Lake Catchment Interaction Analysis by Using Remote Sensing and GIS Techniques – the case study of Kolleru Lake, South India

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Declaration by the Author

I declared that this thesis is composed of my original work, and contains no material previously published or written by another person except where due reference has been made in the text.

Meena Kumari Kolli

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Abbreviation

No.	Abbreviation	Meaning
1	NBSS&LUP	National Bureau of Soil Survey and Land Use Planning
2	MoEF	Ministry of Environment and Forests
3	SAC	Space Application Centre
4	GIS	Geographic Information System
5	NDVI	Normalized Difference Vegetation Index
6	DEM	Digital Elevation Model
7	WQMPs	Water Quality Management Plans
8	NPS	Non-point Source
9	KWS	Kolleru Wildlife Sanctuary
10	APSDPS	Andhra Pradesh State Development Planning Society
11	NRSC	National Remote Sensing Center
12	ISRO	Indian Space Research Organization
13	IMD	Indian Meteorological Department
14	USST	United States Soil Taxonomy
15	USDA	United States Department of Agriculture
16	NRCS	National Resource Conservation Service
17	SWAT	Soil and Water Assessment Tool
18	SCS-CN	Soil Conservation Service Curve Number
19	HRUs	Hydrological Response Units
20	MUSLE	Modified Universal Soil Loss Equation
21	RUSLE	Revised Universal Soil Loss Equation
22	BMPs	Best Management Practices
23	EPA	Environmental Protection Agency
24	APPCB	Andhra Pradesh Pollution Control Board
25	MoEF&CC	Ministry of Environment Forest and Climate Change
26	SPCBs	State Pollution Control Boards
27	CEC	Central Empowered Committee
28	KLDC	Kolleru Lake Development Committee
29	CPCB	Central Pollution Control Board
30	BMPs	Best Management Practices
31	KLFD	Kolleru Lake Forest Department
32	IWMP	Integrated Water Management Plan
33	GCSD	German Council for Sustainable Development
34	CSA	Centre for Sustainable Agriculture
35	KFCS	Kolleru Fisherman Cooperative Society
36	APGWD	Andhra Pradesh Ground Water Department

Abstract

Wetlands belong to the most productive ecosystem on Earth. They provide many essential services to humans. They play an important role and possess ecosystem services, for example, in biodiversity conservation, for the hydrologic cycle, to buffer regional climate change, and for human health. Among the different types of wetlands, lakes (lacustrine wetlands) play a crucial role in maintaining global and regional water balances, natural and socio-economic resources, and habitats. Over the last decades, the lakes have gone through enormous changes derived from both natural processes and anthropogenic activities. Particularly, freshwater lakes are endangered through point and non-point pollutions, and such impacts are coming from agricultural runoff and industrial pollution, domestic waste, through municipal sewage, which may deteriorate the water quality and their ecological integrity. The Kolleru Lake wetland ecosystem in South India has been taken here as a case study, based on a comprehensive data analysis and modeling of Spatio-temporal variability of the pollutant loads, to achieve a better understanding of the man-environmental problems of the lake and its surrounding catchment. This is a necessary requirement for both better management of the agricultural, industrial, and water resources in the whole area and better lake protection and conservation.

Kolleru Lake is the largest freshwater lake in India. It is a huge natural flood balancing reservoir and also a wildlife sanctuary. In 2002, the Ramsar Convention recognized the lake as a wetland of international importance. The lake is predominately fed by rivers. Among them, Budameru and Tammileru rivers are contributing to the lake influx substantially, plus supported by 68 minor irrigation (drainage) canals. The Kolleru Lake covers a total area of more than 90,100 hectares and holding approximately 1,350 cubic miles of freshwater. Additionally, Kolleru Lake provides drinking water to the inhabitants of the surrounded villages. The lake area up to 3' ft contour is consistent with water, while the 5' ft contour level of the Kolleru Lake belongs to the wildlife sanctuary. Further, it is mostly occupied by aquacultures followed by paddy cultivation, weed infests, and marshy land. There are many small scales to large scale industries growing steadily in order to support successful aquaculture. Before the 1970s, the lake area up to 5' ft contour was not occupied by any type of economic activity; however, the lake is saturated with water during the rainy season, and it remains dry during summer. Furthermore, it was completely free from contamination by aquaculture and agricultural activities before the 1970s. After the 1970s, the State Government had distributed the Kolleru Lake up to 5'ft contour area the poor people, migrant workers, and local inhabitants in the promise of whenever the government again needs the lake area, and they can take it back by paying compensation to them. Then farmers have started paddy cultivation in and around the lake. All bed villages in the lake region are frequently severely affected by massive flooding in connection with the submersion of paddy fields. Despite the fact that the state Government had encouraged the farmers to convert the paddy fields into fishponds by providing loans in order to overcome the floods.

However, the maximum of lake area up to wildlife sanctuary is practiced by the aquaculture in the 1990s.

Since 1970 until the current situation, the lake has been facing some severe environmental threats, such as degraded water quality, deteriorated aqua species and birds, and habitat losses, induced by human activities and accelerated by climate change. A major cause of the environmental problems was identified within the lake by the construction of fishponds resulted in pollution by using pesticides and waste food (exposed to bacterial diseases and infection) to enrich the fish growth. As a result, it causes biological magnification diseases, fertility, and respiratory problems to the animals, birds, and humans who live near to the lake. Thereby the ecosystem will become an inhospitable environment for those aqua species and birds. The fish ponds occupied approximately 42% of the lake area while aquaculture had encroached another 8.5%, together covering 50% of the lake region. If the human-induced debasement of the lake will continue, the lake will no longer cease to exist, and the wildlife species soon will disappear. Apart from the aquaculture tradition, the Kolleru Lake catchment is known for its intensive paddy cultivation. However, the massive application of pesticides and chemical fertilizers to agricultural lands across the catchment area is one reason for the eutrophication in Kolleru Lake. In addition to the several factors that influence the lake ecosystem, industrial pollution causes deteriorating water quality and makes them unfit for drinking water for the inhabitants of the villages around the Kolleru Lake. Both point and non-point sources issued threatens to the lake area becomes more sensitive by anthropogenic activities.

The **main focus of the present research** was to analyze the problems related to the lake catchment and give recommendations to the government about the insight view of the land use cover and enlighten the public perception towards the lake degradation. However, sedimentation in a lake is a natural consequence of the inflow of respected tributaries, rivers, and streams. In addition to the natural influence, man-made activities like land use and others are also responsible for erosion in the catchment and the sediment transport and accumulation of the sediments in both the lower sections of the catchment and the lake basin itself, as discussed in **the first research objective**. Extensive use of land and the indiscriminate rise of embankments for the construction of fishponds as well as agricultural functions has resulted in widespread soil erosion in the catchment and sedimentation over the deltaic part of the Kolleru Lake catchment. In addition, the perennial rivers of Krishna and Godavari drift down to the lake about 68,000 tons/yr of sediments that coming from the whole catchments after passage from the river banks and river beds. The objective of this part was to analyze both the average annual soil loss rate and its change from the catchment and the sediment yields by using the RUSLE model both for the terrestrial part and the semi-aquatic deltaic part of the Kolleru Lake catchment for the years 1972 and 2012. The results indicated that the average annual soil loss was estimated with 13.6 t/ha/yr, classifying the Kolleru Lake Basin under a very high erosion rate category. Whereas, the average annual sediment yield was determined with 7.61 t/ha/yr. The resultant difference of the sediment balance is temporally interbedded within the terrestrial sites and within the river banks and river beds. However, this study has found that tributaries and streamlines of the catchment carry high sediment loads to the lake.

This research has proved how intensive agricultural activities in wetland catchments interact with the pollution levels of the lake, causing a deteriorated water quality. Agricultural runoff (runoff from catchment areas dominated by agricultural use) is the main driving factor of accumulated non-point source pollution of the lake water, with side-effects on sediments and silts near the downstream areas of the Kolleru Lake catchment. It primarily caused eutrophication in the lake subsequently that led to proliferating the weeds. However, **the second objective** of the research was to estimate the tributaries' sub-basin loads and to highlight the diffuse critical sources against the village communities. For this purpose, the Soil and Water Assessment Tool (SWAT) was used to model the diffuse sources in the catchment. The spatial distribution of nitrate-nitrogen (NO_3-N) and total phosphorus (TP) emissions were quantified. Some sub-basins contribute more pollutant load to the lake. Alternately, the first and second BMPs (Best Management Practices) level priority areas were identified. Further, suggestions for the implementation of agricultural management practices have been provided for the crucial protection of the lake ecosystem.

Consequently, the Kolleru Lake wetland ecosystem is known for its both abundant water availability as well as water scarcity. The river and streams water diverted into the agricultural lands, and still, there is a dire need for groundwater too. When the monsoon rain was weak, and after rainless summer periods, the lake falls more or less dry. Therefore there is a high demand for groundwater, which is continuously increasing. An effective way to analyze groundwater recharge and groundwater availability is a remote sensing and GIS based mapping. The theoretical concepts are involved in this objective is more useful for t further research of the link between surface emission and groundwater contamination. That is why the present research has been investigated as **the third objective,** the potential groundwater resources in the catchment. A simple mathematical equation was derived from the catchment hydrologic characteristics. The catchment characteristics were analyzed and based on the previous literature sources, and the thematic weight was assigned to evaluate potential groundwater zones. About 13% of the catchment area falls under poor conditions, 38% of the area falls under moderate conditions, 42% of the area falls under good conditions, and about 7% of the area is under excellent condition. These results are a contribution to future groundwater management projects and artificial recharge plans of the Kolleru Lake catchment to maintain sufficient groundwater levels.

Due to the still existing lack of observed data of the tributaries, i.e., runoff, sediment, water quality parameters, nutrient load, the used methods are limited and suitable just for an estimation. Sufficient calibration and validation of the results were also limited because the access to the study area and to an onside research institute was not allowed for the Ph.D. candidate, because of its status as a Ph.D. student from Germany. Field investigations on the interaction of pollutant loads with the runoff would be advantageous for a better calculation of the pollutant load and its dynamic. Because of the limited funding capacity, it is challenging to do a field survey to control every remote sensing and GIS result of this research. That is why, without a few exceptions, this study was conducted dominantly based on remote sensing data and accessible weather and soil data.

From the research results emphasized that the Kolleru Lake water level and water quality are highly degraded, respectively polluted with metals, agricultural contaminants, which makes the lake water not advisable for human consumption. The erosion and sedimentation loads are also high, and the priority management practices should be targeted already in the middle catchment region. These results give a general understanding of the pollutant levels in the lake, which should be useful for government management plans.

Zusammenfassung

Feuchtgebiete gehören zu den produktivsten Ökosystemen der Erde. Sie verfügen deshalb über viele essentielle Dienstleistungen für die Menschen. Bedeutende Funktionen oder Ökosystemdienstleistungen stellen sie z.B. für die Aufrechterhaltung der Biodiversität, für den Wasserkreislauf, zur regionalen Abpufferung des Klimawandels und für die menschliche Gesundheit zur Verfügung. Unter den verschiedenen Feuchtgebieten kommt den Seen (lakustrine Feuchtgebiete) eine besondere Bedeutung bei der Aufrechterhaltung bzw. dem Dargebot der globalen und regionalen Wasserbilanz, der natürlichen und sozio-ökonomischen Ressourcen und den Habitaten zu. Während der letzten Dekaden unterlagen Seen enormen Veränderungen, ausgelöst sowohl durch natürliche Prozesse als auch durch anthropogene Aktivitäten. Süßwasserseen sind vor allem gefährdet gegenüber Punkt- und diffusen Stoffeinträgen, die häufig durch die Landwirtschaft, durch die Industrie, aber auch in Verbindung mit Hausmüll und kommunalen Abwässern eingetragen werden und dadurch die Wasserqualität in den Seen und damit deren ökologische Intaktheit sowie deren Funktionen enorm verschlechtern bzw. erniedrigen. Das Kolleru Lake Feuchtgebiet Ökosystem in Südindien wurde als Untersuchungsobjekt ausgewählt, um auf Basis der Analyse und Modellierung der raum-zeitlichen Variabilität der Verschmutzungsbelastung zu einem besseren Verständnis der Mensch-Umweltprobleme dieses Sees und seines Einzugsgebietes zu gelangen. Das ist eine notwendige Voraussetzung sowohl für ein besseres Management der landwirtschaftlichen, industriellen und aquatischen Ressourcen des gesamten Gebietes als auch für den Schutz und die Erhaltung des Kolleru Lake.

Der Kolleru Lake ist der größte Süßwassersee in Indien. Er stellt ein gewaltiges Hochwasserausgleichsreservoir dar; zugleich ist er auch ein Wildtierschutzgebiet. 2002 wurde der See durch die Ramsar Konvention als ein Feuchtgebiet von internationaler Bedeutung anerkannt. Der See wird vor allem durch Flusswasser gespeist. Die Flussläufe des Budameru und des Tammileru tragen substantiell zum Wasser-Input des Sees bei; daneben erfährt er aber auch Zuflüsse von insgesamt 68 kleineren Bewässerungs- (Drainage-) kanälen. Die gesamte Seefläche des Kolleru Lake beträgt mehr als 90.100 Hektar, was einem Volumen von 1.350 Kubikmeilen 2.172.614 m^3 Süßwasser entspricht. Der Kolleru Lake stellt auch einen Trinkwasserspeicher für die Bewohner der angrenzenden Dörfer dar. Ein 3 Fuß bzw. 0,92 m flacher Wasserkörper ist permanent mit Wasser bedeckt. Das Wildtierschutzgebiet reicht bis zur Marke eines 5 Fuß bzw. 1,52 m temporär mächtigen Wasserkörpers. Die Seefläche wird partiell von Aquakulturen, Nassreisfeldern, Seegras und Marschland eingenommen. Im Umfeld haben sich kleinere bis hin zu größeren Industrieanlagen im Zusammenhang mit der Nutzung der Aquakulturen angesiedelt, deren Anzahl in den letzten beiden Jahrzehnten ständig zunahm. Vor 1970 gab es bis zur 5 Fuß- bzw. 1,52 m Wassertiefen-Uferlinie keine Landnutzungen. Aber während der monsunalen Regenzeit ist der See bis zu

dieser Marke mit Wasser gefüllt, das nach viel Zufluss dort auch während der trockenen Sommermonate nahezu verbleibt. Dieser Wasserkörper war vor 1970 weitestgehend kontaminationsfrei. Ab 1970 hat die Provinzregierung solche Flächen bis zur 5-Fuß-Marke zur Nutzung an arme Bevölkerungsgruppen, Arbeitsmigranten und die lokale Bevölkerung abgegeben, mit der Option, dass sie diese Flächen, wenn sie benötigt werden, gegen eine Kompensationszahlung zurück kaufen kann. Daraufhin haben Bauern im See und in dessen Umfeld Nassreis angebaut. Alle seebettnahen Dörfer sind deshalb häufig massiven Überschwemmungen in Verbindung mit dem Wässern der Nassreisflächen ausgesetzt. Ungeachtet der Tatsache, dass die Provinzregierung die Bauern ermutigt hat, die Nassreisfelder in Fischteiche umzuwandeln, indem sie Darlehen zur Überwindung der Überschwemmungsfolgen gewährt hat, wurden in den 1990er Jahren auf dem größten Teil der Seefläche, einschließlich des Wildtierschutzgebietes, nach wie vor Aquakulturen betrieben.

Seit 1970 bis zur Gegenwart war und ist der See einigen schwerwiegenden Umweltbelastungen ausgesetzt, die meist anthropogen, d.h. durch die Nutzung ausgelöst wurden und durch den Klimawandel nicht selten noch verstärkt werden. Das äußert sich in einer solch schlechten Wasserqualität, dass bestimmte Wassernutzungen nicht mehr möglich sind, in Schädigungen an Wasserorganismen und Vögeln und in Form von generellen Habitatverlusten. Ein Hauptgrund für die Umweltprobleme sind die innerhalb des Sees angelegten Fischteiche. Durch Pestizideinsatz und Speisenabfälle, die eigentlich das Fischwachstum stimulieren sollten, kommt es zu Verschmutzungen, die wiederum bakterielle Erkrankungen und Infektionen verursachen können. Infolge dessen kam es zu einer Zunahme von Erkrankungen bei Wasserlebewesen, Vögeln und Menschen im Umfeld des Sees. Eine Folge für die See-Ökosysteme ist, dass sie zunehmend nicht mehr als Habitatstandorte für Wasserorganismen und Vögel fungieren können. 42% der Seefläche werden von Fischteichen, weitere 8.5% von Aquakulturen eingenommen. Wenn sich die anthropogene Ausbeutung und Übernutzung der Naturresourcen des Sees fortsetzt, wird der See nicht mehr lange existieren und die Tierarten werden hier aussterben. Neben der Aquakulturnutzung ist der Kolleru Lake traditionell für die intensive Nassreiskultivierung bekannt. Aber auch hier ist der massive Pestizid- und Düngereinsatz auf den Landwirtschaftsflächen des Einzugsgebietes ein Grund für Eutrophierungsprozesse im Kolleru Lake. Neben diesen Einwirkungen auf das See-Ökosystem tragen auch industrielle Emissionen zu einer Verschlechterung der Wasserqualität bei und führen letztlich dazu, dass der See als Trinkwasserreservoir für die Bewohner der den Kolleru Lake umgebenden Dörfer nicht mehr genutzt werden kann. Sowohl Punkt- als auch diffuse Stoffeinträge in den See sind bedeutende Belastungsursachen infolge anthropogener Aktivitäten.

Hauptzielstellung des vorliegenden Promotionsprojekts war es, eine Problemanalyse für den See und sein Einzugsgebiet durchzuführen und daraus Empfehlungen für die Provinzregierung für eine belastungsarme Landnutzung abzuleiten sowie die öffentliche Wahrnehmung über die Seedegradierung zu verbessern.

Die Aufsedimentierung eines Sees ist ein natürlicher Prozess infolge des Sedimenteintrags durch die Zuflüsse bzw. aus dem Einzugsgebiet. Zusätzlich zum natürlichen Sedimenteintrag sind auch anthropogene Aktivitäten wie die Landnutzung u.a. verantwortlich für Bodenerosion im Einzugsgebiet sowie den daraus resultierenden Sedimenttransport und die Sedimentakkumulation im gefällearmen Unterlauf bzw. im Seebecken selbst. Das wird im Rahmen des **ersten Teilzieles** untersucht. Extensive Landnutzung und die nahezu ungehinderte Zunahme der Eindeichungen für die Anlage von Fischteichen, aber auch landwirtschaftliche Aktivitäten haben zu weit verbreiteten Erosionsprozessen im Einzugsgebiet und zu einer Aufsedimentation im gesamten Deltabereich des Kolleru Lake geführt. Unabhängig davon transportieren die permanent Wasser führenden Flüsse Krishna und Godavar 68.000 Tonnen Sedimente pro Jahr zum Kolleru Lake, z. T. unter „Nutzung“ der Sedimentreservoire der Flussufer und der Sohlbetten. Das Ziel dieses Teils des Promotionsprojekts bestand darin, die durchschnittliche Bodenabtragsrate und deren zeitliche Veränderung sowie das Sedimentaufkommen mit Hilfe der Allgemeinen Bodenabtragsgleichung (RUSLE) für den terrestrischen Teil des Einzugsgebietes und den semi-aquatischen Teil des Deltas des Kolleru Lake Einzugsgebietes für die Jahre 1972 und 2012 zu ermitteln. Im Ergebnis konnte festgestellt werden, dass der durchschnittliche Bodenabtrag 13,6 t/ha/Jahr beträgt, was das Kolleru Lake Einzugsgebiet als ein Gebiet mit einer hohen Erosionsrate kennzeichnet. Das jährliche Sedimentaufkommen wurde mit 7,61 t/ha/Jahr ermittelt. Die resultierende Differenz an Sedimenten in der Sedimentbilanz wird zeitlich befristet sowohl auf den terrestrischen Standorten als auch in den Flussufern und Sohlbetten der Zuflüsse zwischengespeichert und steht als Sedimentreservoir zur Verfügung. Unabhängig davon konnte nachgewiesen werden, dass die Zuflüsse zum Kolleru Lake eine hohe Sedimentzufuhr zum See gewährleisten.

Durch die Untersuchungen konnte nachgewiesen werden, welche Interaktionen zwischen den intensiven landwirtschaftlichen Aktivitäten im Einzugsgebiet des Feuchtgebietes und den Verschmutzungsniveaus der Wasserqualität im See bestehen. Der Landwirtschafts-Abfluss (d.h. Abfluss von den Flächen des Einzugsgebietes, die dominant landwirtschaftlich genutzt werden) ist ein Hauptfaktor der Verschmutzung des Seewassers aus diffusen Quellen, mit Nebenwirkungen auf die Sedimente und Schlämme des Sees und des seenahen Unterlaufgebietes der Zuflüsse. Vor allem kommt es dadurch zur Eutrophierung im See und zur vermehrten Ausbreitung von Seegras. Das **zweite Teilziel des Forschungsprojekts** war es, den Beitrag der Zuflüsse aus den Teileinzugsgebieten an der Belastung des Seewassers abzuschätzen und die diffusen kritischen Belastungsquellen gegenüber den Punktbelastungen, welche von den Kommunen ausgehen, heraus zu stellen. Für dieses Teilziel wurde das Soil and Water Assessment Tool (SWAT) genutzt, um die diffusen Quellen im Einzugsgebiet zu identifizieren. Die räumliche Auflösung der Nitrat-Stickstoff (NO_3-N)- und der Gesamt-Phosphor (TP)-Emissionen konnten quantifiziert werden. Es konnte gezeigt werden, dass einige Teileinzugsgebiete stärker zur Seeverschmutzung beitragen als andere. Darauf basierend konnten Nutzflächeneignungen detektiert und ausgewiesen werden, welche eine Nutzung im Sinne der BMP (Best Management Praxis) ersten und zweiten Grades erlauben. Als Schlussfolgerung daraus wurden Empfehlungen für die Implementierung anderer landwirtschaftlicher Bewirtschaftungspraktiken erarbeitet, die eine Schlüsselfunktion für den Schutz der See-Ökosysteme darstellen.

