valuable co-products.

The purpose of this study is to provide understanding of the resource potential in India for algae biofuels production and assist policymakers, investors, and industry developers in their future strategic decisions. To achieve this goal, the following two project objectives were defined:

1. Examine the resources available for algae production in India.
2. Identify areas suitable for algae production in the country.

To accomplish these objectives, the study integrates relevant resource data from various public and private institutions in India and uses state-of-the-art geographic information systems (GIS) technology to analyze the collected information and visualize the results.

[1] Green diesel is chemically different from biodiesel. It is composed of hydrocarbons with chemical properties identical to petroleum diesel, while biodiesel is not a pure hydrocarbon, but rather a mixture of fatty acid methyl esters (FAMEs). One method for producing green diesel is through hydroprocessing, the process of reacting the lipid feedstock with hydrogen under high temperature and pressure. Another method is through indirect liquefaction: first, the biomass is converted to a syngas, a gaseous mixture rich in hydrogen and carbon monoxide; then, the syngas is catalytically converted to liquids. The production of liquids is accomplished using Fischer-Tropsch (FT) synthesis.

Biofuels from Microalgae: Opportunities and Challenges

Microalgae for Lipid Production

The term "algae" refers to a very large group of photosynthetic, aquatic organisms that lack the true roots, stems, and leaves of higher plants. Eukaryotic algae are generally divided into the multicellular "macroalgae" (such as seaweeds) and the unicellular "microalgae." Algae represent an enormous amount of biodiversity, with over 40,000 species characterized so far. These organisms are remarkably adaptable and occupy virtually every environment on the planet. They can be found in waters of widely varying temperature, pH, and salinity (from freshwater to hyper-saline). For some time it has been known that many species of microalgae have the ability to accumulate lipids in the form of triacylglycerols (TAGs). This oil can reach 20%–60% of the dry cell weight and is typically synthesized in response to conditions of stress, such as lack of nitrogen. This response allows cells to store carbon and energy during times when cell division is limited. Of the 12 or more major divisions of algae, the best studied for this oil accumulation phenomenon fall into the Chlorophyceae (green algae) and Bacillariophyceae (diatoms).

The worldwide interest in exploiting oleaginous algae for their ability to make oil has reached a frenzied pace in recent years. However, the basic concept of growing algae for fuels has been around for more than 50 years (Meier 1955). Under the U.S. Department of Energy's Aquatic Species Program, research in this area accelerated the field with over $25 million and 18 years spent isolating algal strains from the wild, characterizing their physiology and biochemistry, developing genetic systems, exploring downstream processes, demonstrating mass culture systems, and analyzing the economics and resource requirements. A comprehensive overview of the program was published (Sheehan et al. 1998). The conclusion from these studies was that the technology is extremely promising, but major advances will be required to make it a cost-effective source of fuel, particularly given the fact that petroleum was trading for less than $20/barrel in 1995 when the program was winding down.

Benefits of Microalgal Oil Production

Why has the potential of producing fuels from microalgae been receiving so much attention in recent years? The answer lies both in externalities, such as recent escalations in the price of oil, and the inherent attractiveness of the technology. Microalgae can be grown with minimal inputs: land, sunlight, water, some macro- and micro-nutrients, and carbon dioxide (CO_2). The land need not be fertile, productive land; the ability to grow algae in wasteland regions means that the technology does not compete directly with food cropping. Similarly, low quality water is also applicable. Species of microalgae can be found that thrive in a wide range of salinities, thus brackish and saline water resources that are unsuitable for traditional crops will work well for microalgae cultivation. The requirements for macro- and micro-nutrients are similar to those of higher plants—nitrogen, phosphorous, and iron are key. Because these elements do not end up in the fuel product, there is the potential to recycle most of these nutrients in the process. Another avenue is the potential for domestic, industrial, and agricultural wastewater streams to be used as both water and nutrient sources for algal cultivation, which has the added benefit of remediating these waste streams. Finally, it is important to provide CO_2 at elevated concentrations for productive growth. Algae can be grown using industrial CO_2 streams, such as flue gas from electricity generation stations (typically 10%–15% CO_2). Thus, there is the potential to provide

the algae's key nutrient (CO_2) while capturing and recycling the primary gas responsible for global warming.

Given the right resources, microalgal oil productivities can be quite high. This is a result of their rapid growth rates (often > 1 doubling per day) and their potential for high oil content. Land and water resource limitations associated with using traditional oil crops, such as soybean or oil palm, prevent them from ever providing a large fraction of the world's demand for diesel and aviation fuels. Microalgae, on the other hand, can be conservatively expected to produce two times the oil yield per hectare of oil palm or 25 times the oil yield per hectare (ha) of soybean. This means that the land impact becomes reasonable for making a very significant contribution to the supply of hydrocarbon fuels. The oil (TAGs) from microalgae typically contains fatty acids that are very similar to those of conventional oil crops and can be converted readily to biodiesel or other fuels.

Compared to conventional petroleum-based fuels, the energetics and greenhouse gas (GHG) emissions associated with the production of microalgal fuels have the potential to be very attractive. The ultimate source of energy in these fuels is the sun, captured by the photosynthetic machinery of the algal cells. The carbon in the fuels is captured from waste streams, such as power plant flue gas; thus, a second use of this carbon is achieved before release to the atmosphere. Early life cycle analysis (LCA) studies, however, indicate that the overall energy and GHG balance is very sensitive to the design of the process (e.g., Huesemann and Benemann 2008; Lardon et al. 2009). Since an active industry producing microalgal biofuels does not yet exist, it is difficult to know the appropriate inputs and assumptions to use in such LCA modeling. The source of key nutrients and the need for drying algal biomass before oil extraction are particularly important determinants of the LCA results. Utilization of wastewater can improve the LCA, as can methods of extraction that do not require drying the biomass. These and other factors must be carefully considered before any large-scale implementation of the technology.

Algal Cultivation Systems

Microalgae can be cultivated in any system that provides the right environment for growth, including sufficient light, gas exchange (CO_2 delivery and O_2 removal), temperature control, and mixing. The ultimate goal is to optimize all of these parameters so as to approach the theoretical efficiency of energy capture through photosynthesis, which is difficult in practice. Balanced against providing the ideal growth environment is the system cost, which must be kept to a minimum. Proposed growth systems vary from simple open ponds to complex photobioreactors (PBRs). Growth systems are currently an area of active research worldwide.

Open ponds are the most cost-effective algal growth systems. Unstirred ponds tend to have very low productivity rates. Raceway designs, however, which use paddlewheels to provide laminar flow of the culture and keep the algae suspended, can be very productive. These shallow, artificial ponds are typically 15–30 cm deep and can be lined with clay or plastic to prevent percolation through the bottom. CO_2 is generally sparged into the culture in a deeper section known as the sump. These systems scale up very well and have the advantage of less severe temperature swings due to good thermal contact with the ground and evaporative cooling from the surface.

There are many designs for PBR growth systems, the most common of which fall into the categories of flat panel, tubular, and vertical column systems (for reviews, see Richmond 2004; Chisti 2007; Eriksen 2008; Ugwu et al. 2007). By optimizing the surface-to-volume ratios, PBRs can offer higher volumetric productivities than ponds, but not necessarily higher areal productivities. They have the potential for better culture stability due to decreased risk of contamination, although at large scale it is impossible to keep such systems axenic. Water consumption can be reduced relative to open ponds due to decreased evaporation, unless evaporative cooling needs to be employed for temperature control. PBRs suffer from the complexities of gas exchange (CO_2 introduction and O_2 removal), mixing, temperature control, and prevention of fouling (biofilm formation). But even more critical is the capital costs of such systems because of their complexity and the expensive materials used for construction (e.g., steel, glass, and plastic). Some authors have predicted that the increased performance of PBRs will never compensate for the added economic and life cycle costs of such systems (Huesemann and Benemann 2008; Sheehan et al. 1998).

Hybrid systems have also been proposed in which a combination of open ponds and PBRs are used to optimize growth and lipid induction. Heterotrophic growth, in which algae are fed biomass-derived sugars, is also an option; however, this approach relies on agricultural feedstocks that have other uses. Artificial light systems have been proposed, allowing better control of temperature and sterility, but such concepts are clearly not feasible due to energy and cost considerations. Finally, offshore cultivation is an option to consider, although reliable infrastructure for such systems has not yet been devised. For the purposes of this paper we will consider only land-based, phototrophic systems.

Downstream Processing to Fuels

Productive growth of oil-rich algae is only half of the equation. Equally important is the harvesting of the algal biomass, extraction and purification of the oil (TAGs), and conversion to usable transportation fuel. All three steps are important to the overall economics and the subject of ongoing research.

Microalgal harvesting, or "de-watering," has the potential to be a very cost- and energy-intensive process. Even a "dense" algal culture may only contain 1 g of dry cell weight per liter of culture (i.e., 0.1% solids). A 1 hectare, 20 cm deep open pond would contain 2,000 m^3 ($2x10^6$ liters) of culture, and it may be necessary to harvest half of the pond volume (1 million liters) every day. The harvesting system must therefore be rapid and efficient. Some of the options being considered include spontaneous settling of the cells, autoflocculation, bioflocculation, chemical flocculation, centrifugation, filtration, and dissolved air flotation. In reality, harvesting will likely include a combination of such techniques, such as using flocculation to achieve 1%–2% solids, followed by centrifugation or tangential flow filtration to achieve 20% + solids. Many of these methods are somewhat strain-dependent, and more research is needed in this area.

The TAGs in microalgal cells are contained in oil droplets within the cells, and the cell wall can pose a significant barrier to removal of the oil. Extraction of algal oil probably involves three steps: 1) disruption of the cell wall, 2) separation of the oil from the remaining biomass, and 3) purification or upgrading of the oil to remove impurities. Many approaches to extraction are being studied. Solvent extraction, using hexane, for example, can be used successfully to extract oil from intact cells of many species, and the algal biomass need not be fully dried. Drying the

algae is extremely energy intensive and must be avoided if possible; ideally a technique will be able to deal with an aqueous slurry or paste (e.g., 20% solids). Solvent extraction, however, can be costly and pose serious environmental concerns. Other approaches being studied involve more benign ("green") solvents, supercritical CO_2, enzymatic extraction, and ultrasonic cell disruption, among others. Again, methods can be very strain-specific, and much more research is needed to find inexpensive, safe, and scaleable methods for oil extraction.

Finally, the extracted TAGs need to be converted into a fuel that is compatible with the existing transportation infrastructure. This means converting the oil into diesel or aviation fuel substitutes that meet all of the relevant specifications for fuel quality. Two main pathways are being considered. The first is the conversion of the TAGs into alcohol esters (i.e., biodiesel) using conventional transesterification technology. The second is to use catalytic hydroprocessing methods to generate a renewable "green" diesel product which does not contain oxygen. Both approaches have their merits and are based on well-understood processes. The hydroprocessing approach, which essentially uses conventional oil refinery operations, has the benefits of more process flexibility and the ability to address aviation fuel markets as well as diesel. The chosen process must also be able to deal with variability in the oil feedstock, as the fatty acid composition of oils can vary based on algal species and growth conditions.

Economics

The technical feasibility of algal biofuels has been demonstrated. The challenge comes in making the system cost-competitive with other fuel sources. While government incentives and monetization of externalities (e.g., environmental benefits) can help to give this nascent technology a boost, becoming directly competitive with the cost of petroleum-derived fuels is the best way to ensure growth of an algal biofuels industry. Unfortunately, current estimates of the cost of algal-derived biofuels vary over two orders of magnitude, depending upon how optimistic the assumptions are. Until large-scale facilities are operational and we have a better understanding of the performance and production costs, it is difficult to make accurate assumptions in cost models. Probably the most important determinant of the economics is the biological productivity, that is, using a productive strain of microalgae and optimizing the growth system (Sheehan et al. 1998). However, other factors such as the cost of CO_2 and water and the harvesting and extraction systems also play important roles. Other inputs, such as the cost of land, are somewhat less significant.

One of the major areas of uncertainty in the cost modeling is the value to be gained from co-products. Even if cells are 50% oil, it means that the residual biomass comprises another 50% of the mass. This is at worst a disposal issue and at best a revenue opportunity of even more value than the oil itself. Most microalgal cells are quite high in protein, which has potential applicability to food and feed markets. Residual carbohydrates can also have feed value or could be fermented to ethanol as a gasoline substitute. Anaerobic digestion of the entire residual biomass could produce biogas for heating and power generation. Higher value products can also be found in many species of algae, including pigments (e.g., carotenoids and astaxanthin) and specialty lipids (e.g., omega-3 fatty acids). Co-products are critical to the overall economic viability of algal biofuels, and care must be taken to match the size of the co-product market to the projected size of algal fuel production facilities.

Challenges to Overcome

Despite the promise of algal biofuels, sustained yields obtained so far for algal mass culture efforts have fallen significantly short of the levels required for cost-effective fuel production (Hu et al. 2008). Further strain improvement and culture optimization may allow the necessary yields to be achieved. However, there are challenges throughout the process chain that need to be addressed.

Large-scale cultivation of microalgae is still in its infancy. First, robust, highly productive strains must be identified that exhibit consistently both high growth rates and high oil content. The stability of cultures is critical, as culture "crashes" will take a severe toll on overall productivity. Stability will be affected by invasion of weed algal species, pathogens (e.g., viruses and fungi), and predators/grazers that feed on microalgae. CO_2 supply, gas exchange, and temperature control could be problematic in many situations. Nutrient sourcing and recycle can be critical to the economics. The overall cost of cultivation systems, especially the capital infrastructure costs, must also be reduced.

The downstream processes also pose significant challenges. As discussed above, the harvesting and extraction of algal cells are critical cost components for which economically viable solutions may not yet exist. The characteristics, stability, and consistency of the final fuel product need to be addressed. Finally, the management of water throughout the process is of paramount importance, particularly in arid regions. This includes sourcing water for cultivation systems, makeup water to replace losses due to evaporation, and treatment of incoming and outgoing water streams (e.g., removing nutrient residues, organics, heavy metals, salt, and live organisms). Of course, the regulatory requirements, environmental impacts, and life cycle benefits of the entire process must also be carefully considered.

It is clear that one of the keys to the success of this industry is to align the necessary resources at the required costs. The benefits of the technology will not be realized unless the process can be made economical and the overall benefits shown to be beyond dispute. Although demonstration and pilot studies are now beginning, the only way this technology will have an impact on providing transportation fuels in a sustainable and cost-effective manner is for the required resources to be available to cultivate microalgae on a truly massive scale. For that reason, siting and resource issues are at the fore. India's capacity to provide those resources for a large-scale and sustainable algae-to-biofuels industry is the focus of this paper.

Resource Evaluation

The decision for locating an algae production facility in a given area, as with many other technologies, starts with evaluating the resource potential. Favorable climate conditions and availability of water, CO_2, and other nutrients (primarily nitrogen and phosphorous) must be aligned with suitable land characteristics—topography, soil, and use—to determine the most promising areas for algae production. Because these resources vary considerably from one geographic location to another, optimal siting of algae farming systems requires knowledge of the specific resource characteristics—availability, magnitude, and variability—at any given location. An overview of the critical resources for algae production systems in India—climate, water, CO_2, other nutrients, and land is presented below.

Climate

The impact of climate on algae production is comparable to the impact of climate on terrestrial plants. Like higher plants, algae need abundant sunlight and have differing tolerances to temperature. Closed photobioreactors can be less sensitive to climate variability than open pond systems due to the somewhat more controlled environment they provide. Solar radiation and the number of daily sunshine hours directly affect algae productivity, precipitation and evaporation affect water supply, and severe weather (hail, dust storms, and floods) impacts water quality.

Equally important to both open and closed algae cultivation systems is the availability of abundant sunlight. Figure 1 illustrates the annual average global horizontal solar radiation in India. Global solar radiation is the sum of the direct, diffuse, and ground-reflected radiation arriving at the earth's surface, also called total solar radiation. *Direct* beam radiation comes in a direct line from the sun; *diffuse* radiation is scattered out of the direct beam by molecules, aerosols, and clouds; *ground-reflected* is the solar radiation reflected back into the atmosphere after striking the earth. Solar radiation of 4.0 kWh/m²/day (approximately 14MJ/m²) is considered adequate for algae production. Therefore, almost the entire country (except parts of Arunachal Pradesh) is suitable for algae production from the standpoint of receiving sufficient solar radiation on an annual basis. There are, however, monthly variations as illustrated in Figure 23 (Appendix). Lower solar radiation values are experienced during the monsoon season in the central, northeastern, and western coastal states and during the post-monsoon season/early winter in the northern states. Algae productivity in those locations would be low during these months.

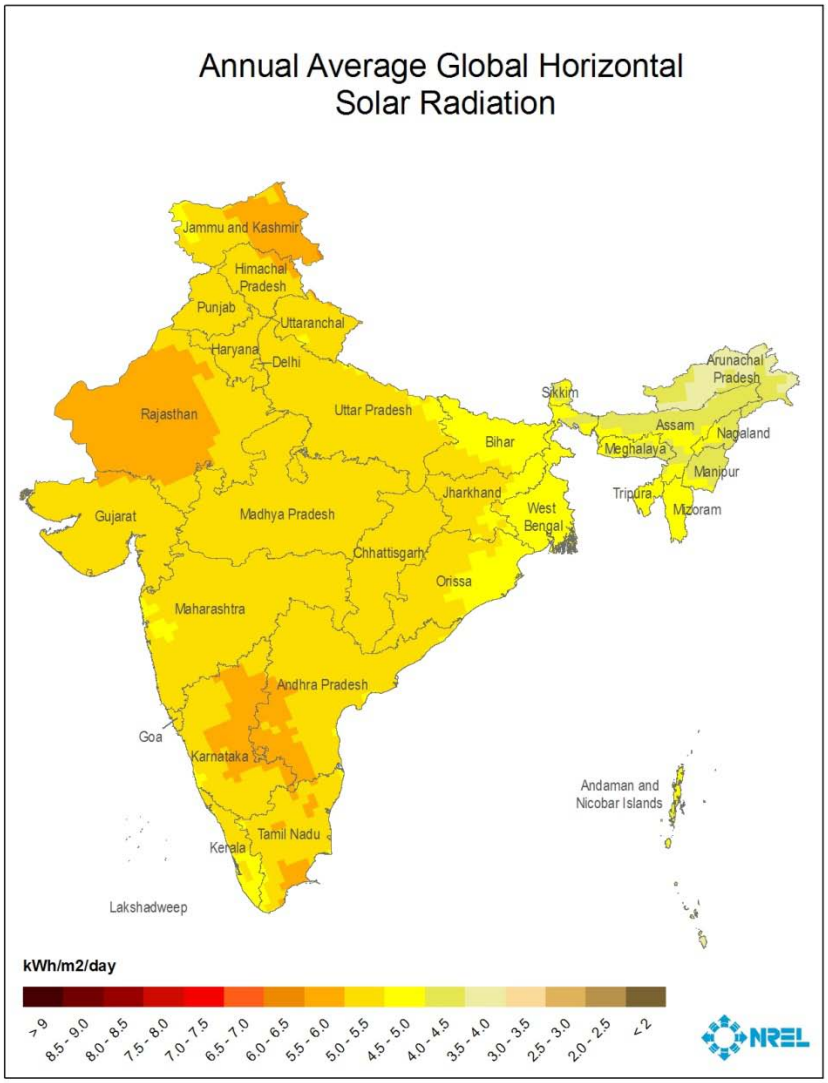


Figure 1. Annual average solar radiation

Another important climate element affecting algae growth is the number of sunshine hours during the day. In most parts of India, clear sunny weather is experienced 250 to 300 days per year with the sunshine hours ranging between 2,300 and 3,200 per year depending upon the location (Muneer, Asif, and Munawwar 2004). Figure 2 illustrates the annual average daily sunshine hours in India. The values vary from less than five hours for locations in the northeastern states to more than nine hours for places in the western and central states.

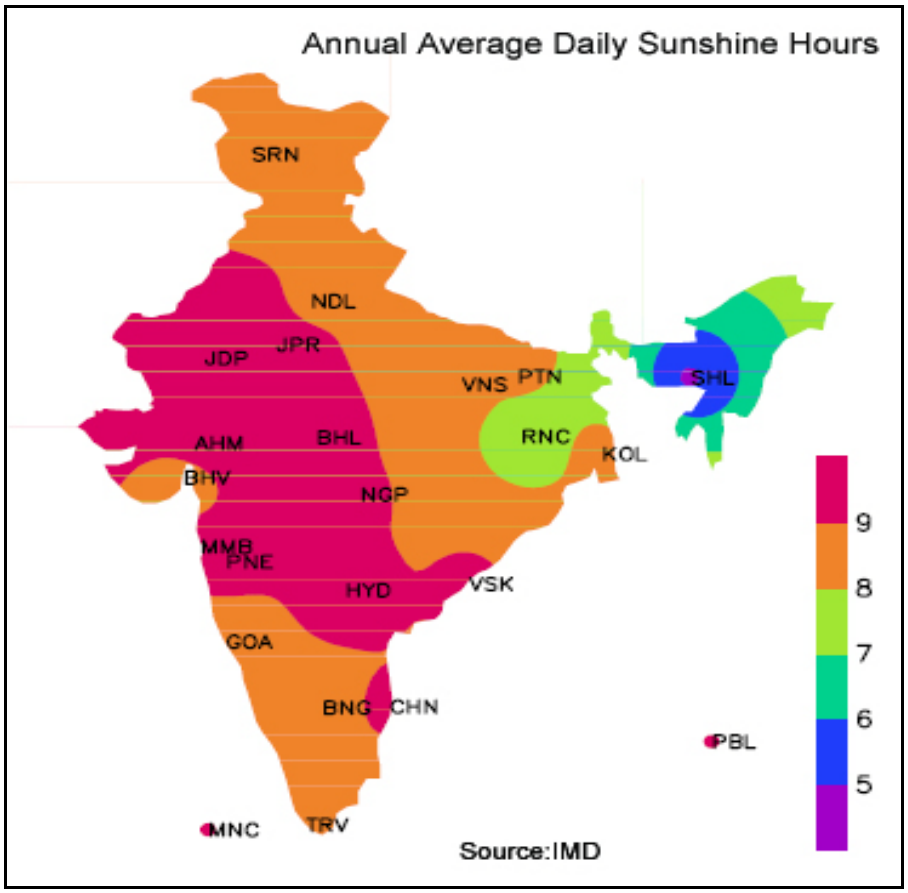


Figure 2. Annual average daily sunshine hours

The India Meteorological Department (IMD 2009) designates four official seasons: winter (January through March), summer or pre-monsoon season (April through mid-June), monsoon season (mid-June through September), and post-monsoon season (October through December). On average, the lowest number of daily sunshine hours is experienced during the monsoon months—for some locations less than four hours. During the other seasons, the sunshine hours are high (more than eight hours) for most of the country. The monthly variations are shown in Figure 24 (Appendix). Days with less than six hours of sunshine are considered inadequate for algae growth; therefore, productivity would be low during the rainy season in some areas of the country. Although algae productivity would be low at these locations during the monsoon months, the remaining 8 to 9 months of the calendar year provide a sufficiently long growing period for algae.

The various species of microalgae grow under a wide range of temperatures; thus, temperature per se is not a critical climate element. However, most algae species are sensitive to freezing; therefore, areas reaching 0°C (32°F) and below in the winter months would be challenging locations for algae farming. Thermal mass of the cultivation system and high salinity growth medium might protect microalgae during temperature excursions below 0°C, but productivity would be negligible under such conditions. Areas prone to freezing weather include the mountain areas in Northern India: the states of Jammu and Kashmir, Himachal Pradesh, Uttaranchal,

Sikkim, and Arunachal Pradesh (Figure 3). Portions of these states, at the sub-Himalayan and sea-level elevation, generally experience subtropical climate with mild winters, but temperatures even in these areas may fall to 0°C during the coldest months. Similarly, temperatures in some areas of western Rajasthan can drop below freezing due to waves of cold air from central Asia during winters. If algae farming is considered in these areas, the facilities may need to be equipped with a heating mechanism to keep the ponds at an optimal temperature for algae growth. This, however, would add substantially to the farms' operating costs and defeat the purpose of algal fuels production, which is to reduce GHG emissions, if fossil fuel sources are used. Alternative sources of energy could be considered to improve the environmental impact of these facilities, such as geothermal resources (available in areas with cold temperatures as shown in Figure 25; Appendix), but this approach may not be cost competitive. Geothermal resources are being researched in the United States as a heat source for algae farms, particularly in Nevada (a state with wide local temperature variations), but the cost of this method is yet to be evaluated. Another option is to consider waste heat from power plants and other CO_2 emitting industrial facilities.

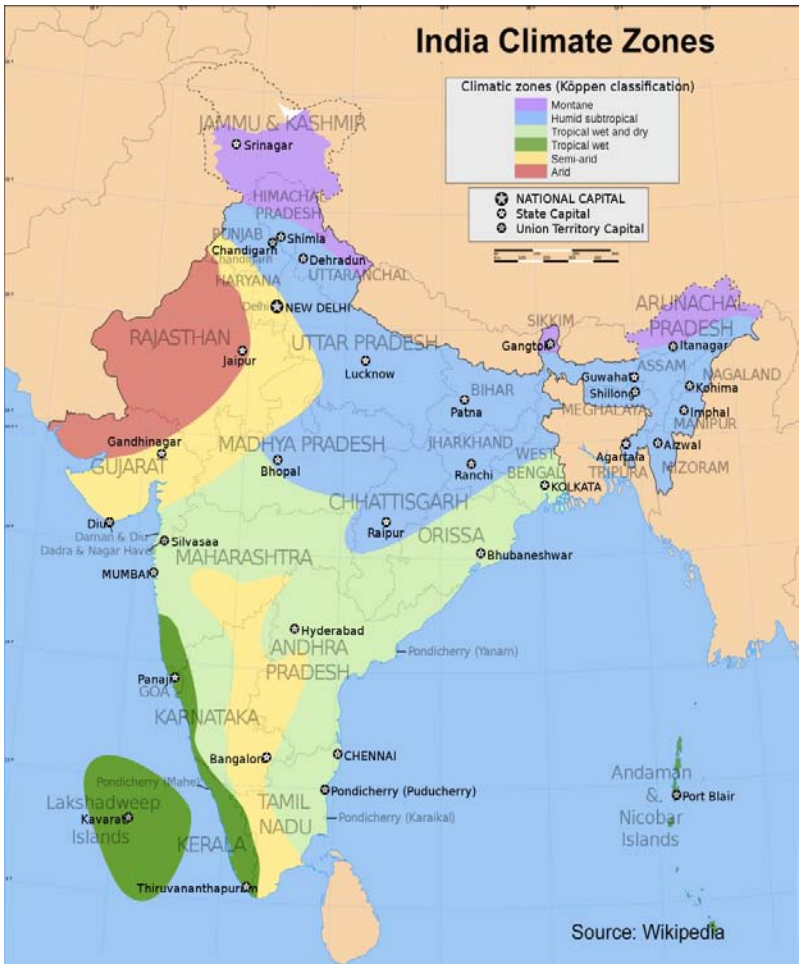


Figure 3. India climate zones

As mentioned earlier, precipitation and evaporation do not affect algae productivity directly. However, they are important climate elements to consider in siting algae farms as they relate to

water supply and loss. Precipitation affects water availability (surface and groundwater) at a given location. The IMD estimates the annual average rainfall in India during 2000–2005 at 1,117 mm (Hindustan Times 2005). More than 75% of the rainfall is received during the four monsoon months (Harihara Ayyar 1972). Of the remaining volume, a large fraction is received during the winter months. Areas with sufficient precipitation (more than 1,000 mm/year) include northeastern states, western Ghats, central states, and the eastern part of Ganges Valley (Figure 4). A recent study by the Indian Tropical Meteorology Institute in Pune looked at data from 1871 to 2006 and concluded that the rainfall patterns in the country are changing: rainfall is decreasing along the Ganges Valley and in the northeastern states (Figure 5; Singh et al. 2005). Rainfall is increasing in West Bengal, Jharkhand, Assam, parts of Gujarat (historically dry), and most coastal regions of the country. The observed rainfall trends will affect water abundance/deficit in those regions; therefore, it will have an impact on the water available for algae production.

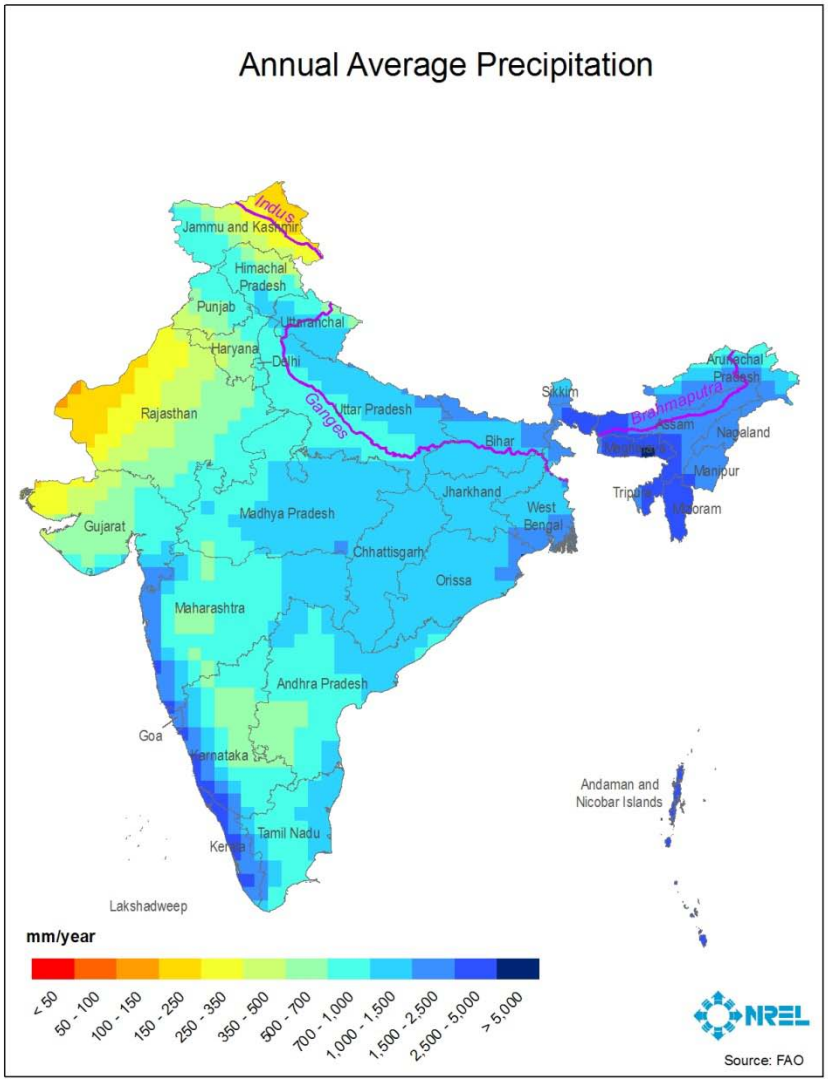


Figure 4. Annual average precipitation

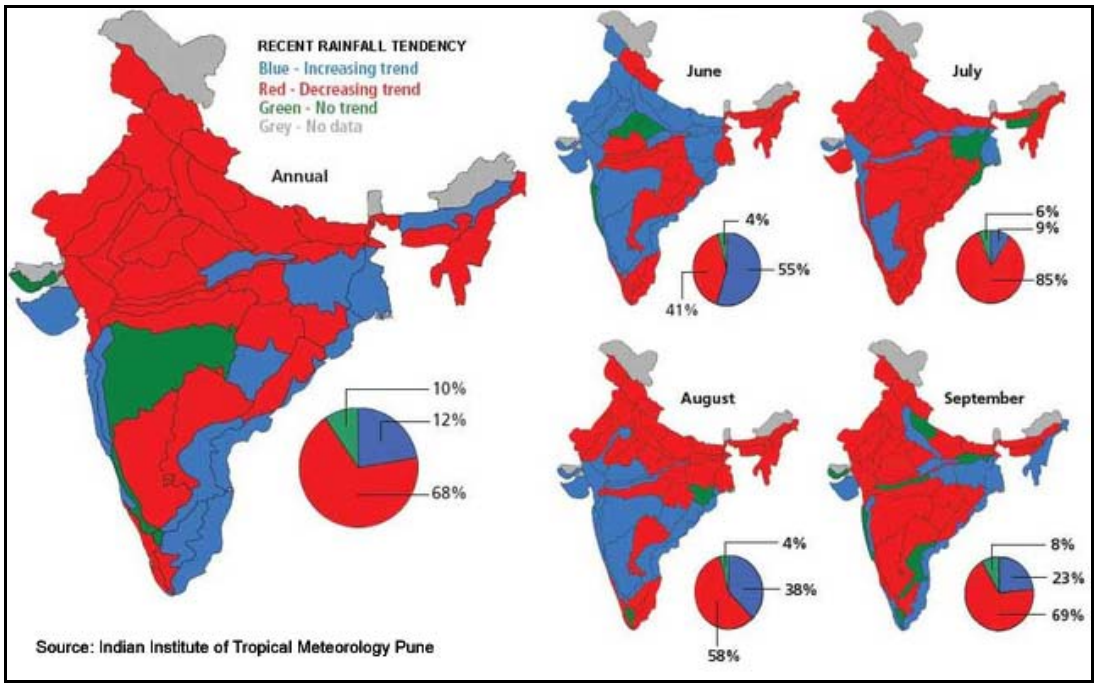


Figure 5. Rainfall trends, 1813–2006

Evaporation contributes to water loss. It is a very important factor to consider when choosing locations for open pond farming because it can significantly increase operating costs. This is less of an issue for closed PBRs, although evaporation is necessary to help regulate the temperature of both open and closed systems. The western, central (Maharashtra), and southern (Tamil Nadu) states in India have the highest evaporation rates in the country with more than 275 cm annually (Figure 6). Evaporation rates follow closely climatic seasons: they are low during the winter (2–6 mm/day), monsoon (4–10 mm/day), and post-monsoon (4–8 mm/day) months and reach their peak in the summer months of April and May (5–16 mm/day) (NIH 2009). Saline water surfaces evaporate less than freshwater surfaces. Therefore, algae ponds using brackish or saline water should be considered in areas where the evaporation rates are high.