Das Kolleru Lake Feuchtgebiet ist bekannt sowohl für seine reiche Wasserverfügbarkeit als auch für seine Wasserknappheit. Flüsse und Kanäle werden abgezweigt, um landwirtschaftliche Flächen zu bewässern, und selbst Grundwasser wird entzogen. Wenn der monsunale Niederschlag unterdurchschittlich war, fällt der See während der niederschlagsfreien Sommermonate mehr oder weniger trocken. Dann besteht ein erhöhter Bedarf, Grundwasser zu nutzen. Dieser Bedarf stieg in den letzten Jahren stetig an. Aus diesem Grund bestand das **dritte Teilziel des Forschungsprojekts** darin, die potentiellen Grundwasserresourcen im Einzugsgebiet des Kolleru Lake zu untersuchen. Aus der Analyse der hydrologischen Charakteristika des Einzugsgebietes wurde eine einfache mathematische Gleichung erarbeitet. Die Einzugsgebietscharakteristika wurden auf Grundlage von Literaturangaben analysiert und deren Einfluss mittels einer thematischen Gewichtung unterschieden, um potentielle Grundwasserzonen zu detektieren. Dabei wurde festgestellt, dass 13% des Einzugsgebietes über ein geringes Grundwasseraufkommen, 38% über moderate, 42% über gute und 7% über ausgezeichnete Grundwasservorkommen verfügen. Diese Ergebnisse stellen einen wichtigen Beitrag für zukünftige Grundwassermanagement-Projekte und Grundwasserneubildungspläne im Kolleru Lake Einzugsgebiet dar, um einen hinreichendes Grundwasserdargebot zu gewährleisten.

Weil Datenlücken zum Abfluss, zur Sedimentführung, zur Nährstofffracht und zur Wasserqualität der Zuflüsse bestanden weisen die hier gewählten Methoden bzgl. der Ergebnisse auch Einschränkungen auf, weshalb z. T. nur Abschätzungen getroffen werden konnten. Eine Kalibrierung und Validierung der Ergebnisse vor Ort konnte nur sehr eingeschränkt durchgeführt werden, da der Bearbeiterin als in Deutschland eingeschriebene Doktorandin der Zutritt zum Untersuchungsgebiet und zu einem Forschungsinstitut vor Ort von den örtlichen Behörden untersagt wurde. Vor-Ort-Geländemessungen vor allem der Schadstofffracht in Abhängigkeit vom Abfluss würden eine bessere Abschätzung der Schadstoffbelastung und deren Dynamik erlauben. Auch standen nicht genügend Mittel zur Verfügung, um jedes der Fernerkundungsergebnisse und GIS-Modellierungen durch eigene Vor-Ort-Messungen zu überprüfen bzw. abzusichern. Deshalb basiert, bis auf wenige Ausnahmen, dieses Promotionsprojekt vor allem auf Fernerkundungsdaten sowie zugängliche Klima- und Bodendaten.

Insgesamt konnte gezeigt werden, dass sowohl der Seespiegel als auch die Wasserqualität im Kolleru Lake in hohem Maße erniedrigt sind, dass das Wasser mit

Metallen und aus der Landwirtschaft stammenden schädlichen Stoffen angereichert ist, weshalb das Seewasser nicht mehr für die Trinkwassernutzung empfohlen werden kann. Die Erosionsraten im Einzugsgebiet und Sedimentationsraten im Delta sind hoch. Deshalb sollten Maßnahmen zur Eindämmung der Erosion schon im mittleren Einzugsgebiet beginnen.

Die Ergebnisse tragen zum generellen und verbesserten Verständnis der Verschmutzungsniveaus im See bei. Sie stellen deshalb nützliche Basisinformationen für Managementpläne der Provinzregierung dar.

CHAPTER 1

Introduction

1. 1 Current wetland studies – a literature review

Wetlands are stagnated with water either permanently or seasonally. They are belonging to the most productive ecosystems on earth and provide many essential services to humans (Padmalal, et al. 2011; Ghermandi et al. 2008). However, they are ecologically sensitive and adaptive systems (Turner et al. 2000). Wetlands found on every continent and in every kind of environment, from mountains to deserts and lowlands. They exhibit enormous diversity according to their place of origin, physiological structure, slope, water regime, chemistry, land use, soil, and sediment characteristics as well as river flow patterns and play a crucial role in the hydrological cycle (Chatterjee et al. 2015; Bassi et al. 2014; Ramsar Convention Secretariat 2004). The global extent of wetland ecosystems ranges from 917 million hectares (m ha) to more than 1,275 m ha (Lehner & Döll 2004; Finlayson & Davidson 1999) as a whole. Wetlands occupy an estimated 6% of the world's earth surface. Detailed inventories of types, locations, however, are substantially incomplete, and information on functions, values, and status is minimal on a global scale.

Wetlands play a vital role in biodiversity, hydrology, climate change, and human health (Ramsar Convention Bureau 2001). In terms of biodiversity, although freshwater wetlands cover only 1% on the eath surface, it supports more than 40% of the world species (Mitra et al. 2003). Hydrologically wetlands regulate the water movement, purify the organic and inorganic nutrients, more indispensable sources for groundwater recharge, and maintain sustainable environments (MEA 2005). Not only during the period of climate change, but wetlands also exhibit an enormous effect on both global and regional climate by supplying atmosphere with potential or near-potential evapotranspiration and by taking up carbon dioxide and emitting methane (Hu et al. 2017; Russi et al. 2013). From the aspect of human health, they provide natural medicines on which 80% of the world's population depending on primary health care (Mitra et al. 2003).

The wetlands were classified into five categories by Cowardin et al. (1979), depending on physiological, geological, and hydrological structures. Those are marine (coastal wetlands), estuarine (including deltas, tidal marshes, and mangrove swamps), lacustrine (lakes), riverine (along rivers and streams), and palustarine (swamps and bogs). Globally, many wetlands are potentially valuable. However, they are providing essential services and contributions to people's livelihoods. Besides, they support rich biodiversity, groundwater recharge, they act as water purifiers, they protect or buffer floods, droughts, and natural disasters, and they store more carbon than any other semi-terrestrial ecosystem (Mitsch et al. 2013; Prasad et al. 2002; Mitsch & Gosselink 2000; Meybeck 1995). Due to the lack of attention on wetlands, many internationally recognized wetlands are under threat and significantly lose their biodiversity. Most of them are degraded by increasing urbanization and small scale to large scale economic activities. Especially, inland ecosystems are under stress by industrialization and ever-increasing population. Additionally, coastal wetlands are disappearing by port expansion and industrial activities (Pinder & Witherick, 1990). The Global Wetland Outlook of the Ramsar Convention emphasized that about 35% of wetlands have been lost around the world between 1970 and 2015, and the rate is three times faster than that of forests lost (Ramsar Convention on Wetlands 2018). This figure originates from the lack of sufficient data during the mid-20th century. Nevertheless, many researchers are reported that the world's wetland losses were anticipated to be more than 50% on the eath's surface (Davidson 2014; Finlayson 2012).

The world's mangrove forests cover at least 14 million ha and are largely concentred in some of the developing countries (Maltby 1988). The greatest concentrations are in the Indian Ocean – West Pacific region, with about 20% of the world's total area bordering the Sunda Shelf region. The Niger Delta has 700000 ha, and the Sundarbans forest covers nearly a million hectares of the Ganges delta (Christensen 1983). The Sundarbans mangrove forest is reserve for the man-eating Royal Bengal Tiger. One-third of the mangrove forests located in India and two-thirds of the area belong to Bangladesh.

The maximum of river channels and valley sides forms unique ecological flooded zones, that produces a complex variety of wetlands depending on the hydrology, climate, water regime, and form the floodplain. In the United States, the periodical flood zones produce bottomland hardwood forests. Such forests mostly covered vast areas of the South East, East, and the Central United States; however, the largest areas concentred in the lower Mississippi River Valley. Similarly, the two largest rivers of the Krishna and Godavari in the Southern part of India formed a natural, unique flood-balancing zone of Kolleru catchment between these two river deltas. The wetland complexes, once characterizing the floodplains of Europe and North America, have gradually disappeared through the depleting of river channels, levee construction, and significant land-use changes. The world's remaining flood zones are now limited to the tropic and sub-tropic regions, most of them are under pressure for development projects.

Nearly half the total wetland area of Africa consists of forested or savanna floodplain (Drijver & Marchand 1985). In particular circumstances, deltas form and produce a mosaic of wetland types on the African continent. These may be inland, such as the Inner Niger and the Okavango or coastal such as the Nile. Some of the largest sheet flood regions are in South America. The Gran Pantanal of the Paraguay River comprises shallow interconnecting lakes and wetland complexes, which in some years can cover 10,000,000 ha and the Apure-Aranca tributaries of the Orinoco in Venezuela produces a floodplain of 7,000,000 ha (Maltby 1988).

In order to protect and conserve the global wetland ecosystems, the Ramsar Convention on Wetlands of International Importance was formed in 1971. The main objective of the Ramsar Convention on wetlands, which is to restore, regain its original view and make them ecologically balanced. However, the Ramsar wetland ecosystems considered as to whether areas of marsh, fen, peatland or water, natural or artificial, permanent or temporary, static or flowing, fresh, brackish or salt, including areas of marine water the depth of which at low tide does not exceed six meters (Bassi et al. 2014). According to the Ramsar Secretariat (2013), the global wetlands sites do have a huge distribution in Europe in 1,052 sites, which among 289 sites in Asia, 359 sites in Africa, 175 sites in South America, while 211 sites in North America, and 79 sites in Oceania region. Wetlands are the only single group of ecosystems having their international convention. The call for wetland protection gained momentum in the 1960s, primarily because of their importance as a habitat for migratory species. (Turner et al. 2000).

1. 1. 1 Introduction to lakes

Lakes are one of the most productive ecosystems in the world. Their existence on a global scale accounts for 0.8% of the earth's surface (Downing et al. 2006). It is estimated that more than 8 million lakes that are larger than 1 ha exist in the world (Meybeck 1995). They play a crucial role in maintaining global and regional water balance, natural and socio-economic resources, and habitats (Browne 1981).

Water on earth is mainly comprised of saline and freshwater, which accounts for 97% and 3%, respectively. Freshwater is further distributed as ice caps and glaciers (68.7%), groundwater (30.1%), surface water (0.3%), and others (0.9%) (Reddy 2018). Among them, lakes are very important and contribute about 87% of all the surface freshwater bodies on the earth's surface, which are considered as a great value to human livelihood, economic support, habitat for biodiversity, recreation, flood control and acts as sinks for inflowing waters received from lake's catchment area (Masahisa & Rafik 2006). The human population is living on and around lakes, mainly for water consumption, food, recreation services, and various economic purposes. For many decades, lakes have been subjected to anthropogenic pressure, caused by overexploitation of the lake's sources for economic growth, and water for irrigation and industrialization. Freshwater lakes are endangered through point and non-point pollutions and such impacts coming from agricultural runoff and industrial pollution, domestic waste through municipal sewage may deteriorate the water quality and their ecological integrity.

Lake catchments have gone through enormous changes derived from both natural and anthropogenic activities. Comparing to their relative quantity, lakes are influenced by two impact categories, and many studies emphasized that how mankind has become a single threat to both the lake functions and their ecosystems (Geller 1998; Macklin 1992). Historically the research has focused on different regional climate regimes to generate the spatial and temporal records. The maximum of the records depicted that the human impacts caused by land use and exploitation of natural resources now became a scientific topic for management interests (Dearing et al. 2006). Longterm environmental records are prerequisites to establish a general understanding of the lake's functions, ecological systems, and their internal structure. However, palaeolimnological analyses, the study of physical, chemical, and biological characteristics of lakes and wetland sediments, provide valuable information on past generations of lakes to reestablish natural and anthropogenic changes for periods pre-dating instrumental observation (Dubois et al. 2018). The gradual changes have been observed in lake functions caused by natural and anthropogenic activities, which enable the focus towards the future preservation of lake ecosystems.

Lake systems are fundamentally important to the environment, biosphere, and human populations. They are becoming more sensitive to anthropogenic stress, and a significant change occurs to them, it is more challenging to maintain a stable environment that alters the hydrological cycle is a climatic concern. However, the first evaluations on lake ecosystems do not necessarily imply human impacts, somewhat changes happening because of ignorance, their culture, and less sophisticated technologies. Nevertheless, with a small or negligible change, some lake systems may have the capacity to adapt rather than change into an alternative state. This analysis might be true when the technologies are growing steadily through time. For example, in Europe (Bradshaw et al. 2005) and China (Shen et al. 2006), the lake systems are slowly changing with time. However, when the catchment modifications were started often with intensive agricultural practices to a certain extent, distinct transitions have been observed in the lake's functions. With the advancement in recent technologies with intense agricultural activities that were introduced within the last two centuries (i.e., Australia, New Zeland), the effects on lake ecosystems are severe, though this could also reflect the sensitivity of the systems (Gell & Reid 2014; Kattel et al. 2014). Previous studies discussed that from amid 20th century many lakes started to show the negative impacts that attributed by the natural-anthropogenic system in the form of desiccation, sanitization, and eutrophication (Sun et al. 2018; Opp et al. 2017; Groll et al. 2013). These changes and effects are most extreme that eventually alter the hydrological processes.

Many studies report the rapid loss of lakes over recent decades, for example, Bai et al. (2010) investigated the inland lakes (i.e., nine lakes) in arid regions of Central Asia had experienced significant decreases in surface area during the period from 1975 to 2007. The results indicated that the total surface areas of these nine lakes had decreased from 91,402.06 km^2 to 46,049.23 km^2 from 1975–2007, while the water area had decreased by 56.7% since 1975. The lakes are mainly affected by climate regimes as a result of human activities in Central Asia. Karthe et al. (2014)

have pointed out that a substantial part of the management problems and challenges regarding water resource availability in Central Asia are related to lakes. Especially lakes in dryland areas of Central Asia and East Asia are heavily affected by both climate change and human activities, such as water withdrawal within the catchment (Karthe 2017). Similarly, in China, drastic changes were found in both lake number and lake area. Two hundred forty-three lakes disappeared between 1960-1980s and 2005-2006, mainly in the northern provinces (Ma et al. 2010). Meanwhile, in southern provinces, 60 new lakes appeared on the Tibetan Plateau and neighboring provinces. The study demonstrated that the actual changes in lake distribution and occurrence might be associated with climate change in northern China, and human activities in southern China resulted in that the lakes became more sensitive to these impacts. In another study in Mongolian Plateau, Tao et al. (2015) reported that the rapid loss of lakes on the plateau, however, it had experienced significant lake shrinkage and grassland degradation between 1970 and 2000. The deterioration of lakes is not only subjected to climate change, but it is mainly from over-exploitation of underground mineral and groundwater resources in this region. Additionally, lakes in remote regions affected to transboundary pollution during the last few decades, with the change of anthropogenic nutrient loading via atmospheric deposition (Bergstrom & Jansson 2006).

The sensitivity of lake systems to any given driver not only depends on the human disturbances but also on how the lake systems process the environmental changes. Some lakes may immediately respond to particular changes; in contrast, others take significant time to react to the same change (Scheffer et al. 2012). For example, large and deep lakes have relatively higher nutrient and sediment loading capacity from a catchment that exhibit by a delayed response whereas small lakes express little lag difference between the land-use change and lake response (Dearing & Jones 2003). Not seldom, lakes and wetlands under both climatic change and anthropogenic pressures can also be, besides others, source areas of health problems for people (Karthe & Stähle 2008).

Several factors influence lake catchments that included soil erosion, sedimentation, non-point source, eutrophication, land-use change, turbidity, pollution, and other minor factors that are responsible for the lake ecosystem degradation (Wang et al. 2017; Guo et al. 2014). These factors are often interrelated with natural and human processes. However, many studies have dealt with either individual aspects or combined the two and more relative factors to asses the lake systems (Opp 2007, Smith et al. 2007; Aladin & Plotnikov 2003). Aside from the lake level dynamic induced by natural factors in human activities, mainly land-use changes, have a severe impact on lake systems.

Landuse changes are major threats to the lake catchments that trigger the hydrological processes invariably. For example, Lake Victoria, characterized by high population densities, posing severe threats to watersheds as a result of a wide range of farming activities, grazing, and macrophyte harvesting and coupled with catchment degradation-deforestation (Thenya et al. 2005). These factors were closely related to demographic dynamics and land management practices. Similarly, between 1967 and 1990, Lake Naivasha lost over 3000 ha to agriculture expansion (Bemigisha 1998). However, ecosystems of the northern US Great Lakes region perceived the degradation of the lake due to the widespread and destructive logging of the original forests that occurred 100–150 years ago, from the mid-1800s to the early 1900s (Williams 1989).

Landuse change is a major driver of the functioning of lake ecosystems results in massive sediment loads and the high volume of peak flows. Many studies demonstrated that land-use changes alter the surface runoff and sediment yields at different spatial and temporal scales (Guzha et al. 2018, Welde & Gebremariam 2017). For example, Welde & Gebremariam (2017) proved that increasing bare land and agriculture resulted in more surface runoff and high sediment yield in volumes, at two different land-use scenarios (1986 and 2008) in Tekeze Dam watershed, northern Ethiopia. In another case study, Buendia et al. (2016), had disseminated the results of increased forest area was a major driver of low peak stream flows as well as sediment yields in an upland Mediterranean catchment. Previous studies have shown that runoff responses to the land-use changes at annual, seasonal, or monthly time scales, are limited to the daily scales. Lin et al. (2015), showed the individual variation of runoff responses at annual, monthly, and daily time scales at two different land-use scenarios (for 1985 and for 2006, with reduced forest, increased cropland, and urban area). However, daily runoff caused the largest changes with increased flood peaks, while annual runoff had the smallest change, and the monthly runoff had medium rates in the Jinjiang catchment. Also, the land-use had modified the runoff trends, and sediment loads dramatically from the Upper Blue Nile basin during the last four decades (Gebremicael et al. 2013).

A large encroachment of urbanization, increasing deforestation, and the day to day mankind activities result in widespread soil erosion, which progressively effects on physical and chemical characteristics of lake catchments (Rawat & Kumar 2015). Many studies have extensively reported that deforestation is the driving factor that increases soil erosion in lake catchments. The rate of soil erosion in lake catchments can be identified from changes in the rate of sediment accumulation in lakes (Richard et al. 1984). Alternately, including vegetation clearance, agricultural and urban expansion, slope, and runoff lead to rapid dynamics in soil erosion rates. Pollutants released from agricultural and residential areas combined with industrial sludge, which are released into the aquatic environments, have been introducing many impairments in lake ecosystems around the world (Guo et al. 2014). These nutrients can be transported into adjacent water bodies by surface runoff and erosion (Lesschen et al. 2009). Such excess nutrients foster eutrophication and algae blooms in freshwater ecosystems (Sorando et al. 2019; Ouyang et al. 2017). Sediments, including silt and suspended particles, enter surface waters during erosion and runoff, thus increasing turbidity in the water (Greig et al. 2005). The complex of several functions that exist in lake catchments was adversely affected by surface water quality in freshwater lakes (Banadda et al. 2010).

Many studies extended their focus to the large scale lake catchment interactions, in order to gain knowledge about the nature of lake functions, and maintaining sustainable management services. Lake catchment management studies and mitigating the effects of water quality threats are among the most important challenges of this time (Abbaspour et al. 2007). Detailed studies and comprehensive databases are essential for a better understanding of the catchment-landscape system and the interactions of the involved parameters (Dai et al. 2018). As these parameters and the climate change impacts reach across a wide range of spatial and temporal scales (Beaumont et al. 2011), studies on different catchment scales are needed to provide the required data. This complexity is further increased by the variety of different landscape units with distinct reactions to the observed processes.

1. 2 Distribution of Wetlands in India

India has supported a wide range of sustaining diverse and unique wetland habitats varying its topography and climate regimes. The natural wetlands in India consist of the high altitude Himalayan lakes followed by flood plains of the major river systems, saline, and temporary wetlands of the arid and semi-arid regions, coastal wetlands such as lagoons, backwaters, and estuaries; mangrove swamps; coral reefs and marine wetlands (Prasad et al. 2002). In addition to different types of natural wetlands, man-made wetlands are abundantly available in India, as they have emerged by the needs of irrigation, water supply, food, electricity, fisheries, and many other purposes. The available estimation of the areal extent of wetlands, about the lowest 1% to the highest 5% of the geographical region, holds a fifth of the known biodiversity (Space Applications Centre 2011). These distributions of wetlands found in different geographic regions of India, ranging from the Himalayas to Deccan Plateaus.

Wetlands in India constitute various types, including inland wetlands, Indo-Gangetic wetlands, coastal wetlands, Himalayan wetlands, and man-made wetlands. The majority of the inland wetlands are directly or indirectly dependent on major rivers like Ganga, Brahmaputra, Narmada, Godavari, Krishna, Kaveri, and Tapti. They have distributed in the hot arid regions of Gujarat and Rajasthan, the deltaic parts of the east and west coasts, highlands of central India, wet, humid zones of south peninsular India and the Andaman and Nicobar & Lakshwadeep islands (Prasad et al. 2002).

Wetlands in India, such as lakes, ponds, reservoirs, tanks, have been providing multiple-purposes, which include irrigation, nutrient removal, domestic use, fisheries, recreational uses, flood control, silt capture, and groundwater recharge (Bassi et al. 2014). The southern states of Andhra Pradesh, Karnataka, and Tamil Nadu have largely extended irrigation tanks about 0.12 million and account for nearly 60% of India's tank-irrigated area (Hennig 2006, Palanisami et al. 2010). Similarly, there are traditional tank systems about 25% of net irrigated area adopted by the states of Bihar, Orissa, Uttar Pradesh, and West Bengal (Pant & Verma 2010). Tanks play a major role in harvesting surface runoff during monsoon season, and later it is used for irrigation. Meanwhile, there are also used for fisheries, domestic purposes, and livestock consumption (Hennig 2006).

Lakes in India, Carambolim (Goa); Chilka (Orissa); Dal Jheel (Jammu and Kashmir); Deepor Beel (Assam); Khabartal (Bihar); Kolleru (Andhra Pradesh); Loktak (Manipur); Nainital (Uttarakhand); Nalsarovar (Gujarat); and Vembanad (Kerala), have been providing tourism, recreational purposes, fisheries, irrigation, nutrient removal, drinking, and attracts millions of migratory birds. They are also important for groundwater recharge and supports rich in flora and fauna.

Further, reservoirs also supply a large quantity of water for irrigation and domestic purposes for both urban and rural areas. Approximately 4,700 large reservoirs (capacity of not less than 1 million cubic meters) have been built in India so far for municipal, industrial, hydropower, agricultural, and recreational water supply; and for flood control (Central Water Commission 2009). The total water storage capacity of these reservoir projects is about 225 billion cubic meters (BCM), and the area covered by reservoirs is around 2.91 m ha (Central Water Commission 2010). These reservoirs support a wide variety of wildlife.

However, wetlands in India provide many essential services, but increasing recent technologies contribute to their degradation too. Urban expansions are a major threat to wetlands, as they contribute to pollution, industrial waste, and domestic supplies. Similarly, agricultural supplies of inorganic compounds are nitrogen (N) and phosphorus (P) entering into the rivers and streams and finally find its way to reach wetlands. The agricultural runoff and other pollutant loads are adversely affected the water quality. Also, increased urbanization and land-use changes, the nutrient loading in wetlands far exceed their capacity to retain pollutants and remove them through nitrification, sedimentation, adsorption, and uptake by aquatic plants (Bassi et al. 2014). All these influences and factors are leading to the loss of biodiversity and changes in nutrient cycling rates and species loss (Verhoeven et al. 2006).

1. 2. 1 Wetland mapping – a status review

Wetlands play an essential role in maintaining the social, economic, and ecological health of the sustainable ecosystem. The Wildlife Protection Act protects the few sensitive wetlands where they are subjected to severe anthropogenic pressure. Approximately 147 wetland sites across various agro-climatic zones identified for maintenance and protection of these wetlands under inevitable anthropogenic interference (The Directory of Indian Wetlands 1993). The National wetland committee of the Ministry of Environment and Forests (MoEF), Government of India, has recommended some proactive steps. Accordingly, 22 sites were declared tentatively as wetlands of National and International significance for long term protection of wetland ecosystems. The objective is to develop a wetland inventory for the entire country. This will be carried out based on the available data and new data using modern geospatial technologies. The digital remote sensing data for wetland location, spatial extent, analysis, and mapping at any scale of all wetlands will be available according to the management and conservation requirements. After realizing the importance of the wetlands, the International Ramsar Convention in 1971 had formed to urge the countries to monitor, conserve, protect, and management of wetlands.

As per the Ramsar Convention definition, most of the natural water bodies such as rivers, lakes, coastal lagoons, mangroves, peatland, and coral reefs, as well as human-made wetlands while ponds, reservoirs, canals, sewage farms, salt pans, irrigated fields, farm ponds, gravel pits are considered as wetland ecosystems in India. Among them, there are only 26 wetland sites were designated as Ramsar Sites (Fig.1. 1) (Ramsar 2013). However, many potentially valuable wetlands were neglected by the decision policies; as a result, most of them are already degraded due to increasing population, urbanization, and economic growth (Central Pollution Control Board 2008).

The first initial steps to prepare wetland inventory in India were formulated between 1980 and early 1990s (Tab 1. 1). The total area of wetlands in India during the 1980s was about 58.3 m ha, according to the Directory of Asian Wetlands (Woistencroft et al. 1989) and the Directory of Indian Wetlands (WWF and AWB 1993). However, paddy fields accounted for 71% of the area of these wetlands (Bassi et al. 2014). The first scientific map of wetlands in India was prepared using satellite data of 1992-1993 by the Space Application Centre (SAC) in Ahmedabad. The number of classified wetlands considered as per the Ramsar Convention definition of about 7.6 m ha areal extent of wetlands was estimated (Garg et al. 1998). However, they excluded from rivers, irrigation channels, canals, and paddy fields, which leads to an inadequate understanding of wetlands definition and characteristics of wetlands (Gopal & Sah 1995).

Table 1.1 Number and size of various wetlands inventories in India

Inventory	Year	Total number of wetlands		Total area of wetlands (m ha)	
		Natural	Manmade	Natural	Man-made
Directory of Asian Wetlands and Directory of Indian Wetlands (WWF and AWB)	1989 and 1993	Not specified		58.3	
Directory of Indian Wetlands (MoEF, GoI)	1990	2167	62,253	1.45	2.59
Wetlands of India (Space Application Centre)	1998	18,154	9249	5.31	2.27

Source: Bassi et al. (2014) [Adapted from Garg et at. (1998), Woistencroft et al. (1989), and WWF and AWB (1993)].

Fig. 1. 1 illustrates the internationally recognized Ramsar sites in India, which are under special protection and conservation of their ecosystems. The first two

wetlands in India are Chilika lagoon in Orissa and the Keoladeo National Park in Rajasthan designated as Ramsar sites in 1981. Since then, a total number of 26 wetlands in the country have been designated as Ramsar sites by 2012. Though India has numerous wetland types, there are specific criteria followed for the selection of sites by the Ramsar Convention.

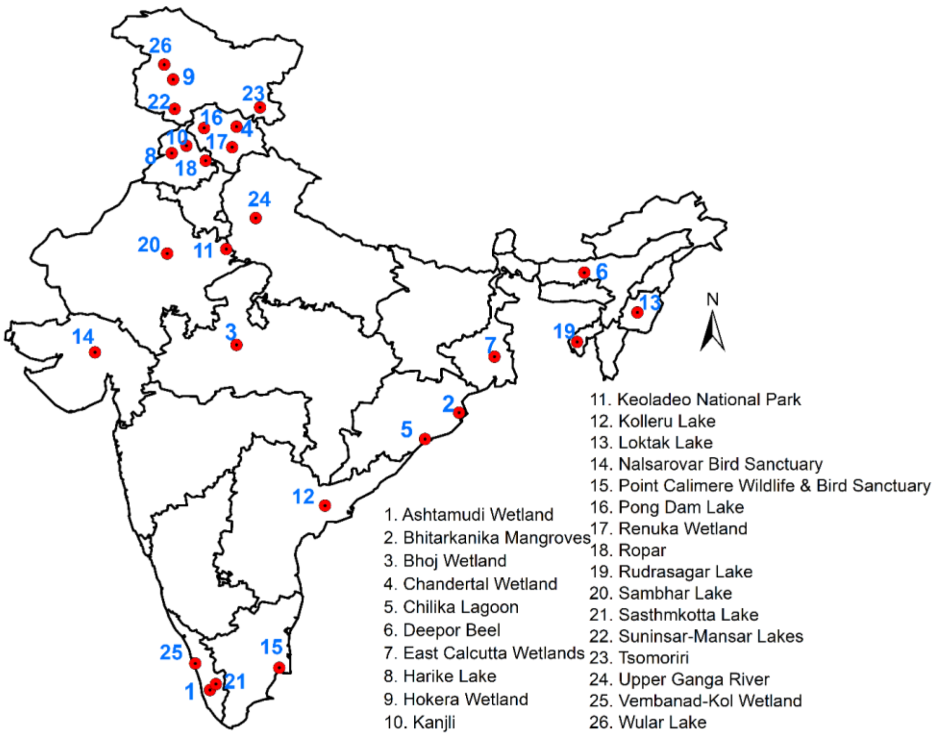

Fig. 1. 1 Location map of Indian Ramsar sites (Data source: Ramsar Convention 2013)

Fig. 1. 2 depicts the internationally recognized Ramsar sites in India based on the satellite images from a false-color composition. They include lakes, rivers, mangroves, and wetlands. Fig. 1. 2a, 1. 2b & 1. 2d show examples of the most productive natural resources that support millions of migratory birds. Fig. 1. 2f shows the wise use of the construction of fishponds in the Kolleru Lake wetland ecosystem. Fig. 1. 2c represents the holy river Ganga, while Fig. 1. 2e shows mangroves in Odisha.

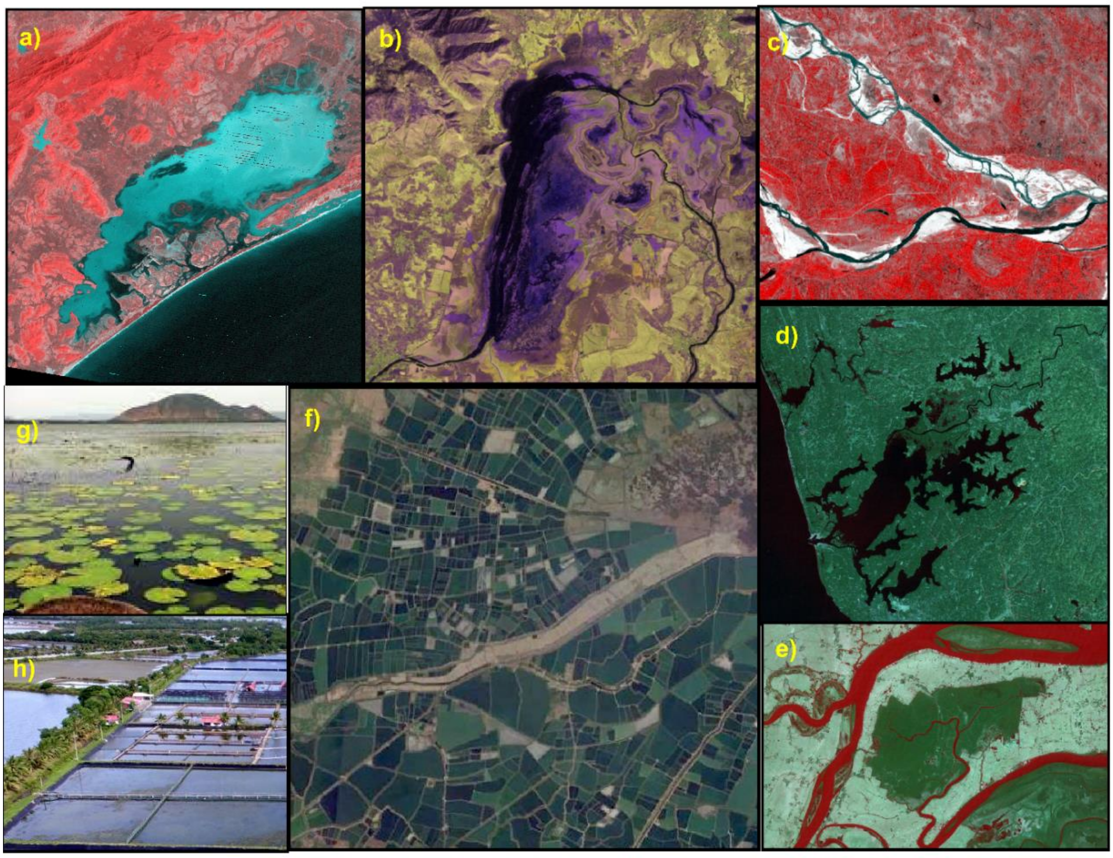

Fig. 1. 2 Location of the Ramsar wetlands in India **a)** Chilika Lagoon, Odisha (1976) **b)** Wular Lake, Jammu & Kashmir (2010) **c)** Upper Ganga River, Uttar Pradesh (1980) **d)** Ashtamudi Wetland, Kerala (1988) **e)** Bhitarkanika Mangroves, Odisha (2011) **f)** Kolleru Lake aquaculture, Andhra Pradesh **g)** Chilika Lake, Odisha **h)** Fishponds, Kolleru Lake [data source: from a-e: Landsat images, f: Google image, g, f: National wetland atlas].

1. 2. 2 Current loss of wetlands in India

India has experienced a rapid degradation of its wetlands from the last three decades alone, nearly one-third of the wetlands have been lost to urbanization, agricultural expansion, and pollution (Dasgupta 2020). The maximum rate of wetlands degradation has mainly seen in urban areas become more severe. The current loss of wetlands leads to severe consequences in large dense populated countries like India, where 68% of the population are living in rural areas (Census of India 2011), and most of them are natural-resources dependent. Wetlands are one of the most threatened habitats of the world; however, in India considered them as wastelands (Banerjee 2013). The landscape of India had composed numerous wetlands in the past, regardless of many wetlands were converted into mere drains, paddy farms, and industrial sectors. It is an unlikely prospect of restoring wetlands once an alternative had occupied the site for non-wetland purposes. Therefore, the demand for wetland products (i.e., food, water consumption, fish production, wood, medicinal plants) has exponentially increased as the same trend followed by the population. Healthy wetlands are essential in India for food production, and potable water availability for humans and livestock, and also necessary for wildlife habitats, plant species, and migratory birds.

Wetland ecosystems often interconnected between multiple components that exchange energy between waterways, habitats, plants, and animals through energy flows, chemical and physical transfers, moving biota and water flows. Depending on the factors that impact watershed alteration, grazing, and biodiversity, that significantly contributed to the loss of wetlands in India. Further, the individual factors influenced by wetlands degradation are discussed below.

Agricultural conversion

The gross extent of rice farming is largely expanded in the wetlands region in India; as a result, the wetlands in the Indian subcontinent are most likely bigger today than that was 3,000 years ago. Rice farming is a wetland-dependent activity that is suitable for all kinds of flood plains, riparian zones, river deltas, and savannah regions in India. Rice paddy conversion areas include Dipor bil (Assam), Hokarsar Lake (Kashmir), and the Pyagpur and Sitadwar Jheels (very wet marshy areas) near Lucknow in Uttar Pradesh (Fig. 1. 3). Besides, Kolleru Lake in Andhra Pradesh had lost 34,000 ha of natural wetlands to agriculture thus far (Anon 1992). In addition, as a result of rainwater harvesting and diversion of river flows into catchment areas, paddy cultivation and fishponds aquaculture also occupy the areas that are not previously designated as wetlands, thereby extracting the water from downstream natural wetlands. There existed 1.6 million ha of freshwater fishponds in India. Although the rice fields and shallow fishponds function like natural wetlands, technically they are human-made wetlands. Over 58.2 million ha of wetlands in India, out of the 40.9 million ha was under paddy cultivation in 1993.

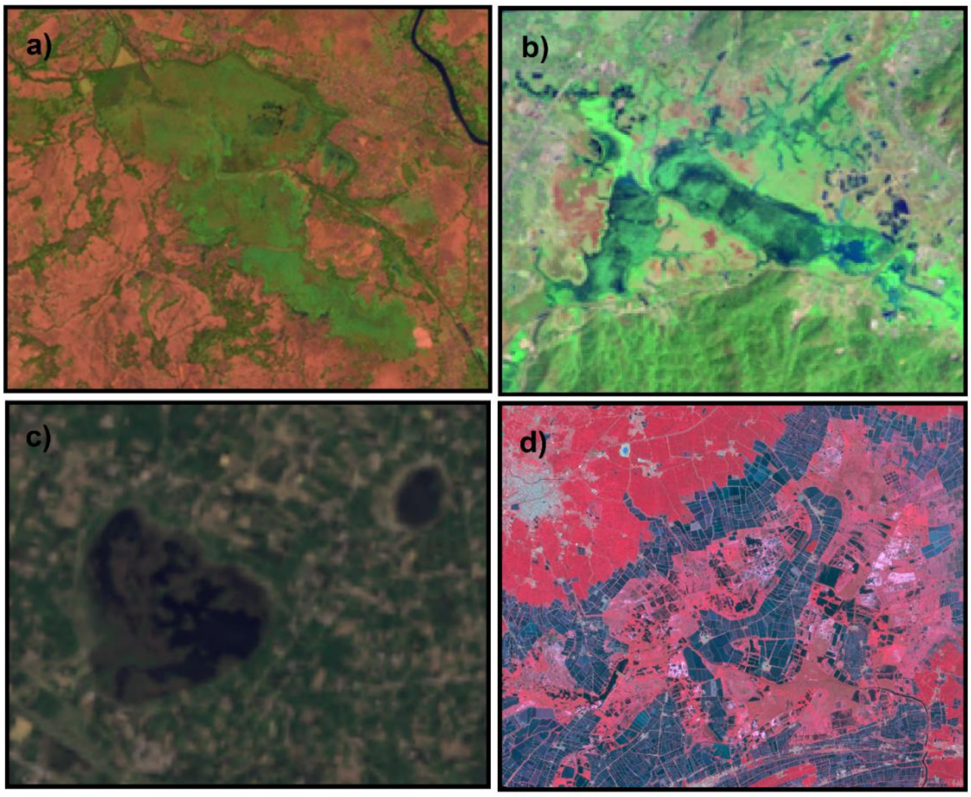

Fig. 1. 3 Agricultural conversion areas into paddy fields **a)** Hokarsar Lake (Kashmir) **b)** Dipor bil (Assam) **c)** Sitadwar Jheels (UP) **d)** Kolleru Lake (AP) (Source: Landsat images, USGS Earth Explorer).

Degradation of water quality

Human activities are continues to pose water quality threats to wetlands. More than 50,000 small and large Indian lakes are polluted to the point of being considered as 'dead' (Chopra 1985). The primary pollutant sources are being considered as agricultural runoff, industrial waste, and sewage sludge, which may contain pesticides, fertilizers, and inorganic compounds. Meanwhile, extreme organic pollution levels from sewage can be put to constructive use in some situations. For example, the Calcutta wetland sewage system is an excellent example of the beneficial use of wetlands to filter sewage and use the nutrients profitably (Fig. 1. 4). Furthermore, the water and sewage should divert into the lakes, to proliferate algal blooms for introducing fish and prawn species. This sewage fishery from the Calcutta markets produces approximately 7,000 tons of fish annually or 2.81 per ha per year (Edwards 1985). Unfortunately, the dumping of industrial wastes into the sewage ponds thus creates a toxic environment to the nutrients, causing a loss of huge fish production. The wetland not only treats the city's sewage, but the treated water is utilized for aquaculture and agriculture.

Alternately, pollution of the largest lake in Kashmir, Dal Lake, made unfit for drinking, and further, it is not suitable for fishing and bathing (Fig. 1. 5). Therefore, a local government had introduced for an intricate and very expensive clean-up involving dredging, the laying sewer pipe on the lake bottom, water diversions, and artificial aeration until organic pollution is reduced (Bhargava 1994). There are several wetlands in India subjected to water quality threats, including the largest freshwater Lake Kolleru. The detailed Kolleru lake pollution levels are documented in Chapter 4.

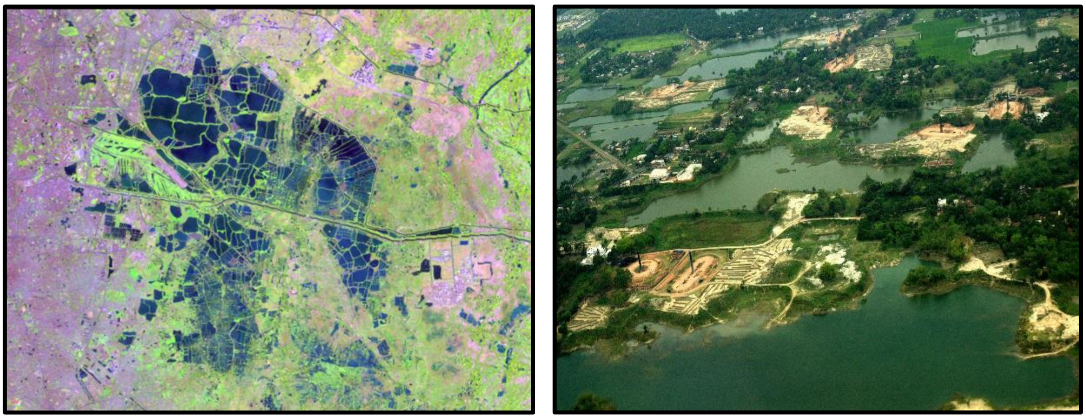

Fig. 1. 4 Calcutta sewage wetland system (Landsat-7 image (left)), google image (right) [1]

Fig. 1. 5 Dal Lake in Kashmir (Souce: Landsat-7 satellite image (left), google image (right) [2]

Hydrologic alteration & defoliation

Altered hydrology can easily influence the character, functions, values, and appearance of the wetlands. The changes in hydrology witnessed from either removal of water from the wetlands or raised the elevation to no more prolonged effect from the floods. Since the early 1880s, major canal dredging operations have been conducted in India and have raised its 3,044 km^2 of irrigated land to 4,550 km^2 in 1990 (Anon 1994). An initial increase in crop productivity has reduced the fertility and salt accumulations in soil due to irrigated farming of arid soils. India has 32,000 ha of peat-land remaining, and drainage of these lands will lead to rapid subsidence of soil surface.