Severe weather can have a major impact on aquaculture. In India, natural disasters that could be devastating to algae farming include cyclones along the coastal areas, hail and dust storms in northern states, widespread floods along the rivers, and flash floods during the monsoon season (Figure 26 and Figure 27; Appendix). These weather events could contaminate the open pond environment or damage covered systems; therefore, the potential for such natural disasters should be taken into account when looking at prospective sites for algae production in India.

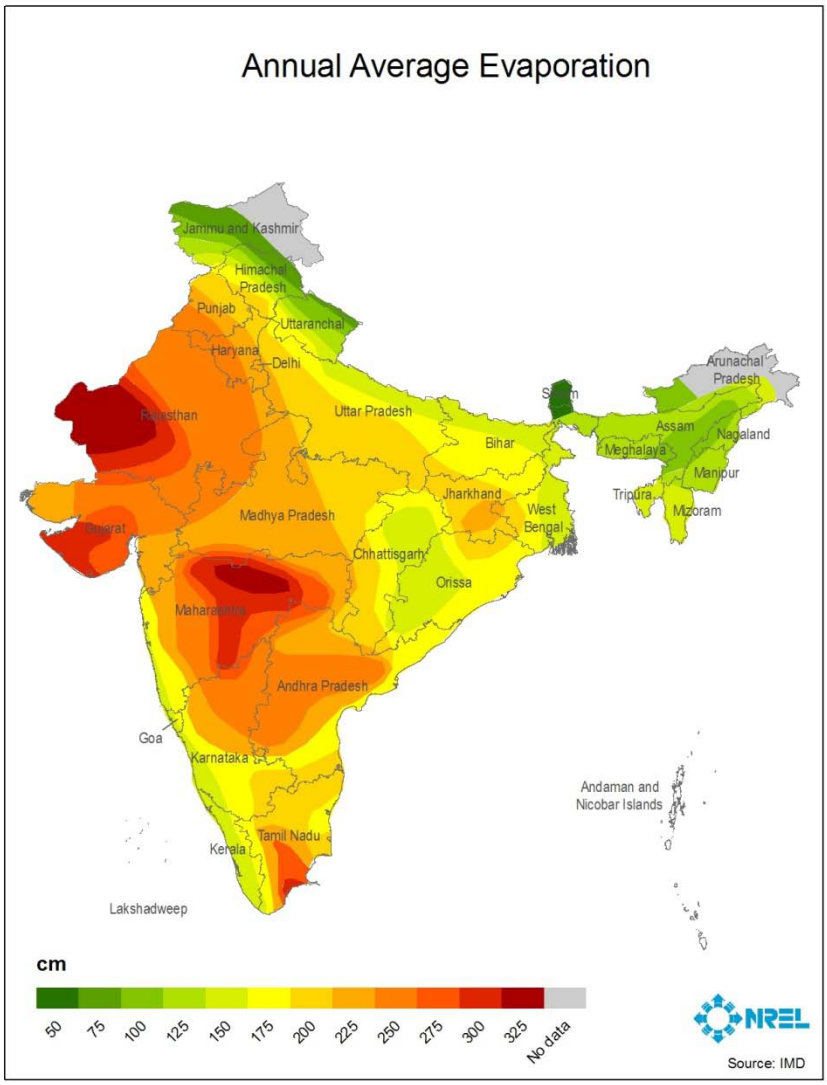


Figure 6. Annual average evaporation

Water Resources

The renewable water resources in India are estimated at 1,869 km^3 annually (MWR 2009). The country ranks ninth in the world; in comparison, Brazil has more than 8,000 km^3, Russia has 4,500 km^3, and Canada and the United States have more than 3,000 km^3 each (CIA 2009). Due to topographic, hydrological, technological, and other constraints, however, the amount of water that can actually be utilized in India is less—about 1,123 km^3. Of this amount, surface water represents 61% or 690 km^3, and groundwater is about 433 km^3; although, considering natural discharge during non-monsoon season, groundwater availability is actually closer to 399 km^3/year.

India has more than 20 major river systems providing irrigation, drinking water, transportation, electricity, and the livelihoods for many people all over the country as illustrated in Figure 7. The rivers of India are broadly classified into four groups: Himalayan rivers, Deccan rivers, coastal rivers, and rivers of the inland drainage basin. Some of these rivers are perennial and others

seasonal (Figure 8). The Himalayan rivers—Ganges, Brahmaputra, and Indus—are formed by melting snow and glaciers, and therefore, continuously flow throughout the year. Together, these river basins provide about 50% of the surface water resources in the country (Kumar et al. 2005). Most of the Deccan rivers (e.g., Godavari, Krishna, Cauvery, Mahanadi, Narmada, and Tapti) and coastal rivers are seasonal; their flow depends mainly on rainfall. Therefore, adequate rain during the monsoon season is critical in these parts of the country for a lack of it leads to water shortage. The streams of inland drainage basins are small rivers in sandy areas of Rajasthan with no outlet to the sea, except Luni, and most of them are of an ephemeral character.

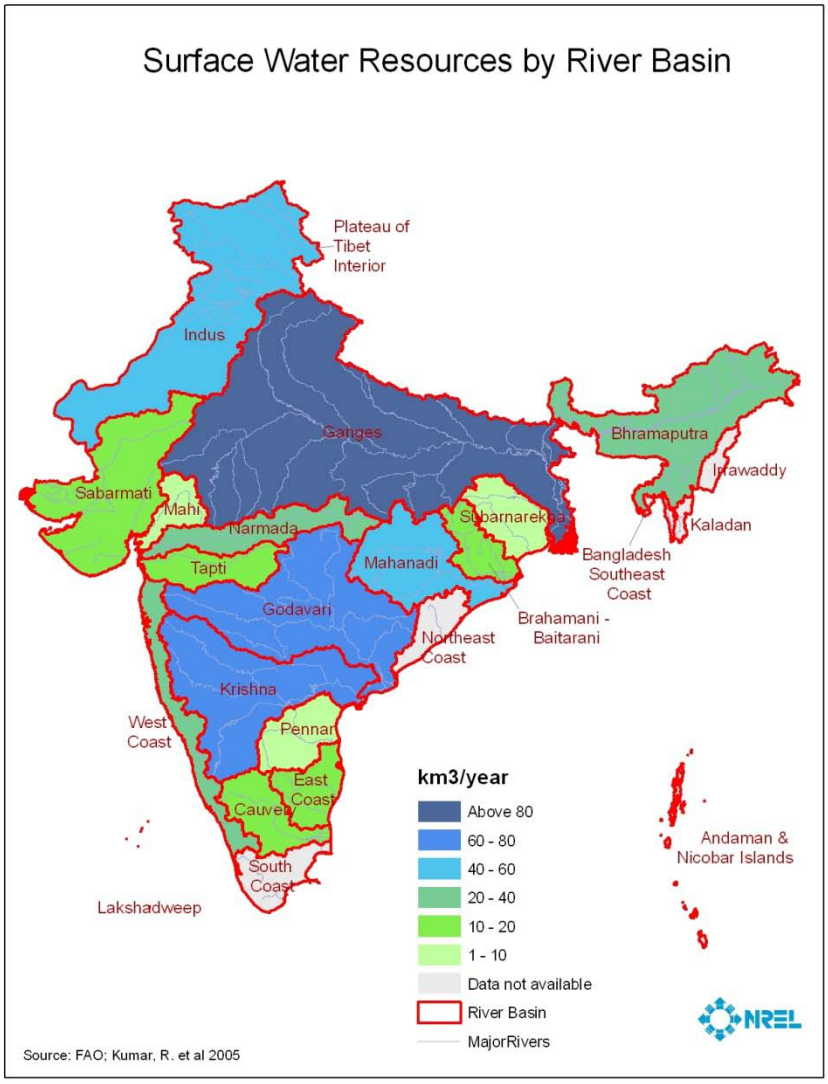


Figure 7. Surface water resources by river basin

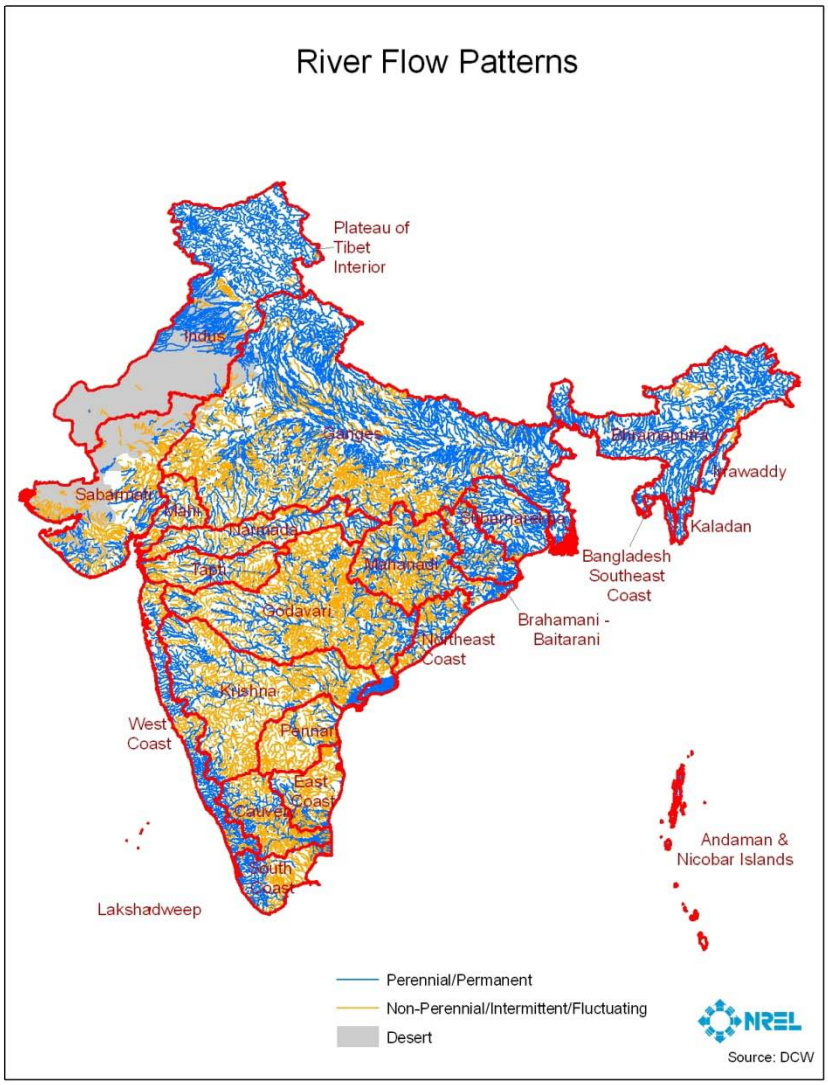


Figure 8. River flow patterns

In addition to surface water, groundwater is also an important resource for irrigation, domestic, and industrial uses in India. It is a strategic source of freshwater during dry periods. It accounts for about 80% of domestic water use and more than 45% of the irrigation in the country (Kumar et al. 2005). Figure 9 illustrates the groundwater resources in the country by district. Districts along the main rivers in the north and in the southern states of Andhra Pradesh and Maharashtra have the highest volume of groundwater resources.

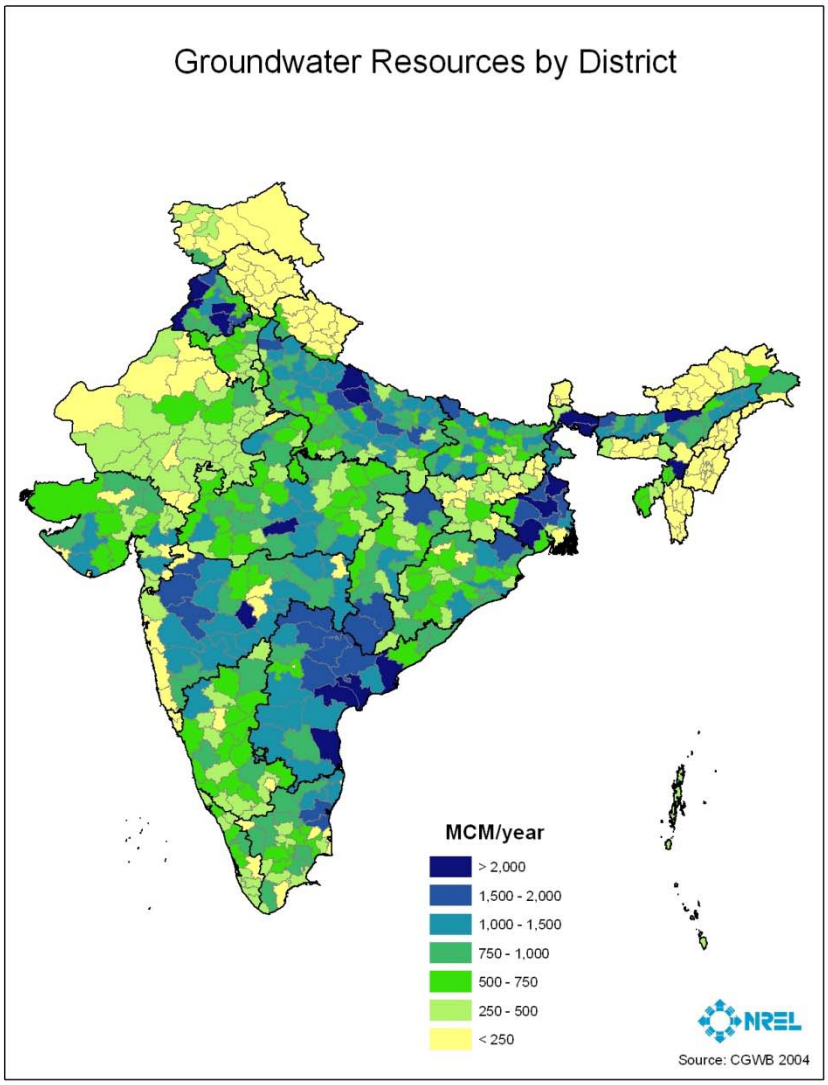


Figure 9. Groundwater resources by district

Groundwater in India is recharged by rainfall (67%) and other sources (canal seepage, return flow from irrigation, seepage from water bodies, and artificial recharge due to water conservation structures). In some areas of the country, groundwater levels have been declining over the past years. This is due to a number of factors—decreased rainfall, deforestation, and soil degradation—but is particularly due to overexploitation resulting from population growth, economic development, and water-intensive farming. The Central Ground Water Board (CGWB) of the Ministry of Water Resources (MWR) evaluated the groundwater resources at the finest administrative unit (blocks, talukas, and mandals) and categorized them into several groups as illustrated in Figure 10 (CGWB 2006a). Groundwater in about 20% of all administrative units—predominantly in the northwestern, western, and southern parts of India—is categorized as "overexploited" and "critical." Approximately 10% of all units have groundwater that is categorized as "semi-critical" and about to reach critical condition if proper management of these resources doesn't take place. Scientists from the U.S. National Aerospace and Space

Administration (NASA) studied satellite images of groundwater storage from 2002 to 2008 in north India and found that the groundwater levels in north India are declining by 33 cm per year and that about 110 km^3 of groundwater have been lost over the six-year study period—double the capacity of India's largest surface water reservoir, the Upper Wainganga (NASA 2009).

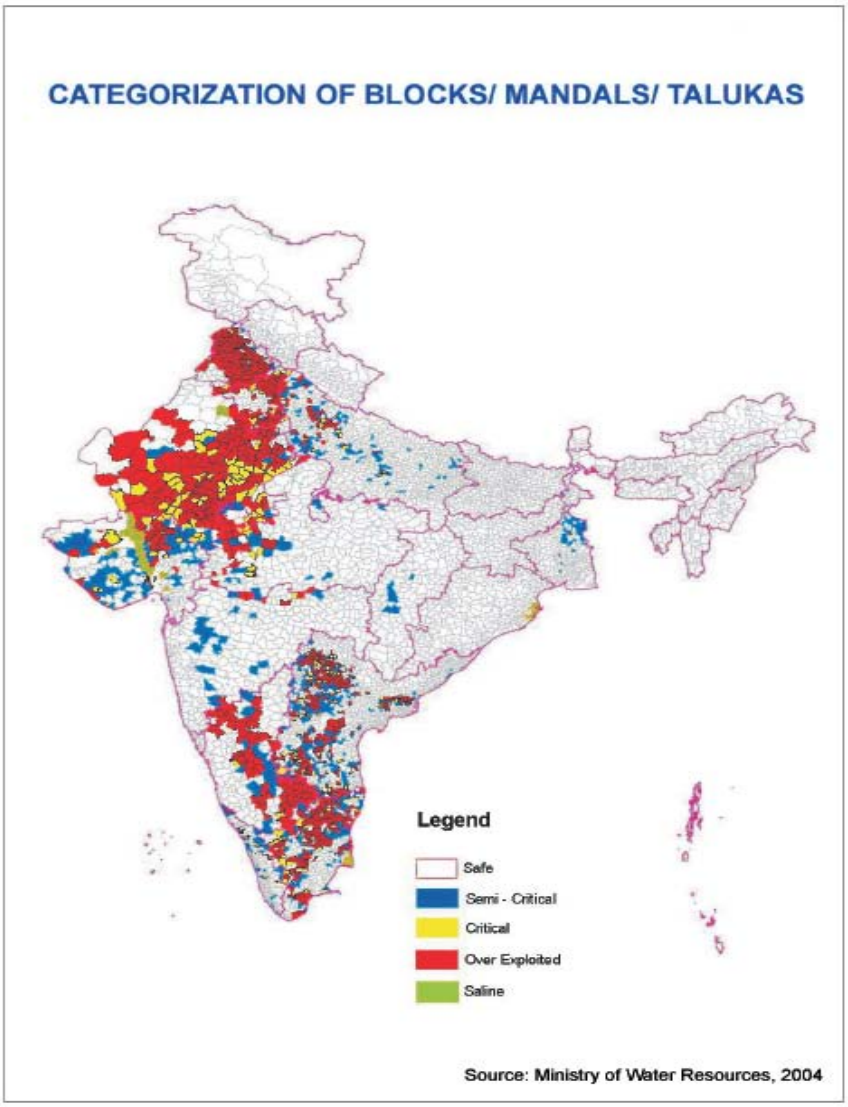


Figure 10. Status of groundwater resources

Overexploitation of groundwater resources, more so than climate variations and land use change, causes a lowering of the water table, which makes the groundwater more difficult and expensive to obtain. In many parts of India, groundwater is increasingly being pumped from lower and lower levels. In some areas, well drillers are using modified oil-drilling technology to reach water, going as deep as 1,000 m (Brown 2007). Groundwater level fluctuations (the rise and fall of the water table) over a decade are shown in Figure 11. The areas where the water table is falling overlap with highly populated places and locations with groundwater overexploitation.

Because depth to water table greatly affects the cost of extraction, this will negatively impact the economics of growing algae in those areas. Naturally, locations with groundwater closer to the surface would provide a cost effective way to produce algae. It is critical that the emerging algae industry be wary of regions where added consumption will exacerbate already serious water resource issues.

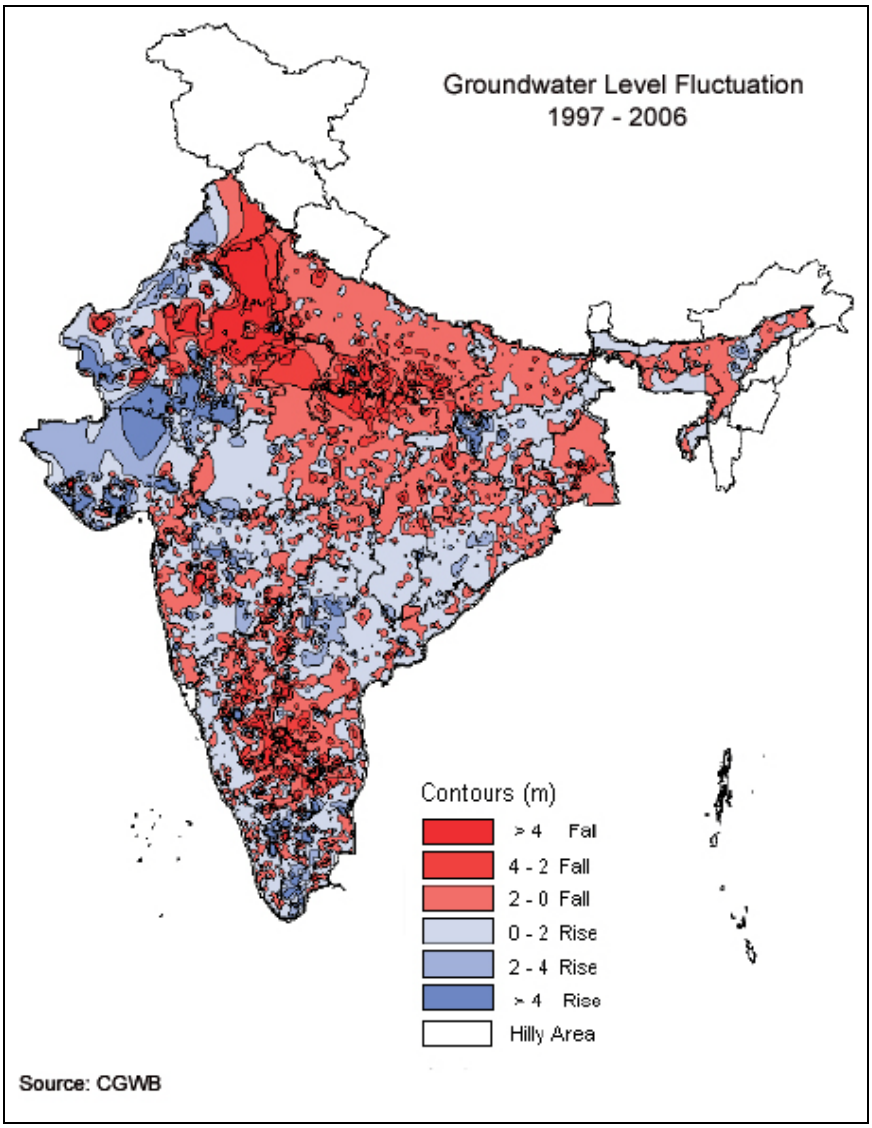


Figure 11. Groundwater level fluctuation

One of the benefits of growing algae is that it can utilize low-quality water with few competing uses, such as brackish/saline groundwater, "co-produced water" from oil and natural gas wells, and wastewater discharged from domestic, industrial, and agricultural activities. Therefore, algae technology need not put additional demand on freshwater supplies. Using poor quality water for algae production can serve two purposes: one is to dispose of water that would otherwise be costly (economically and environmentally) to dispose, and the other is to utilize poor quality

water to create products that have economic value—algal biofuels and biomass for animal feed or fertilizer.

Brackish water is defined as water containing total dissolved solid (TDS) concentrations between 1,000 and 10,000 milligrams per liter (mg/L). This definition includes slightly-saline (1,000 to 3,000 mg/L TDS) and moderately-saline (3,000 to 10,000 mg/L TDS) water (USGS 2009). As a reference, freshwater contains less than 1,000 mg/L, highly-saline water has about 10,000 to 35,000 mg/L TDS (seawater has a salinity of roughly 35,000 mg/L TDS), and brine has more than 35,000 mg/L TDS. Groundwater with TDS concentrations greater than 3,000 mg/L is unusable for irrigation without dilution or desalination and is not safe for most poultry and livestock watering (Warner 2001).

High salt levels occur naturally in some parts of India such as the coastal areas, but in many cases this has been exacerbated where human activities accelerate the mobilization and accumulation of salt. Inland groundwater salinity is present in arid and semi-arid regions of the country. Figure 12 illustrates the geographic distribution of brackish groundwater in India. There are several places in Rajasthan and southern Haryana where TDS in groundwater exceeds 6,700 mg/L making the water unsuitable for agricultural activities without treatment (CGWB 2006b). Desalination of saline or brackish water for use in irrigation and human consumption, in addition to being a costly option, presents some environmental challenges associated with its energy-intensity, GHG emissions, and disposal of the salty brine by-product. Many species of algae have a high tolerance to salinity; therefore, in addition to coastal areas, the algae technology can target parts of the country where the presence of saline groundwater resources prevents their direct use in other applications.

If brackish/saline water is used for algae production, an important consideration is where and how algal growth media is disposed of after cultivation. Although the water can be used for many generations of algal production, evaporation (particularly in open ponds) will concentrate higher levels of salts in the water and ultimately to beyond the range suitable for algal growth. The typical method for dealing with this problem is to dispose of a certain amount of the spent media during harvesting as “blowdown” water. This water is then replaced with new water from the source (fresh or saline). The blowdown water will contain more elevated levels of salts and potential contaminants from flue gas, algal byproducts, and probably some live algal cells. Returning this water to the source (e.g., aquifer) may be problematic. The uses of evaporation ponds or ocean disposals are other potential options but will also impact the siting decision.

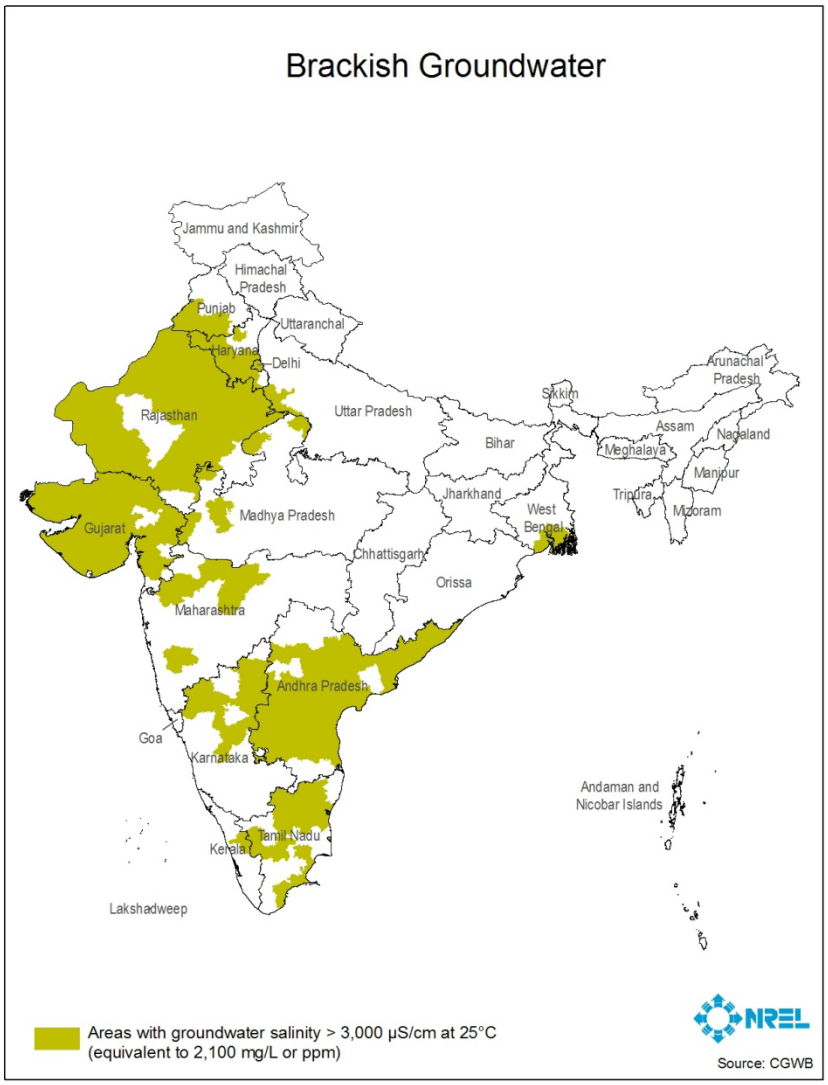
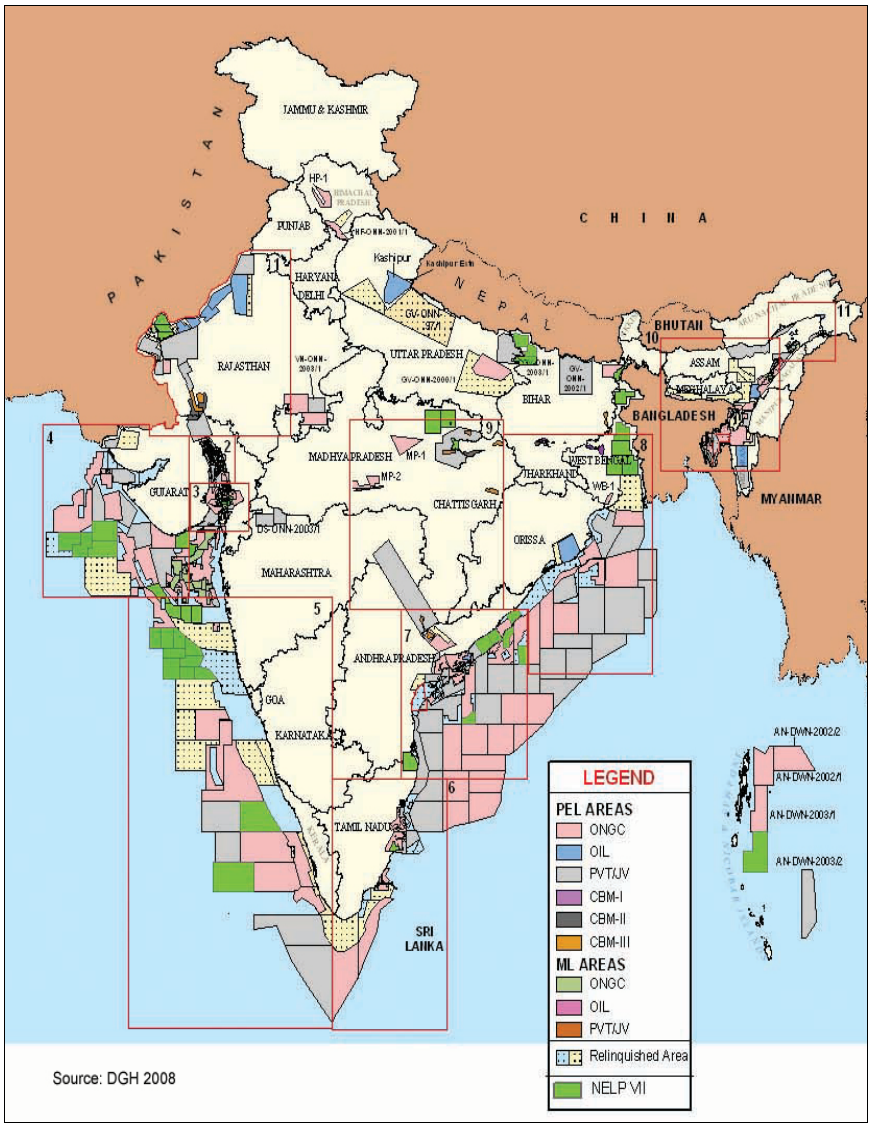


Figure 12. Brackish groundwater in India

As mentioned above, the algae biofuels technology could utilize another source of low-quality water, co-produced water, associated with oil and natural gas extraction. Unfortunately, data on co-produced water volumes and disposal methods in India was not available. It is possible that this information exists but was not obtained due to access constraints given the proprietary nature of this type of information. Figure 13 shows the geographic distribution of oil and natural gas fields in India to illustrate existing locations of produced water resources. This information could be used to guide future, more refined analysis related to this resource potential.



PEL – Petroleum Exploration License; ML – Mining Lease

Figure 13. Oil and gas fields in India

Production of crude oil in India is about 34 Mt annually or approximately 252 million barrels (bbl)[2] (MPNG 2009). The global average water cut (i.e., the ratio of water produced from a well compared to the volume of total liquids) is estimated at about 75% (The Oil Drum 2009). This means that about ¾ of the fluids brought up a well are water; therefore, this resource could be substantial in India. Natural gas wells typically produce much less water than oil wells (ANL 2009).

As shown in Figure 13, oil and natural gas in India are produced both onshore and offshore. Without information on the disposal method practiced in the country, it is difficult to estimate the

[2] 1 tonne = 7.4 barrels, assuming an average density of 0.85 g/cm³ (or kg/L or t/m³) and 159 L/bbl (oil barrel; 1 non-beer fluid barrel = 119 L)

amount of produced water that could be available for algae production. For offshore production activities, produced water is usually disposed of through direct ocean discharge after treatment, although sometimes it is transported to shore for disposal. Most of the production in India (about 70%) comes from offshore fields (MPNG 2009); therefore, it is possible that a large portion of the produced water in India is currently disposed of into the ocean. At onshore fields in many countries, most produced water is re-injected to maintain reservoir pressure and hydraulically drive oil toward a producing well (ANL 2009). A small portion of onshore-produced water is disposed of in onsite evaporation ponds or offsite treatment facilities, and some is used in agricultural and industrial activities if certain water quality conditions are met. The challenge to using produced water in the agricultural sector is its salinity, which is often greater than that of seawater. Moderately-saline produced water, up to 3,000 mg/L TDS, has been used for irrigation, but its continuous use, particularly in arid climates, leads to build-up of salts in the soil surface creating undesirable ecological conditions. The algae biofuels technology could take advantage of this poor-quality water by growing salt-tolerant species, thus avoiding pressure on freshwater resources. In addition to salt, however, there are other contaminants in produced water (oil and grease, inorganic and organic compounds, and radioactive material) that prevent its direct use and mandate treatment. These constituents could be harmful to algae as well. Detailed onsite evaluation of produced water resources would determine their potential for algae production.

Wastewater discharged from domestic, industrial, and agricultural activities is another source of low-quality water that could be used for algae production. Using wastewater effluent as pond medium in co-located algae farms with facilities treating sewage, industrial wastewater, and agricultural drainage waters provides a cost-effective solution not only to water but also to land and nutrients considerations because the wastewater treatment function would cover nearly all costs. There is also an environmental benefit of using the wastewater effluent for growing algae. These waters, particularly sewage effluent and agricultural runoff, are high in nutrients such as nitrate and phosphates and when released into rivers, lakes, or the ocean causes eutrophication—nutrient pollution—leading to negative impacts on water quality and aquatic ecosystems. Algae requires these nutrients to grow, as discussed in the next section of this report; therefore, using the wastewater effluent as an algae pond medium provides an effective way for nutrient removal and prevention of natural waters' pollution while creating a product with an economic value.

According to the Central Pollution Control Board (CPCB 2005), there are about 269 sewage treatment plants (STP) in India, of which 231 are operational and 38 are under construction, located in 160 cities and towns. Given that the majority of the population in the country lives in rural areas (about 70%) and the STP are located in urban areas, it is evident that sewage is not treated in rural areas and it is disposed of in nearby rivers, lakes, or the ocean. Perhaps the development of algae production facilities in rural areas coupled with wastewater treatment would stimulate not only economic growth in these areas but would also improve their environmental footprint. Similar benefits could be provided by using agricultural drainage waters for growing algae. Agricultural drainage water is the excess water that runs off the field at the low end of furrows, border strips, basins, and flooded areas during irrigation or rainfall. In some parts of the country, where water resources are scarce, drainage water is re-used to meet crop water requirements. This, however, is applicable to drainage water with relatively good quality. Often, in addition to high nutrients, drainage water is high in salt content or the salinity increases with each re-use, which prevents its use for irrigation, but it could be suitable for cultivating salt-tolerant algae species.

Sources of industrial wastewater include the iron and steel-manufacturing sector, mines and quarries, chemicals, and the food industries. It is estimated that a large quantity of industrial wastewater is generated in India: about 1,057 trillion cubic meters (Tm^3) in 1997 (Ravindranath et al. 2005). Most of this volume comes from steel plants (1,040 Tm^3), followed by the pulp and paper plants (7.2 Tm^3), distilleries (6 Tm^3), cotton plants (1.5 Tm^3), and other food-processing and chemicals facilities.

Figure 14 shows the location of STP and steel plants in India as well as the irrigated lands as a proxy for agricultural drainage waters. These locations should be further investigated as potential sites for co-locating algae farms, thus taking advantage of the existing infrastructure and providing ecological benefits to the area.

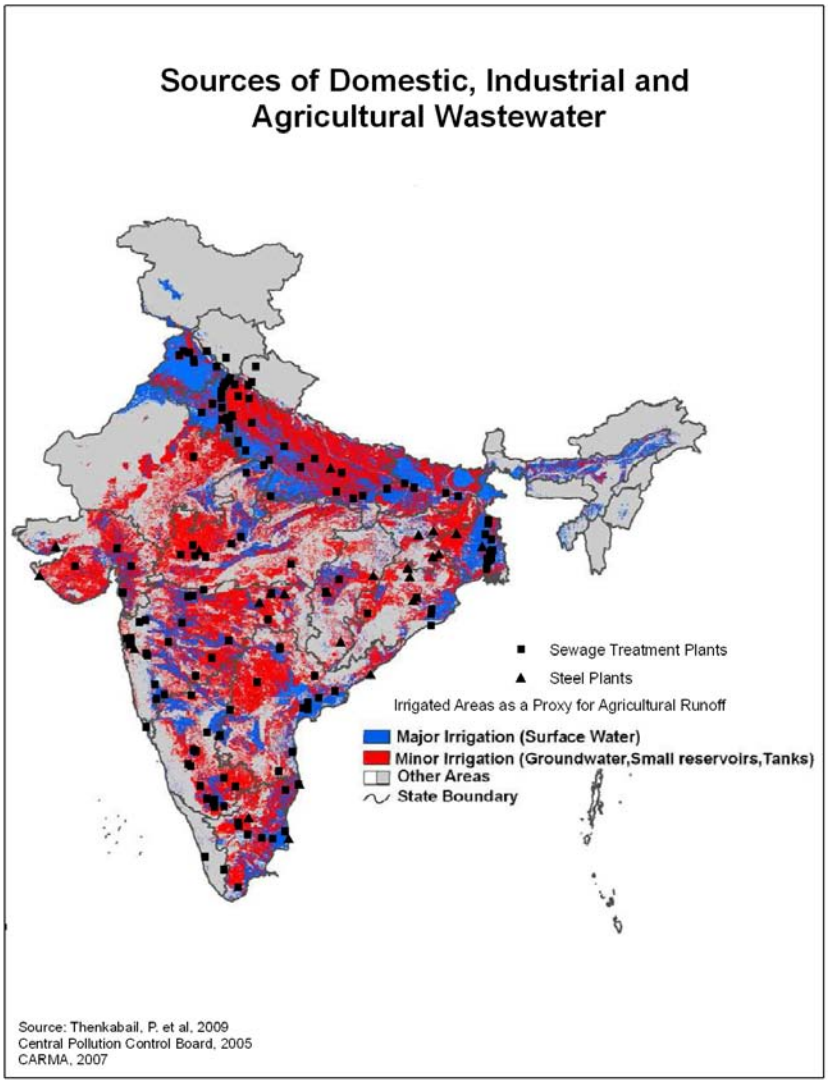


Figure 14. Sources of domestic, industrial, and agricultural wastewater

Carbon Dioxide and Other Nutrients

Optimal algae growth occurs in a CO_2-saturated environment. Therefore, algae production provides an excellent opportunity for the utilization of carbon emissions and serves as a complement to subsurface sequestration. India was the fourth-largest emitter of CO_2 in 2006, releasing 1,510 Mt into the atmosphere, or about 5% of the world total (United Nations 2009). The largest anthropogenic source of CO_2 emissions in India is the combustion of fossil fuels used in power generation, industrial processes, transportation, agriculture, commercial services, and the residential sector. It is expected that India will continue to expand coal power generation given its large coal reserves and increasing energy consumption. It is also expected that the transportation sector will continue to grow as vehicle ownership increases. Therefore, the country's continuous economic development, under a business-as-usual scenario, will lead to more CO_2 emissions in the future. The Indian Government projects that the country's CO_2 emissions will grow three to five times by 2031 (YSFES 2009).

Not all CO_2 emissions are suitable for capture. This is applicable to large stationary sources with high concentrations of CO_2. In India, these include thermal power plants, steel plants, cement plants, fertilizer plants, refineries, and petrochemical plants. Together, these facilities emitted 638 Mt of CO_2 in 2007, nearly half of the total CO_2 emissions in India (CARMA 2007). Figure 15 depicts the location of large stationary sources of CO_2 in India and their emissions in 2007. These facilities are widely distributed throughout the country with some large clusters providing an opportunity for large-scale algae production. The large clusters overlap with India's major industrial regions: Delhi, Mumbai, Ahmadabad, Kolkata, Madras, and Varanasi. There are other smaller clusters of stationary CO_2 sources in central India and around cities in other parts of the country.

The concept of co-locating large point sources of CO_2 with algae farming provides an effective approach to recycle the CO_2 into a useable liquid fuel. To put this into perspective, capturing around 20% of the 638 Mt of CO_2 released into the atmosphere from large stationary sources by algae for conversion to fuels would be enough to displace 30% of diesel fuel currently used in India[3]. This is based upon an estimated 40 gallons of algal oil (about 0.13 tonnes) per tonne of CO_2 consumed during algal biomass production at 30% lipid algal content by weight (USDOE 2009). Therefore, while it will not be practical to assume that algal production could absorb all CO_2 emissions from India's large stationary sources, the CO_2 resources available can yield large quantities of algal oils and ultimately transportation fuels.

[3] India's HSD (high speed diesel) consumption in 2008–2009 was 52 Mt (MPNG 2009).

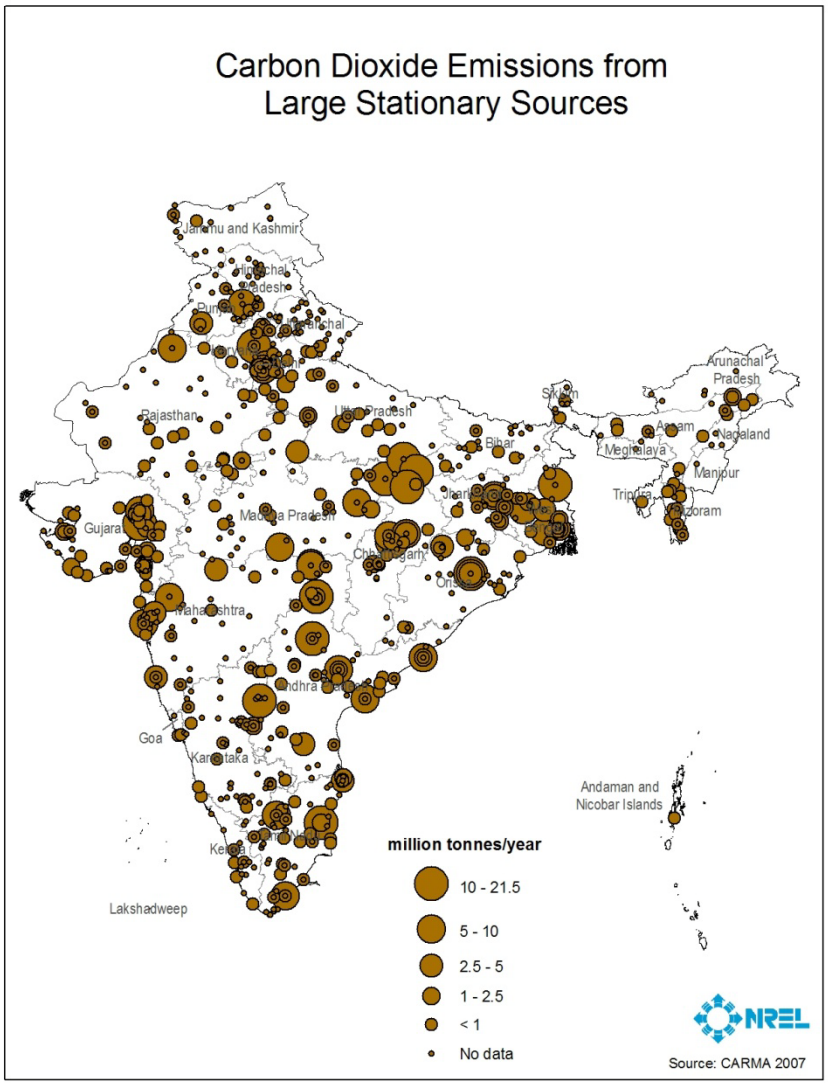


Figure 15. Carbon dioxide emissions from large stationary sources

In addition to CO_2, algae require nitrogen, phosphorous, sulfur, and other trace nutrients to grow; diatoms also require silicon for construction of the cell wall. For co-located algae farms with wastewater treatment facilities, the nitrogen and phosphorus would be provided by the effluent used as pond medium. For dedicated algae farms, sludge (the residual material left from the treatment process) could be used as well as animal manure, another nutrient-rich resource. It is important that dedicated algae farms be located near the nutrient sources to keep transportation costs low. Nitrogen could also be supplied by coal-burning power plants as nitrogen oxide (NOx). Additionally, coal-burning power plants could provide sulfur as sulfur oxide (SOx). Silicon for diatom growth will likely require supplementation. Figure 16 shows the distribution of nutrient sources in India to illustrate areas with opportunities for co-locating algae farms or situating them nearby. It must be noted that nutrient requirements, like growth temperature, must be maintained within an optimal range to promote maximal growth. Too little of any one particular nutrient will reduce the growth rate and conversely, too much of a nutrient can prove

toxic. Nutrient limitation can result in increased overall lipid content in algal cells, but it comes at the expense of overall productivity (USDOE 2009).

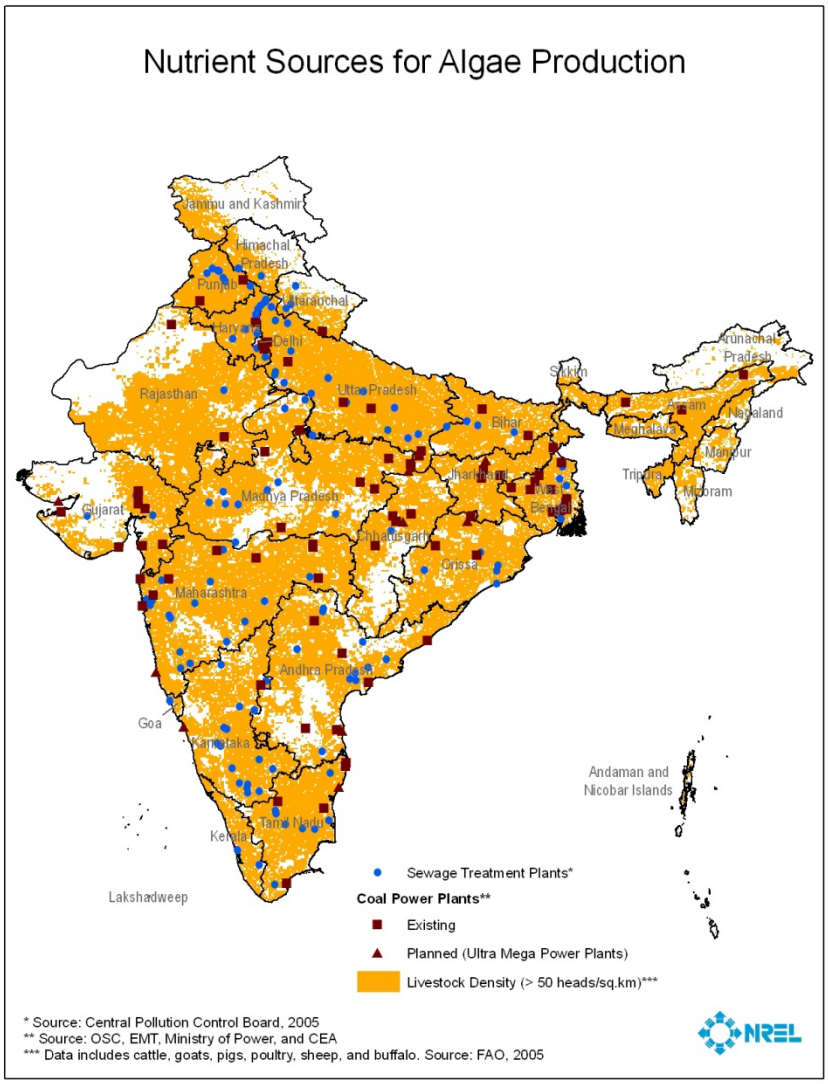


Figure 16. Nutrient sources for algae production

Land

India has a total land area of approximately 297 million hectares (Mha)[4]. The share of agricultural land in 2007 was significant, about 60% (180 Mha) of the total land area (FAOSTAT 2007). The majority of this land is under cultivation for food crops, and only about 3.5% (10.4 Mha) of the total land area is dedicated to pasture. Forest land covers about 22% of the country's area, and the remaining 14.5% is other land (e.g., build-up areas and barren land).

[4] Country area is about 328 Mha.

The availability of land for algae production in India will depend on many physical, economic, legal, social, and political factors. Physical characteristics, such as topography and soil, could limit the land available for algae farming in some locations. Topography would be a limiting factor for these systems since the installation of large shallow ponds requires relatively flat terrain. Areas with more than a 5% slope[5] can be effectively eliminated from consideration due to the increased costs of site development. Soils, and particularly their porosity/permeability characteristics, affect the construction costs and design of open systems by virtue of the need for pond lining or sealing. Soils with low permeability (such as clay soils) are good for aquaculture as the water loss through seepage or infiltration is low. Figure 17 illustrates areas with flat terrain in India as well as locations where they overlap with clay soils. It shows that the majority of the country is suitable for algae production from topography's perspective except the mountain areas in the north, east, and some internal parts of the country. Large portions of central and eastern states such as Madhya Pradesh Maharashtra, Karnataka, and Gujarat have a combination of flat terrain and clay soils. Clay soils suggest challenges for food crop production but are the preferred soil type for installation of algae ponds; thus, they may present an opportunity for algae farming in areas where they exist. A more refined examination of these soils, including spatial distribution and land use, would determine the possibility of siting algae farms in the areas outlined in Figure 17.

[5] Slope is steepness of the landscape. It is measured in degrees or as a percentage. Percent Slope = Rise/Run*100. For example, a rise of 2 meters over a distance of 100 meters describes a 2% slope. In general, 0%–5% slope is considered flat area, gentle slope is 6%–10%, moderate slope is 11%–25%, and steep slope is 25% and greater.

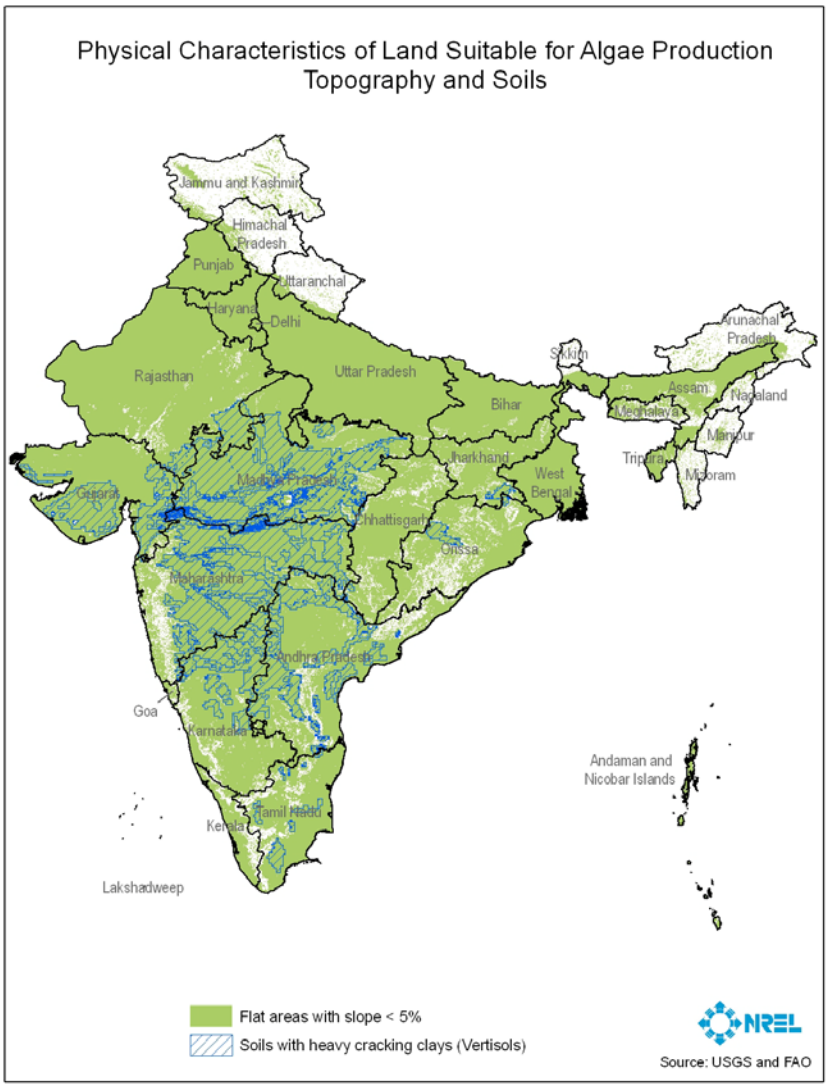


Figure 17. Physical characteristics of land suitable for algae production

Land use is a very important consideration in evaluating locations suitable for algae farming, and certain land use categories will limit the land available to this technology. These categories include agricultural and forest lands, protected areas and other environmentally sensitive areas (such as biodiversity hot spots), and lands with cultural and historic value. Agricultural land in India covers a large portion of the country, as illustrated in Figure 18. Therefore, to avoid competition with food/feed/livestock production, algae technology should focus on the degraded portions of these lands, called "wastelands" in India. The wastelands include degraded cropland and pasture/grazing land as well as degraded forest, industrial/mining wastelands, and sandy/rocky/bare areas. The Ministry of Rural Development's Department of Land Resources and the National Remote Sensing Agency (MRD-NRSA 2005) developed a very detailed assessment of wastelands in India. It estimated that the extent of these lands is about 55 Mha (approximately 17% of total land area). States with the largest amount of wasteland include Rajasthan, Jammu and Kashmir, Madhya Pradesh, Maharashtra, and Andhra Pradesh. The results

of this study are shown in Table 1, and the Appendix contains state-specific maps illustrating the spatial distribution of these lands (Figures 28–59). This information would be very useful to policymakers and industry developers in selecting the most suitable locations for algae farming.

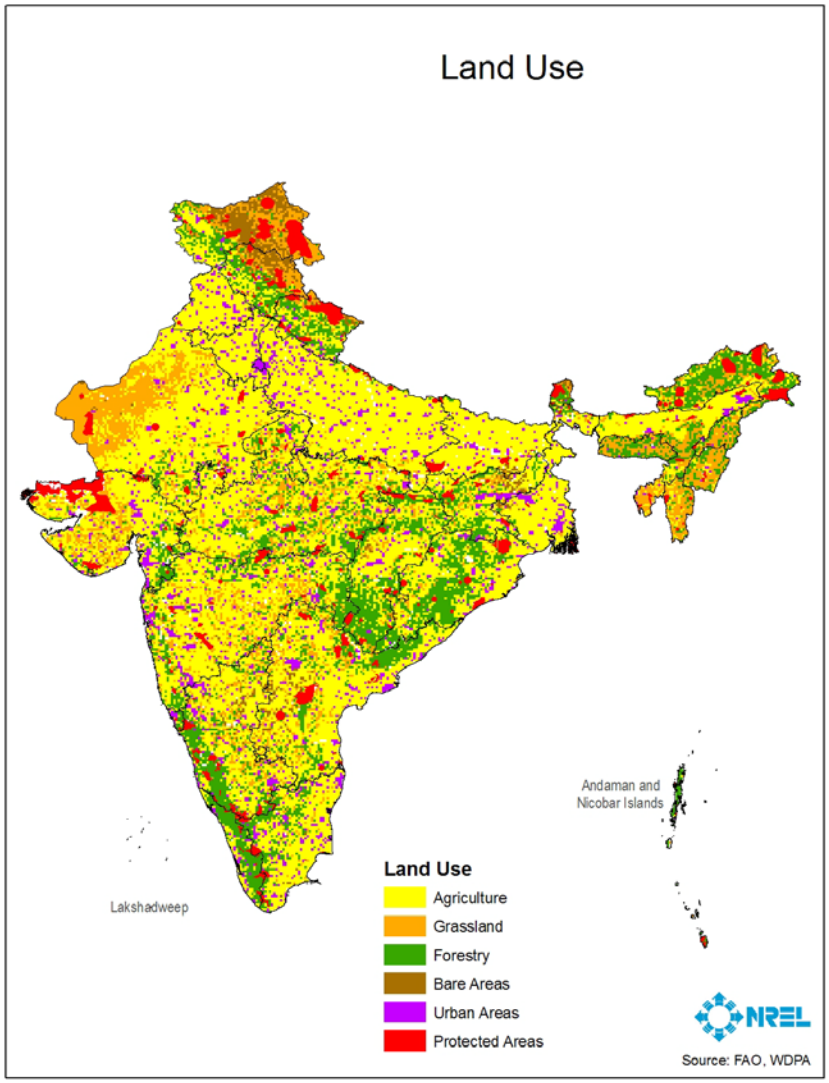


Figure 18. Land use

Table 1. Wasteland in India by State

State	Total Area (ha)	Wasteland	
		ha	%
Andaman and Nicobar	824,900	N/A	N/A
Andhra Pradesh	27,506,800	4,526,700	16.46
Arunachal Pradesh	8,374,300	1,817,600	21.70
Assam	7,843,800	1,403,400	17.89
Bihar	9,417,100	544,400	5.78
Chandigarh	14,400	N/A	N/A
Chhattisgarh	13,519,400	758,400	5.61
Dadra and Nagar Haveli	49,100	N/A	N/A
Daman and Diu	12,200	N/A	N/A
Delhi	148,300	N/A	N/A
Goa	370,200	53,100	14.34
Gujarat	19,602,400	2,037,800	10.40
Haryana	4,421,200	326,600	7.39
Himachal Pradesh	5,567,300	2,833,700	50.90
Jammu and Kashmir*	22,223,600	7,020,200	31.59
Jharkhand	7,970,600	1,116,500	14.01
Karnataka	19,179,100	1,353,700	7.06
Kerala	3,886,300	178,900	4.60
Lakshadweep	3,200	N/A	N/A
Madhya Pradesh	30,825,200	5,713,400	18.53
Maharashtra	30,769,000	4,927,500	16.01
Manipur	2,232,700	1,317,500	59.01
Meghalaya	2,242,900	341,100	15.21
Mizoram	2,108,100	447,000	21.20
Nagaland	1,657,900	370,900	22.37
Orissa	15,570,700	1,895,300	12.17
Puducherry	49,200	N/A	N/A
Punjab	5,036,200	117,300	2.33
Rajasthan	34,223,900	10,145,400	29.64
Sikkim	709,600	380,800	53.66
Tamil Nadu	13,005,800	1,730,300	13.30
Tripura	1,048,600	132,300	12.62
Uttar Pradesh	24,092,800	1,698,400	7.05
Uttaranchal	5,348,300	1,609,700	30.10
West Bengal	8,875,200	439,800	4.96
Total	**328,730,300**	**55,237,700**	**16.80**

Source: MRD–NRSA 2005; * Area not surveyed: 12,084,900 ha

Other considerations that may limit the land available for algae production are land ownership and land price. Land ownership information provides valuable insights on which policies and parties could affect project development. In India, most of the agricultural land is privately owned and some is under the jurisdiction of state governments. State governments often are the middleman in land acquisition and distribution. The majority of farm holdings are small—the average size of operational farms is about 1.18 ha (New Agriculturist 1999). Therefore, acquiring land for large-scale production of algae may present some challenges considering that the process may have to involve many parties; although, land takeover in India is not considered a problem when adequate compensation is offered.

Data on land prices in India is difficult to obtain due to the high variability between and within the states. Land prices are hard to generalize because they depend on numerous factors including location, availability of water, and proximity to transportation infrastructure. Unfortunately, no centralized agency that collects and disseminates this type of information was identified. Given that the algae technology's strategy is to use wastelands and low-quality water, it is expected that the price of those lands would be favorable.

A rather large surface area would be required for commercial-scale algae production (either open ponds or PBRs). This is due to the fact that increasing culture depth does not increase productivity per unit area because solar radiation cannot penetrate deep into the culture. In other words, light is ultimately the limiting resource. Algae productivity is measured in terms of biomass produced per day per unit of horizontal surface area. Assuming a reasonably conservative average productivity of between 8 and 20g/m^2/day with 15% oil content on a dry weight basis, a hectare could produce about 4 to 10 tonnes (t) of algal oil (biodiesel) per year, which is double the value of the next highest producing crop, oil palm, which generates between 2 and 5 t/ha/yr. India's current diesel consumption is 52 Mt per year (MPNG 2009). Therefore, to substitute 20% of this consumption, algae production would need about 1–2.6 Mha while *Jatropha curcas,* another feedstock considered for biodiesel production in the country, with best yield of 1 t/ha/yr would need 10.4 Mha of land (most likely requiring irrigation and fertilizer). Moreover, an aggressive R&D program has the potential to reach much higher productivity—theoretical analyses indicate that productivity of over 37 t/ha/yr are possible (Weyer et al. 2009). Therefore, the land needed for algae production to substitute 20% of current diesel consumption would be much less, about 280,000 ha, and approximately 1.4 Mha would displace the country's entire diesel consumption. Figure 19 and Table 2 illustrate visually and statistically the diesel consumption by state and the land area needed for algae production to meet this demand (indicated by boxes in Figure 19) using an average near-term productivity rate of 7 t/ha/yr.