India has more grazing animals than any other country in the world. Worldwide, India supports 20% of all cattle, 50% of all water buffalos, and 15% of all goats (Hulkarni

1970). The herd of grazing animals is maximum settled in wetlands areas where they remove the top of the vegetation and selective plan species. The forage activities of these animals change the vegetation and soils of the country. The intensive stock on these animals on wetlands through grazing can also reduce the ability of the land to produce vegetation through soil compaction and long-term changes in soil structure.

Introduced species and extinction of native biota

Wetlands in India support around 2,400 species and subspecies of birds. Nevertheless, losses in habitat have threatened the diversity of these ecosystems. Several wetland-dependent animal species are under threat in India. For example, the world's largest tiger (*Panthera tigris*) reserves exist in the tidal mangrove wetlands at the Sundarban deltas (Fig. 1. 6) are endangered. Despite that, there exist numerous wetland species being disappeared without notice. Also, wetlands attract the millions of international migratory bird species every year, have decreased due to its increasing pollution levels. Similarly, the water-dependent plants, such as flora-fauna under threat, because of the rise of unwanted plants in freshwater ecosystems, have threatened the wetlands and clogged the waterways competing with the native vegetation. Many wetland-dependent animals, birds, and plant species are disappearing gradually.

Groundwater depletion

Draining of wetlands could deplete the groundwater recharge too. The demand for groundwater has increased dramatically with the rise of irrigating crops across the wetland catchments. A recent estimate indicates that in rural India, nearly 6,000 villages are without a source for drinking water due to the rapid depletion of groundwater (Prasad et al. 2002). Simple hand-dug wells did not deplete the groundwater significantly because of the replacement of tube wells that extract a large quantity of water for irrigation. This phenomenon is believed to have affected the southern coastal plains of Saurashtra in Gujarat over an area exceeding 100,000 ha (Foote et al. 1996).

Direct deforestation in wetlands

Fig. 1. 6 Sundarban deltas in India **a)** Landsat-8 satellite image **b)** Mangrove forests (Kunal 2019)

Mangrove forests are flood and salt-tolerant and trees that grow along the coasts in the tropics. They are valued for fish and shellfish, livestock fodder, fuelwood, building materials, local medicine, honey, beeswax, and extracting chemicals for tanning leather (Ahmad 1980). Many mangrove vegetation areas are already replaced by agriculture farming and fish production and continue to the present decades. Indian's mangrove forests constitute 8% of about 4,240 $km^{2,}$ where it is largely expanded in Sunderbans and the Andaman and Nicobar Islands (Anon. 1991). Coastal mangrove areas are subjected to severe pressure. Particularly, the demand for shrimp provides economic growth to clear all the coastal mangrove areas that have replaced by the shallow shrimp ponds. The shrimp farms cause the excessive withdrawal of freshwater and increased pollution load on the water like increased lime, organic wastes, pesticides, chemicals, and disease-causing organisms. The most significant impacts were on the people directly dependent on the mangroves for natural materials, fish proteins, and revenue. The ability of wetlands to trap sediments and slow water is reduced.

Inundation by dammed reservoirs

Currently, more than 1,550 large reservoirs are covering more than 1.45 million ha and more than 1,00,000 small and medium reservoirs covering 1.1 million ha in India (Gopal 1994). The government of India has the plan to construct the dams and reservoirs to generate electrical power. For that, they referred to mountains and open areas; however, during construction, many wetlands and open areas submerged by impounding the water that significantly altered the hydrology of the region. Thus it allows for harnessing moving water as a source of energy. While the benefits of energy are well recognized, it also alters the ecosystem as well.

Fig. 1. 7 depicted the factors affecting the lake ecosystem. The factors mentioned above are the major reasons for degrading lake ecosystems in India. Maximum of a small scale to large scale lake catchments are under threat by the human-activities, introducing many impairments to the lake. If human debasement continues, the lakes will disappear soon. The government should implement lake conserve policies across the country through continuous monitoring, checking pollution levels, by imparting information to the farmers, laying demonstrations, and conducting workshops.

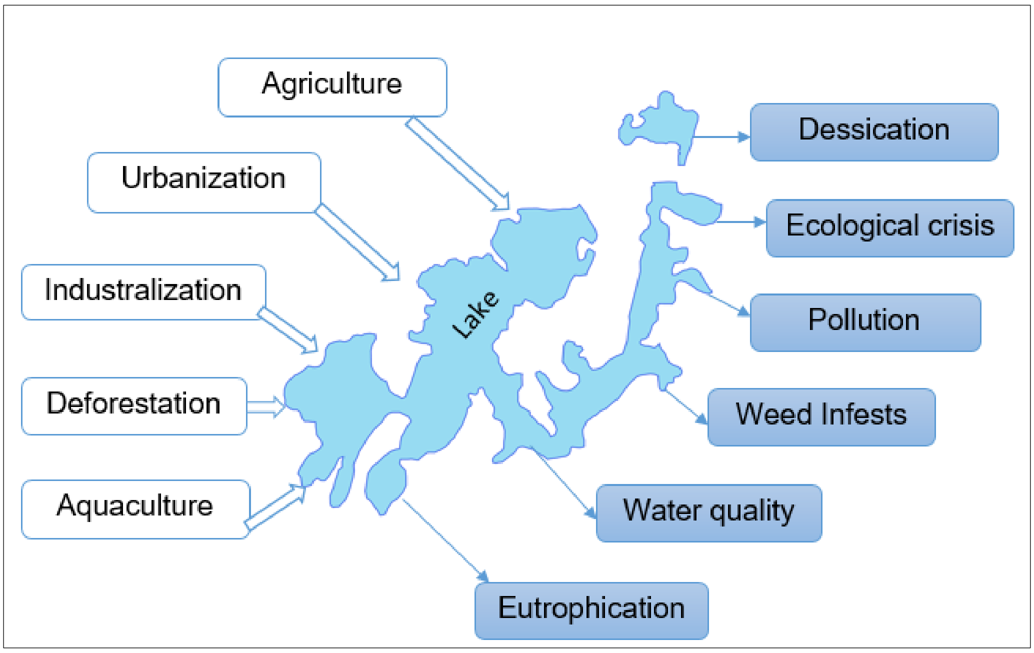

Fig. 1. 7 Lake degradation contributing factors & effects (the example of Kolleru Lake)

1. 3 Use of Remote Sensing & GIS in wetland inventories

Remote sensing data in combination with Geographic Information System (GIS) is an effective tool for mapping wetland areas and its dynamics and monitoring. The application encompasses water resource management, hydrologic modeling, flood mapping, drought monitoring, environmental impact assessment, reservoir capacity surveys, and water quality mapping (Jonna 1999). The general understanding of remote sensing is to acquire information on a particular object or surface while from a distance. The data being collected from satellites and spacecraft about the surface of the earth. Satellite data are used for interpretation and delineation of wetland regions, while temporal data helps to obtain ground truth information about the ongoing projects. The satellite image itself consists of three bands for the distinguishing of the surface properties (Weng et al. 2004). Since the 1900s, remote sensing became an emerging field to determine the physical properties of the land. The first Landsat satellite had launched in 1972, and further, seven more Landsat series were operated, and those serving for various purposes. The outcome of satellite data that has been used for developments in various technological fields. Modern remote sensing system provides satellite images suitable for medium scale mapping used in natural resources surveys and monitoring such as wetlands, forestry, geology, watershed management, urban, and many fields.

After realizing the importance of numerous wetlands in the world landscape, it is necessary to join all the enriching diverse wetlands at scale. Despite the diverse wetland classes, it is challenging to do a field survey from every corner of the world, and it is time-consuming (Edwards & Brown 1960). With a huge advancement in

Remote Sensing and GIS (Geographic Information System) technologies, which brought an immediate solution for wetland tasks, including mapping, identification of specific geographic locations, areas of the extent, and wetland characteristics (Anstee et al. 2001; Everitt et al. 1999; Jensen et al. 1989). Therefore with the help of Remote Sensing and GIS, it became possible, and it is used to acquire, processing, and store geographic information. It refers to visualization, image processing, measurement, and analysis of wetland features (Chopra et al. 2001). For example, change detection analysis is most suitable for the determination of the significance of land use and validate the percentage of land-use changes, considering the wetland ecosystems. It is essential for decision making on wetland management systems, organizations, and wetland monitoring projects. Further, remote sensing data provide valuable information on seasonal water variations, areas of extent, depth, and volume of water levels. The satellite data brightest pixel represents the accumulation of water and its depth. In contrast, low pixel values represent shallow water levels, the data that analyzes the available soil moisture conditions, surface temperatures.

Besides, remote sensing data on aquatic vegetation is an important component of wetland and coastal ecosystems, playing a key role in the ecological functions of these environments (Silva et al. 2008). The wetland vegetation can examine from the NDVI (Normalized Difference Vegetation Index) reflection. The highest values of NDVI indicate vegetation, while the lowest (negative) values indicate water surfaces. However, spectral-reflectance characteristics for individual wetland species through close-range instrumentation, analyzing canopies architectures to facilitate species identification, and assessing the impact on composite spectral signatures of wet soils and variable depths of standing water beneath new canopies (Rundquist et al. 2001).

With the main basic remote sensing data, as referred to Digital Elevation Model (DEM), it is possible to extract the elevation, slope, flow direction, drainage network, and drainage length. Therefore, it is possible to determine the wetland characteristics based on the DEM feature. It is one of the basic tools for the estimation of soil erosion and sediment information on lake beds, river streams, and from a small scale to large watersheds (Lu et al. 2004). Remote sensing data not only provides surface information, while it is more important for groundwater recharge operations. Wetlands signify that they contribute more to potential groundwater recharges.

With the help of satellite data, it became possible to monitor wetland fluctuations and their regular responses to the degradation of rich ecosystems induced by human activities. Furthermore, GIS technologies reveal the information on the estimation of future wetlands degradations based on the mathematical algorithms depending on the past and present land-use datasets (Muller & Middleton 1994). Assessing the extent of land use dynamics and for making possible predictions requires a variety of direct (field survey) and indirect (remote sensing) data. As both data sources can be incomplete and often interrelated, combining both methodological approaches can be the best way to collect the data needed for climate change models. Remote sensing and GIS platforms play a crucial role in wetland inventories from the past few decades.

1. 4 Problem Statement

Wetlands, which include lakes, rivers, marshes, and peatlands as well as coastal and marine areas such as estuaries, lagoons, mangroves, and coral reefs, are currently estimated to cover more than 12.1 million km^2 (Ramsar, 2018). Between 13 and 18 percent of them are on the Ramsar List of Wetlands of International Importance, which are officially recognized protected sites. However, due to the increasing population, urbanization, and industrialization, most of them have been disappeared. The quality of the remaining wetlands is also suffering due to drainage, pollution, invasive species, unsustainable use, disrupted flow regimes, and climate change (Bowers 1983). Wetlands degradation foremost influences on lakes significantly, and causes land-use changes, water quality threats, loss of biodiversity, ecological crisis, and environmental pollution. Lakes are not uniform water bodies but vary in depth, shape, volume, and water temperature and other features (Smith et al. 2007; LaPerriere & Simpson 2003). Especially agricultural activities endanger freshwater lakes. Land-use changes are major threats to the lake catchments. However, it has a widespread impact on the spatial and temporal changes of the lake ecosystem, in which further extended to the river flow patterns and sediment yields from a catchment. A significant change in land-use could alter the hydrological response of lake catchment at a regional scale (Welde & Gebremariam 2017). However, frequent land-use changes triggered the surface runoff flows, reduce the soil fertility, nutrient loss, and land degradation are adversely affected by the economy, where the agriculture practices are the backbone of the developing countries (Guzha et al. 2018). In addition, land-use changes are regarded as the main driving factors which alter the catchment ecosystem, thus accelerates the erosion processes and transport of the NPS pollutants. Hydrological models are the best way of identifying individual sources and evaluating decision-makers for better Water Quality Management Plans (WQMPs) (Shen et al. 2013).

NPS is the major cause of water pollution in developing countries where the economy is majorly dependent on agriculture. Based on their complexity of distribution, it is still challenging to control non-point source (NPS) pollution from small scale to large scale watersheds. Pollutants from agriculture, industrial, urban, and aquatic environments are the major threats that resulted in depleting water quality in recent decades (Yang et al. 2016). Many studies demonstrated that intensive agricultural activities (e.g., fertilizer application) are non-point sources for nitrogen (N) and phosphorus (P) pollution (Ouyang et al. 2014, Ongley et al. 2010). Besides anthropogenic activities, N and P distribution among soil types have close spatial interaction with NPS (Chen et al. 2016). Moreover, frequent land-use changes impact on NPS, by altering the textural pattern, decreasing nutrient loss, are becoming more severe (Zhang et al. 2018, Yang et al. 2016). The complex of several functions that exist in lake catchments was adversely affected by surface water quality in freshwater lakes (Banadda et al. 2010).

Climate change is an additional factor influencing lakes and their catchments, and one that is still relatively new in the scientific discussion on lakes (Fu et al. 2019; Holopainen et al. 2016; Shen et al. 2014). Climate change influences the air temperature and the spatial and temporal precipitation patterns, which, in turn, and among others, affect river discharge, soil erosion, and lake sedimentation processes, leading to a wide range of potential changes in the lake systems.

1. 5 Objective of the Research Investigation

The study area has been chosen the Kolleru Lake as the largest freshwater lake in India and as one of the largest shallow freshwater lakes in Asia for a general understanding of the lake ecosystem and their functions. This study analyzes the existing disputable operations related to the Kolleru Lake catchment based on a field survey data obtained from the Indian government by exploiting with remote sensing and GIS techniques. Since the lake has been receiving constant pressure for several years due to the extensive changes in land use, which influence the physical and chemical characteristics of the lake (Rao and Rao 2001). The research was conducted based on the limited existing data, however, the objectives have defined particularly with remote sensing information. To get a better insight into the research, the research has been carried out under the following **sub-objectives**. Each of these four sub-objectives will be the main focus of three scientific publications, which form the core of the PhD-thesis.

1. Estimation of water quality components of total nitrogen (T.N.), total phosphorus (T.P.), and their critical sources in the Kolleru Lake catchment
2. Investigation of potential groundwater recharge zones in the catchment region
3. Identifying the soil erosion and sedimentation in the Kolleru basin level

The study addresses the following questions to meet the objective of the study.

1. What are the major influencing factors contributing to the deterioration of water quality to the lake?
2. How far has the government been initiated measures for minimizing the pollution levels?
3. How to integrate satellite data on the investigation of potential groundwater zones?
4. How can the Universal Soil Loss Equation estimate the soil loss and sedimentation in the Lake basin?

1. 6 Project design

The dissertation thesis is divided into seven chapters.

Chapter 1 – Introduction: current wetland studies from the literature for the research, wetlands in India, application of remote sensing studies, problem statement, research objectives, and scope of the research to be achieved through this research.

Chapter 2 – Study area: specifies the current water scarcity status in India, water resource development projects, gives a detailed description of the study area, and related general information.

Chapter 3 – Methodology: provides details of the data acquisition, database organization, and methodology adopted for carrying out the study. It also provides information on the research objectives and their methodological approaches.

Chapter 4 – **The first research objective**: discusses the soil erosion and sediment yield concentration analysis across a typical basin level by using the RUSLE method.

Chapter 5 – **The second research objective**: discusses an integral approach for the identification of critical diffuse pollution sources in the Kolleru Lake catchment based on the SWAT model, tributary pollutant load estimation, highlighting the Best Management Practices to protect water quality. Furthermore, suggestions were provided for the crucial significance of lake protection.

Chapter 6 – **The third research objective**: discusses the investigation of potential groundwater recharge zones in the catchment by using weighted overlay analysis in a GIS framework.

Chapter 7 – Conclusion and recommendations: give brief outlines of the findings from the previous chapter and the conclusions drawn from the results and recommendations for future prospects.

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CHAPTER 2

Study area

2. 1 Introduction

The Kolleru Lake is the largest freshwater lake in India and forms one of the largest shallow freshwater lakes in Asia. Because of its rich biodiversity, the international Ramsar Convention designated the Kolleru Lake as a wetland of international importance in 2002 (Pattanaik et al. 2010; RIS 2002).

It is also famous for a hospitable environment for aquatic life estimated 20 million residents and international immigrant birds. Due to its richness in flora and fauna, it attracts migratory birds from northern Asia and Eastern Europe between October and March. Kolleru Lake has a distinctive characteristic of the wetland ecosystem. The lake basin area is saturated with water either permanently or seasonally. The average water covered area of the lake is 901 km^2 falling below +10 ft above MSL (mean sea level) contour level. Apart from that, the 5' ft contour level of the lake area was designated as the Kolleru Wildlife Sanctuary (KWS) with a surface area of 308 km^2, and the 3' ft contour level with 245 km^2 is the actual lake area (Azzez et al., 2011). The lake sources became a great treasure to local communities for fishing, paddy cultivation, and other recreational purposes. Aquaculture and agriculture is the major economic activity in this region. For this reason, people from other regions are migrating to the lake surrounding areas for work based on a daily wage.

2. 2 Geographical location

The Kolleru Lake is situated between 16º 24′ 10″ and 17º 23′ 44″ North latitude, and 80º 41′ 5.5″ and 81º 39′ 27.5″ East longitude in the south-eastern part of India (Fig. 2.1). The average water depth of 1 m and a maximum water depth of 3 m can be monitored during the southwest monsoon period (Barman 2004).

The lake receives the water from the seasonal rivers, namely Budameru and Thammileru. It has only one outlet river, the meandering channel Upputeru, which runs for a distance of 65 km and connects the Kolleru Lake to the Bay of Bengal. Apart from this, 68 minor irrigation channels are flowing into the lake, which connected the lake to the Krishna and Godavari catchments.

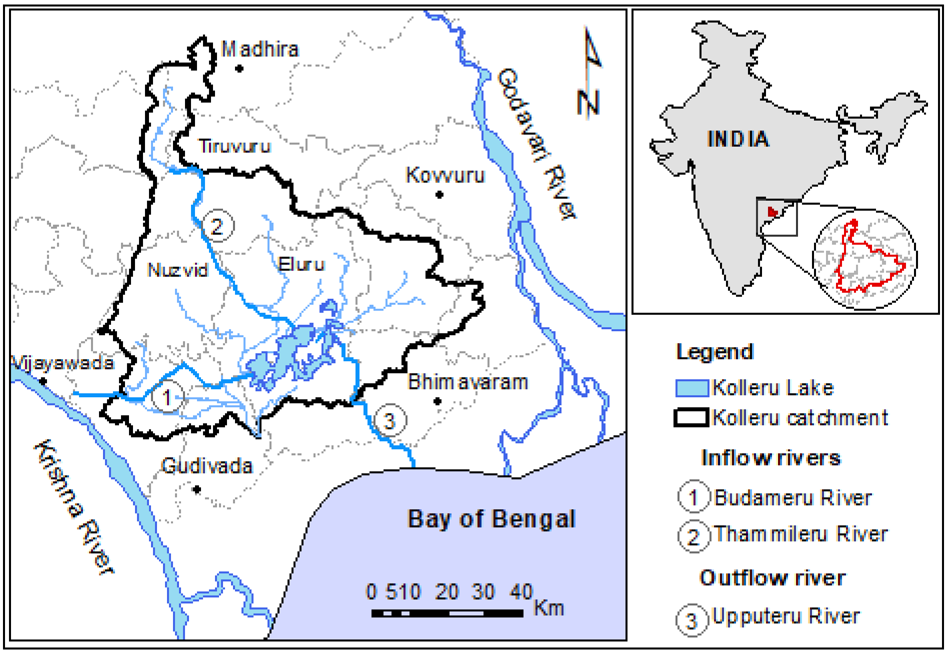

Fig. 2. 1 Location of the Kolleru Lake catchment

2. 3 Climate

The latitudinal extent of the region defines its climate. As the catchment is located between 16º and 17ºN, the climate is exclusively classified under a humid climate. It has a high diurnal change in temperature, the variation between the minimum and maximum temperature range from 14 ºC to 22 ºC from November till February and while 35 ºC to 46 ºC from March till October, respectively. Fig. 2. 2 depicted the temporal variation of maximum, average, and minimum of the temperature from 1973-2012.