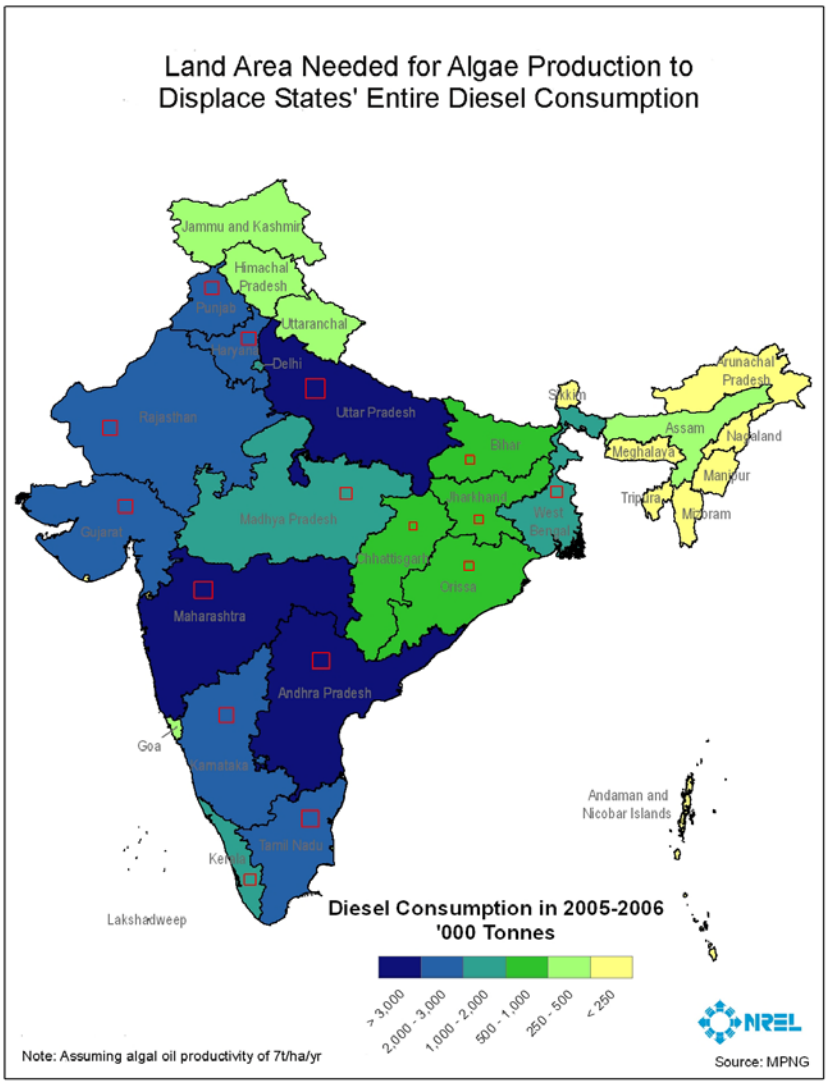


Figure 19. Land area needed for algae production to displace states' entire diesel consumption

Table 2. Land Area Needed for Algae Production to Displace States' Entire Diesel Consumption

State	Total Land Area (ha)	Diesel Consumption in 2005-06 (tonnes)*	Area Needed for Algae Production to Displace States' Entire Diesel Consumption	
			ha	%
Andaman and Nicobar	824,900	73,571	10,510	1.27
Andhra Pradesh	27,506,800	3,232,424	461,775	1.68
Arunachal Pradesh	8,374,300	44,682	6,383	0.08
Assam	7,843,800	446,960	63,851	0.81
Bihar	9,417,100	921,393	131,628	1.40
Chandigarh	14,400	63,578	9,083	63.07
Chhattisgarh	13,519,400	610,297	87,185	0.64
Dadra and Nagar Haveli	49,100	60,403	8,629	17.57
Daman and Diu	12,200	52,055	7,436	60.95
Delhi	148,300	1,163,193	166,170	112.05
Goa	370,200	272,535	38,934	10.52
Gujarat	19,602,400	2,056,946	293,849	1.50
Haryana	4,421,200	2,306,747	329,535	7.45
Himachal Pradesh	5,567,300	306,835	43,834	0.79
Jammu and Kashmir	22,223,600	365,778	52,254	0.24
Jharkhand	7,970,600	889,122	127,017	1.59
Karnataka	19,179,100	2,387,767	341,110	1.78
Kerala	3,886,300	1,333,875	190,554	4.90
Lakshadweep	3,200	4,323	618	19.30
Madhya Pradesh	30,825,200	1,380,531	197,219	0.64
Maharashtra	30,769,000	3,345,770	477,967	1.55
Manipur	2,232,700	31,939	4,563	0.20
Meghalaya	2,242,900	165,090	23,584	1.05
Mizoram	2,108,100	25,825	3,689	0.18
Nagaland	1,657,900	27,045	3,864	0.23
Orissa	15,570,700	966,823	138,118	0.89
Puducherry	49,200	257,920	36,846	74.89
Punjab	5,036,200	2,110,946	301,564	5.99
Rajasthan	34,223,900	2,412,911	344,702	1.01
Sikkim	709,600	33,293	4,756	0.67
Tamil Nadu	13,005,800	2,981,109	425,873	3.27
Tripura	1,048,600	42,941	6,134	0.59
Uttar Pradesh	24,092,800	4,014,981	573,569	2.38
Uttaranchal	5,348,300	324,086	46,298	0.87
West Bengal	8,875,200	1,593,997	227,714	2.57
Total	**328,730,300**	**36,307,691**	**5,186,813**	**1.58**

*Source: MPNG 2009

Site-Suitability Analysis

This section builds upon the results of the resource evaluation conducted previously to identify areas in India suitable for algae farming. Two algae production facility types are considered: *co-located* facilities, which produce algal biomass as a consequence of another process, and *dedicated* facilities, with the main purpose of algae production. Co-located facilities are those operating in conjunction with wastewater treatment where algae are produced as a byproduct of the wastewater treatment process. In the near-term, algae production at wastewater treatment facilities is considered the "low-hanging fruit" of algal biofuels. The knowledge and experience gained at these facilities could provide the base, in the long-term, for stand-alone, dedicated biofuels production systems. As mentioned earlier, using the wastewater effluent as pond medium provides a cost-effective solution to water, land, and nutrients considerations because the wastewater treatment function would cover nearly all costs. Given the favorable climate conditions in India—considerable sunshine and generally warm weather—and simplicity of construction and operation, engineered waste stabilization ponds (WSP) are successfully operating in the country as one of the main wastewater treatment technologies. WSP are any pond or pond system designed for biological waste treatment. These ponds present an opportunity for early development of algae production systems in India. Microalgae, unlike terrestrial plants that capture CO_2 from the atmosphere, require concentrated sources of CO_2, such as power plants flue gas, for high productivity. Therefore, if algae farming is considered in conjunction with sewage wastewater treatment, additional CO_2 would be needed, preferably from a nearby source to keep the transportation costs low. Figure 20 shows the location of WSPs in India and the proximity of stationary CO_2 sources to illustrate opportunities for co-locating algae farms. It also shows the location of steel plants, a major source of industrial wastewater in the country. The steel industry, in addition to being capable of providing water, can also supply CO_2 for the cultivation of algae. If algae farming is considered in conjunction with steel plants, it most likely will require additional nutrients. The steel plants illustrated in Figure 20 are located in areas with a large concentration of livestock production, which could supply animal manure as algae fertilizer.

The analysis of potential locations for co-located algae facilities considers only domestic (WSP in particular, not all sewage treatment plants) and industrial wastewater treatment facilities (steel plants). Agricultural wastewater (such as drainage water) is not included due to lack of data; therefore, there are additional opportunities for co-locating algae farms in other parts of the country that should be further investigated.

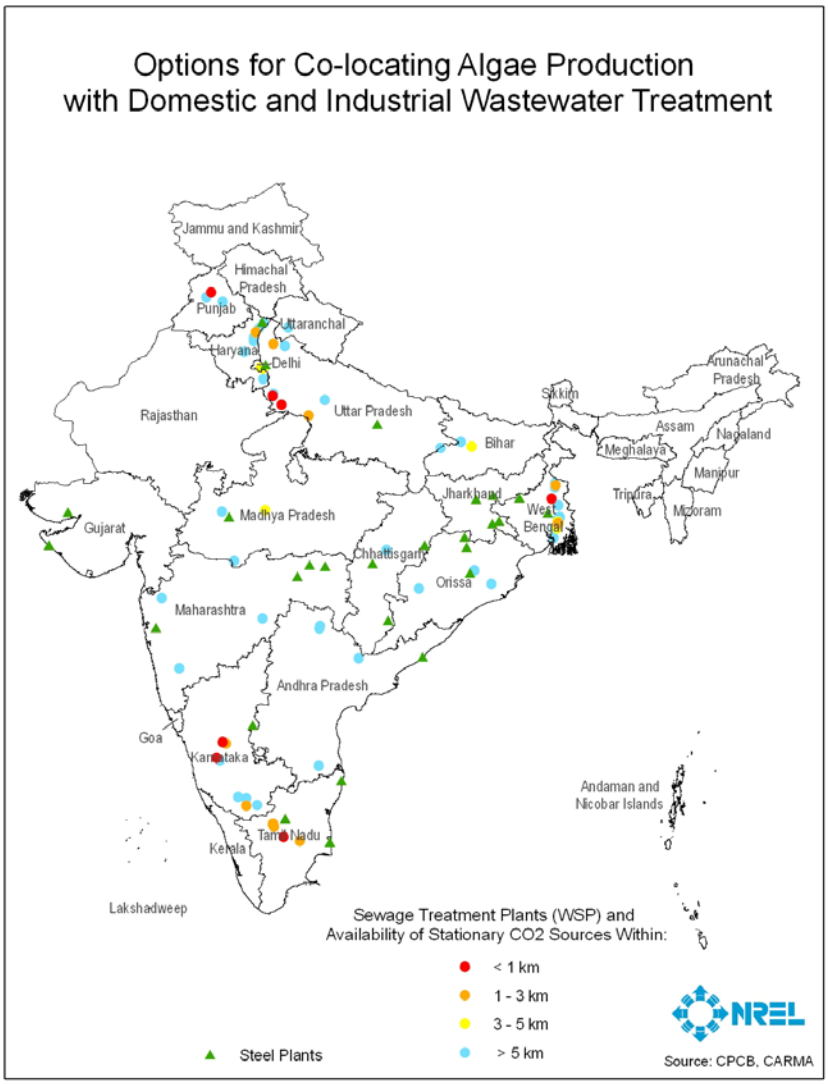


Figure 20. Options for co-locating algae production with domestic and industrial wastewater treatment

To identify suitable locations for dedicated algae farms in India, this study applies a series of steps as outlined in Figure 21 using GIS techniques. The analysis is centered on the stationary industrial CO_2 sources given key advantages of co-locating algae production with these facilities: supplying carbon for enhanced algal growth with low/no transportation costs and a means for capturing CO_2 before it is released to the atmosphere, thus providing potential carbon credits for utilities and industrial facilities. This combination of enhanced algal growth and GHG reduction makes co-location of algal cultivation with industrial CO_2 sources a promising option for future dedicated algae farms in India.

The analysis begins with the location of stationary CO_2 sources in India and looks for areas where these facilities coincide with other inputs necessary for algae growth or conditions that meet the engineering, economic, environmental, and social requirements for this technology.

These include flat terrain, sufficient solar radiation and daily sunshine hours, and availability of low-quality water and nutrients. In addition, these locations and their surrounding areas need to be outside of protected areas and wetlands, road accessible, and in proximity to populated places (labor availability). The results of this analysis are illustrated in Figure 22. Based on the available information, the most suitable locations for algal cultivation facilities in India are in the western and southern parts of the country and along coastal areas.

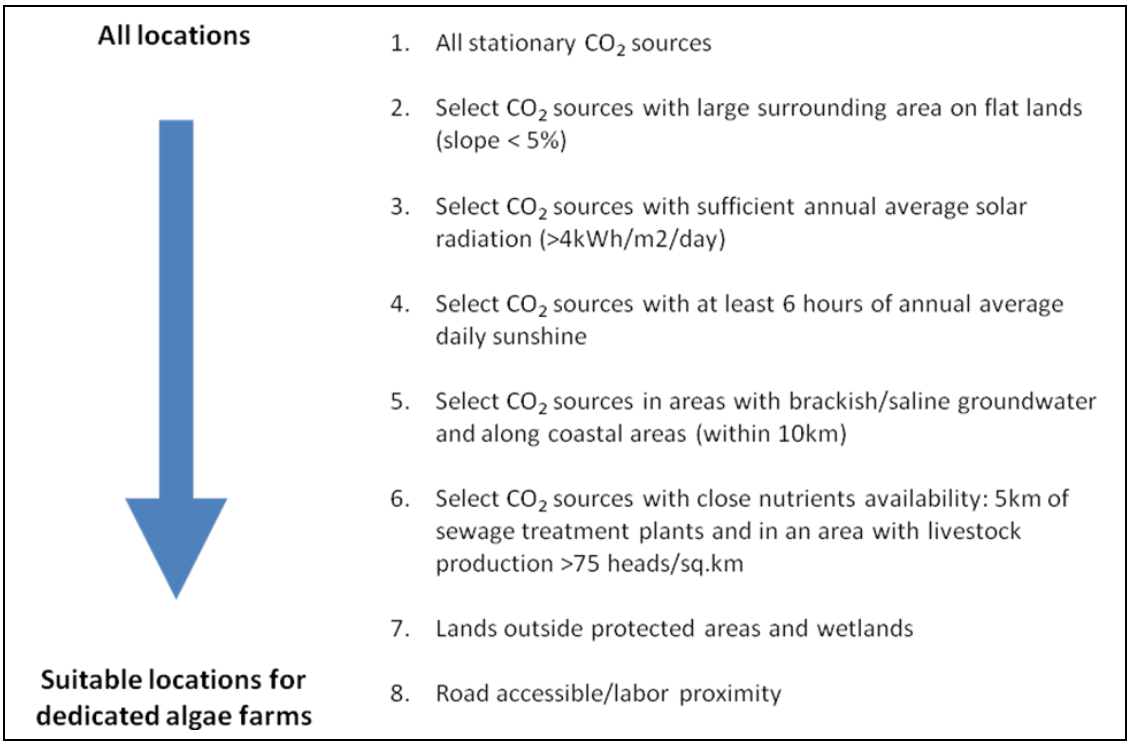


Figure 21. Methodology for selecting suitable locations for dedicated algae farms

The next step in the analysis, which is beyond the scope of this project, is to evaluate the land availability for algae farming around the suitable stationary CO_2 sources, preferably wastelands, to avoid competition with valuable fertile agricultural land. This evaluation would be able to determine whether or not the wastelands estimated by the MRD-NRSA (2005) are actually available for algae production because some of these lands could already be in use. This detailed level of information is not readily available; thus, the analysis should be performed on site. Also, the land availability would be determined by the size of potential algae farms. A general examination of the suitable stationary CO_2 sources (Figure 22) and wastelands in India (Appendix) suggests that most of these sources are surrounded by or in close proximity to wastelands. Further, more detailed analysis would reveal the potential for algae production on these lands.

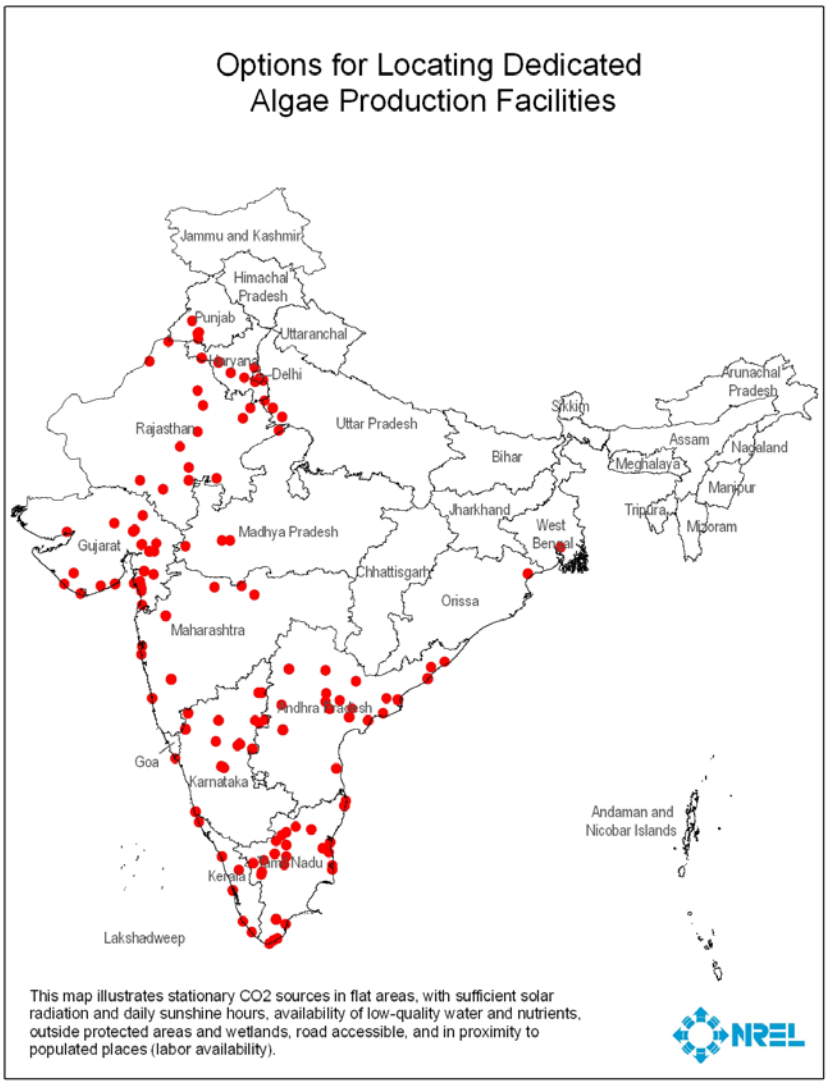


Figure 22. Options for locating dedicated algae production facilities

Conclusions

The results of this study indicate that India has very favorable conditions to support algae farming for biofuels production. Most of the country meets the climate requirements for growing algae: sufficient solar radiation, sunshine hours, and warm temperatures. A large number of stationary CO_2 sources—thermal power plants, steel plants, cement plants, fertilizer plants, refineries, and petrochemical plants—are scattered throughout the country thereby providing opportunities for co-locating algae farms and recycling the CO_2 into a useable liquid fuel. Given the country's large concentration of population and agricultural activities, human and animal organic wastes are available as sources of nutrients such as nitrogen and phosphorous needed for algae growth.

Water resources in many parts of India are limited. Therefore, in order to be sustainable, the algae biofuels technology should not put additional demand on freshwater supplies and use low-quality water such as brackish/saline groundwater, co-produced water associated with oil and natural gas extraction, agricultural drainage waters, and other wastewaters. Although information on the quantity of these water resources in India is not available, the intensity of activities associated with their production suggests that there is a vast potential in the country.

Sustainable algae production also implies that the farming facilities would not be located on valuable fertile agricultural lands but on marginal lands (classified as wastelands in India). These lands include degraded cropland and pasture/grazing land, degraded forest, industrial/mining wastelands, and sandy/rocky/bare areas. It is estimated that the extent of these lands in the country is about 55.27 Mha (approximately 18% of the total land area). If India dedicates only 10% (5.5 Mha) of its wasteland to algae production, it could yield between 22–55 Mt of algal oil[6] which would displace 45%–100% of current diesel consumption[7]. The production of this amount of algae would consume about 169–423 Mt of CO_2[8] which would offset 26%–67% of the current emissions[9].

This study illustrated options for siting two algae production facility types: co-located facilities, which produce algal biomass as a consequence of another process, and dedicated facilities, with the main purpose of algae production. Co-located facilities are those operating in conjunction with wastewater treatment where algae are produced as a byproduct of the wastewater treatment process. Using the wastewater effluent as pond medium provides a cost-effective solution to water, land, and nutrients considerations because the wastewater treatment function would cover nearly all costs. Domestic and industrial wastewater treatment facilities were considered in the analysis as potential sites for co-locating algae farms. This opportunity exists in most of the states in India.

The site-suitability analysis for dedicated algae farms was centered on the stationary industrial CO_2 sources given key advantages of co-locating algae production with these facilities:

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[6] Assuming algal oil productivity between 4–10 t/ha/yr.
[7] India's HSD (high speed diesel) consumption in 2008–2009 was 52 Mt (MPNG 2009).
[8] Assuming for every 40 gallons of algal oil (about 0.13 tonnes), a tonne of CO_2 is consumed during the algal biomass production at 30% lipid algal content by weight (USDOE 2009).
[9] Stationary CO_2 sources emitted 638 Mt of CO_2 in 2007, nearly half of the total CO_2 emissions in India (CARMA 2007).

supplying carbon for enhanced algal growth with low/no transportation costs and a means for capturing CO_2 before it is released to the atmosphere, thus providing potential carbon credits for utilities. The study considered stationary CO_2 sources in areas where these facilities coincide with other inputs necessary for algae growth or conditions that meet the engineering, economic, environmental, and social requirements for this technology. The results of this analysis indicate that suitable locations for dedicated algae farms are in the western and southern parts of the country and along coastal areas.

It is important to note that the quality of the data used in this study is uncertain (most datasets were not checked for accuracy), and that due to lack of data, some resources were not evaluated (particularly co-produced water and agricultural wastewater). Therefore, the results of the site-suitability analysis are not complete and additional opportunities for co-located or dedicated algae farming systems most likely exist in other parts of the country. The purpose of this site-suitability analysis was to illustrate a methodology for refining the prospecting process of site identification and serve as a base for further analysis. This methodology could be revised to include other inputs if additional data are made available.

Future work could focus on validating the quality of existing data and gathering additional information such as the location of agricultural runoff collection sites, evaporative ponds used by the oil/gas production and mining industry, and other wastewater treatment facilities. It would also be helpful to collect information on the volume of wastewater. An analysis of the location and volume of low-quality water resources in India would be particularly useful in understanding better this resource potential not only for the production of algae biofuels but for other technologies as well.

India is a large country with diverse landscape and resources. Therefore, future work could focus on a state or even smaller geographic area to provide a more detailed examination of the resource potential for algae production and pinpoint the most suitable locations. The authors believe that the information provided in this study will serve as a base for further analysis of the algae biofuels potential in India and assists policymakers and industry developers in their strategic decisions.

References

Argonne National Laboratory (ANL). (September 2009). "Produced Water Volumes and Management Practices in the United States." http://www.ead.anl.gov/pub/doc/ANL_EVS__R09_produced_water_volume_report_2437.pdf. Accessed May 27, 2010.

Brown, L. (2007). "Aquifer Depletion." The Encyclopedia of Earth. http://www.eoearth.org/article/Aquifer_depletion. Accessed May 27, 2010.

Carbon Monitoring for Action (CARMA). (2007). http://carma.org/. Accessed December 2009.

Central Ground Water Board (CGWB), Ministry of Water Resources. (2006a). "Dynamic Groundwater Resources of India." http://cgwb.gov.in/GroundWater/GW_assessment.htm. Accessed May 27, 2010.

Central Ground Water Board (CGWB), Ministry of Water Resources. (2006b). "Groundwater Quality Monitoring." http://cgwb.gov.in/GroundWater/Gw_quality.html. Accessed November 2009.

Central Ground Water Board (CGWB), Ministry of Water Resources. (2006c). "State Profile: Districts Affected by Salinity." http://cgwb.gov.in/gw_profiles/st_ap.htm. Accessed November 2009.

Central Intelligence Agency (CIA). (2009). "Total Renewable Water Resources." The World Factbook. https://www.cia.gov/library/publications/the-world-factbook/fields/2201.html. Accessed November 2009.

Central Pollution Control Board (CPCB). "Status of Sewage Treatment in India". November 2005. New Delhi, India.

Chandrasekharam, D. (2009). "Geothermal Energy Resources in India." http://www.geosyndicate.com/dchandra/geoenergyresource.html. Accessed December 2009.

Chelf, P.; Brown, L.M. (1989). "Microalgae Mass Culture and the Greenhouse Effect: Resources Update." Aquatic Species Program Annual Report (Bollmeier, W.S.; Sprague, S., eds.). SERI/SP-231-3579. Golden, CO: Solar Energy Research Institute, pp. 9-15.

Chisti, Y. (2007). "Biodiesel from Microalgae." *Biotechnology Advances* (25); pp. 294-306.

Directorate General of Hydrocarbons (DGH), Ministry of Petroleum and Natural Gas. (2008). "Petroleum Exploration and Production Activities in India 2007-08." Noida, India.

Eriksen, N.T. (2008) "The Technology of Microalgal Culturing." *Biotechnology Letters* (30); pp. 1525-1536.

FAO. (2004). "Land and Livelihoods: Making Land Rights Real for India's Rural Poor." http://www.fao.org/docrep/007/j2602e/j2602e00.htm. Accessed May 27, 2010.

FAOSTAT. (2007). "Land Use Database" http://faostat.fao.org/site/377/default.aspx#ancor. Accessed February 2010.

Feinberg, D.A.; Karpuk, M.E. (1990). *CO_2 Sources for Microalgae Based Liquid Fuel Production.* SERI /TP-232-3820. Golden, CO: Solar Energy Research Institute.

Harihara Ayyar, P.S. (1972). "Water Resources of India in the Form of Rainfall." India Meteorological Department. New Delhi-110003.

Hindustan Times. (August 2005). "Annual Average Rainfall During Last Five Years Estimated." http://www.highbeam.com/doc/1P3-1093149621.html. Accessed May 27, 2010.

Hu, Q; Sommerfield, M; Jarvis, E; Ghirardi, M; Posewitz, M; Seibert, M; et al. (2008). "Microalgal Triacylglycerols as Feedstocks for Biofuel Production: Perspectives and Advances." *Plant Journal* (54); pp. 621–639.

Huesemann, M.H.; Benemann, J.R. (2008). "Biofuels from Microalgae: Review of Products, Processes, and Potential, with Special Focus on Dunaliella Species." Ben-Amotz, A.; Polle, J.E.W.; Subba Rao, D.V., eds. *The Alga Dunaliella: Biodiversity, Physiology, Genomics, and Biotechnology,* New Hampshire: Science Publishers.

India Meteorological Department (IMD). (2009). "Solar Radiant Energy Over India." New Delhi.

Indian Institute of Tropical Meteorology Pune (via India Water Portal). "Physiographic Rainfall Variations Across India 1813-2006". http://www.indiawaterportal.org/image/6126. Accessed October 2009.

International Energy Agency. (2007). "World Energy Outlook 2007: China and India Insights." http://www.iea.org/weo/2007.asp. Accessed May 27, 2010.

International Energy Agency, Greenhouse Gas Programme. (May 2008). *A Regional Assessment of the Potential for CO_2 Storage in the Indian Subcontinent.* Report No.2008/2. Cheltenham, UK

Jain, K.S.; Agarwal, P.K.; Singh, V.P. (2007). *Hydrology and Water Resources of India.* Dordrecht, The Netherlands: Springer.

Kumar, R., Singh. R.D., Sharma K.D. (September 2005). "Water Resources of India." Current Science. Volume 89, No 5

Lardon, L.; Helias, A.; Sialve, B.; Steyer, J.P.; Bernard, O. (2009). "Life-Cycle Assessment of Biodiesel Production from Microalgae." *Environmental Science and Technology* (43: 17); pp. 6475–6481.

Meier, R.L. (1955). "Biological Cycles in the Transformation of Solar Energy into Useful Fuels." Daniels, F.; Duffie, J.A., eds. *Solar Energy Research,* Madison, WI: University of Wisconsin Press; pp. 179–183.

Ministry of New and Renewable Energy (MNRE). (2009). "National Policy on Biofuels", New Delhi, India. http://www.mnre.gov.in/policy/biofuel-policy.pdf. Accessed January 13, 2010

Ministry of Petroleum and Natural Gas (MPNG). (2009). "Basic Statistics on Indian Petroleum and Natural Gas 2008-09." New Delhi, India.

Ministry of Rural Development (Department of Land Resources) and National Remote Sensing Agency (MRD-NRSA). (2005). "Wastelands Atlas of India." http://dolr.nic.in/WastelandsAtlas2005/Wasteland_Atlas_2005.pdf. Accessed May 27, 2010.

Ministry of Water Resources (MWR). "National Water Resources at a Glance." http://wrmin.nic.in/index2.asp?sublinkid=290&langid=1&slid=412. Accessed November 2009.

Muneer, T.; Asif, M.; Munawwar, S. (2004). "Sustainable Production of Solar Electricity with Particular Reference to the Indian Economy." *Renewable and Sustainable Energy Reviews*, Volume 9, Issue 5, October 2005, Pages 444-473

U.S. National Aerospace and Space Administration (NASA). (2009). "NASA Satellites Unlock Secret to Northern India's Vanishing Water." http://www.nasa.gov/topics/earth/features/india_water.html. Accessed October 2009.

National Informatics Centre, National Portal of India.(2005). "Rivers." http://india.gov.in/knowindia/rivers.php. Accessed November 2009.

National Institute of Hydrology (NIH). "Evaporation in India." http://www.nih.ernet.in/nih_rbis/india_information/evaporation.htm. Accessed November 2009.

New Agriculturist. (May 1999). "Country Profile – India." http://www.new-ag.info/country/profile.php?a=883 . Accessed May 27, 2010.

The Oil Drum. (2009). "Produced Water, GOSPs and Saudi Arabia." http://www.theoildrum.com/node/6052 . Accessed May 27, 2010.

Ravindranath, NH and Somashekar, HI and Nagaraja, MS and Sudha, P and Sangeetha, G and Bhattacharya, SC and Salam, Abdul P. (2005). "Assessment of Sustainable Non-Plantation Biomass Resources Potential for Energy in India." *Biomass and Bioenergy* (29); pp. 178–190.

Richmond, A. (2004). "Mass Cultivation of Microalgae." *Handbook of Microalgal Culture.* Blackwell Science Ltd.; pp. 95-252.

Rubin, E. (2005). "Carbon Dioxide Capture and Storage." IPCC Technical Summary.

Sheehan, J.; Dunahay, T.; Benemann, J.; Roessler, P. (1998). *A Look Back at the U.S. Department of Energy's Aquatic Species Program – Biodiesel from Algae.* NREL/TP-580-24190. U.S. Department of Energy's Office of Fuels Development, Washington DC.

Singh, N.; et al. (2005). Indian Institute of Tropical Meteorology. "Spatial Variation of Moisture Regions and Rainfall Zones of India During 1871-2003." Pune, Maharashtra, India.

Prasad S. Thenkabail, Venkateswarlu Dheeravath, Chandrashekhar M. Biradar, Obi Reddy P. Gangalakunta, Praveen Noojipady, Chandrakantha Gurappa, Manohar Velpuri, Muralikrishna Gummaand, Yuanjie Li (2009). "Irrigated Area Maps and Statistics of India Using Remote Sensing and National Statistics." *Remote Sensing Journal* (1); pp. 50-67.

Ugwu, C.U.; Aoyagi, H.; Uchiyama, H. (2007). "Photobioreactors for Mass Cultivation of Algae." *Bioresource Technology* (99); pp. 4021-4028.

United Nations: Millennium Development Goals Indicators. (2009). "Carbon Dioxide Emissions 2006." http://mdgs.un.org/unsd/mdg/SeriesDetail.aspx?srid=749&crid=. Accessed January 2010.

U.S. Department of Energy Biomass Program (USDOE). (2009). "National Algal Biofuels Technology Roadmap." https://e-center.doe.gov/iips/faopor.nsf/UNID/79E3ABCACC9AC14A852575CA00799D99/$file/AlgalBiofuels_Roadmap_7.pdf. Accessed May 27, 2010.

U.S. Geological Survey (USGS). (2010). "Saline Water" http://ga.water.usgs.gov/edu/saline.html. Accessed January 2010.

Warner, D.L. (2001). *Technical and Economic Evaluations of the Protection of Saline Groundwater Under the Safe Drinking Water Act and the UIC Regulations.* Report submitted to the Ground Water Protection Council, http://www.gwpc.org.

Weyer, K.M.; Bush, D.R.; Darzins, A.; Wilson, B.D. (2009). "Theoretical Maximum Algal Oil Production." *Bioenergy Research* DOI 10.1007/s12155-009-9046-x.

Yale School of Forestry and Environmental Studies (YSFES). (September 2009). "India's CO2 Emissions To At Least Triple in Next 20 Years." http://e360.yale.edu/content/digest.msp?id=2038. Accessed May 27, 2010.

Appendix

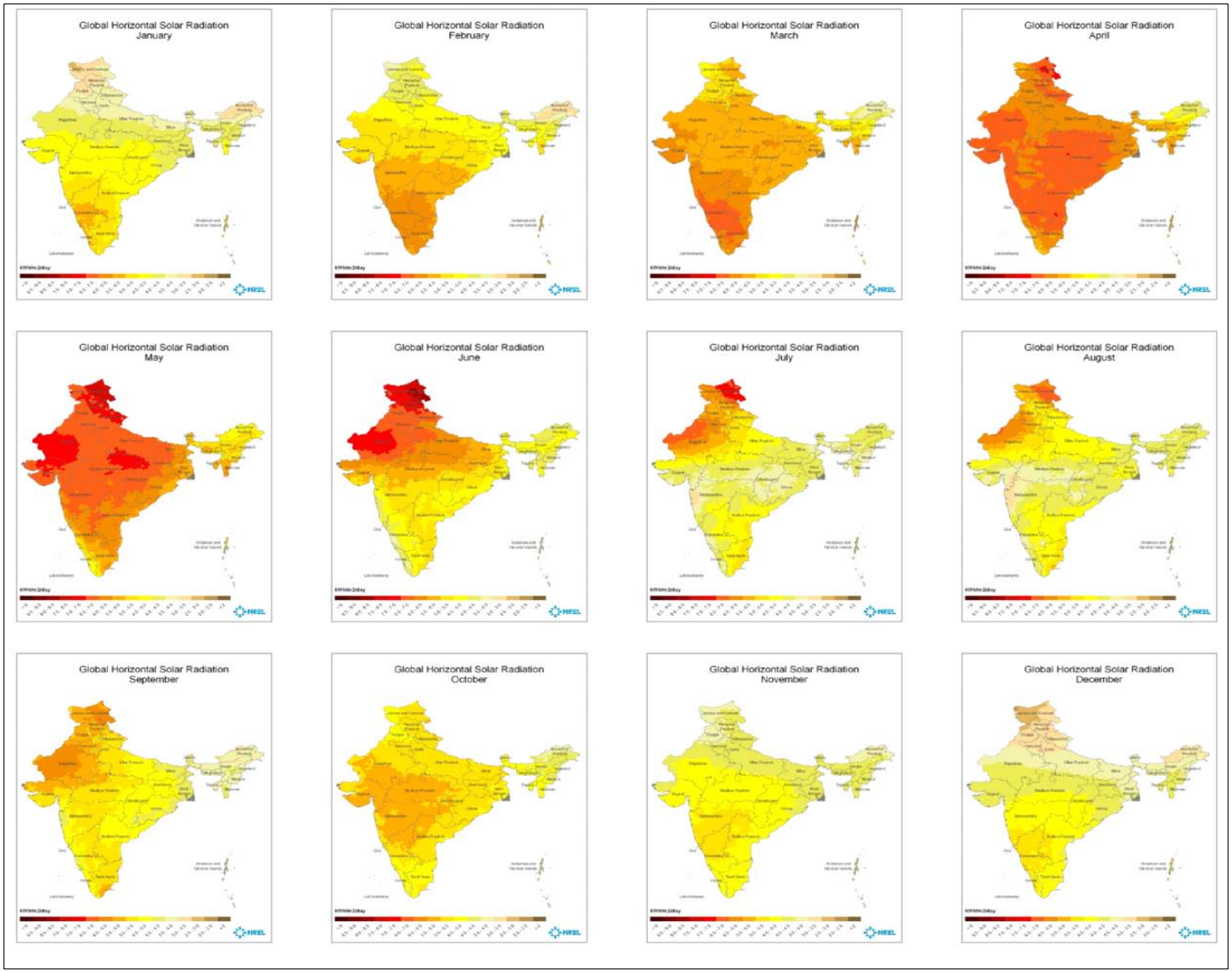
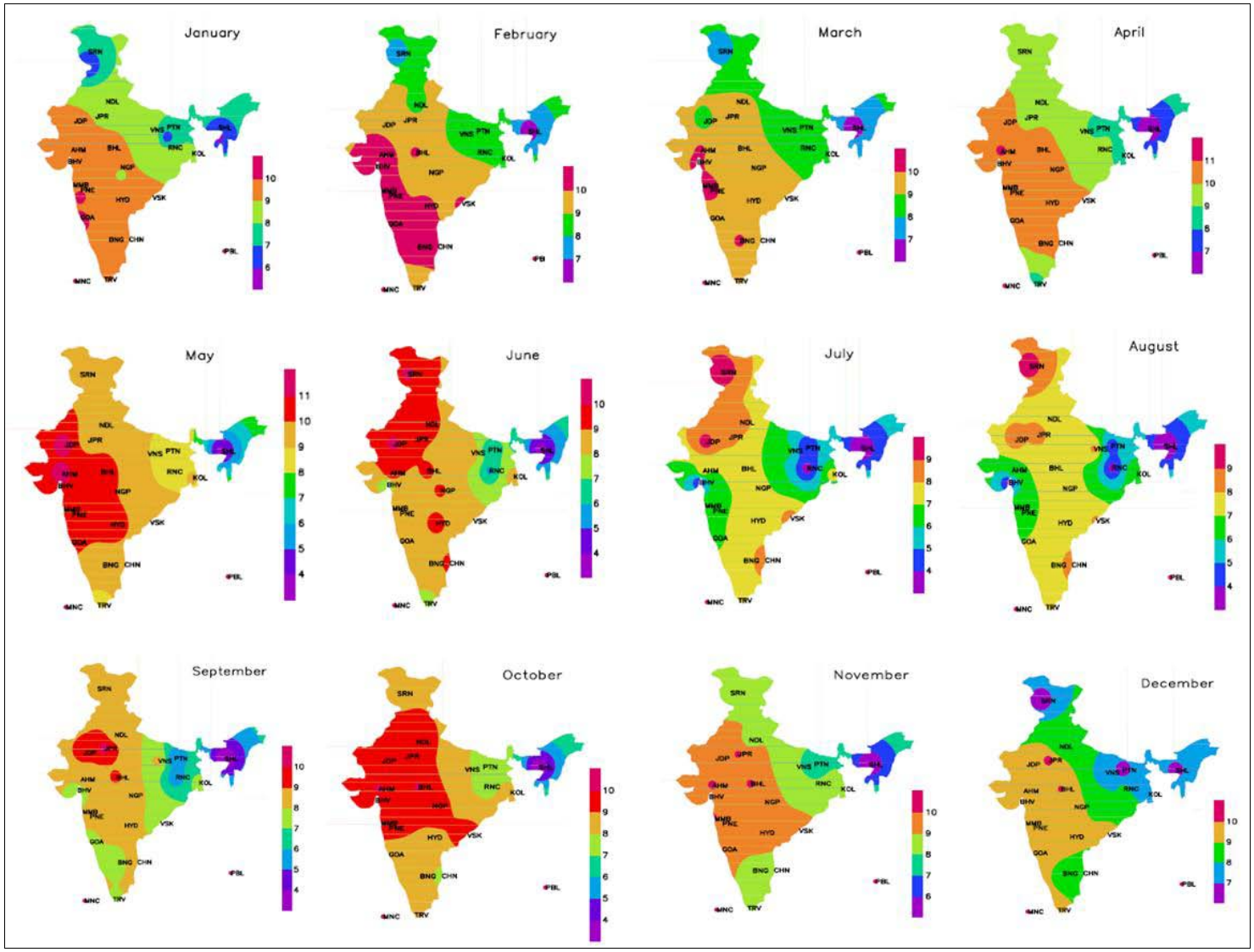
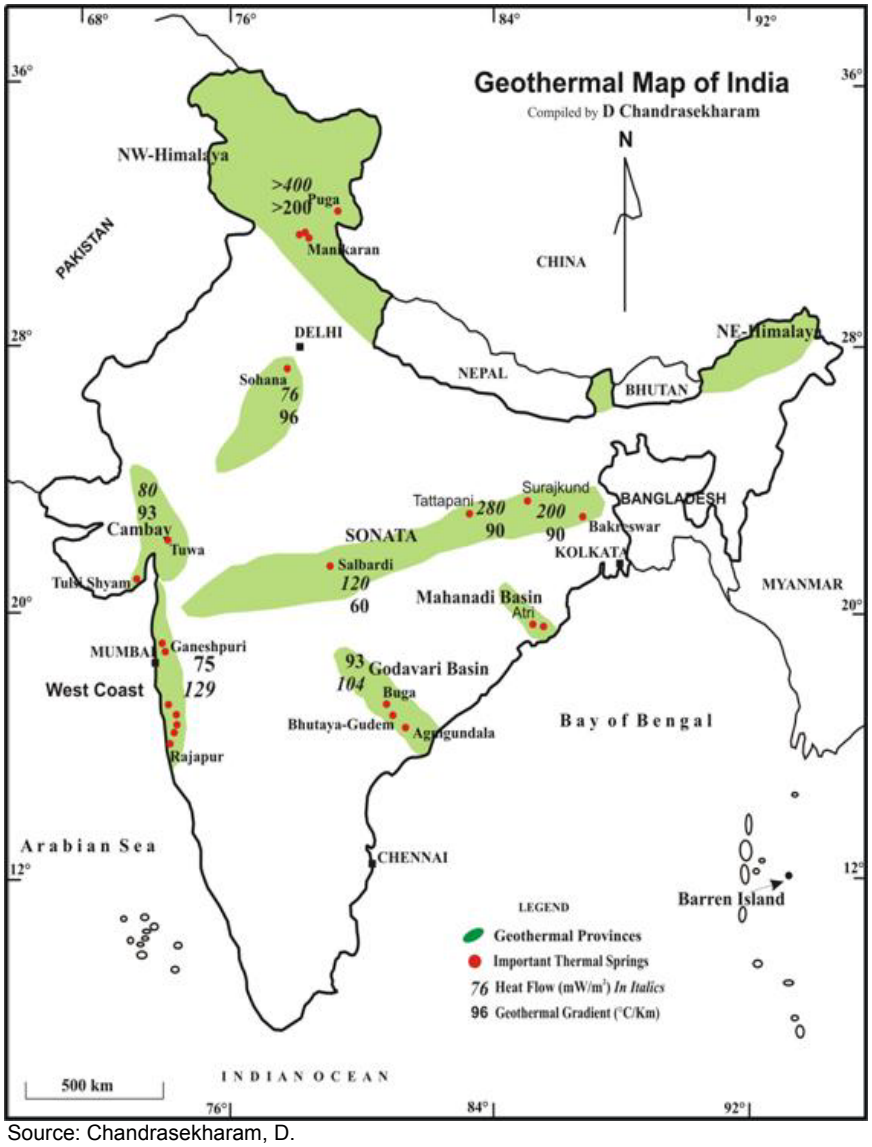


Figure 23. Monthly average solar radiation



Source: IMD 2009

Figure 24. Monthly average daily sunshine hours



Source: Chandrasekharam, D.

Figure 25. Geothermal resources in India

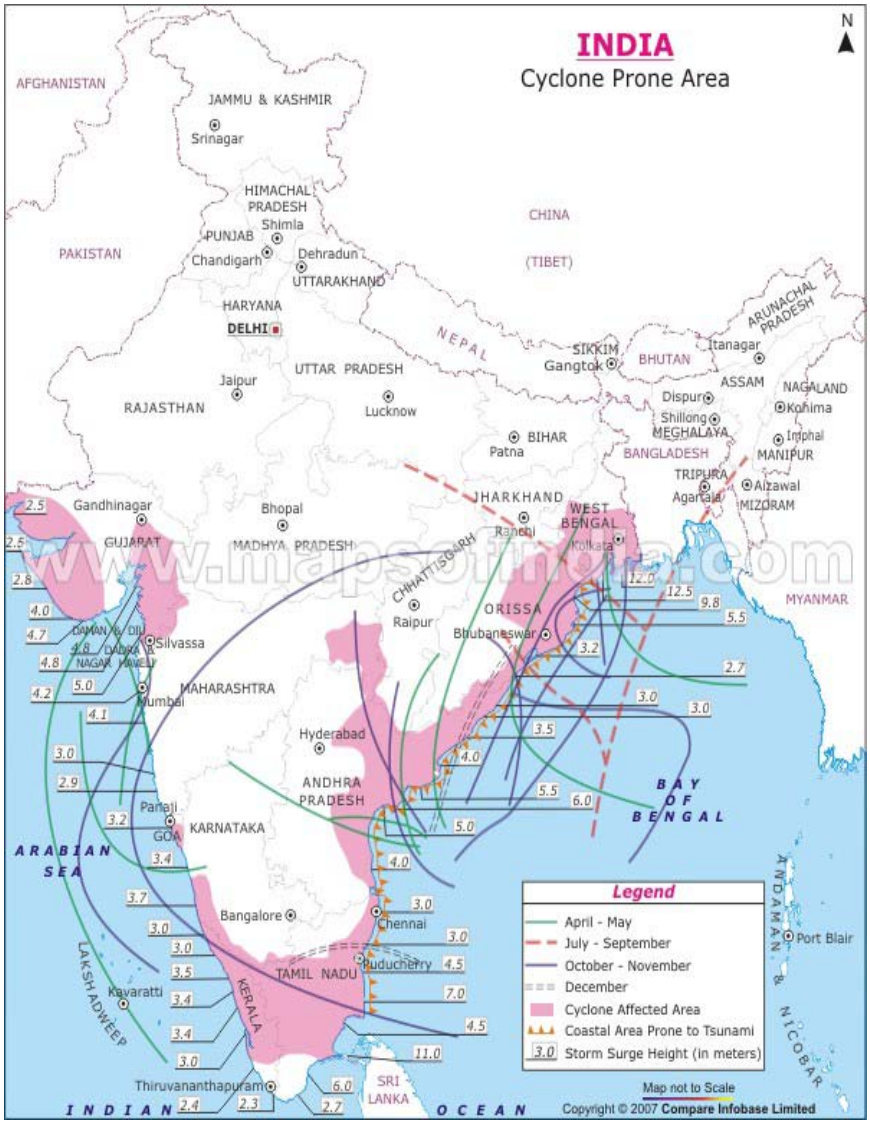


Figure 26. Cyclone prone areas

Figure 27. Flood zones

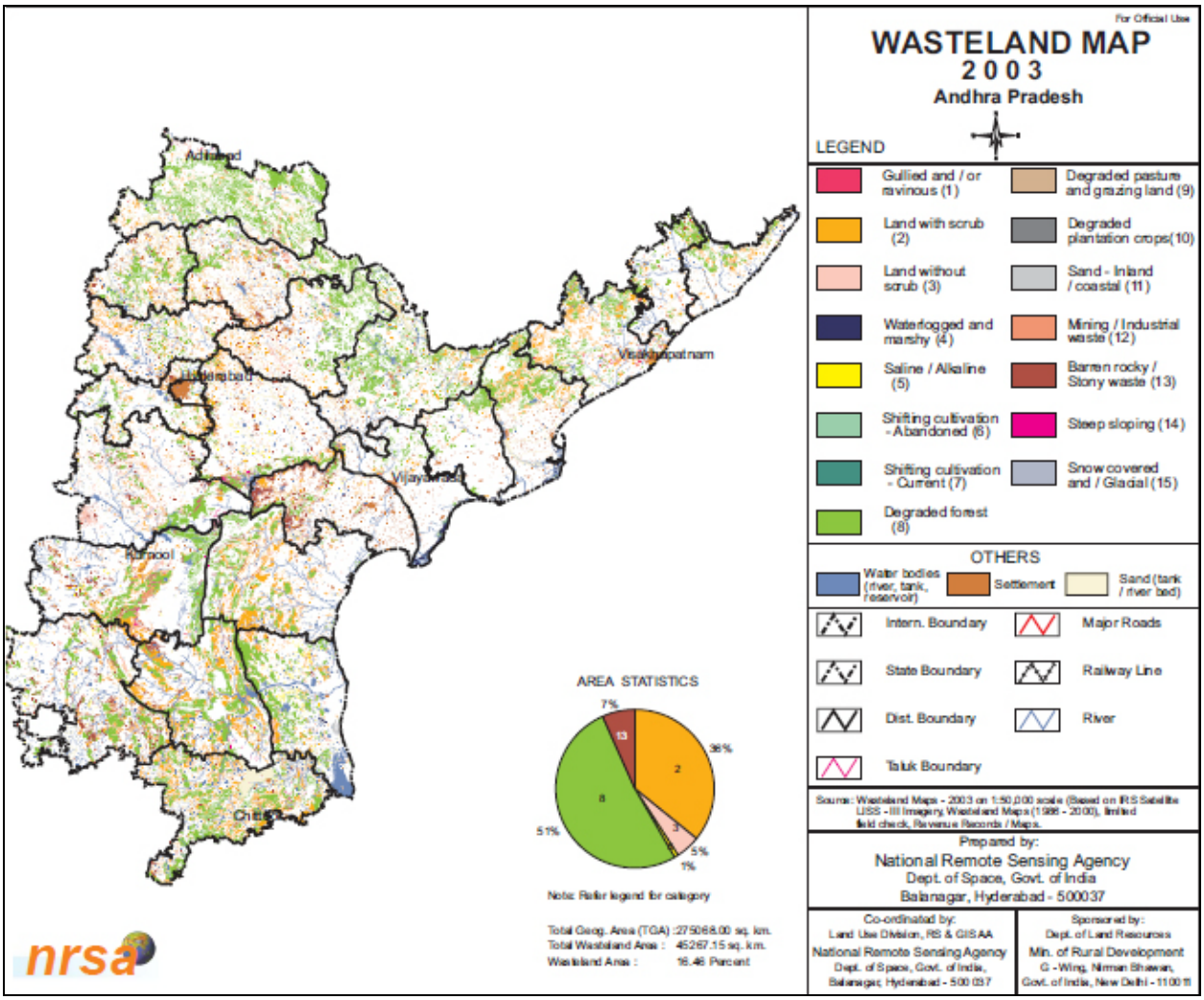


Figure 28. Wasteland in Andhra Pradesh

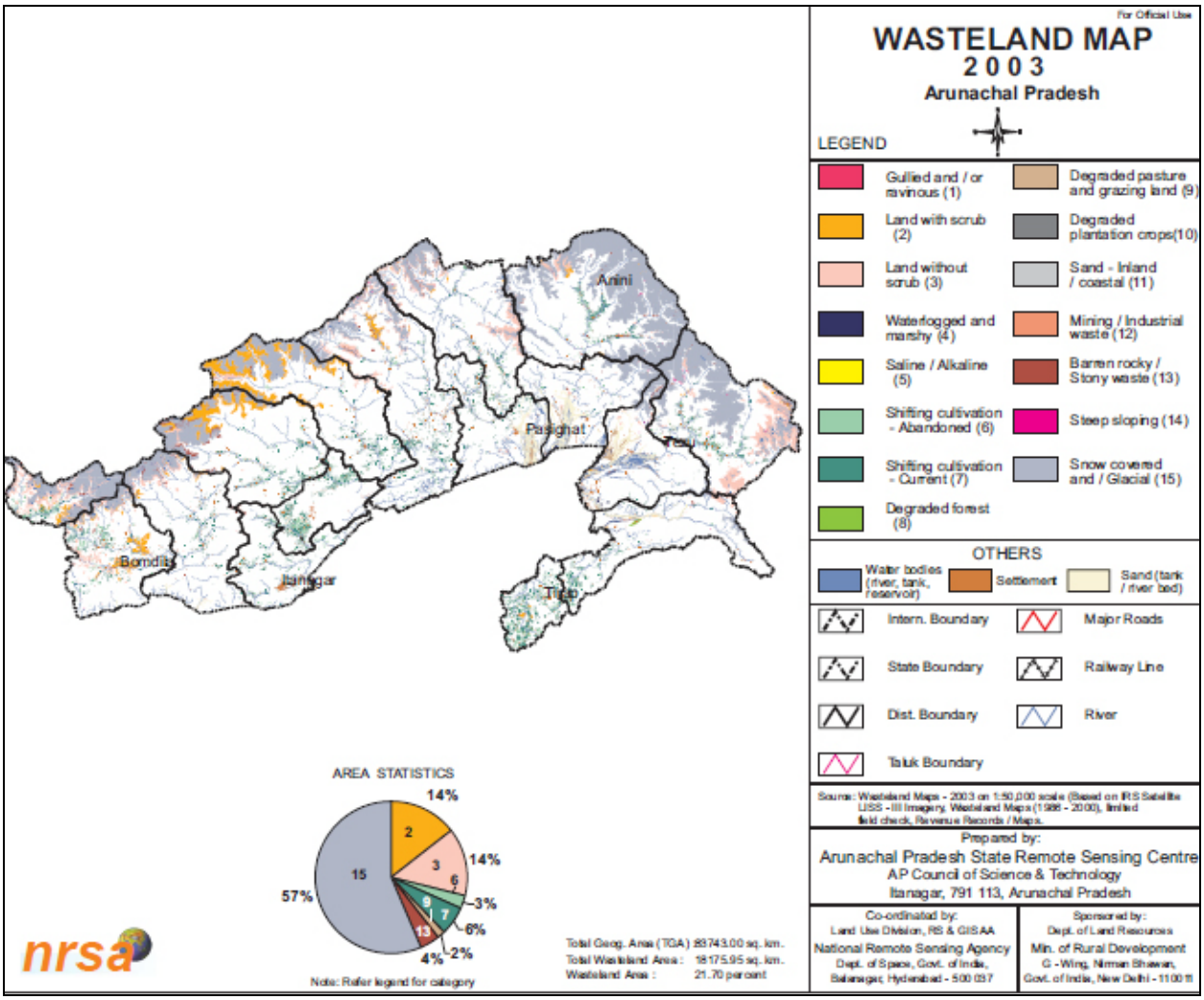
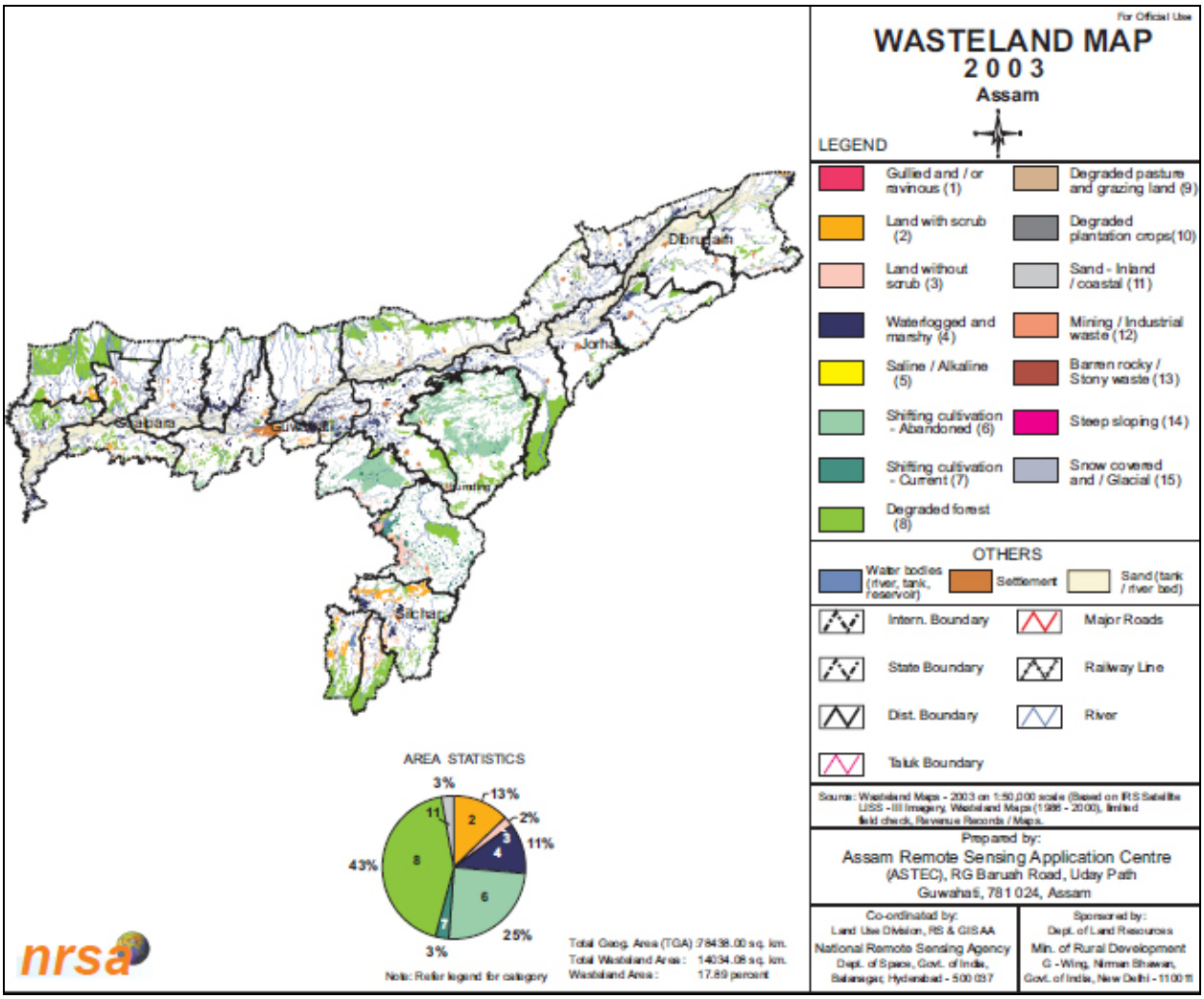


Figure 29. Wasteland in Arunachal Pradesh



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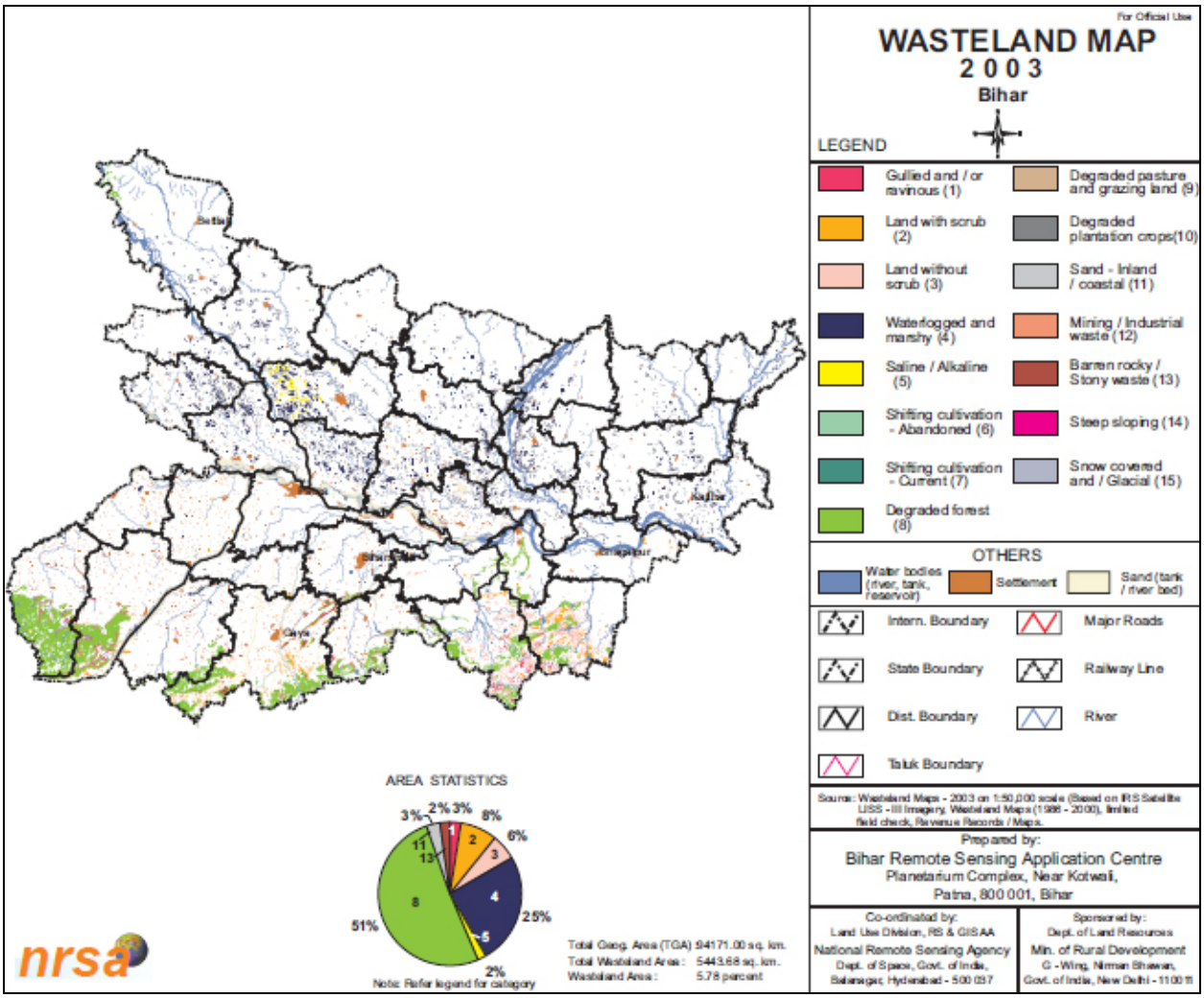

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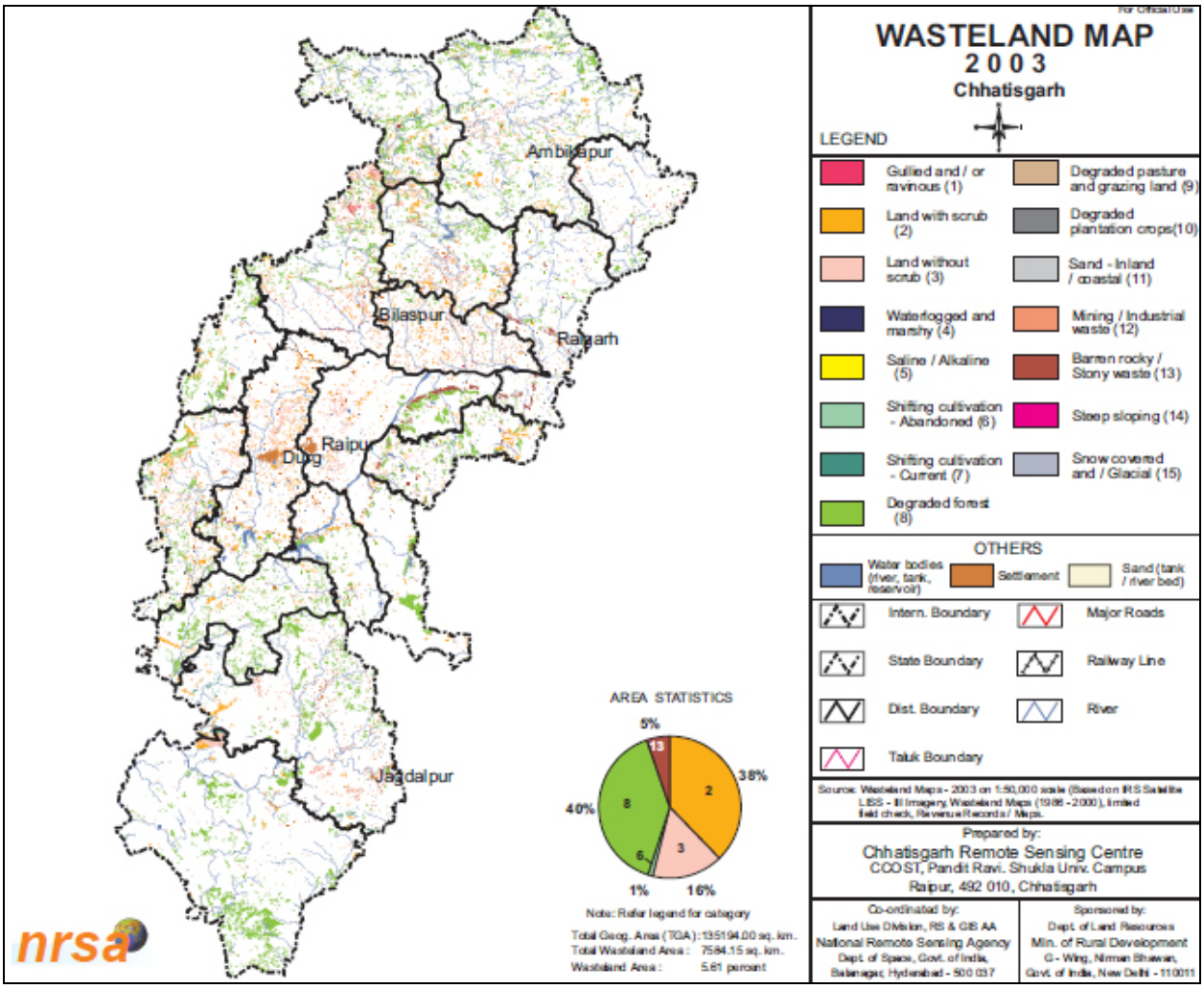
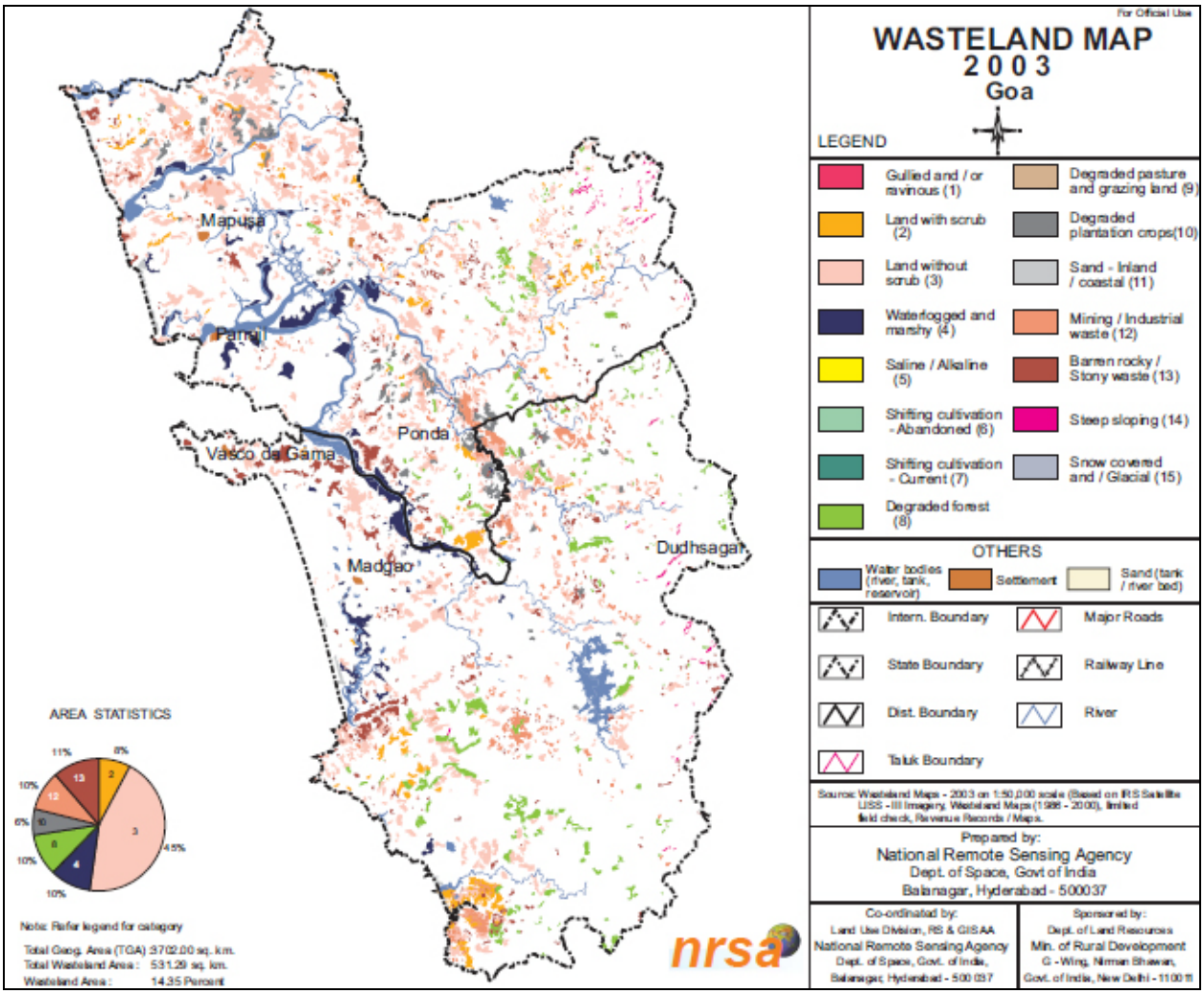