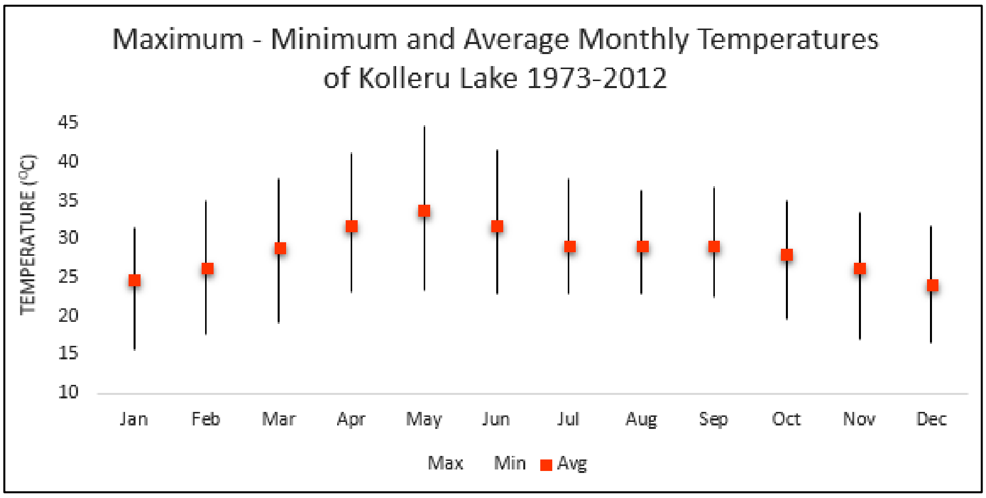

Fig. 2. 2 Annual mean temperature (Maximum and Minimum) of the Kolleru Lake area (1973-2012). Data source: APSDPS (Andhra Pradesh State Development Planning Society), 2017.

The annual mean precipitation is 1,094 mm. More than 70% of the annual rainfall occurs between June and September by South-West monsoons. The North-East monsoons bring one-third of rainfall in October. The catchment receives abundant rainfall, and the region is one of the most developed agricultural areas in Andhra Pradesh, as well as the state which historically called the "Rice Bowl of India."

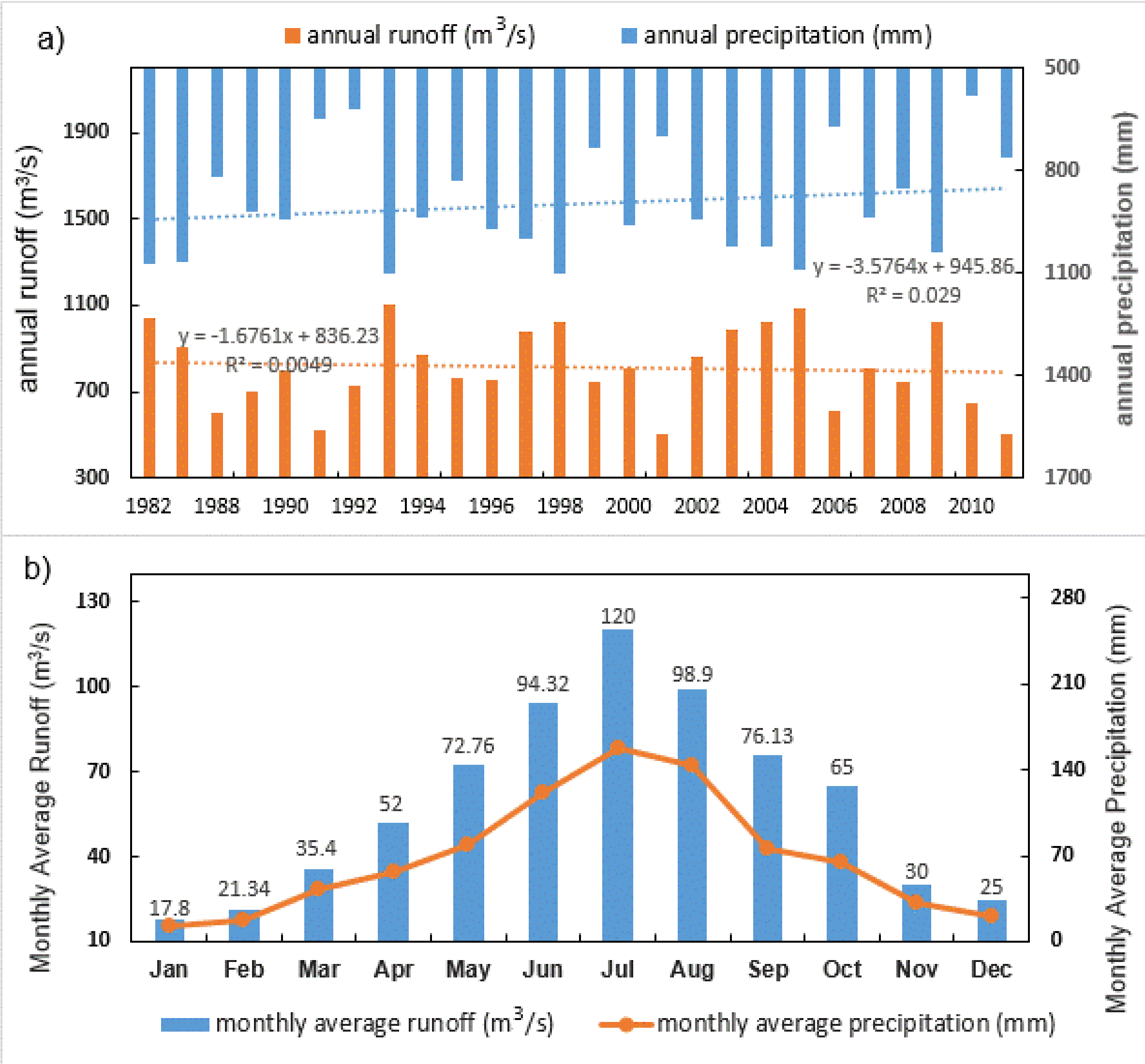

Fig. 2. 3 The annual variations of precipitation and runoff in 30 years, **a)** annual precipitation and runoff trends, **b)** monthly average precipitation curve, and runoff from the gauge stations. Data source: APSDPS (Andhra Pradesh State Development Planning Society), 2017.

The correlation between the precipitation and runoff analysis in Kolleru Lake is shown in Fig (2. 3). Except for the annual variations, the precipitation shows a decreasing trend, which does not reach its significant level (see in Fig 2. 3 (a)). The annual climate tendency rate is -3.57 mm. The high and low annual precipitation rates appeared in 1993 and 2010. Similarly, the annual runoff shows a decreasing trend. The annual variation rate is -1.67 m^3/s. The monthly average precipitation and runoff for Kolleru Lake shown in Fig 2. 3 (b). The runoff follows the precipitation rate, and the curve shows a single peak type. The average annual runoff registered in

January as 17.8 m^3/s is the minimum of the whole year. The peak reaches a maximum value in June, and the average annual rate is 120 m^3/s. The Kolleru lake receives one-third of precipitation from June to September, which alters the runoff flow and flood variations.

2. 4 Land use conditions overview

Before the 1970s, the lake water was completely free from aquaculture pollution. However, frequent flooding from paddy fields has occurred in the submersion of bed villages. Thus changed the behavior of farmers to shift aquaculture. The state government of Andhra Pradesh had encouraged the farmers to shift aquaculture by providing loans and facilitated the relevant information to the farmers. This caused the growth of forwarding and backward industries linked with aquaculture in this region, which paved the way for successful aquaculture.

After the 1990s, man's greed was started exploiting the lake resources, by expanding the illegal fishponds and paddy fields into the lake region. Especially from 1992-93, aquaculture had been practiced on a large scale, which has disturbed the lake ecosystem and caused the ecological imbalance. This wetland ecosystem was under extreme pressure induced by anthropogenic activities, had led to the deterioration of water quality, and further land-use changes are a major concern. The Government of Andhra Pradesh issued D-form Pattas (title deed of land with the condition that the Government can take back the issued land whenever needed) to landless people living around the lake to practice aquaculture. Fig. 2. 4 illustrates the rapid expansion of fishponds in the Kolleru Lake 5'ft contour level. Approximately

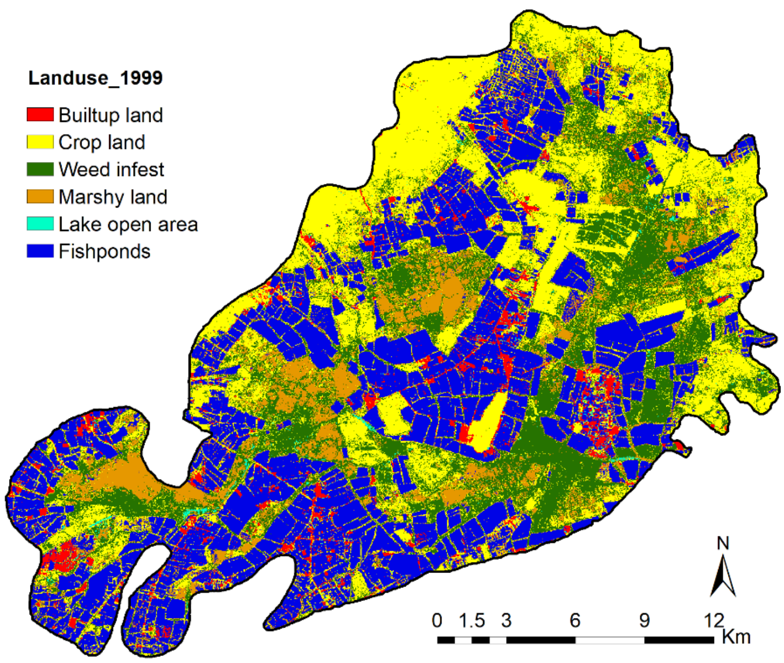

Fig. 2. 4 Landuse land cover of the Kolleru Wildlife Sanctuary during 1999 (5'ft contour level) (Source: own determination, image classification method in Machine

Learning,
(https://code.earthengine.google.com/42e4e84973b5d90ee7f7d19555d06f78)

42% of the lake area was occupied by the fish ponds, while aquaculture had encroached another 8.5% together, covering 50% of the lake sanctuary in 1999. (Rao et al. 2004). If the human debasement is continued, the lake will no longer exist, and the wildlife species soon will disappear (Nagabhatla et al. 2009).

The lake has received much attention in the past decades. In 1999, 308 km^2 of the lake falling below the 5' ft contour line, which was declared as Kolleru Wildlife Sanctuary (KWS). Regularizing the possession of the land, aquaculture, and related activities in the area became a matter of local public concern and political agenda. In 2008, Andhra Pradesh Government passed a resolution to the National Board of Wildlife, Government of India, to recommend for decreasing the boundary of Kolleru Wildlife Sanctuary from +5 feet contour to +3 feet contour to minimize the problems of the farmers (Azeez et al. 2011). Below +5 feet contour levels, all the bed villages are severely affected due to the submersion of crops because of the floods aggravated within the fish ponds. During 2006, the Government initialized the committee called "Operation Kolleru" to demolish all the fishponds within the Kolleru Lake below +5 feet contour level. The "Operation Kolleru" an act undertaken upon judicial interventions, lasted 55 days, in three phases starting from 16 February 2006 and completing on 13 June 2006. As reported, 1,776 large tanks were destroyed, and 89.08 lakh cubic meters of earth forming the tank bunds were removed. Apart from the above issues related to the land use/land cover changes are associated with the numerous problems from past decades.

The lake had gone through enormous changes from the last few decades (Rao et al. 2004; Harikrishna et al. 2013). The statistical analysis of land use/ land cover classifications of the Kolleru lake from 1977 to 2015, as shown in Table 3 (Kumar et al. 2016). It clears that there was no trace of paddy fields and fishponds in 1977, the freshwater completely stagnated the lake bed. However, in 1990, the fishponds appeared into the lake about 16 km^2 (12%), and as much as extended to the 123 km^2 (64%) in 2004. Therefore, the flood holding capacity of the lake was decreased in 2005 and resulted in more flooding causes a huge loss of crop fields and submerged the villages underwater. As a result of this, the Government had introduced the "Operation Kolleru" scheme to demolish the fishponds across the lake. As a result, the lake was retrieved and occupied by the fishponds about 7.25 km^2, while another 144 km^2 was drained out by the Operation Kolleru in 2006 (Table 1). However, again the fishponds were reappeared between 2008 and 2015. Another major identification was the paddy cultivation and weed occupation in the Kolleru lake (Fig. 6). The lake had received tremendous changes from anthropogenic activities from 1977 to 2015.

Fig. 2. 5 depicted the massive expansion of fishponds across the lake after the "Operation Kolleru" program in 2018. The lake is continuously posing severe threats

by land-use dynamics by the aquaculture. In 2018, the maximum wildlife sanctuary was occupied by the fishponds, and illegal encroachment of fishponds in the lake region is causing pollution. However, these issues are laced up with socio-political

Table 2.1 Landuse/ land cover changes in the Kolleru lake from 1977- 2015

Land use/ Land cover category	the area occupied in km^2					
	1977	1990	2004	2006	2008	2015
Lakebed	244.48	226.33	114.40	86.92	209.06	178.45
Lake plain	-	-	-	-	-	-
Paddy crop area	-	1.25	6.47	5.97	5.22	4.45
Settlements	0.52	0.68	1.03	0.75	0.87	1.98
Fishponds	-	16.74	123.10	7.25	11.38	60.12
Fishponds breached	-	-	-	144.11	18.47	-
Total	245	245	245	245	245	245

(Source: Kumar et al. 2016)

Concerns. For decades the Government has allowed people to exploit the lake resources, though it was declared a sanctuary. Now the same people deem it their right to stake claims to the land that was once the lake and now demand legal tenure for the encroached land.

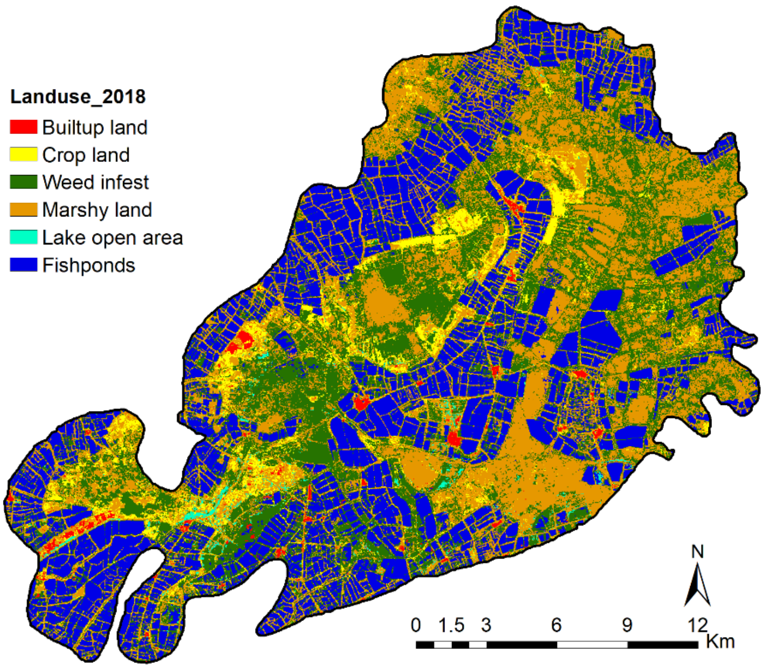

Fig. 2. 5 Landuse land cover of the Kolleru Wildlife Sanctuary during 2018 (5'ft contour level) (Source: own determination, image classification method in Machine Learning (https://code.earthengine.google.com/?scriptPath=users%2Fmeenurgukt%2FAneemKolli%3ALULC_Kolleru%2FLandsat8_2018).

2. 5 Geomorphological units

Geomorphologically the Kolleru Lake's catchment can be divided into five most distinct units; Pediplain complex, Lacustrine Terrain, Active Flood Plain, Coastal Plain, and Deltaic Plain. The major part of the catchment in the northern region underlain by the Pediplain complex consists of hills and ridges, which is overlain by valley-fill sediments. In contrast, the southern part of the area represented by the alluvial plains forming the Krishna and Godavari deltas. The Krishna and Godavari rivers and its tributaries have contributed to the formation of the alluvial plain. The deltaic part is a relatively flat surface. The major course of rivers forms the flood plain deposits. The most important special unit of the catchment overlain by the Lacustrine Terrain is the Kolleru Lake wetland ecosystem. The study area consists of a different composition of landforms such as wetlands, floodplain deposits, alluvial plains, and natural terrains, which together form a unique relief characteristic of the catchment (Fig. 2. 6).

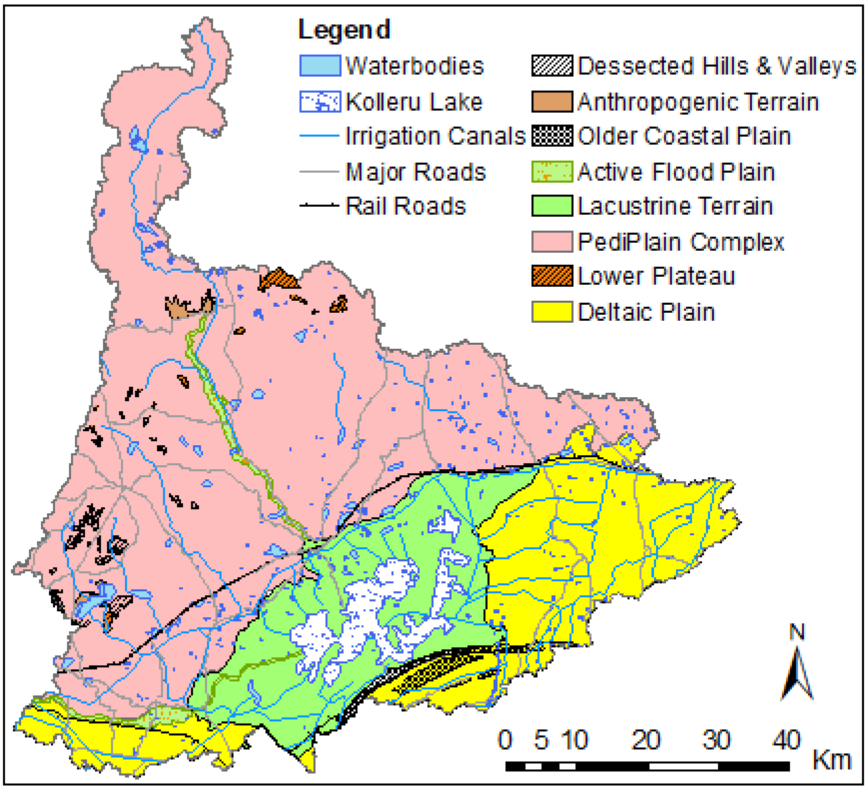

Fig. 2. 6 Geomorphological structure of the Kolleru Lake catchment (data source: NRSC, Bhuvan, Hyderabad)

2. 6 Significance of the study

Covering a total area of more than 90,100 hectares and holding approximately 1,350 cubic miles (2.172.614 m^3) of freshwater, the Kolleru Lake provides drinking water to the inhabitants to the surrounded villages. However, the current situation is that the lake facing some severe environmental threats caused by human activity, plus climate change, degraded water quality, deteriorated aqua species, and birds lead to habitat loss (Harikrishna et al. 2013). A major cause was identified within the lake by the construction of fishponds resulted in pollution by using pesticides and waste food (exposed to bacterial diseases and infection) to enrich the fish growth. As a result, it causes biological magnification diseases to the animals, birds, and humans who live with and near to the lake. Thereby the ecosystem will become an inhospitable environment for those aqua species and birds. Alternately, the lack of regulation of the seaward flow of the Kolleru waters during monsoon is progressively increasing the high-flood line, causing major flood problems in the surrounding cities of Eluru and Gudivada (Irrinki & Irrinki 2007). Besides submerging second-crop paddy lands and fish-tanks below the 5' ft contour of the lake spread area. The lack of regulation also causes the drying up of the major inlets into the lake during the summer, reducing the lake extension to about 10,000 acres and that too in patches of shallow, weed-infested ponds, useful mainly for animal washing and basket-fishing. Intermittent floods during the monsoons, occurring every four to five years due to the back – up of rainwater and agriculture runoff, have caused major economic losses. This research extended to the whole catchment region level to analyze the insights of land-use changes, agricultural runoff, soil erosion, and sedimentation, including potential groundwater recharge zones in this region. Chapters 4, 5, & 6 reflect the catchment analyses to distinguish the spatial and temporal distribution of pollutant levels.

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CHAPTER 3

Data Used and Methodology

This chapter deals with the data used and the methodology adopted for the study. Hence this chapter is divided into two parts: database preparation and methodology framework. The research methodology is further divided into three segments, which will be discussed about the methodological approach of each sub-objective.

3. 1 Database Preparation

The data used in this research are summarized in Table 3. 1.