Figure 32. Wasteland in Chhatishgarh



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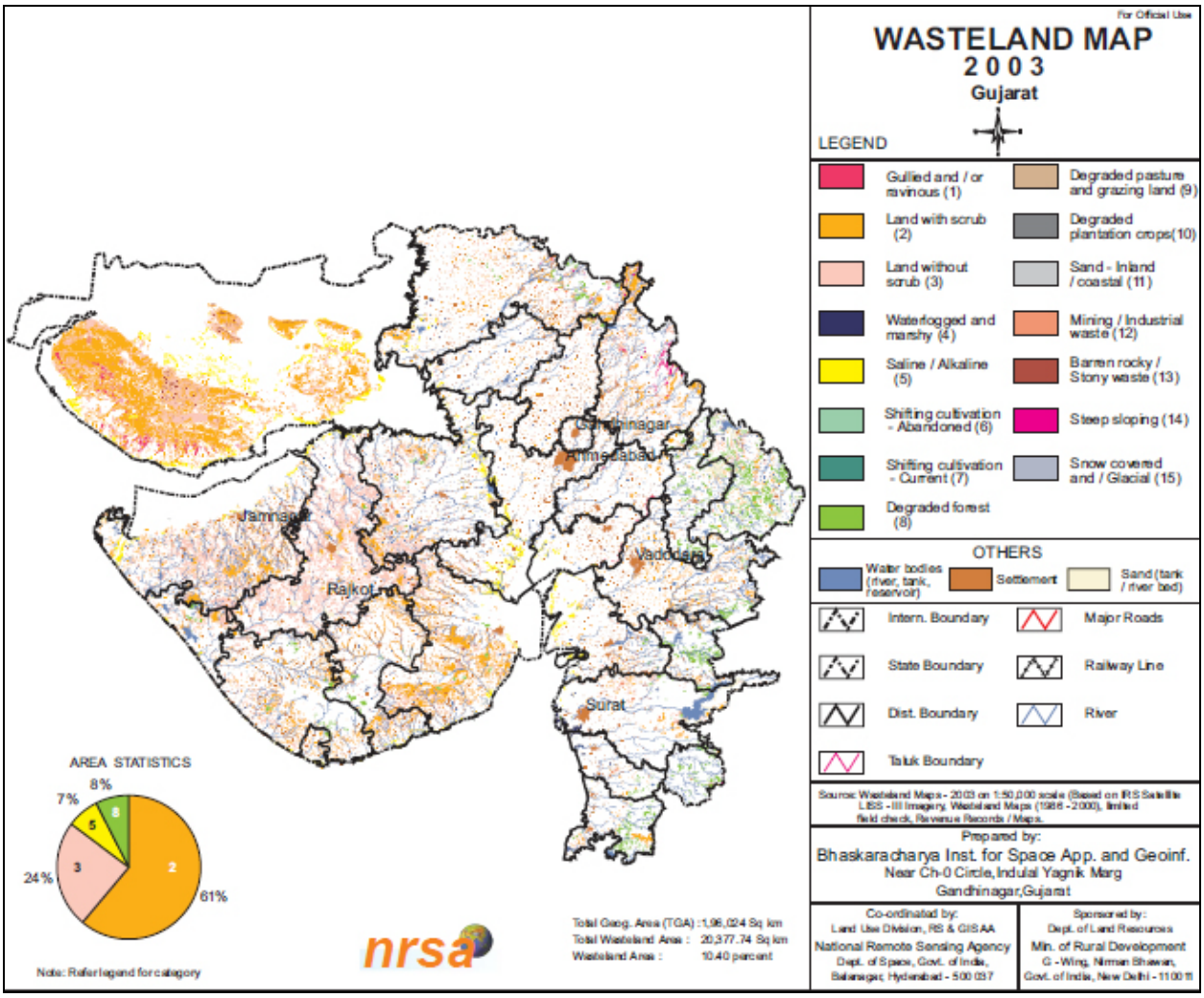

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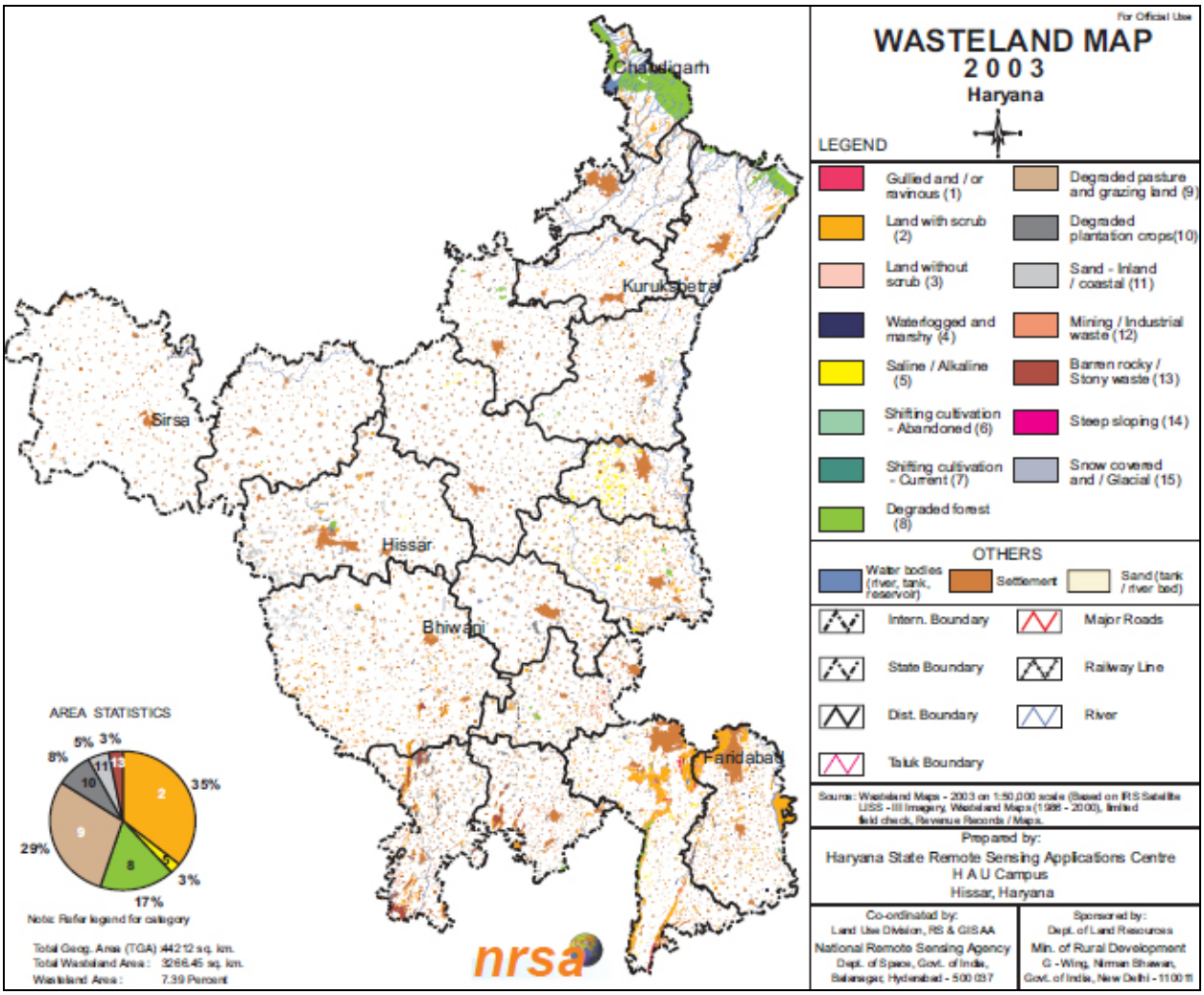

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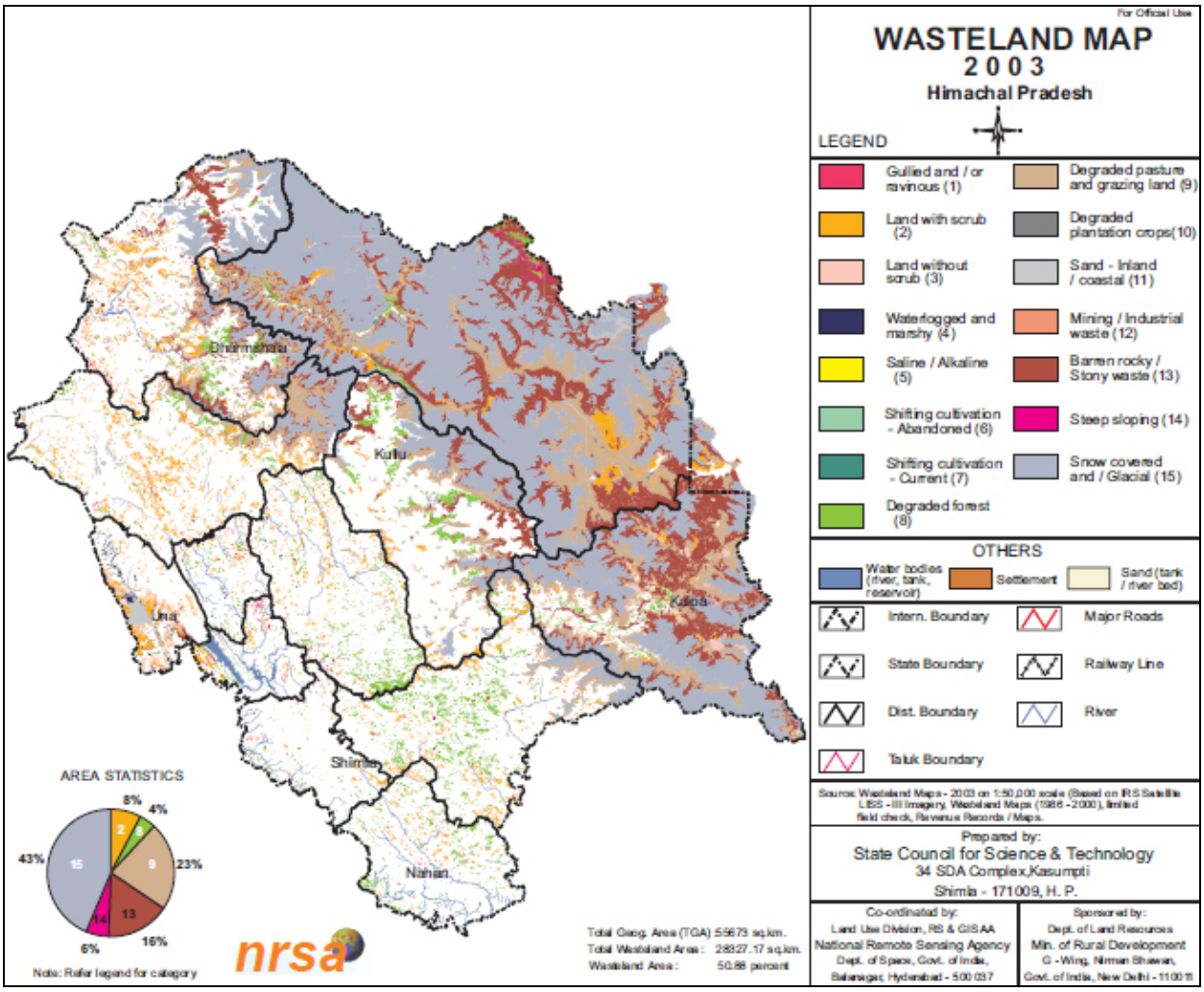

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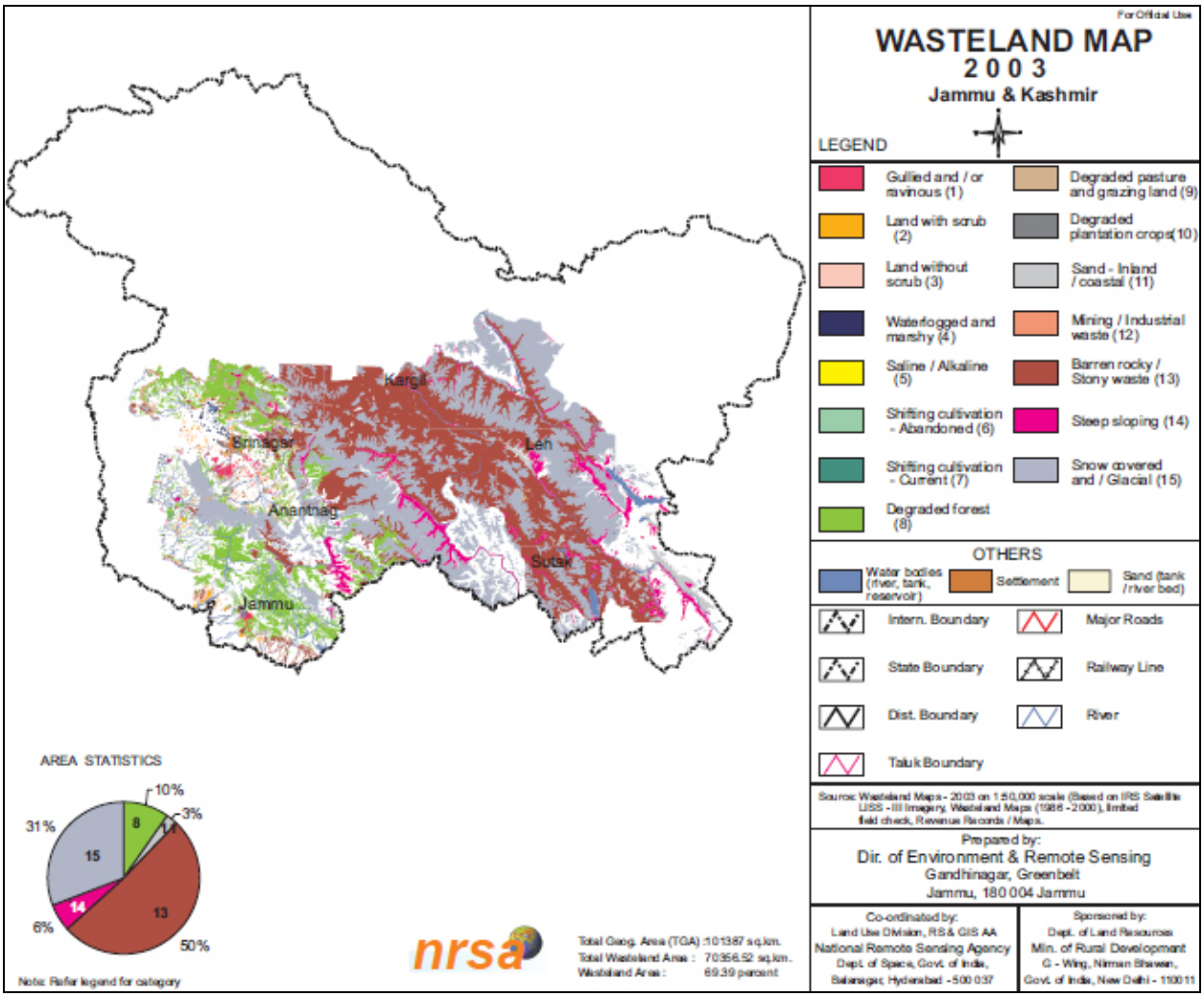


Figure 37. Wasteland in Jammu & Kashmir

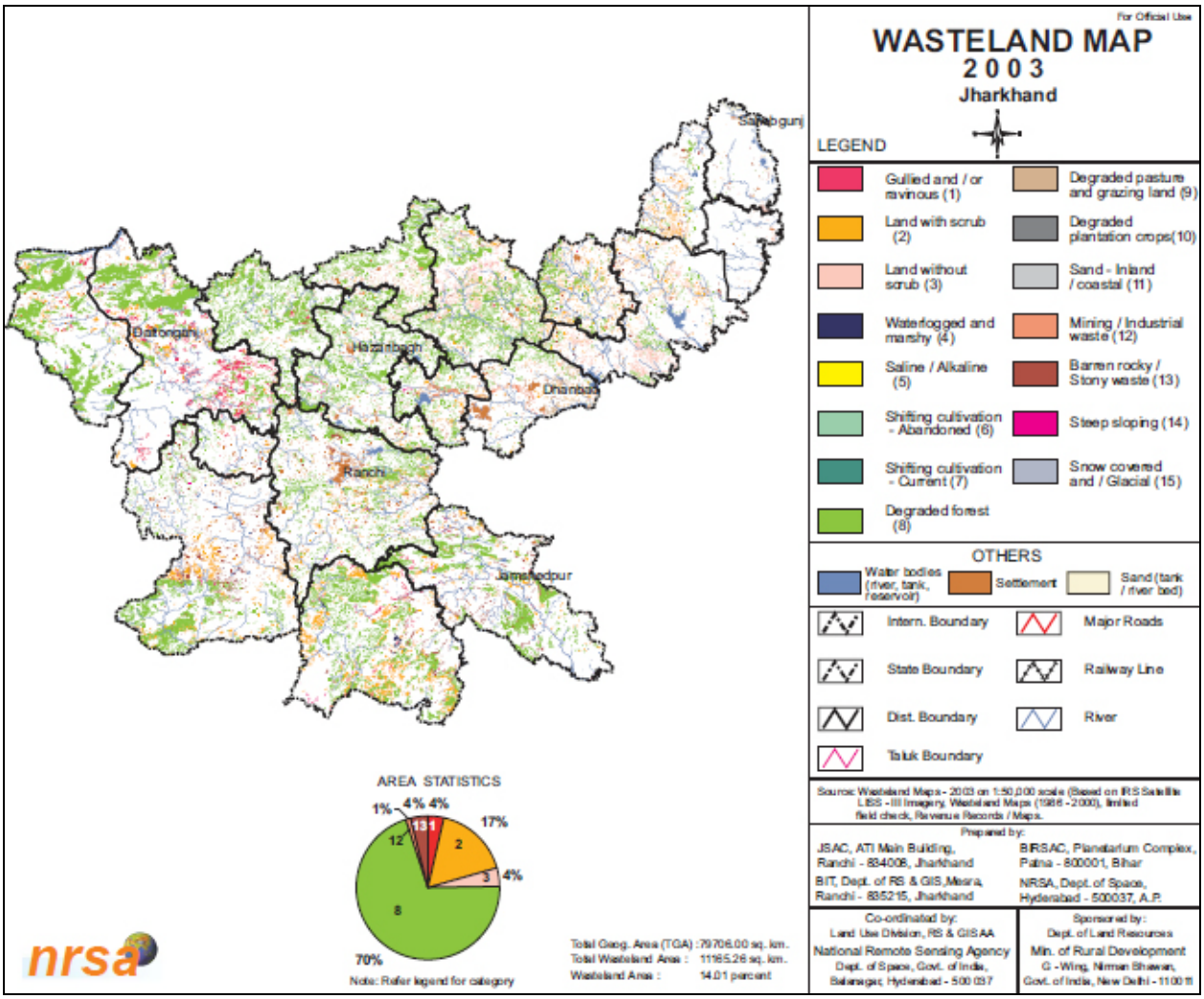


Figure 38. Wasteland in Jharkhand

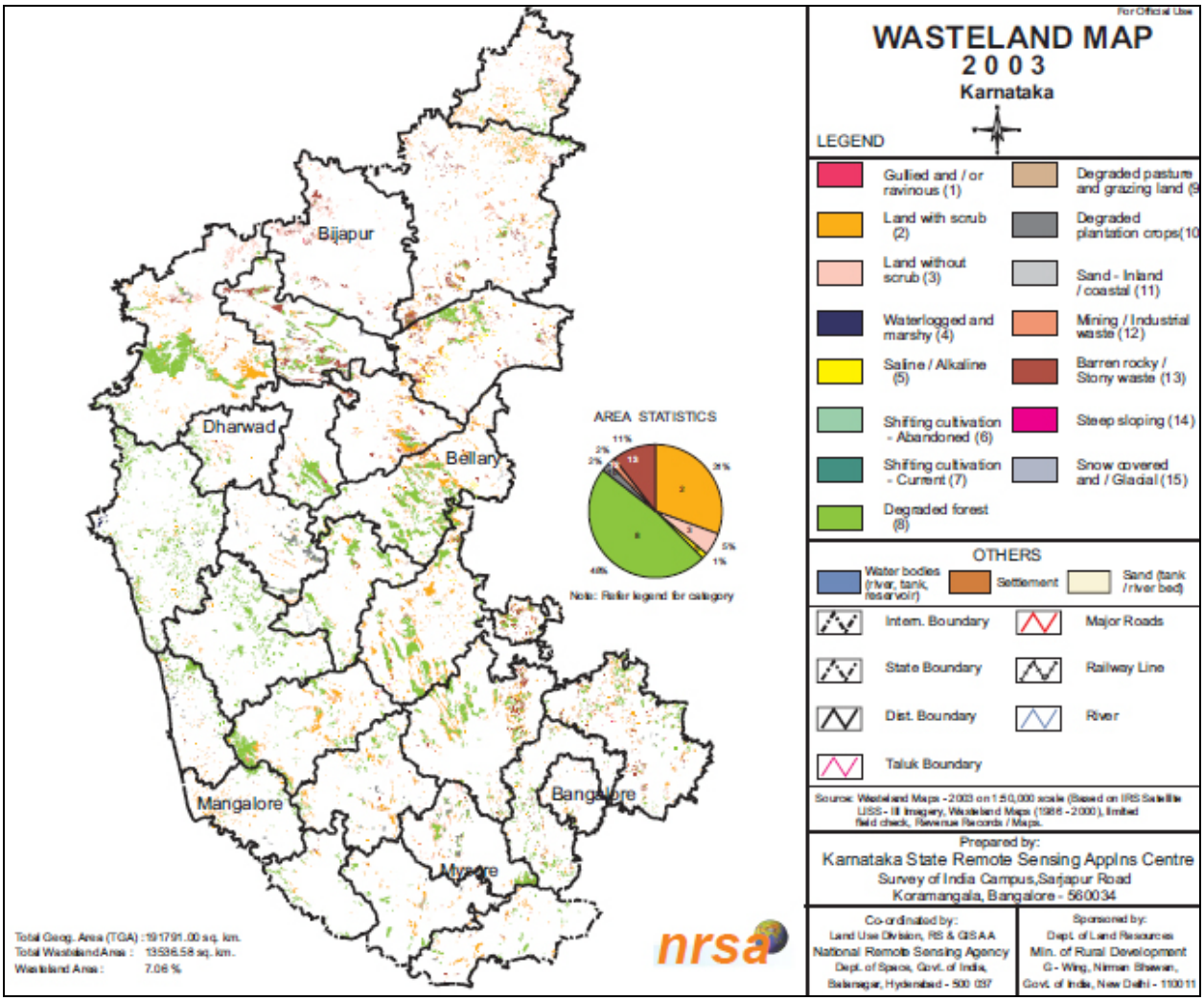
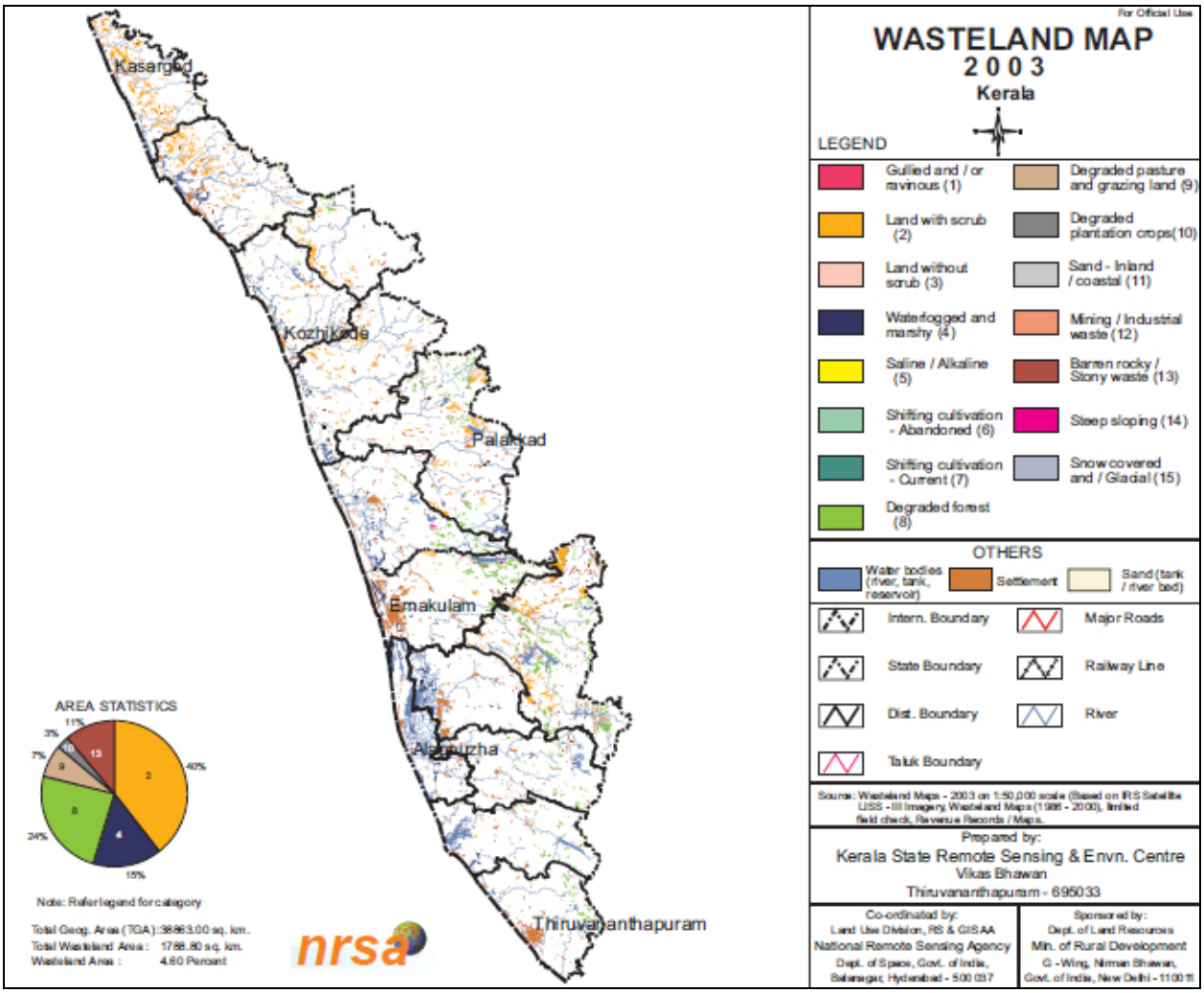


Figure 39. Wasteland in Karnataka



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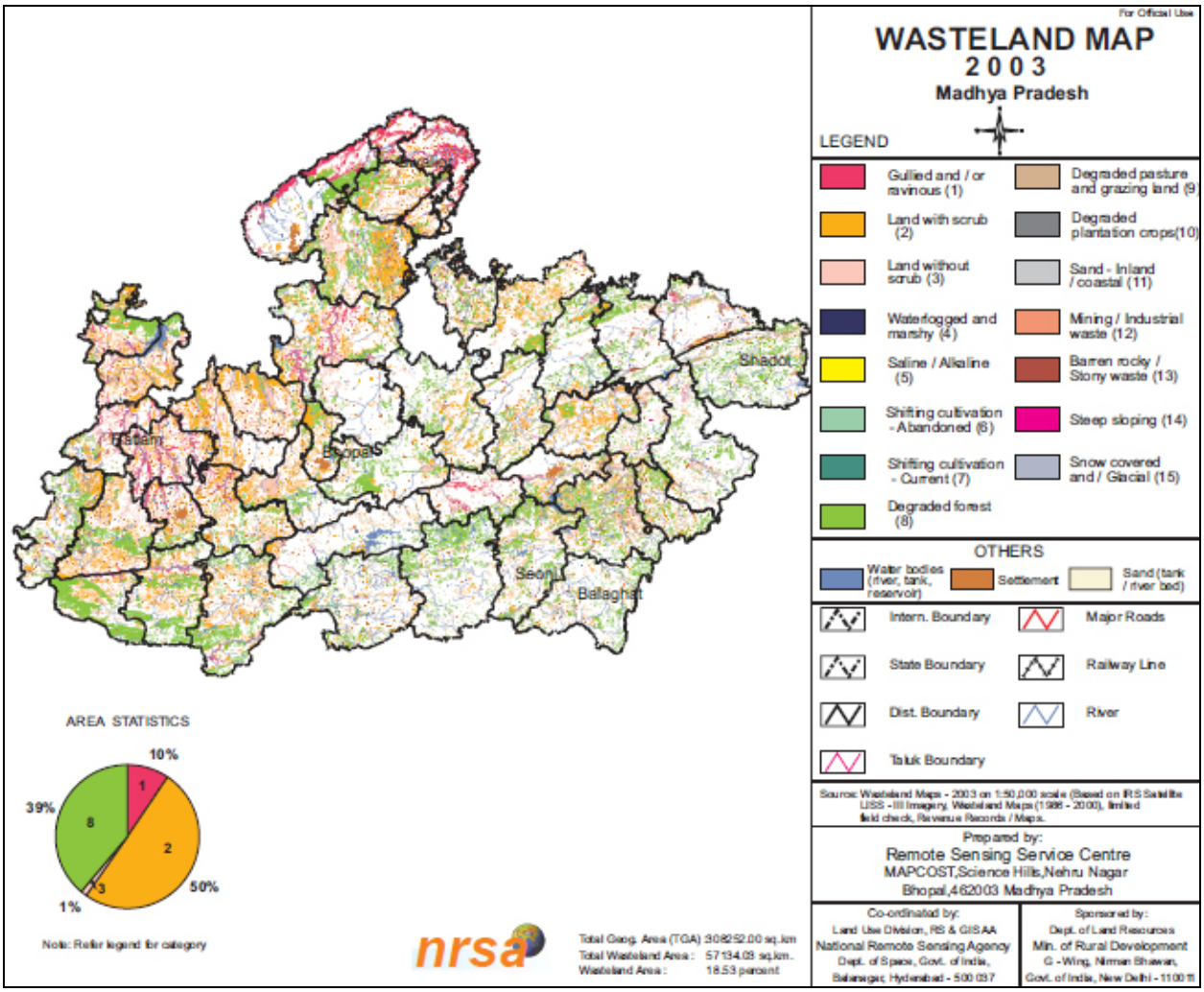

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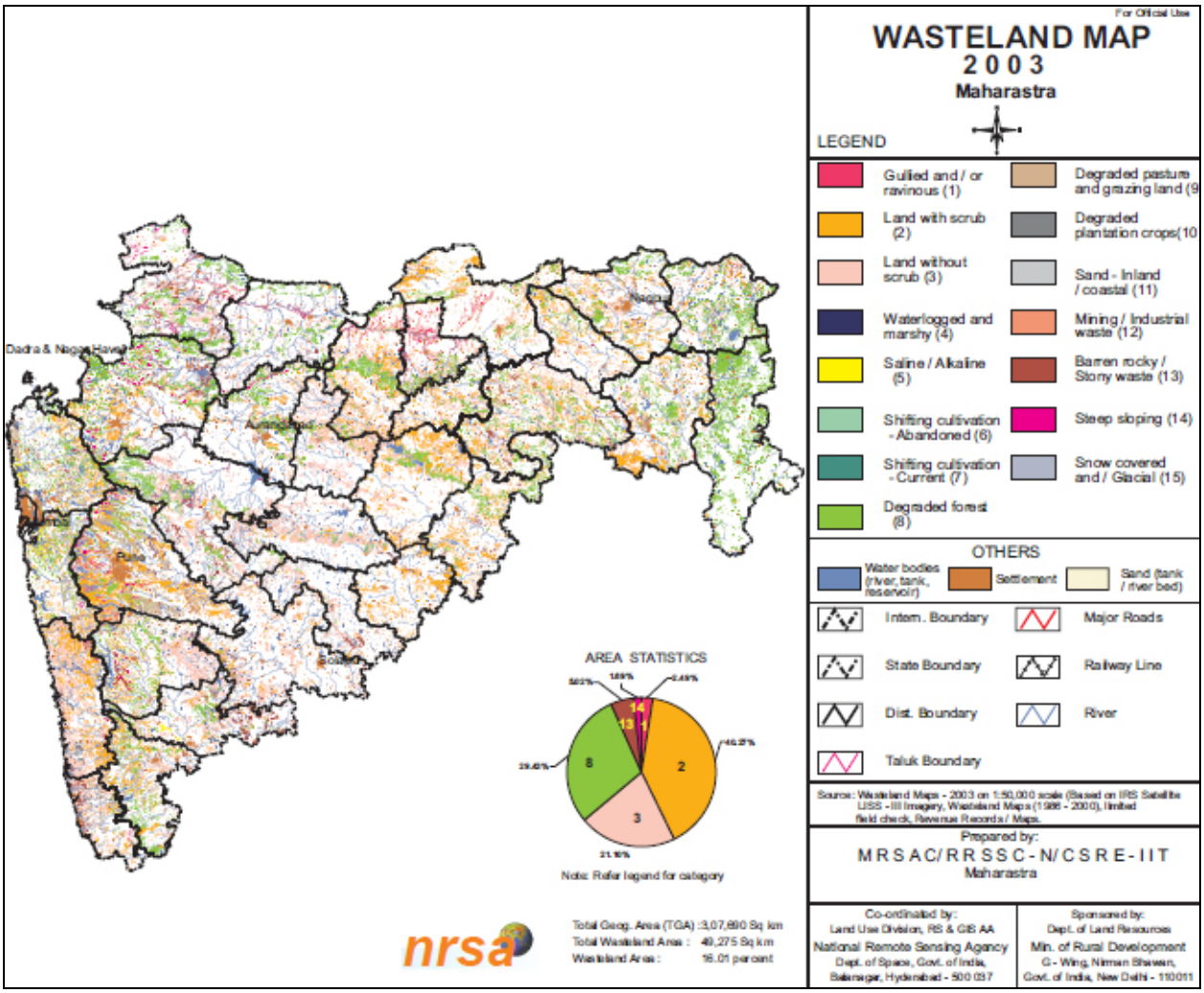
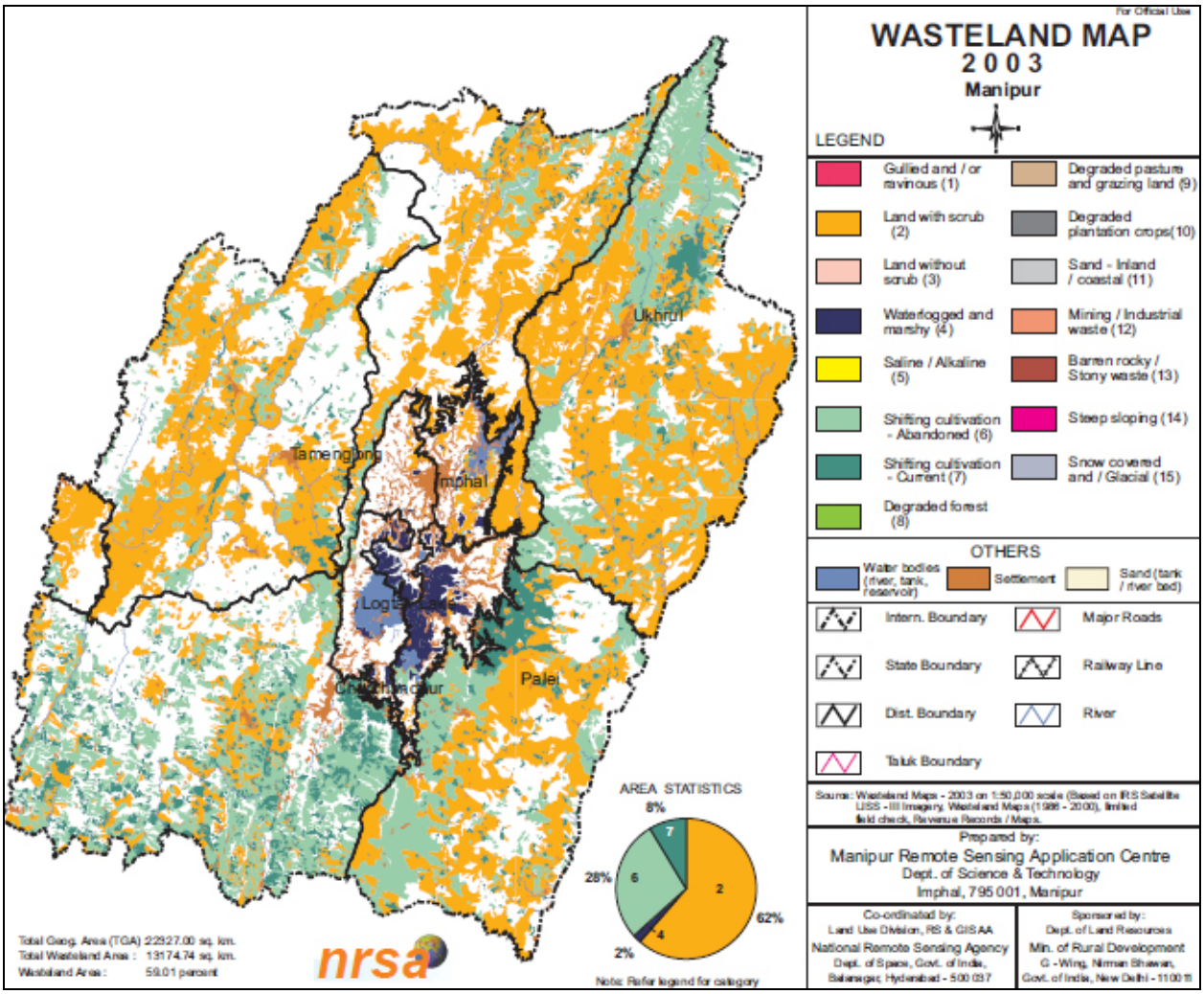


Figure 42. Wasteland in Maharastra



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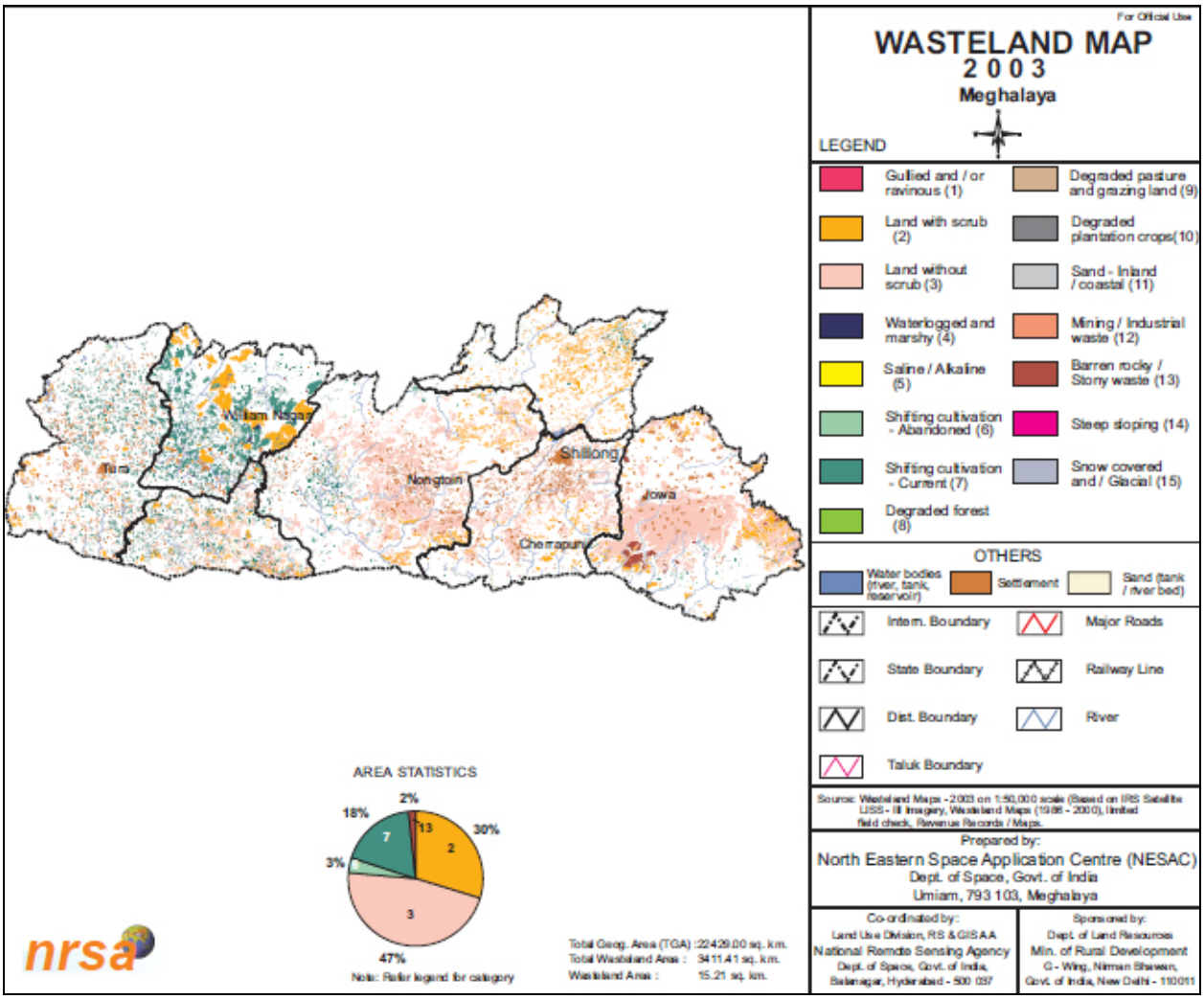

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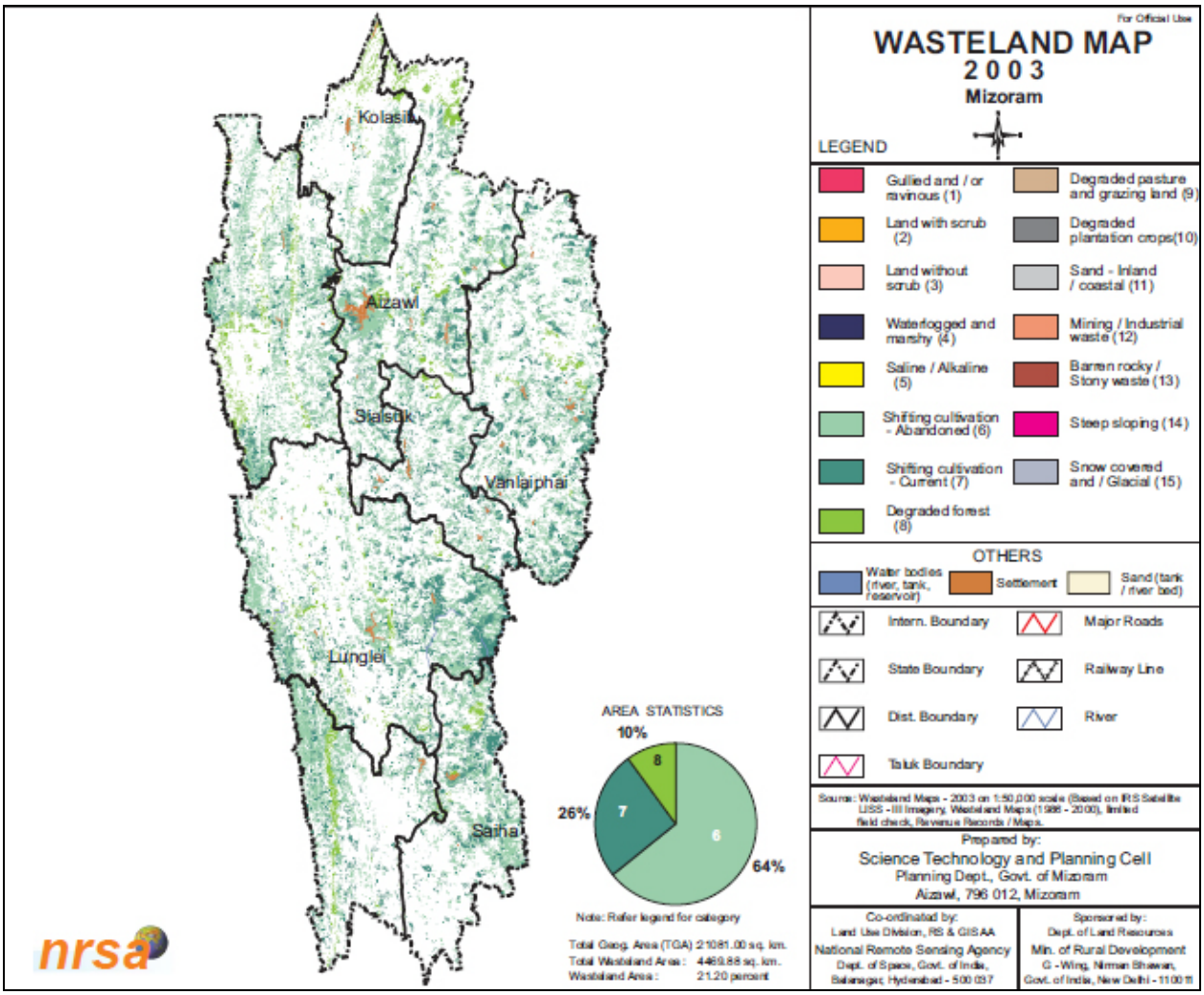

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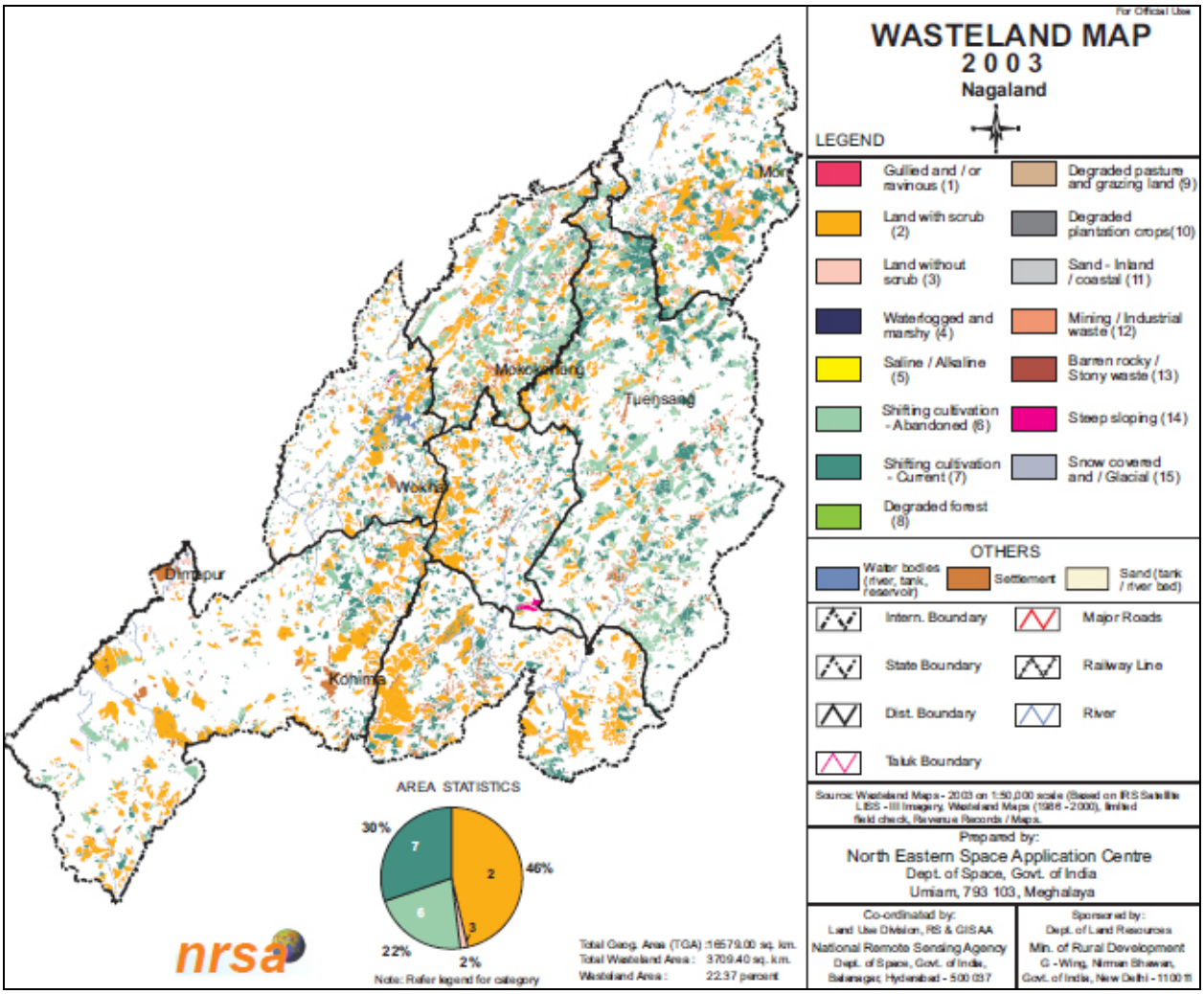
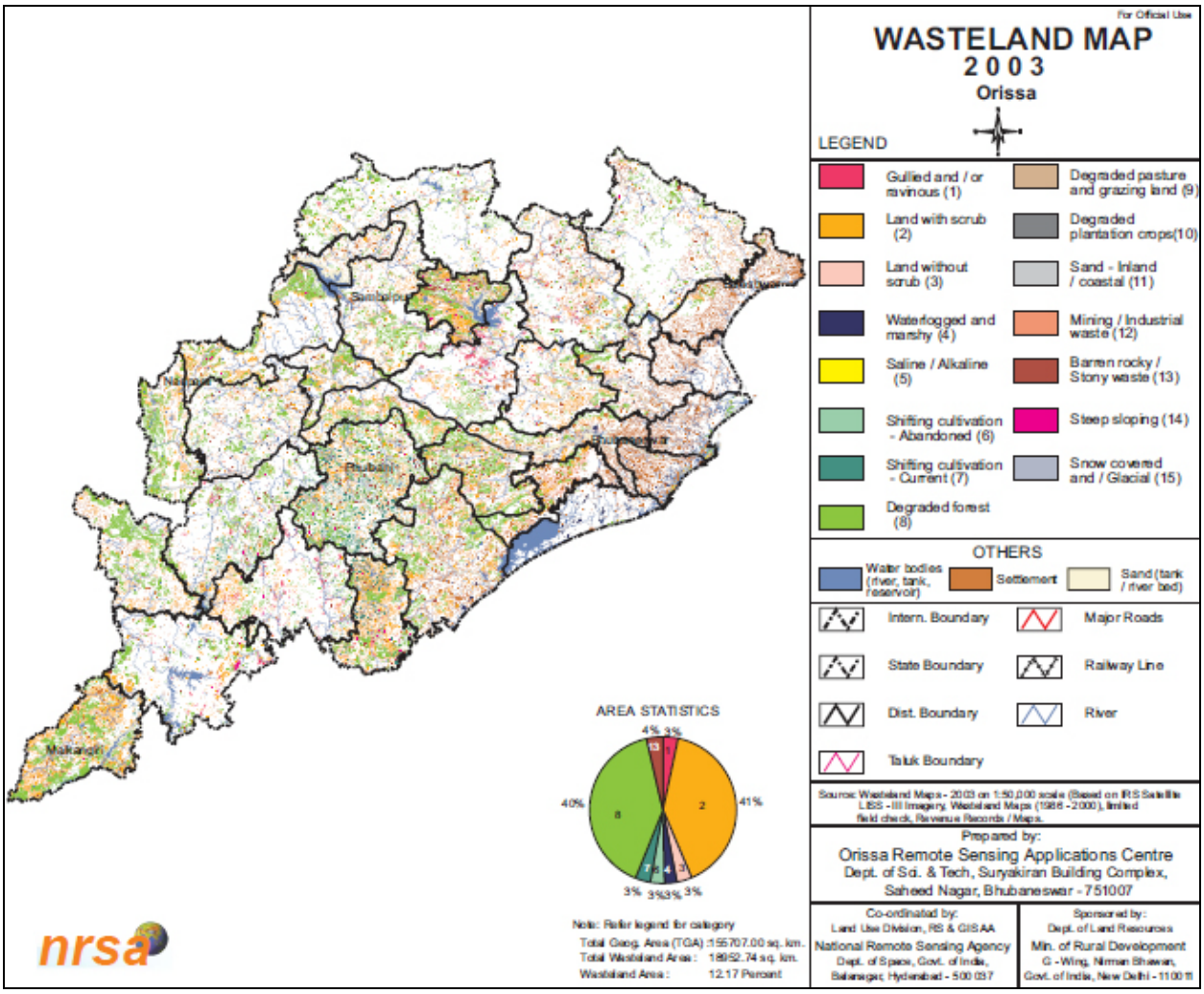


Figure 46. Wasteland in Nagaland



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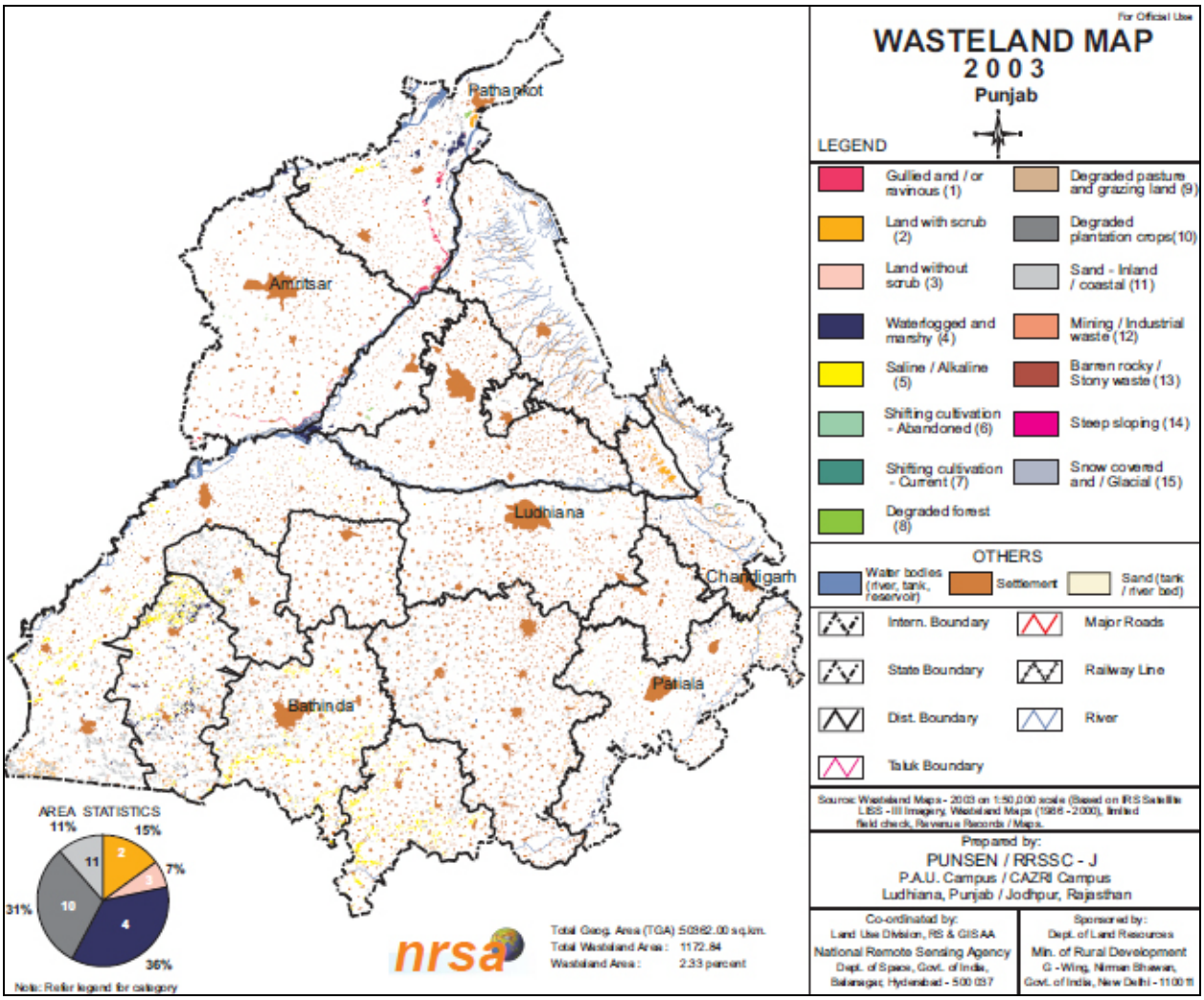
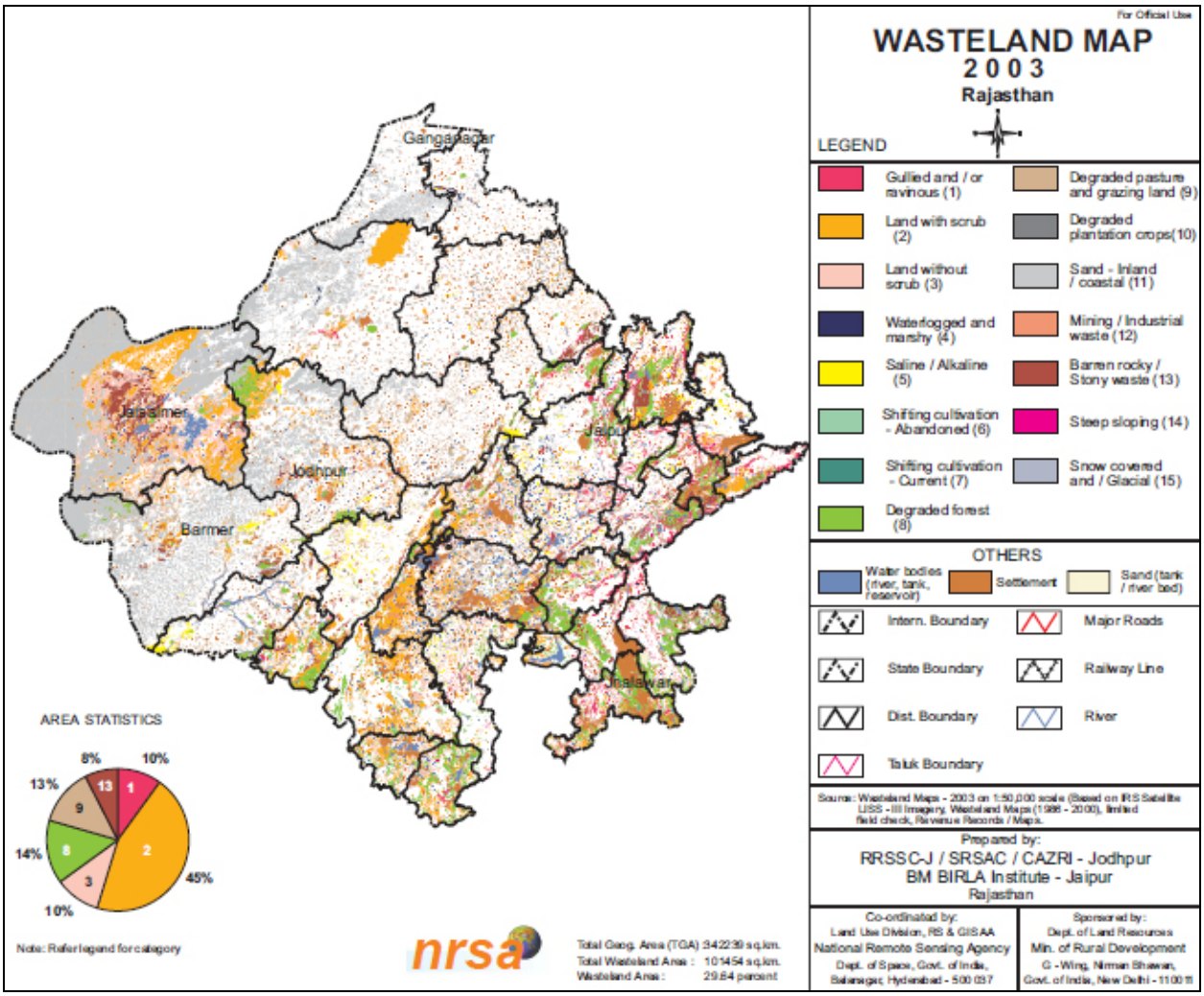


Figure 48. Wasteland in Punjab



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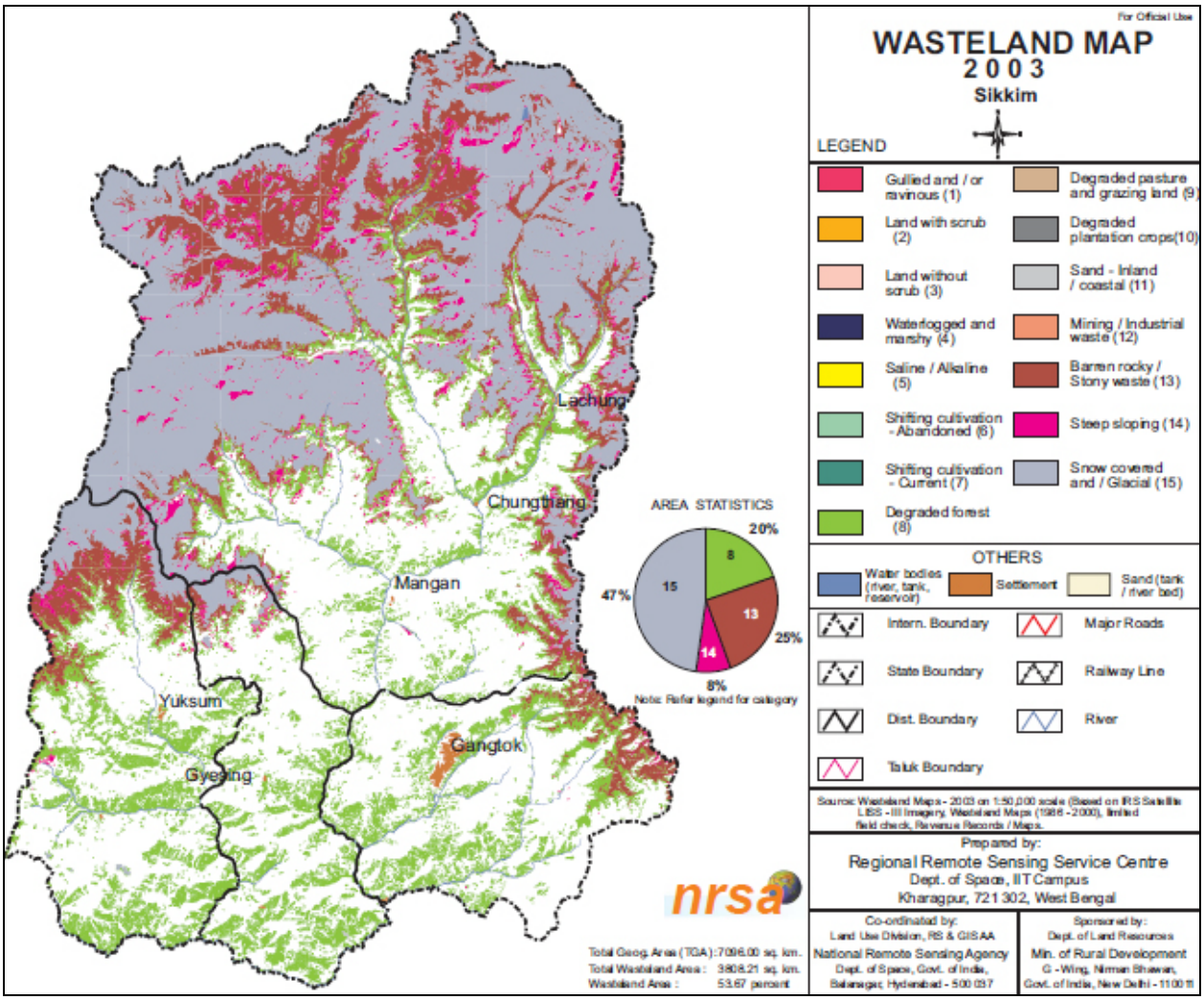