Table 3.1 Available data for the research work of the Kolleru Lake catchment

Data availability	Scale	Resolution	Data description	Data Source
DEM	1:12,500	30 m × 30 m	Elevation, slope, streams, lengths	National Remote Sensing Center (NRSC), Hyderabad
Land use	1:50,000	30 m × 30 m	Landuse classifications	Indian Space Research Organization, (ISRO) Bangalore
Soil properties	1:500,000	250 m × 250 m	Soil physical and chemical properties	National Bureau of Soil Survey and Landuse Planning (NBSS&LUP), Nagpur
Climate data	Rain gauge	Daily records	Precipitation, temperature, wind, relative humidity, solar radiation	Indian Meteorological Department (IMD), Hyderabad
Manage-ment practice	-	Seasonal variation	Planting, fertilizer application and harvesting	Andhra Pradesh Agriculture Contingency Plan (Yearbook), 2008
Geomorphology	1:50,000	30 m × 30 m	Landform & topography	National Remote Sensing Center (NRSC), Hyderabad
Lineament map	1:50,000	30 m × 30 m	Faults, joints, fractures	National Remote Sensing Center (NRSC), Hyderabad

3. 1. 1 Soil data

Soil data have been used in this study because soils are a substantial element of the catchment ecosystems. Soils are able to store water and other substances, for instance, pesticides (sink function). On the other hand, soils are functioning as a source of water, nutrients, and gases (source function). And soils have a production function for agriculture because of their fertility, but also a production function (recherché) of the groundwater. Additionally, soils do also have habitat functions, especially for plants and animals, site functions for different kinds of land use, and functions for both natural and cultural history (Opp 1998).

The NBSS & LUP (Indian Council of Agricultural Research) as a premier soil survey institution had been adopted the U.S. Soil Taxonomy (USST) to group Indian soils for agricultural land-use planning (Bhattacharyya & Pal, 2016). However, based on the percentages of sand, silt, and clay fractions, soil substrates can be divided into four major textural classes: (1) sands, (2) silts, (3) loams, and (4) clays. Fig. 3. 1 depicts the soil textural classification, which contained the percentage of textural classes. The soil texture triangle is an application to develop sand, silt, and clay low, representative, and high values. There are twelve textural classes identified in Figure, as defined by the U.S. Department of Agriculture (USDA): sand, loamy sand, sandy loam, loam, silt loam, silt, sandy clay loam, clay loam, silty clay loam, sandy clay, silty clay, and clay (Abraham et al., 2019).

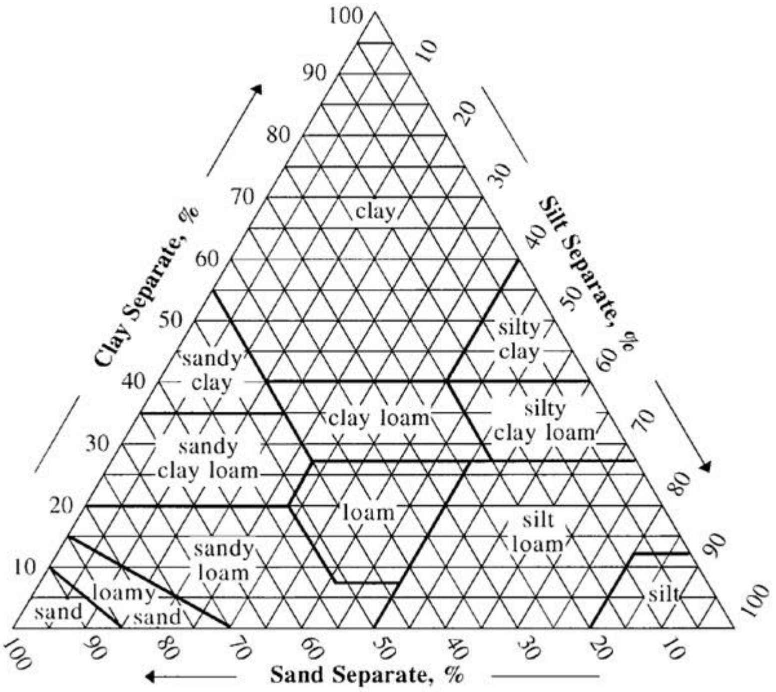

Fig. 3. 1 Soil textural triangle is used to classify the soil textural class containing the percentage of sand, silt, and clay in soils (source: Natural Resources Conservation Service Soil Texture Calculator; Thien. 1979)

According to the U.S. Natural Resource Conservation Service (NRCS), depending on the infiltration characteristic of the soil had been classified into four groups (A, B, C, or D). Those are A: deep and well to excessively drained condition of gravel or sands; B: moderately deep to deep, and moderately well to well-drained soils of coarse textures. C: moderately fine to fine texture soils; D: shallow depth of clay texture soil, with low infiltration potential. Alternately a soil texture calculator can be used for the determination of texture class based on the specific relationship between sand, silt, and clay percentages as outlined in Table 3. 2. The mode details of the hydrologic group can be found in NRCS Soil Survey Staff (1996) handbook. However, the Kolleru Lake catchment soil hydrologic groups inferred from the NRCS classification. Further, the data has been processed into the Soil and Water Assessment Tool (SWAT) model (Kang et al. 2006).

Table 3. 2 Soil texture calculations and mapping of Hydrologic Soil Groups

Percentage of sand, silt, and clay	Textural class	Hydrologic Soil Group
(silt + 1.5 * clay) < 15)	SAND	A
((silt + 1.5 * clay ≥ 15) AND (silt + 2 * clay < 30))	LOAMY SAND	A
((clay ≥ 7 && clay < 20) AND (sand > 52) AND ((silt + 2 * clay) ≥ 30)	SANDY LOAM	A
((clay ≥ 7 AND clay < 27) AND (silt ≥ 28 AND silt < 50) AND (sand ≤ 52))	LOAM	B
((silt ≥ 50 AND clay ≥ 12) AND (clay < 27)) OR ((silt ≥ 50 AND silt < 80)	SILT LOAM	B
(silt ≥ 80 AND clay < 12)	SILT	B
((clay ≥ 20 AND clay < 35) AND (silt < 28) AND (sand > 45))	SANDY CLAY LOAM	C
((clay ≥ 27 AND clay < 40) AND (sand > 20 AND sand ≤ 45))	CLAY LOAM	D
((clay ≥ 27 AND clay < 40) AND (sand ≤ 20))	SILTY CLAY LOAM	D
(clay ≥ 35 AND sand > 45)	SANDY CLAY	D
(clay ≥ 40 AND silt ≥ 40)	SILTY CLAY	D
clay ≥40 AND sand ≤ 45 AND silt < 40	CLAY	D

(source: NRCS; Abraham et al. 2019)

The soil map of the whole state of Andhra Pradesh was obtained from the ICAR-National Bureau of Soil Survey & Land Use Planning (NBSS&LUP), Nagpur, upon a scale of 1:5,00,000 in six sheets, were georeferenced to the UTM projected coordinate system in ArcGIS. Further, the map was precisely geo-coded to each soil profile extracted to the Kolleru Lake catchment area at different categoric levels in classifying soils (i.e., soil map sheets were depicted in Appendix A). The study area falls under the sheet number 3. The soil profile for this study area is composed of 38 different range of soil classes is depicted in Fig. 3. 2. The insight of data provides soil depth, drainage, texture, slope, erosion, and soil taxonomy are outlined in Table 3. 3 (Sehgal et al. 1987, Soil Survey Division Staff 1995). Based on the analysis, approximately 46.7 percent of the study area is largely extended to the well-drained condition, 19.9 percent are the moderately well-drained condition, 27.8 percent of the study area composed of imperfectly drained, and 2.45 percent of the study area is excessively drained. The field capacity of the soil for this study imperatively depends upon the soil depth and drainage condition. Very deep soils are predominantly identified in a range of 55 percent; moderately deep soils are found to be 13.9

percent, and while shallow type soils are rarely identified is less than 5 percent. The soils are dominantly clayey in texture, hence nonporous, resulting in flooding.

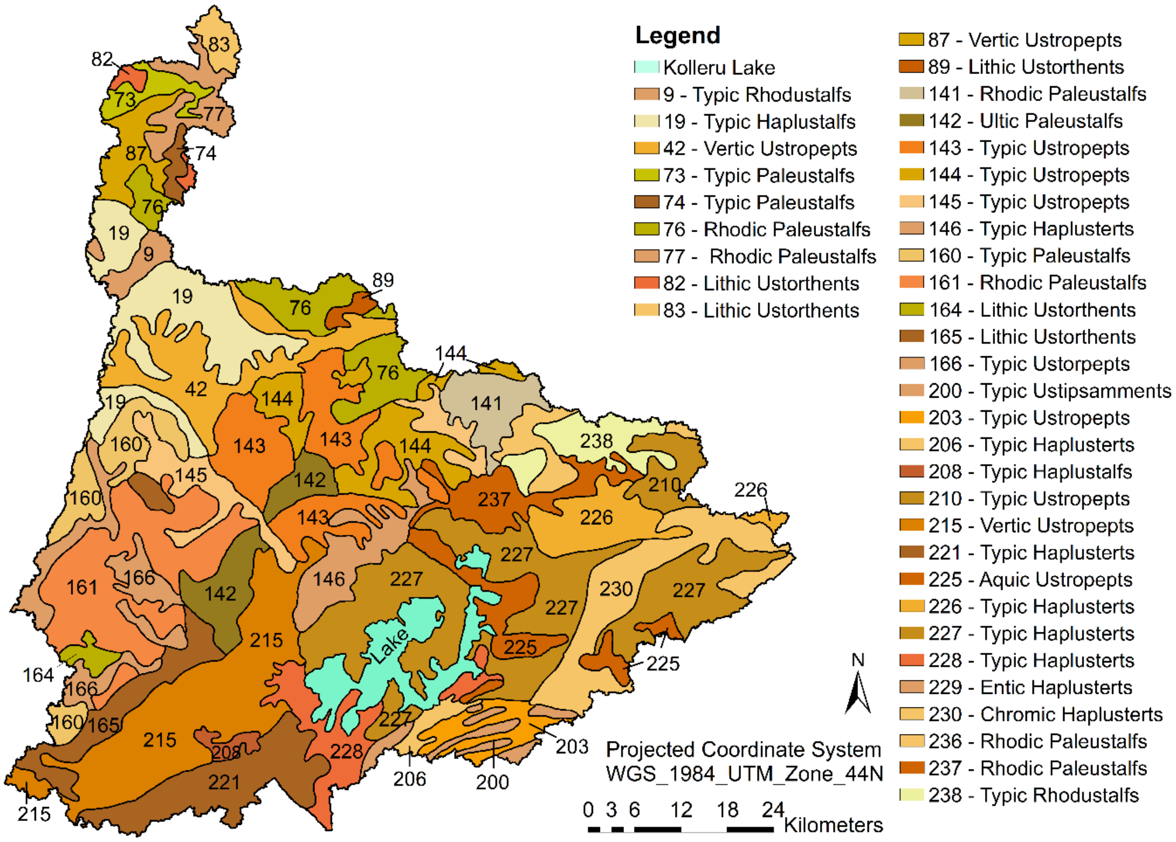

Fig. 3. 2 Soil map of the Kolleru Lake catchment (The author partially developed this map in the courtesy of ICAR - National Bureau of Soil Survey and Land Use Planning (NBSSLUP) Nagpur, Maharashtra).

Table 3. 3 Soil classification legend inferred from Fig 3. 2.

Code	Soil Depth	Drainage	Texture	Slope	Erosion	Soil Taxonomy	Area (ha), (%)
9	Moderately deep	Well-drained	Gravelly clay soils	Rolling lands	Moderately eroded	Clayey – Skeletal, Typic Rhodustalfs	37.34 (0.73)
19	Moderately deep	Well-drained	Clayey soils	Gently sloping lands	Moderately eroded	Fine, mixed, Typic Haplustalfs	269.36 (5.33)
42	Very deep	Moderately well-drained	Cracking-clay	Level valleys	–	Fine, montmorillonitic, Vertic Ustropepts	208.51 (4.12)
73	Deep	Well-drained	Loamy soils	Gently sloping interhill basins	Moderately eroded	Fine loamy, mixed, Typic Paleustalfs	42.64 (0.84)
74	Very deep	Well-drained	Loamy soils	Very gently sloping plains	Moderately eroded	Fine loamy, mixed, Typic Paleustalfs	19.5 (0.38)
76	Very deep	Well-drained	Clayey soils	Gently sloping lands	Moderately eroded	Fine, mixed, Rhodic Paleustalfs	171.62 (3.39)

77	Very deep	Well-drained	Clayey soils	Gently sloping lands	Moderately eroded	Fine, mixed, Rhodic Paleustalfs	72.2 (1.42)
82	Shallow	Excessively drained	Gravelly loam soils	Hills and ridges	Severely eroded	Loamy-skeletal, Lithic Ustorthents	16.77 (0.33)
83	Very shallow	Excessively drained	Loamy soils	Hills and ridges	Very severely eroded	Loamy, mixed, Lithic Ustorthents	31.8 (0.62)
87	Very deep	Moderately well-drained	Cracking-clay	Gently sloping valleys	Slightly eroded	Fine, montmorillonitic, Vertic, Ustropepts	72.45 (1.43)
89	Very shallow	Excessively drained	Gravelly loam soils	Hills and ridges	Severely eroded	Loamy-skeletal, Lithic Ustorthents	14.84 (0.29)
141	Very deep	Well-drained	Clayey soils	Gently sloping lands	Moderately eroded	Fine, mixed, Rhodic Paleustalfs	91.27 (1.81)
142	Deep	Well-drained	Clayey soils	Very gently sloping plains	Moderately eroded	Fine, mixed, Ultic, Paleustalfs	127.31 (2.51)
143	Very deep	Well-drained	Clayey soils	Gently sloping lands	Slightly eroded	Fine, mixed, Typic Ustropepts	291.13 (5.76)
144	Very deep	Well-drained	Clayey soils	Rolling lands	Severely eroded	Fine, mixed, Typic Ustropepts	189.12 (3.74)
145	Very deep	Well-drained	Clayey soils	Very gently sloping valleys	Slightly eroded	Fine, mixed, Typic Ustropepts	132.51 (2.62)
146	Very deep	Moderately well-drained	Cracking clay soils	Very gently sloping plains	Moderately eroded	Fine, momtmorillonitic, Typic Haplusterts	112.62 (2.22)
160	Deep	Well-drained	Clayey soils	Undulating lands	Moderately eroded	Fine, mixed, Typic Paleustalfs	125.56 (2.48)
161	Very deep	Well-drained	Clayey soils	Gently sloping lands	Moderately eroded	Fine, mixed, Rhodic Paleustalfs	316.03 (6.25)
164	Shallow	Excessively drained	Gravelly loam soils	Hills and ridges	Severely eroded	Loamy-skeletal, Lithic Ustorthents	21.18 (0.42)
165	Very shallow	Well-drained	Gravelly loam	Gently sloping lands	Severely eroded	Loamy-skeletal, Lithic Ustorthents	129.23 (2.55)
166	Deep	Moderately well-drained	Loamy soils	Very gently sloping plains	Slightly eroded	Fine loamy, mixed, Typic Ustorpepts	146.69 (2.90)
200	Very deep	Excessively drained	Sandy soils	Very gently sloping sandy plains	Slightly eroded	Mixed, Typic Ustipsamments	40.04 (0.79)
203	Deep	Moderately well-drained	Clayey soils	Flatlands	Slightly eroded	Fine, mixed, Typic Ustropepts	70.46 (1.39)
206	Deep	Imperfectly drained	Cracking clay	Falt lands	Slightly flooded	Very fine, Typic Haplusterts	25.02 (0.49)
208	Deep	Well-drained	Loamy soils	Gently sloping lands	Moderately eroded	Fine loamy, mixed, Typic Haplustalfs	19.38 (0.38)
210	Deep	Well-drained	Clayey soils	Very gently sloping plains	Slightly eroded	Fine, mixed, Typic Ustropepts	66.97 (1.32)

215	Moderately deep	Moderately well-drained	Cracking clay	Very gently sloping plains	Slightly eroded	Fine, montmorillonitic, Vertic Ustropepts	399.18 (7.90)
221	Very deep	Imperfectly drained	Cracking clay	Flatlands	–	Fine, montmorillonitic, Typic Haplusterts	184.11 (3.64)
225	Very deep	Imperfectly drained	Clayey soils	Swamps and marshes	Slightly flooded	Fine, montmorillonitic, Aquic Ustropepts	119.9 (2.37)
226	Very deep	Imperfectly drained	Cracking clay soils	Flatlands	Slightly flooded	Fine, montmorillonitic, Typic Haplusterts	123.38 (2.44)
227	Very deep	Imperfectly drained	Cracking clay soils	Flatlands	Slightly flooded	Very fine, montmorillonitic, Typic Haplusterts	597.14 (11.8)
228	Deep	Imperfectly drained	Cracking clay	Flatlands	Slightly flooded	Very fine, Typic Haplusterts	124.14 (2.45)
229	Very deep	Imperfectly drained	Cracking clay soils	lowlands	Slightly flooded	Very fine, Entic Haplusterts	14.02 (0.27)
230	Deep	Imperfectly drained	Cracking clay soils	lowlands	Slightly flooded	Very fine, Chromic Haplusterts	220.92 (4.37)
236	Very deep	Well-drained	Clayey soils	Gently sloping plains	Moderately eroded	Fine, mixed, Rhodic Paleustalfs	57.76 (1.14)
237	Deep	Well-drained	Clayey soils	Gently sloping plains	Moderately eroded	Fine, mixed, Rhodic Paleustalfs	109.64 (2.16)
238	Deep	Well-drained	Gravelly clay soils	Gently sloping plains	Moderately eroded	Clayey-skeletal, Typic Rhodustalfs	100.24 (1.98)

3. 1. 2 Landuse data

Land-use of 2005 data was acquired from the Indian Space Research Organization ISRO). The spatial resolution of the data is 30 m. Land-use data were mainly classified into agricultural land (for paddy cultivation), fishponds, urban, barren land (unused or uncultivated land), and forest areas (Fig. 3. 3). Agricultural land is the dominant land use cover (68%) of the catchment, followed by fishponds (16%), mangrove forests on gently sloped areas (10%), and the urban area does not exceed 3% of the total area. The land use map of the year 2005 is used for data processing for the whole catchment region.

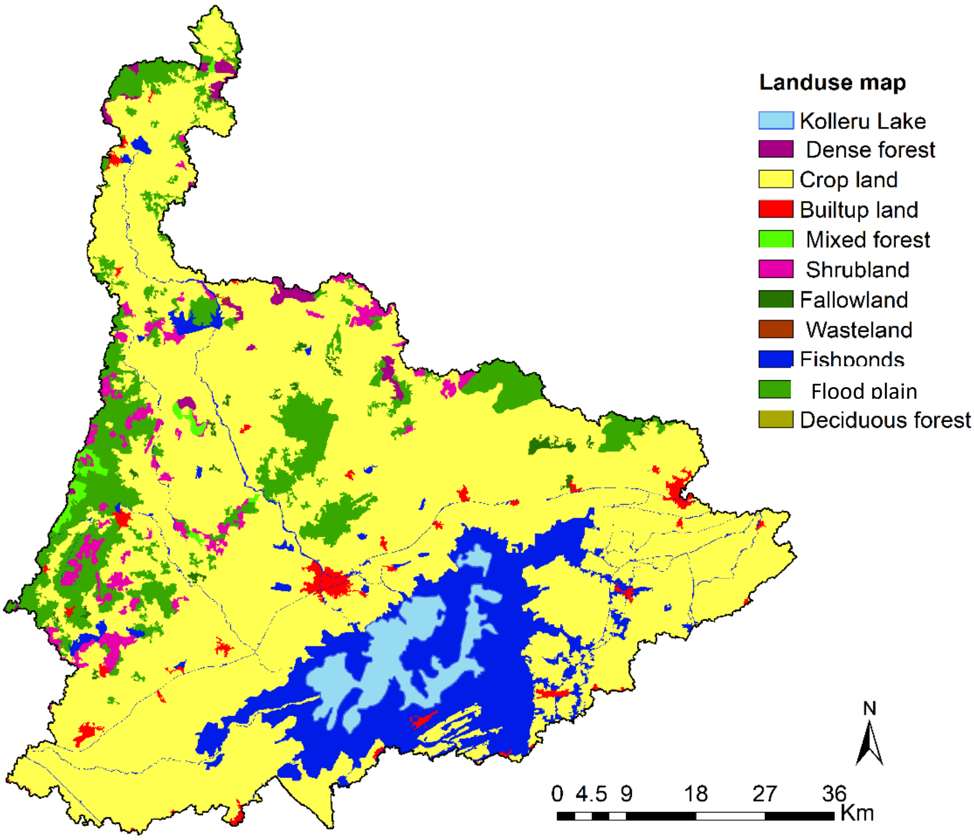

Fig. 3. 3 2005 land use classification of Kolleru Lake catchment

3. 2 Methods

With corresponding to the main objectives which were formulated in the introduction, there are several specific sub-objectives that will be treated in the results as manuscripts in the same order as set out briefly below.