Figure 50. Wasteland in Sikkim

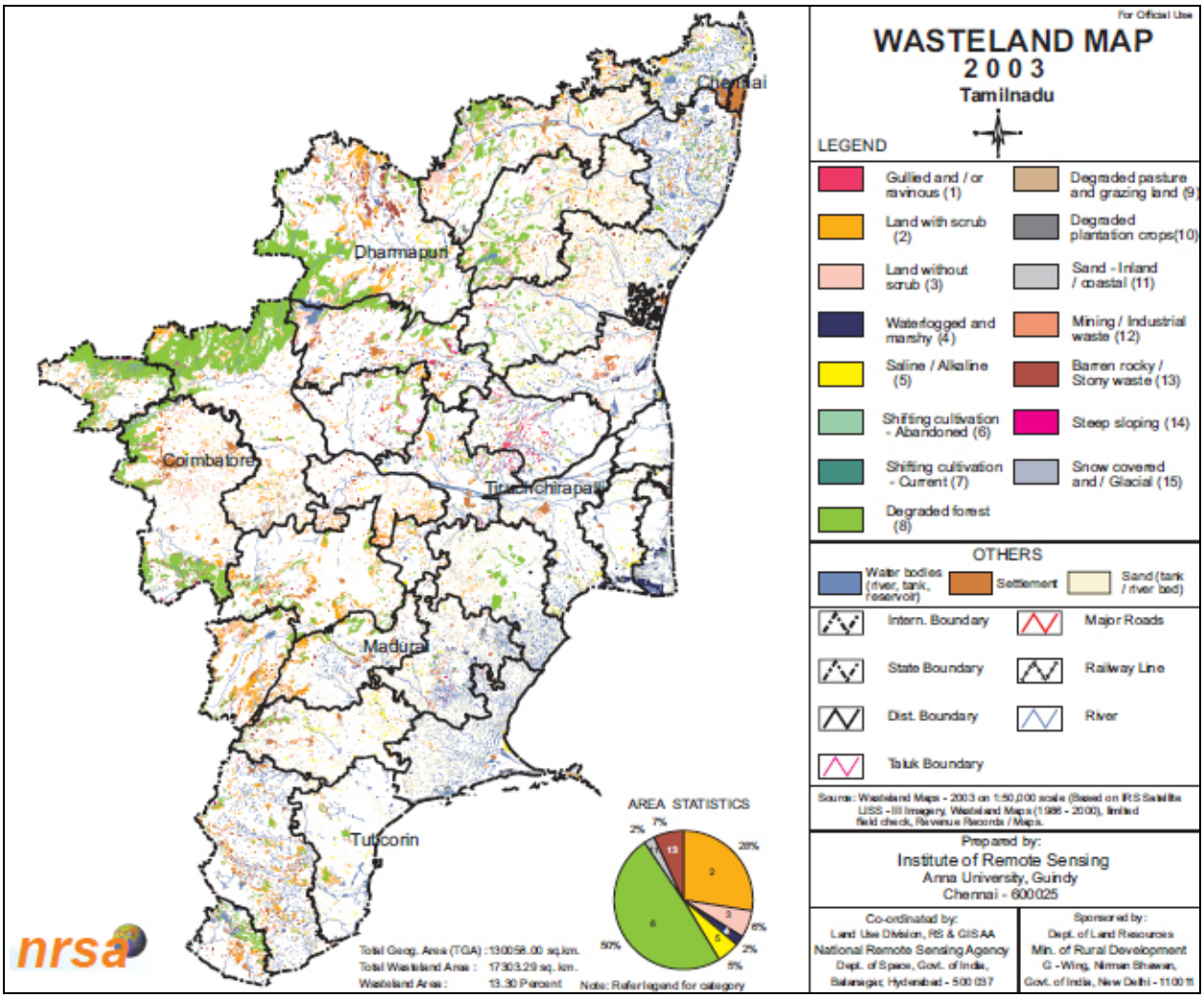
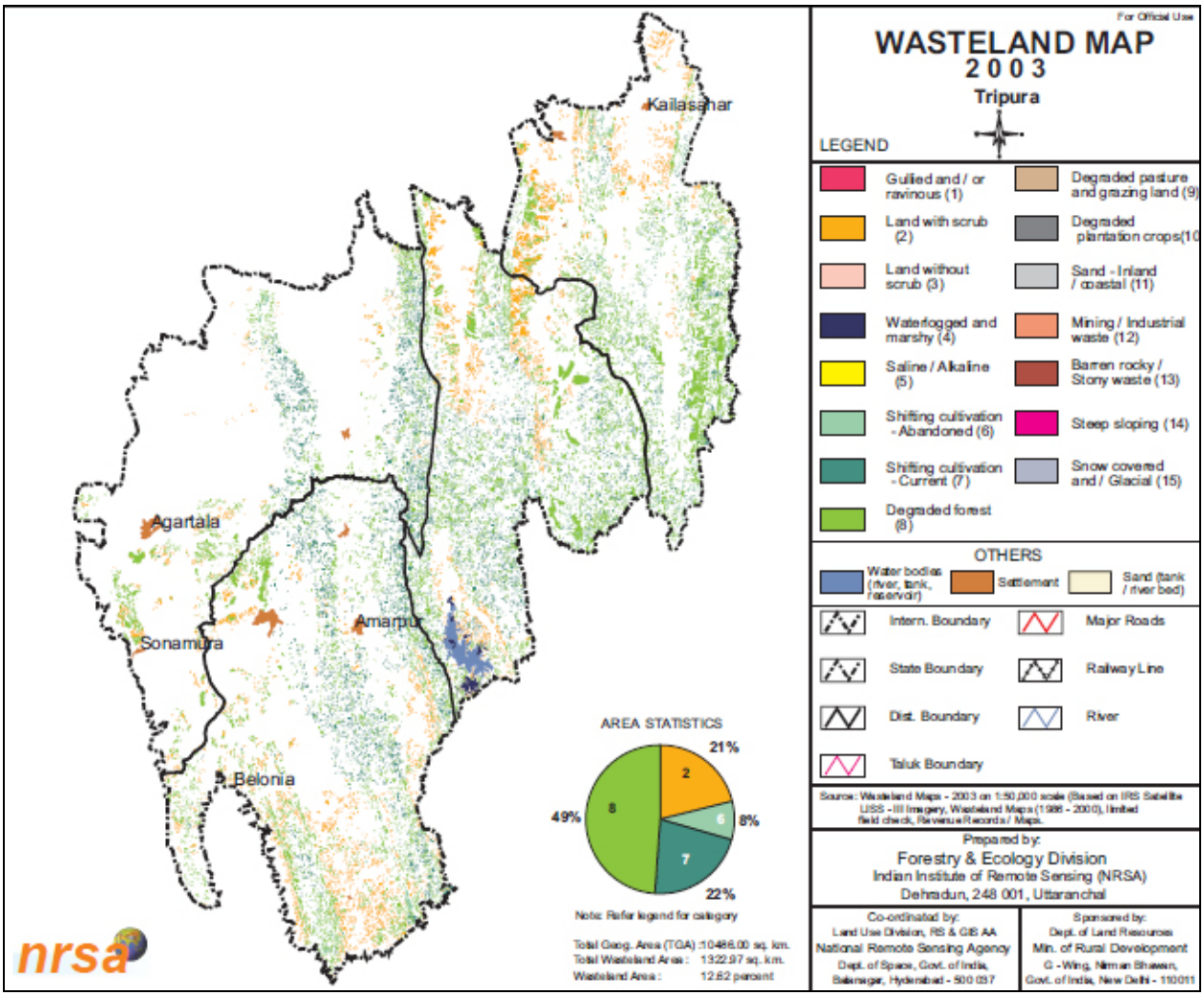


Figure 51. Wasteland in Tamil Nadu



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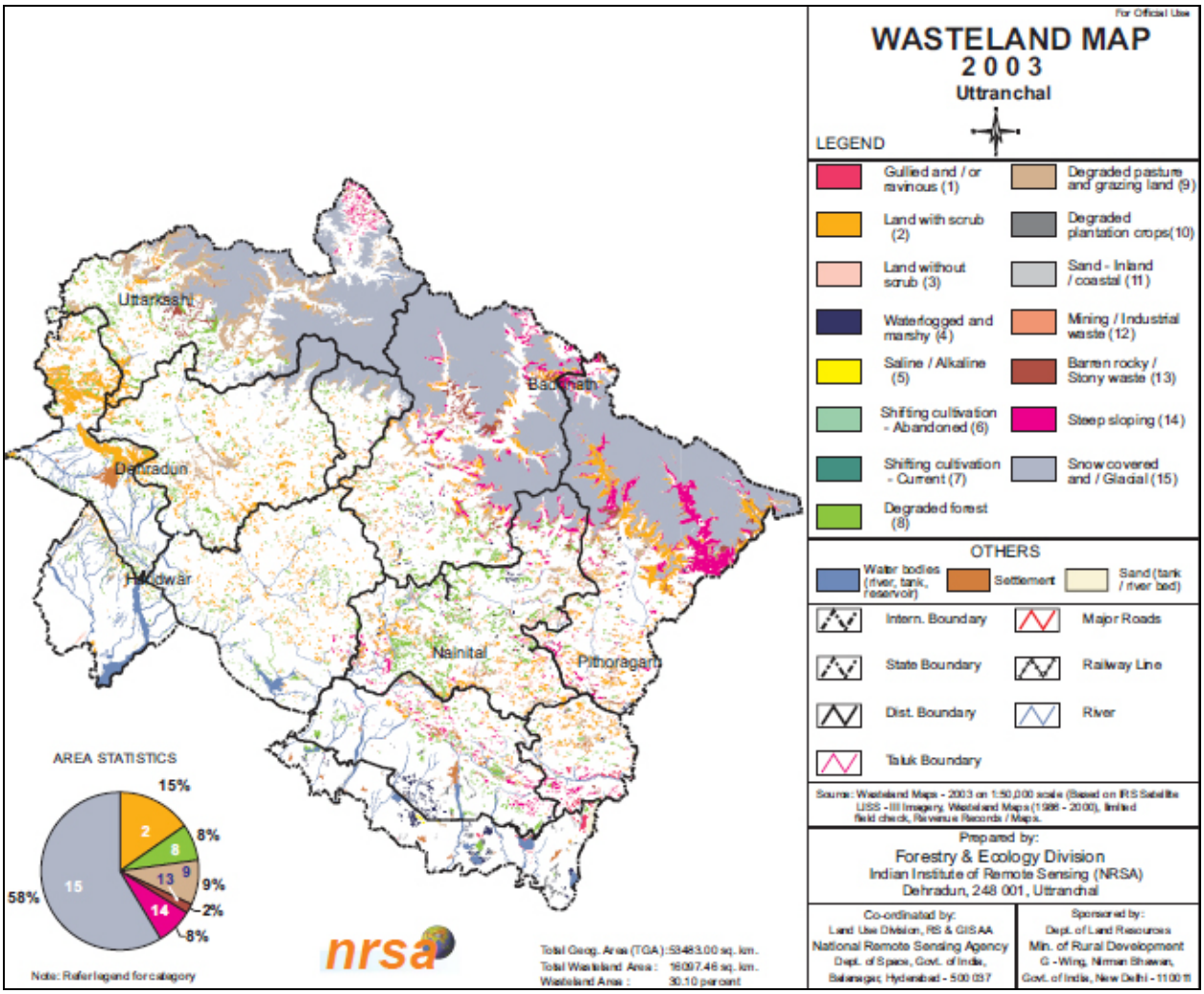

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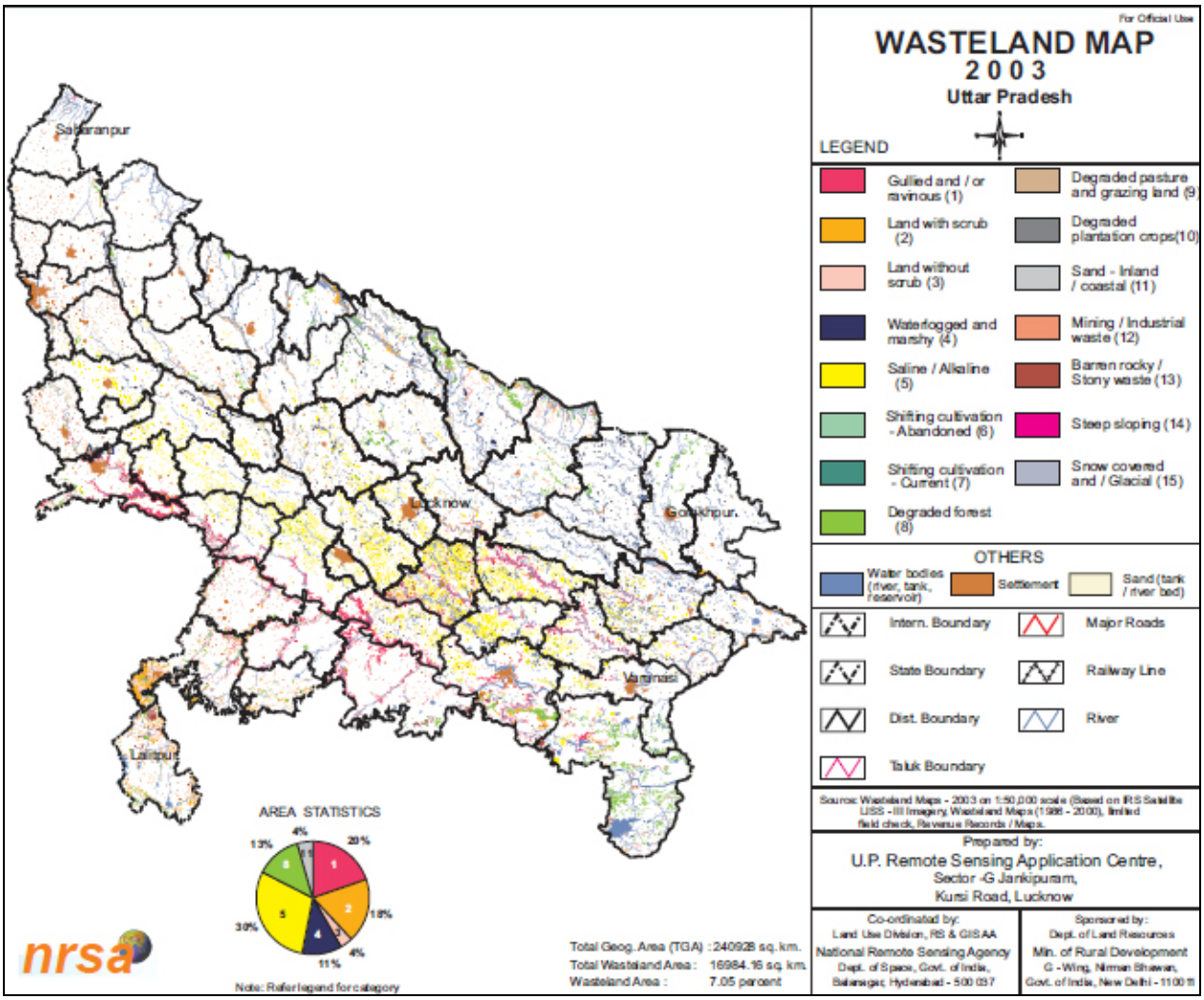

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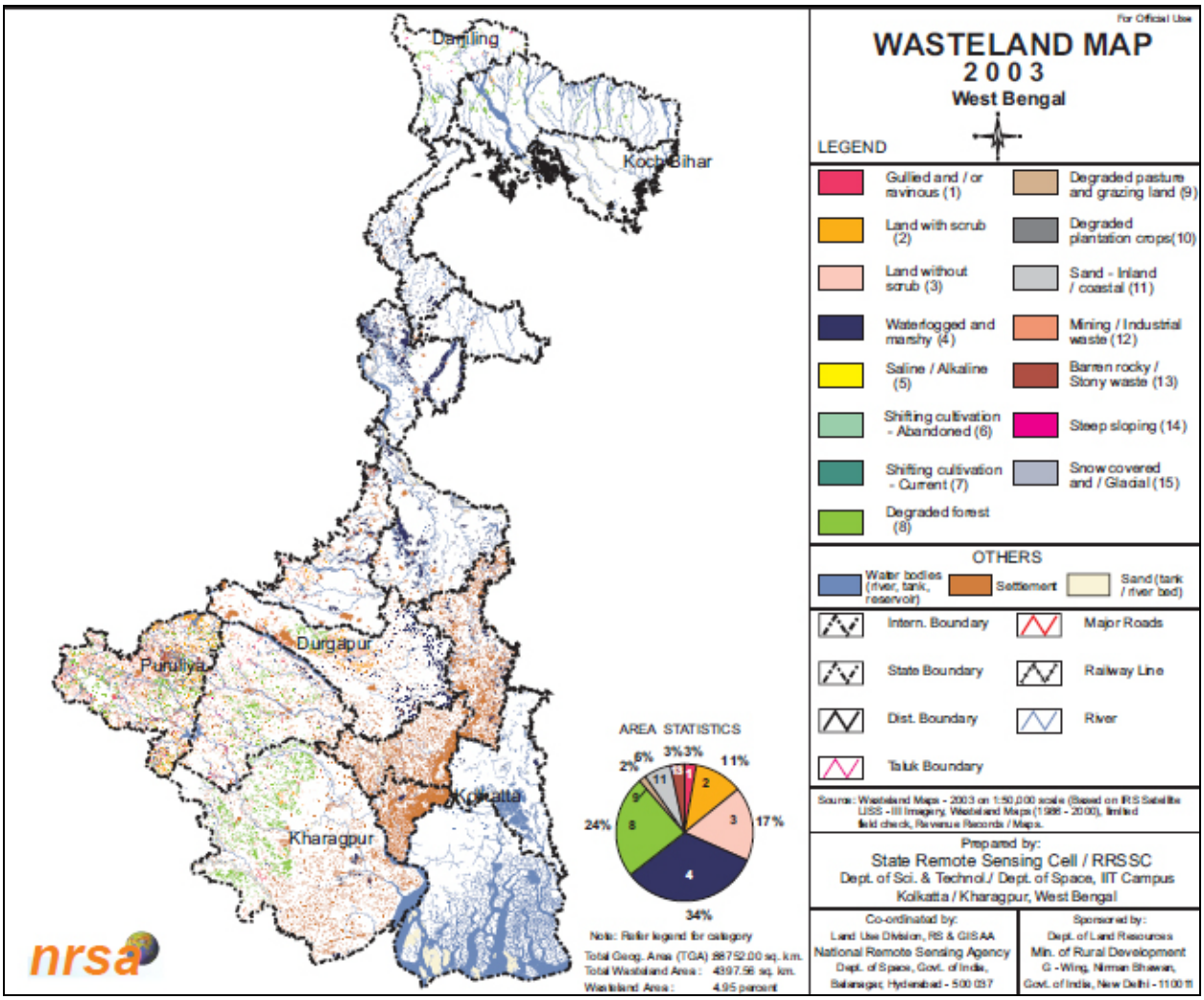

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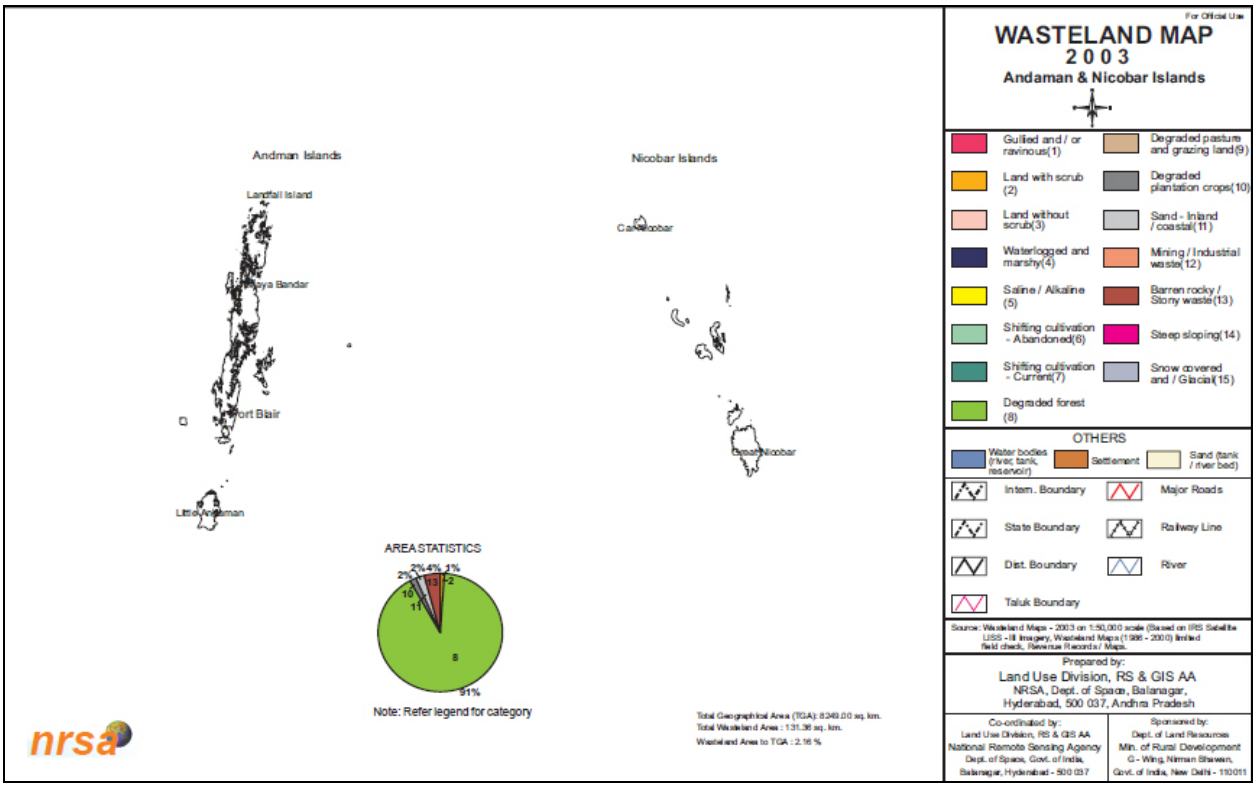

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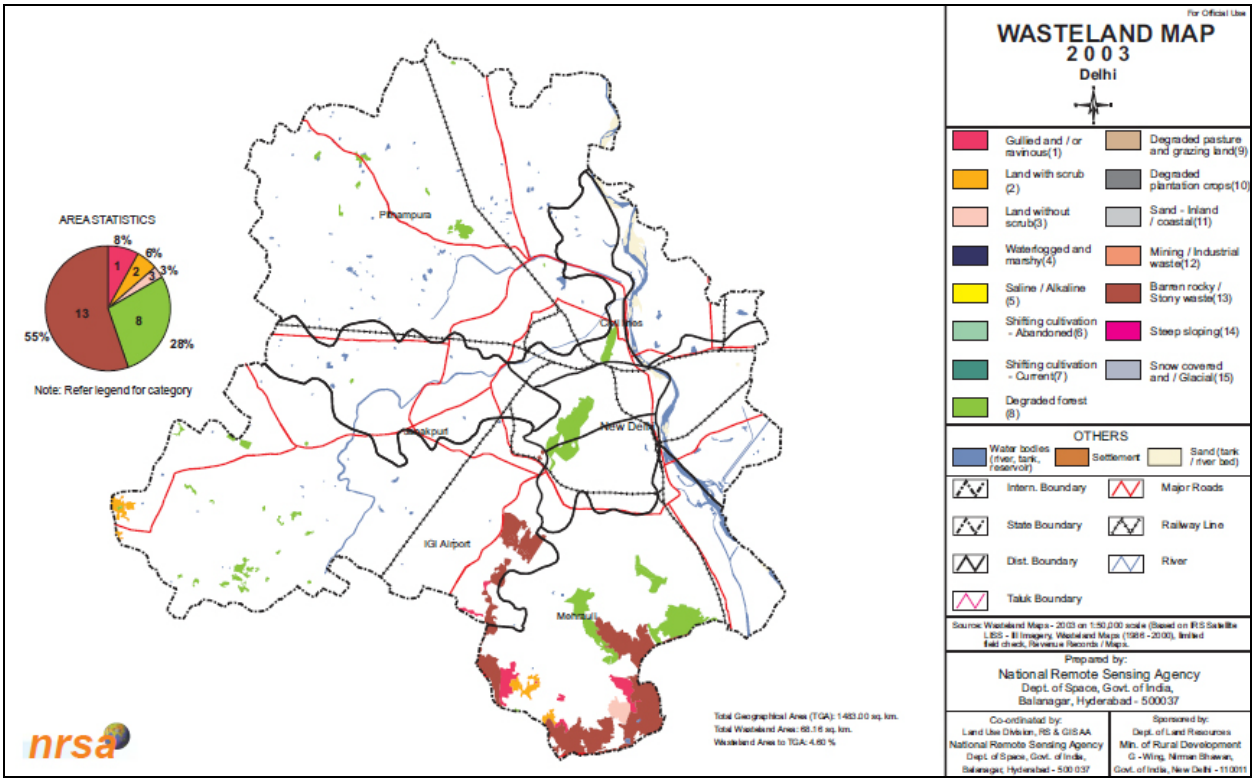

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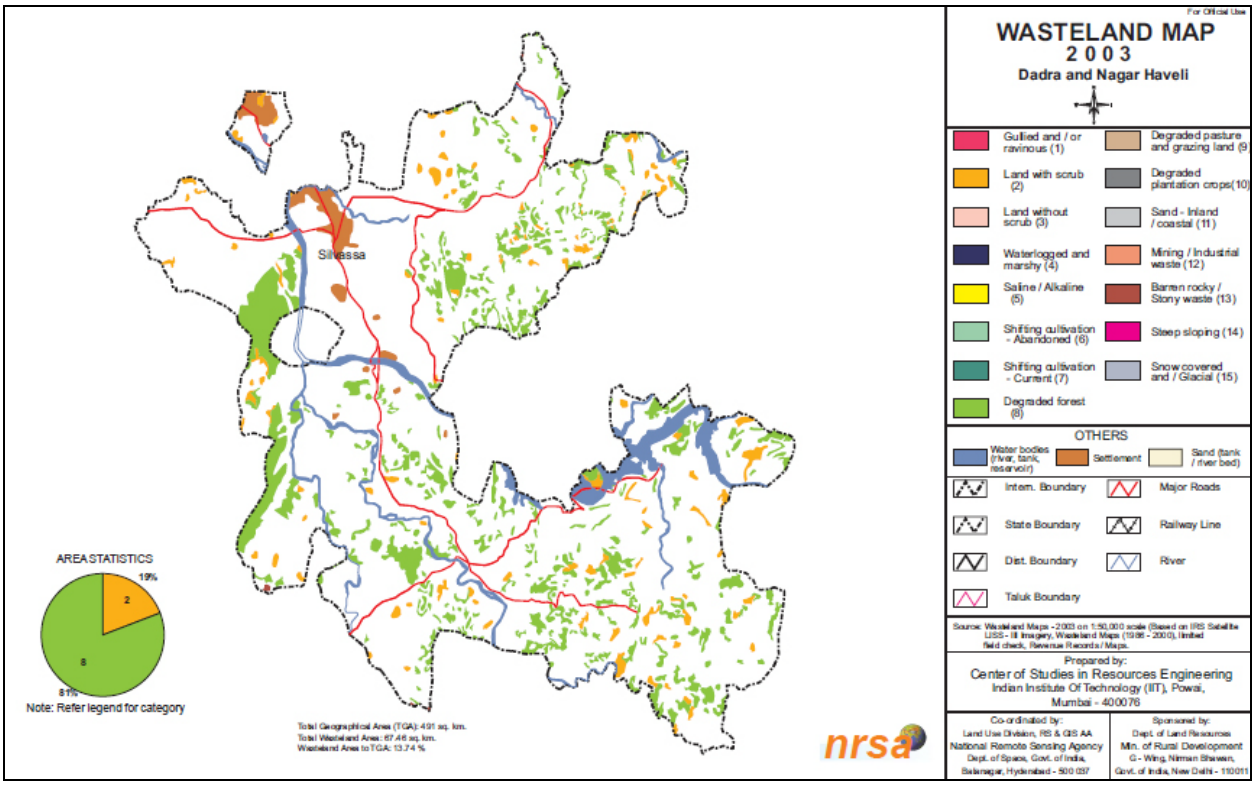

Figure 58. Wasteland in Dadra and Nagar Haveli

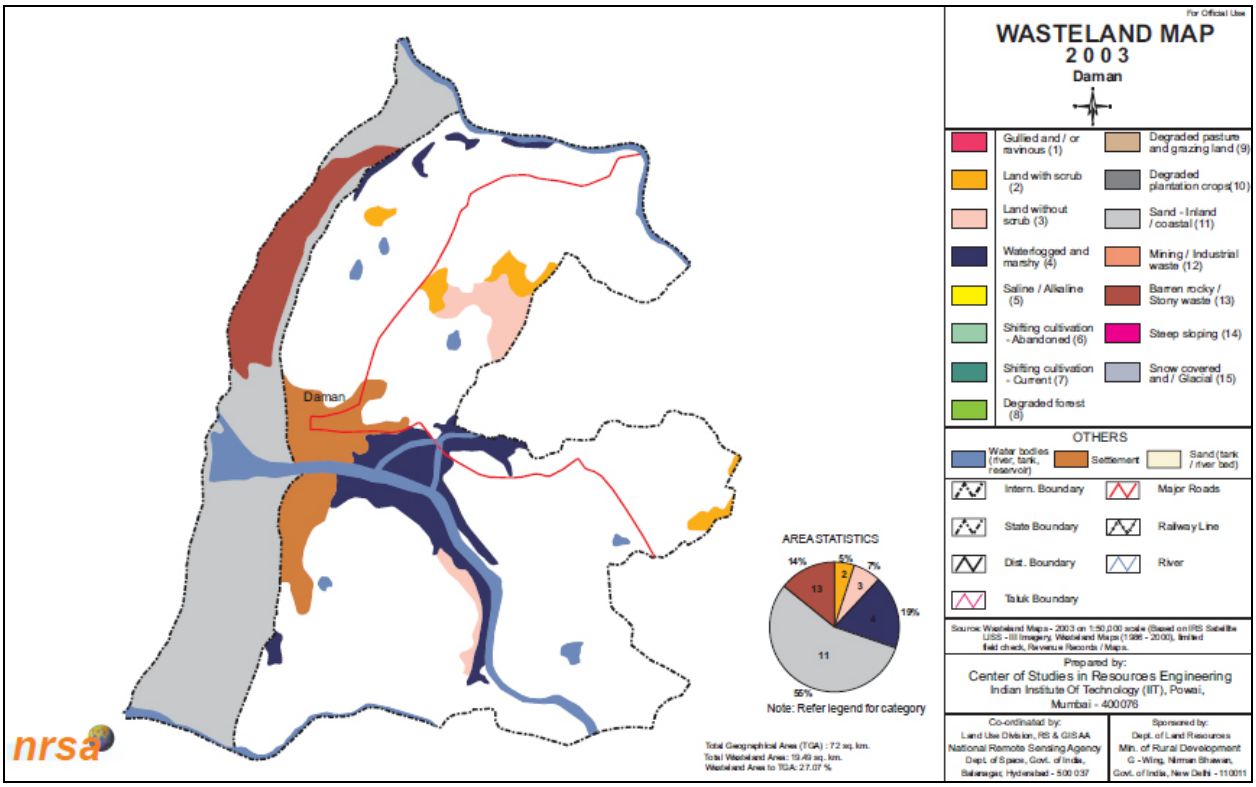

Figure 59. Wasteland in Daman

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14. ABSTRACT *(Maximum 200 Words)*

The study evaluates climate conditions, availability of CO2 and other nutrients, water resources, and land characteristics to identify areas in India suitable for algae production. The purpose is to provide an understanding of the resource potential in India for algae biofuels production and to assist policymakers, investors, and industry developers in their future strategic decisions.

15. SUBJECT TERMS
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