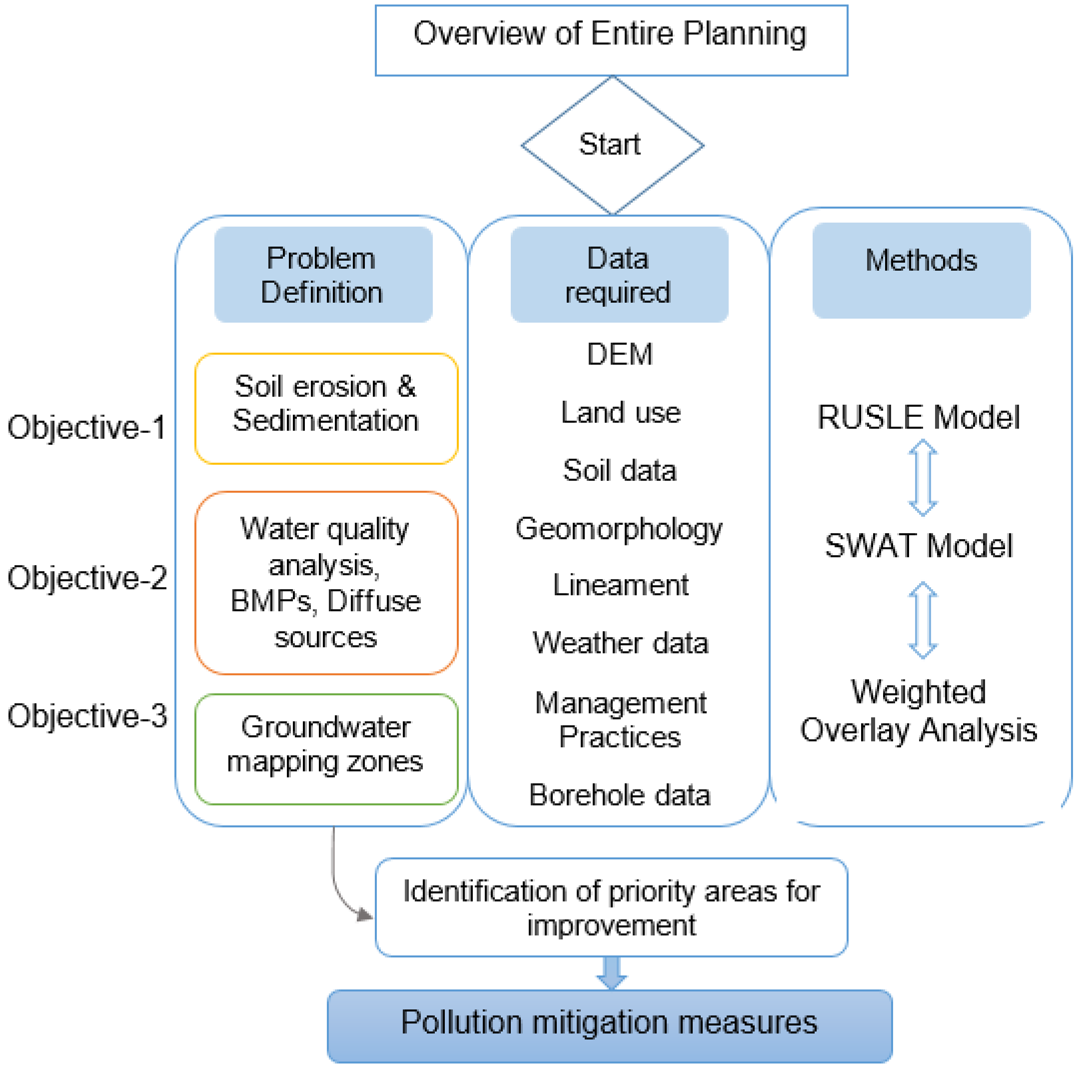

Fig. 3. 4 Methodology flowchart

3. 2. 1 SWAT model

For minimizing the water quality threat to the Kolleru Lake catchment, it is necessary to identify the diffuse critical sources. However, it is difficult to trace the pollution levels where the fishponds surround the lake. The inflow of the rivers, irrigation canals, streams, and tributaries into the lake can carry the agricultural fertilizers that are nitrogen (N) and phosphorus (P), leading to the one reason for water quality threat of the lake. Still, there are limited water quality studies for the whole catchment region. Probably this is the reason for the lack of management plans. Therefore, the contribution of agricultural pollutants and interaction with their sources is discussed in the **first research objective**. For the modeling of an agricultural catchment, the Soil and Water Assessment Tool (SWAT) was used.

The SWAT model was developed by the Agriculture Research Service of the United States Department of Agriculture (Arnold et al., 1998). SWAT is a physically-based, semi-distributed hydrological model. The SWAT model is widely used around the world for the management of agricultural practices. It is capable of estimating the runoff simulation, sediment analysis, land use changes on runoff trends, and non-point sources from a small watershed to the large watershed on the basis of daily, monthly, and seasonal basis (Abbaspour et al., 2015; Kang et al., 2006). The model uses the physical properties of soil, land use, elevation, weather data to simulate the runoff by using the SCS curve number equation (Abbaspour, 2007). The model delineates the watershed into a number of sub-watersheds depending on the stream network. It creates the feature classes with similar land use, soil, and slope, into the Hydrologic Response Units (HRUs). The hydrological component of the SWAT is based on the following water balance equation:

$$SW_t = SW_o + \sum_{i=1}^{t}\left(R_{day} - Q_{surf} - ET_i - W_{seep,i} - Q_{gw}\right) \quad (1)$$

where, SW_t is the final soil water content (mm), SW_0 the initial soil water content on day i (mm), t the time (days), R_{day} the precipitation on day i (mm), Q_{surf} the surface runoff on day i (mm), ET_i the evapotranspiration on day i (mm), $W_{seep,i}$ the amount of water entering the vadose zone from the soil profile on day i (soil interflow) (mm) and Q_{gw} the amount of return flow on day i (mm) (Arnold et al., 1998).

SWAT uses several hydrologic equations to simulate the runoff and sediment analysis. For soil erosion, the Modified Universal Soil Loss Equation (MUSLE) (Wishmeier & Smith 1978), further potential evapotranspiration by the Penman-Monteith method (Allen 1998), the SCS curve number method for the surface runoff generation (National Engineering Handbook 2004). The complete methodology and mechanism of the SWAT structure, which incorporates the hydrological equations, can be found in the SWAT technical documentation (Arnold et al., 1998). The detailed methodology part can be explained in chapter 4.

3. 2. 2 Weighted overlay analysis

Groundwater scarcity is a general problem in many dryland areas of the world (Prokurat 2015; UNDP 2006). But it is being recognized as an especially critical problem facing India (Scheider 2018). It is an essential natural resource to meet the water requirements of the country. Groundwater irrigation has been expanding rapidly in India, and now accounts for 60% of the total irrigated area in the country (CGWB, 2019). There is a dire need for the sustainable management of groundwater for a small region to the larger catchments. The objective of this study was to map the potential groundwater resources in the Kolleru Lake catchment by using the satellite data sources and as well as with the ground truth data. A GIS framework is an important solution to identify the spatial distribution of groundwater resources, depending on the various parameters. According to the catchment area characteristics, the most sensitive parameters to the groundwater potential recharge are expressed in equation 1:

$$GWP = f(L_u, S, G, L, D, R, S_l, N_v) \quad (1)$$

Where GWP (Kolli et al., 2020) refers to the groundwater potential, L_u is the land-use classification, S is the soil type, G is the geomorphology, L is the lineament density, D is the drainage density, R is the mean annual rainfall, S_l is the slope classification and N_v is the normalized difference vegetation index (NDVI). The groundwater analysis and the detailed methods summarized in chapter 5.

3. 2. 3 RUSLE Model

Sedimentation is a significant contribution to the flooding of fishponds in the Kolleru Lake catchment. The rivers, streams carry the sediments, and their respected tributaries reach downstream of the lake catchment, create water circulation problems. Extensive use of land and the indiscriminate rise of embankments for the construction of fishponds as well as agricultural functions has resulted in widespread soil erosion over the deltaic part of the Kolleru Lake catchment. The objective of this work is to analyze the average annual soil loss rate using the RUSLE model ((Wishmeier & Smith 1978) for the deltaic part of the Kolleru Lake catchment for the years 1972 and 2012. The USLE equation can be expressed as:

$$A = R * K * LS * C * P \tag{1}$$

A = average annual soil loss in (t/ha/yr)

Data such as precipitation, soil classification type, topography, crop cover management, and support practice factor were integrated for soil modeling using RUSLE and ArcGIS. They are used in this study as raster formats such as rainfall erosivity (R), soil erodability (K), steepness factor (LS), crop factor (C), and support practice factor (P). The detailed approach for soil erosion and sedimentation is discussed in chapter 6.

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CHAPTER 4

Estimation of Soil Erosion and Sediment Yield Concentration across the Kolleru Lake Catchment using GIS

Abstract

Flat lakes with a large catchment area are especially affected by sediment inputs. The Kolleru Lake catchment (South-eastern India) with a surface area of approximately 6,121 km^2 belongs to such types of lake basins. The main objective of the study was the assessment of both soil erosion and sediment yield concentration rate of the Kolleru catchment. The study was conducted using the Revised Universal Soil Loss Equation (RUSLE) model due to its simple and good applicability for soil erosion estimation. Data such as rainfall, soil texture, topography, crop cover management, and support practice factor were integrated into the modeling using RUSLE and ArcGIS. Field data were used both to analyze the soil texture and the slope length factor. The results showed that average annual soil loss was estimated with 13.6 t/ha/yr, classifying the Kolleru Lake Basin under a very high erosion rate category. About 38% of the catchment area has encountered with slight soil loss. Areas covered with moderate, strong, severe, very severe erosion potential zones are 29%, 17%, 9%, and 5.5%, respectively. This study identified that upland areas with less vegetation cover exported high potential erosion rates. Unlike the soil loss, the sediment delivery ratio values for the catchment did not affect by the land use, while it showed a strong relationship with the catchment drainage system. Whereas, the average annual sediment yield was determined with 7.61 t/ha/yr, had identified with the same pattern of the soil erosion. Catchment topography, vegetation, drainage system, soil properties, and land use cover played a major role in the export of the highest sedimentation. The outcome of these studies can be used among others for the identification of critical erosion areas on a pixel basis for the planning of erosion management practices.

Keywords: Soil erosion, Lake catchment, RUSLE, Remote Sensing, GIS, field data

4. 1 Introduction

Soil erosion is a severe problem in agriculture and where it has the foremost economic aspect in developing countries (Mekonnen et al., 2016; Erkossa et al., 2015). However, soil erosion by runoff is a global land degradation problem (Restrepo et al., 2018; Novara et al., 2016; Seutloali & Beckedahl, 2015; Oldeman, 1992). The runoff is a major driving factor that accelerates the erosion rates from mountain to low-land regions (Oliveira et al., 2019; Dutta et al., 2017; Civeira et al., 2016). Besides, human-induced erosion is a typical phenomenon of regions with intensive agricultural production, construction activities, mining, deforestation, high-density population, and a lack of integrated approaches (Nyssen et al., 2015; Mekonnen & Melesse 2011; Amsalu et al., 2007). This has been developed by significant changes in land use/land cover patterns. However, frequent land-use changes triggered surface runoff flows, reduce soil fertility, nutrient loss, and land degradation (Ang & Oeurng 2018; Buendia et al. 2016; Hassen et al. 2016; Kim et al. 2013; Gebremicael et al. 2013; Setegn et al. 2010). Many studies demonstrated that land-use changes alter the surface runoff and sediment yields at different spatial and temporal scales (Guzha et al. 2018; Welde & Gebremariam 2017; Lin et al. 2015). Therefore, sustainable development and strategic methods are needed to prevent more soil erosion and massive sediment loads.

Several methods for the estimation of the surface soil losses are known (Brenner, 2013; Auerswald, 2008). The RUSLE (Revised Universal Soil Loss Equation) is the most spread method and widely acceptable all over the world (Borelli et al., 2017; Addis & Klik 2015; Sheikh et al., 2011; Brown et al. 1987; Wishmeier & Smith 1978) from the last few decades. Despite its disadvantages, the RUSLE model is best adapted to the developing countries where the application of other complex models could be limited to the lack of input data (Pervić et al., 2011). It has been used worldwide for a range of small scale (Farhan et al., 2013; Sheikh et al., 2011; Pandey et al., 2009; Lee 2004; Fistikoglu & Harmancioglu 2002) to large scale watersheds (Kumar et al., 2012; Chen et al., 2011; Irvem et al., 2007) to predict the longterm average annual rate of erosion. The RUSLE equation is a function of rainfall erosivity, soil erodability, slope length, crop management factor, and conservation practice (Sheikh et al. 2011). However, each factor has its own characteristic influence on the erosion risk depending on the topography, vegetation cover, and soil type (Kumar et al. 2012, Farhan et al. 2013). Remote sensing and GIS applications are the best way to digitize the land cover maps (Rao 2003), including topography features.

The management of soil erosion and sedimentation losses are extremely complex due to the spatial distribution of large catchments (Mati & Veihe 2011). Therefore, it is essential to identify the critical erosion-prone areas for applying Best Management Practices (BMPs). It is cost-effective to control soil erosion, mainly for an agricultural dominant land-use class (Sorando et al., 2019; Shen et al., 2014). However, there is a requirement of knowledge to prevent soil erosion in Kolleru lake basin studies are imperative (Jayanthi et al., 2006). At present, in the Kolleru Lake catchment, there is no gauge station to estimate soil loss; however, conventional methods are time consuming and cost-effective. Therefore, the USLE method was developed by Wischmeier and Smith (1978) can be used to model the erosion rates in the Kolleru Lake catchment.

The objectives of this study are to ascertain both the spatial distribution of soil erosion and the sediment yield concentrations and to identify the highly polluted variability ranges. The objectives were achieved by following tasks: (i) Application of the RUSLE model to the entire Kolleru lake basin (ii) Identification of the spatial distribution of soil erosion and sediment delivery ratio factors (iii) Estimation of the sediment yield concentration across the Kolleru lake basin. However, due to the insufficient data, stream erosion and sediment deposition were not included in this study. Remote sensing data, such as land use classification, NDVI, elevation profile (DEM), and topography models, were used. While precipitation and soil texture data were acquired from the Indian Meteorological Department (IMD), and the Department of Agricultural Development, Andhra Pradesh, respectively.

4. 2 Study Area

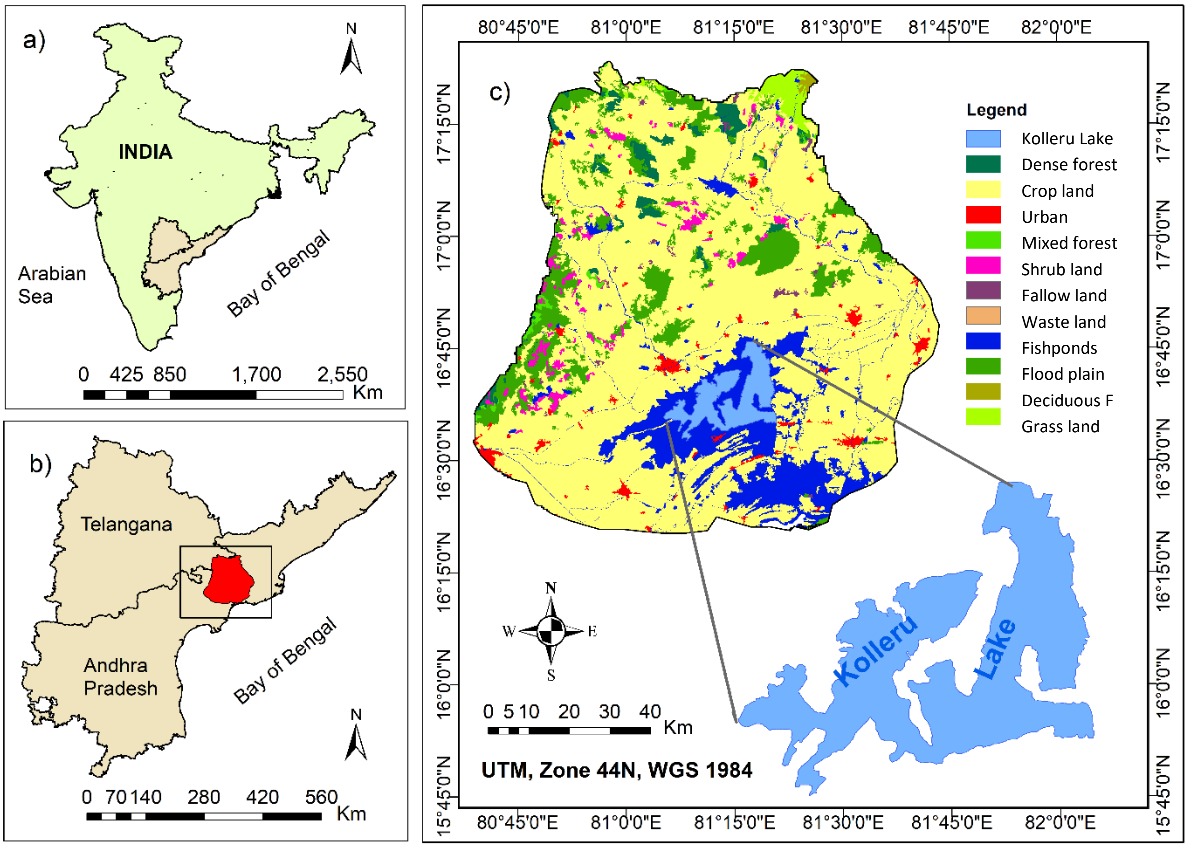

Fig. 4. 1 Study area (Kolleru Lake) location map, **a)** top-left (India map shapefile, NRSC-Hyderabad), **b)** location of Kolleru Lake basin **c)** top-right (Land use map of Kolleru Lake basin, source: NRSC, Bhuvan)

The Kolleru Lake (16º 32′–16º 46′ N, 81º 04′–81º 24′ E) is the largest freshwater lake in India (Fig. 4. 1). It is also famous for a hospitable environment for aquatic life. Two large basins of Krishna and Godavari rivers formed its catchment. They act as natural flood reservoirs between these basins. The landform of the Kolleru lake catchment is mainly composed of upland (77.8%) and deltaic (22.1%) ecosystems (Azeez et al. 2011). The catchment of the lake expands up to 6,121km^2. It consists of mountains, streams, agricultural lands, industrial, and built-up areas. The major soil groups in this area are Black Cotton Soils (57.6%), Sandy Clay Loams (22.3%), Red Soils (19.4%), and minor soil group types are Coastal Sands (3%), and Alkaline Soils (1%) (Raju 2012). The mean annual temperature of the catchment area is 29°C (Patil 2005), with the minimum temperature ranges from 14°C to 22°C, and the maximum temperature ranges from 35°C to 46°C. The mean annual precipitation is 1,094 mm. 70% of the precipitation acquires from June to September (Azeez et al. 2011). Additionally, the Kolleru lake receives water from the seasonal tributaries Tammileru and Budameru, and it has only one outlet channel: Upputeru, which connects the lake with the Bay of Bengal. Due to the recent advancement in man-made activities in this region, land-use changes have been accelerated erosion processes.

4. 3 Material and methods

The longterm analysis of soil erosion is carried out by the RUSLE method for this study (Wishmeier & Smith 1978). Five parameters are influencing the USLE equation. They are used in this study as raster formats such as rainfall erosivity (R), soil erodability (K), steepness factor (LS), crop factor (C), and support practice factor (P) (Auerswald 1992). The USLE equation can be expressed as:

$$A = R * K * LS * C * P \quad (1)$$

A = average annual soil loss in (t/ha/yr)

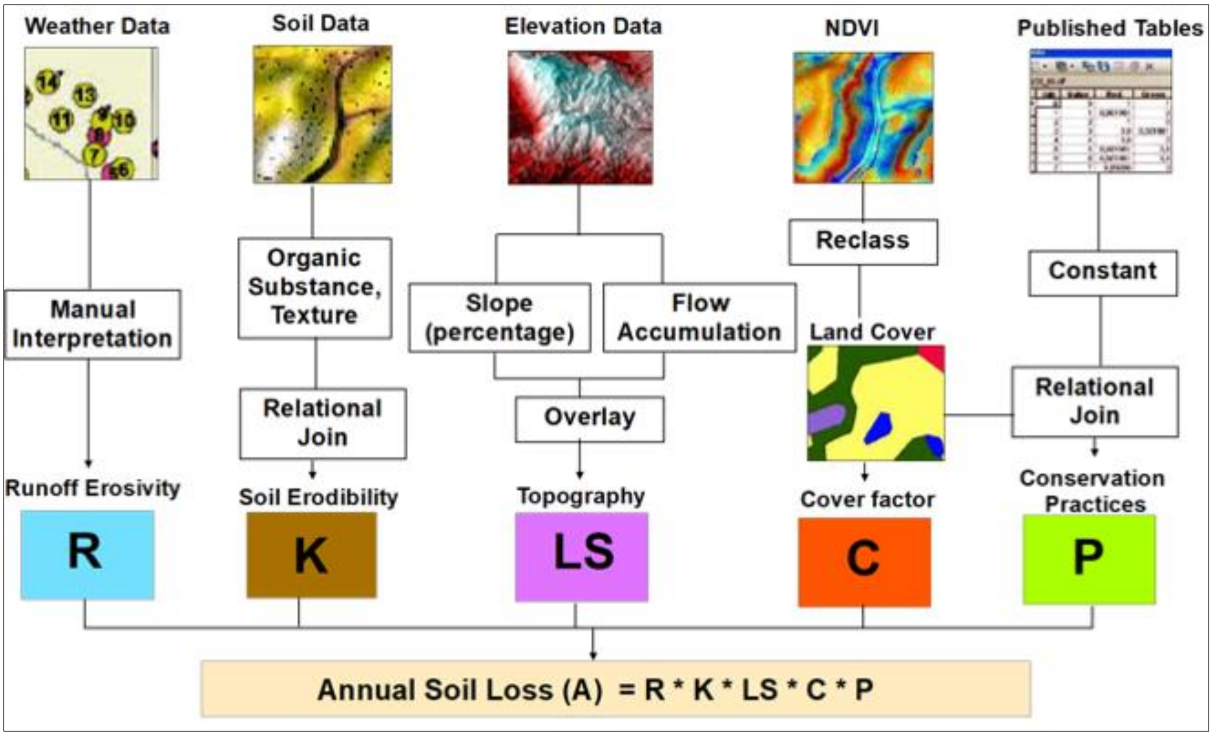

Fig. 4. 2 Methodology flowchart of the study

An overview of the used data and their contribution to the USLE shown in Fig. 4. 2 & Fig. 4. 3 reflecting the topographic and hydrographic conditions of the Kolleru Lake catchment, including the rain gauge stations. Fig. 4. 4 highlights the stream network in dependence on the scale of used pixels.

4. 3. 1 Rainfall Erosivity Factor (R)

The rainfall erosivity factor (R) expresses the erosion rate, which was caused by the rainfall intensity, duration, and volume. Also, velocity, the shape of raindrops, and the kinetic energy of the rain to promote a high impact on soil erosion (Renard et al. 1997). There is a direct proportion between rainfall intensity and erosion; a high rate of rainfall intensity affects more runoff and subsequently results in more soil erosion. The R-factor varies between regions due to the precipitation patterns and slope conditions (Farhan et al. 2013). Plain areas have low erosivity R values because of low inclination, respectively low slope degree, whereas larger R-values indicate higher erosion amounts. Based on the climate data, the R-value represents the product of the rainfall energy (E) and the maximum 30-minute intensity (I30) (Brown et al. 1987). On the other method, the R-value can be estimated by the Fourier index (F), proposed by Arnoldus (1977), to establish the erosion risk.

$$F = \sum_{i=1}^{12} \frac{r_i^2}{P} \quad (2)$$

where r_i is the precipitation for one month and P is the annual precipitation.

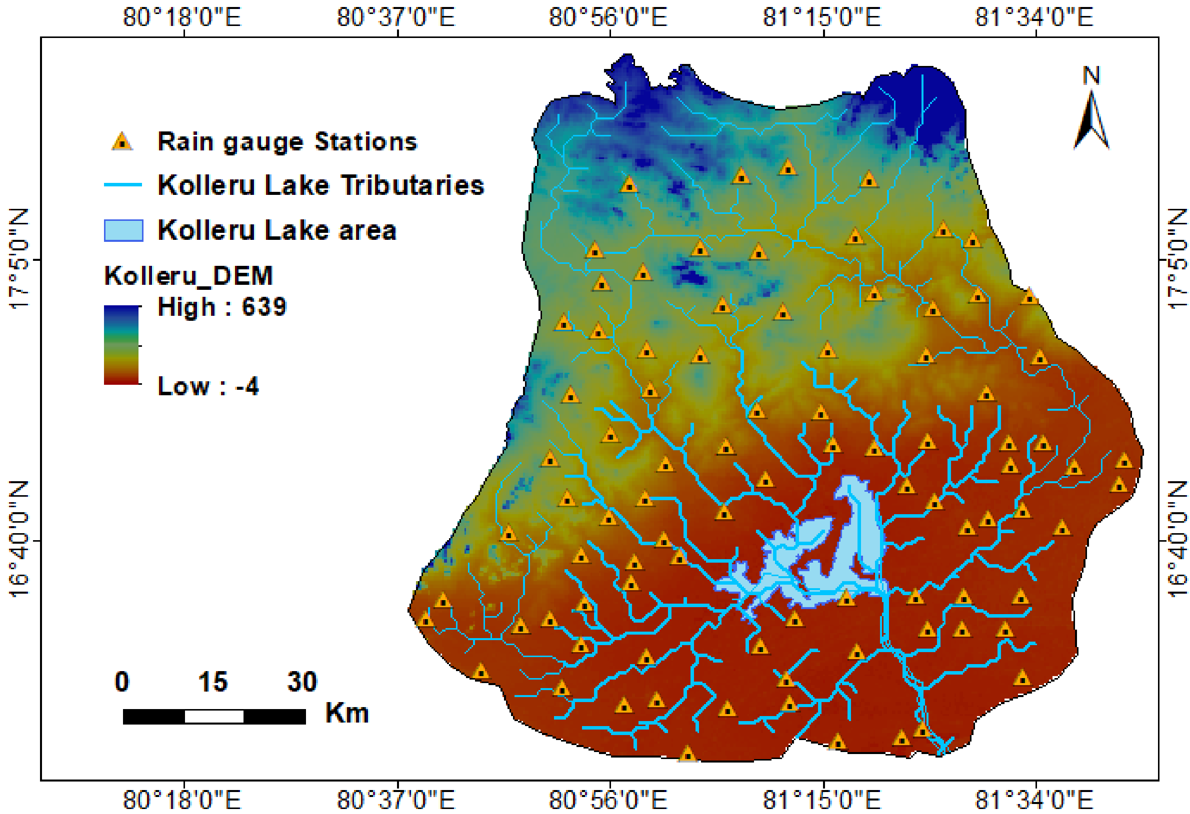

Fig. 4. 3 Digitization of Kolleru Lake catchment along with tributaries using DEM (Digital Elevation Model), Cartosat-1, USGS Earth Explorer.

The estimation of the R-value from F can be determined by regression analysis. There is a number of regression equations for obtaining the R-factor. For this study, R=0.3598 $F^{1.9462}$ was used because it was derived from climatic conditions similar to the study area proposed by Zhang & Fu (2003).

4. 3. 2 Slope Length and Steepness Factor (LS)

The LS factor in USLE represents the combined effect of the length (L) and slope (S) factors, merely depend on the topography of an area. In addition to this, the LS-factor, which depends on flow direction, flow accumulation, and topography of the soil, was also considered while calculating the LS-factor. Slope length was defined by Wischmeier & Smith (1978), as the distance from the point of origin of overland flow to the point where runoff becomes concentrated in a defined channel. Many equations have been developed to estimate the LS factor by Wischmeier & Smith (1978), Moore & Burch (1986), Griffin et al. (1988), McCool et al. (1989), Moore & Wilson (1992), Desmet & Govers (1996). However, they are confined to the distinctive characteristics of the topography of an area. Most of the algorithms are already implemented to calculate LS factor within GIS platforms, such as ArcGIS, SAGA GIS, GRASS, IDRISI, etc. However, according to Desmet & Govers (1996), the LS factor derived from such methods gives higher values than obtained by the manual method. In another case study, LS values are derived from the GIS method were lower by 10-30% than obtained from the manual method (Hrabalikova & Janecek 2017), while 22% higher values obtained by Griffin's method. Therefore, a comparison between different approaches determining the LS factor, based on manual and GIS methods, Hrabalikova & Janecek (2017) extensively documented that the best results obtained from Wischmeier's method, where slope length was replaced by a specific catchment area, and Moore's method.

The LS-factor was calculated for the catchment area of Kolleru Lake by following equation (3) proposed by Moore & Burch (1986a,b).

$$\mathbf{LS} = (\boldsymbol{Flow\ accumulation} \times \boldsymbol{Cell\ size}/\mathbf{22.13})^{\mathbf{0.4}} \times (\mathbf{sin}\ \boldsymbol{slope}/\mathbf{0.0896})^{\mathbf{1.3}} \quad (3)$$

Where LS is the combined slope length and steepness factor, flow accumulation determines the upslope contributing area for a given cell, size of the cell was considered by the resolution of the DEM (for this study a 30 m resolution DEM was available), and sin slope is slope degree value in sin (Moore & Burch (1986a, b)). The stream network was derived from the DEM by changing the threshold value (Fig. 4. 4). A detailed flow network can be observed from the smaller chosen value. For the calculation of the LS factor, 100 pixels threshold value has been used in this study.

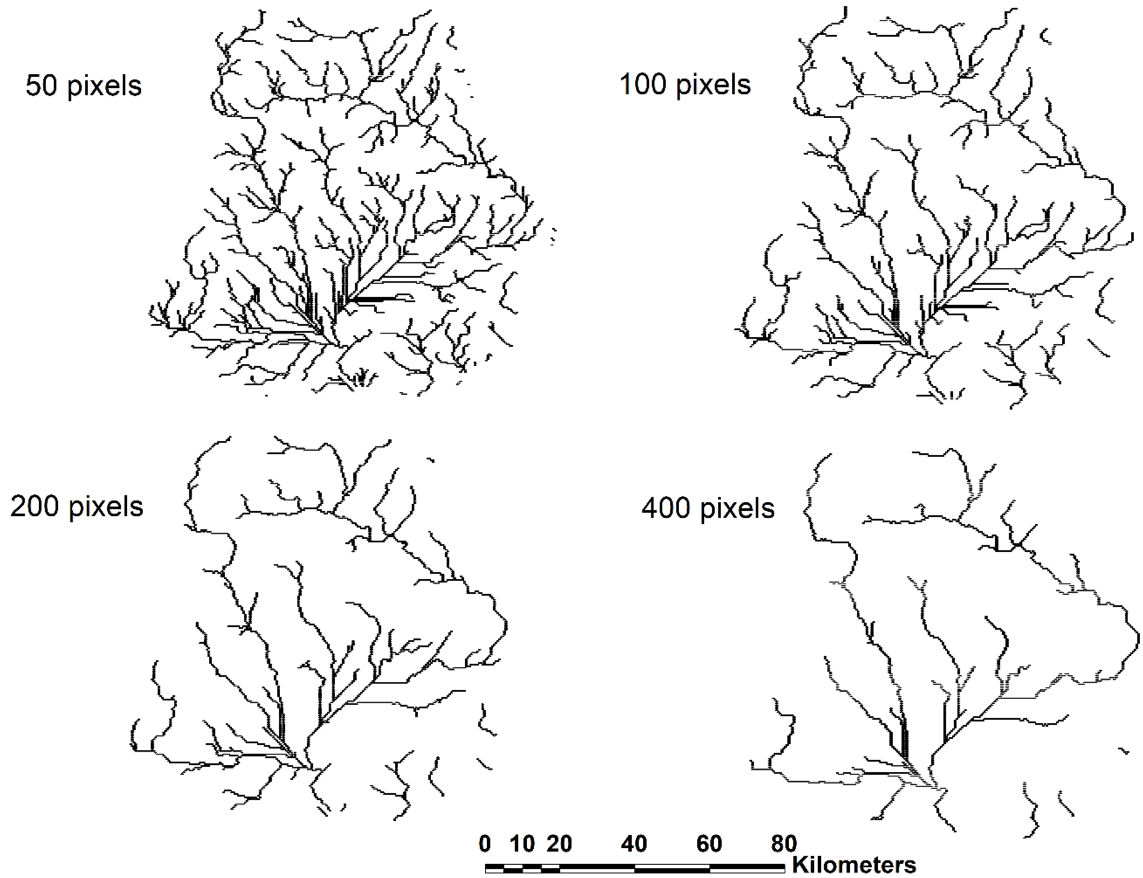

Fig. 4. 4 Stream network of the Kolleru Lake catchment inferred from DEM

4. 3. 3 Support Practice factor (P)

P-factor indicates the effect of support practices on the average annual erosion rate. It represents the ratio of soil loss with contouring and/or strip cropping to that with a straight row farming up-and-down slope (Renard et al. 1997). On the other hand, it indicates the rate of soil loss according to the various cultivated lands on the earth (Sheikh et al. 2011). For satisfactory results, the P-factor depends on contour, strip cropping, and terraces, which control erosion. According to the cultivating methods and slope conditions, the support practice factor value is shown in Table 4. 1 (Shin 1999). The value of the P-factor ranges from 0 to 1. Some agricultural support practices, such as contour farmland and surrounded by fish farmlands, occur within the Kolleru Lake catchment.

Table 4. 1 Support practice factor according to the slope (after Shin 1999)

Slope (%)	Contouring	Strip Cropping	Terracing
0.0 – 7.0	0.55	0.27	0.10
7.0 – 11.3	0.60	0.30	0.12
11.3 – 17.6	0.80	0.40	0.16
17.6 – 26.8	0.90	0.45	0.18
26.8 >	1.0	0.50	0.20

4. 3. 4 Soil Erodibility Factor (K)

The soil erodibility factor (K) expresses the disintegration of soil particles from parent rock material respectively the soil body under the action of rainfall intensity, wind, and natural or human activities results in sediment transport and runoff for a specific condition (Bancy et al. 2000, Pandey et al. 2007, Addis & Klik 2015). A wide range of soil eroded particles is known to belong predominantly to the silt and clay texture classes (Kim & Julien, 2006). But also, sand particles are very less resistive to erosion (Buttafuoco et al. 2012, Karydas et al. 2013) because of their cohesive behavior towards the origin. The K-factor can be selected by measurements from field unit plots, for instance of 72.6 ft long with 9% slope, continuously maintained fallow, tilled up and down the hill slope (Weesies 1998, Bagarello et al. 2009; Addis & Klik 2015). Direct measurements of runoff plots can also determine k values. However, field measurements are more accurate than other studies. For this study, the K factor was determined on the basis of soil texture classes and organic matter contents proposed by Williams et al. (1995). In this study, the soil samples (Fig. 4. 5) were collected from different locations around the lake (c.f. Fig. 4. 6), where the inflow of water debouches into the lake and the outflow of the water discharges into the sea (Fig. 4. 3 and 4. 6). The corresponding K-values for the soil types were identified based on the particle size distribution and organic matter content in addition to the soil texture data from the Department of Agriculture Development, Andhra Pradesh, in India.

Fig. 4. 5 Field data processing based on the sieve analysis method of Kolleru Lake

The further soil texture classification of the field samples was done based on the particle size distribution system followed by the sieve analysis method, in which the size of sieves range between 4.75 mm and 0.002 mm (IS 383). Based on the degree of fineness, the soil particles were classified as sand, silt, and clay (in percentages) (Fig. 4. 6). The organic matter content was determined based on the loss-on-ignition (LOI), which is the percentage weight loss of the soil sample due to ignition at a certain temperature. The erodibility values are ranging from 0 to 1, where 0 reflects soil with less water erosion, and 1 reflects soils with high water erosion. In this study, the K factor was derived from the following equation (Williams et al. 1995) across the tributaries.

$$K_{USLE} = f_{csand} \times f_{cl-si} \times f_{orgc} \times f_{hisand} \quad (4)$$

where, f_{csand} is a factor, that lowers the K indicator in soils with high coarse-sand content and increases it for soils with low sand content; $f_{cl\text{-}si}$ gives low soil erodibility factors for soils with high clay-to-silt ratios; f_{orgc} reduces K values in soils with high organic carbon content, while f_{hisand} lowers K values for soils with extremely high sand content:

$$f_{csand} = \left(0.2 + 0.3.\ exp\left[-0.256. m_s\ .\ \left(1 - \frac{m_{silt}}{100}\right)\right]\right) \quad (5)$$

$$f_{cl-si} = \left(\frac{m_{silt}}{m_c + m_{silt}}\right)^{0.3} \quad (6)$$

$$f_{orgc} = \left(1 - \frac{0.25 \cdot orgC}{\mathrm{orgC+exp[3.72-2.95 \cdot orgC]}}\right) \quad (7)$$

$$f_{hisand} = \left(1 - \frac{0.7 \cdot \left(1 - \frac{m_S}{100}\right)}{\left(1 - \frac{m_S}{100}\right) + \exp\left[-5.51 + 22.9 \cdot \left(1 - \frac{m_S}{100}\right)\right]}\right) \quad (8)$$

Where, fm_s is the sand fraction content (0.05-2.00 mm diameter %); m_{silt} is the silt fraction content (0.002-0.05 mm diameter %); m_c is the clay fraction content (<0.002 mm diameter %); and orgC is the soil organic carbon (SOC) content (%). Besides the soil classification, organic matter content was calculated by the loss of weight on ignition (LOI) method as follows:

$$\mathrm{LOI(\%)} = \frac{\text{Weight at 105°C-Weight at 360 °C}}{\text{Weight at 105 °C}} \times 100 \quad (9)$$

The estimation of organic matter from LOI is done by regression analysis. By using the Walkley-Black method is used to convert LOI to total carbon (Gelman et al. 2011). The equation as follows:

$$\text{Total Organic C} = (0.443 \times \mathrm{LOI}) - 2.77 \quad (10)$$

The results are illustrated in Fig. 4. 6.

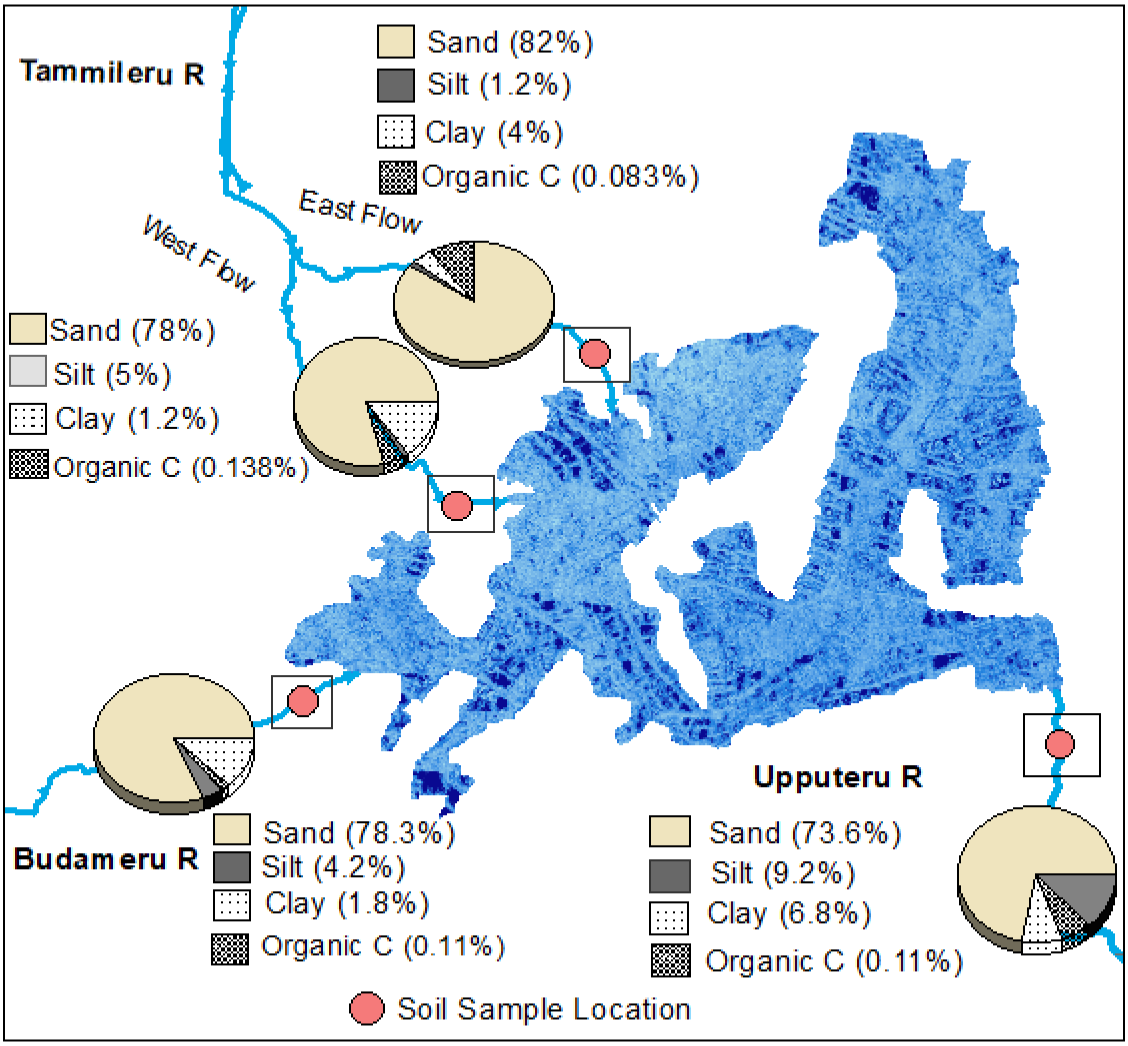

Fig. 4. 6 Texture classification of the soil sample from the Kolleru Lake surrounding areas (actual area shown as in DEM format) area based on the sieve analysis method

4. 3. 5 Crop and management factor (C)

The crop management factor (C) was determined from the existing land use and land cover patterns and NDVI (year 2005) (Kumar et al. 2012). It is expressed as the ratio of soil loss from land covered by the crop patterns under specific conditions to the corresponding loss from the plain area such as clean-tilled, waterbody and fallow land (Wischmeier & Smith 1978). The C-factor values approximately range from 1 to 0, where higher values represent that there is no cover effect and more prone to erosion. In comparison, lower values represent dense cover effects, results in less erosion (Erencin 2000). To find the effective crop factor based on the spatial and temporal variations, satellite remote sensing data were used (Prasannakumar et al. 2012). It depends on the type of crop cover and soil over the area of concern, and it considers the second major factor controlling erosion (Farhan et al. 2013). Despite the availability of land cover patterns, the values were assigned to each cover based on the type of land used.

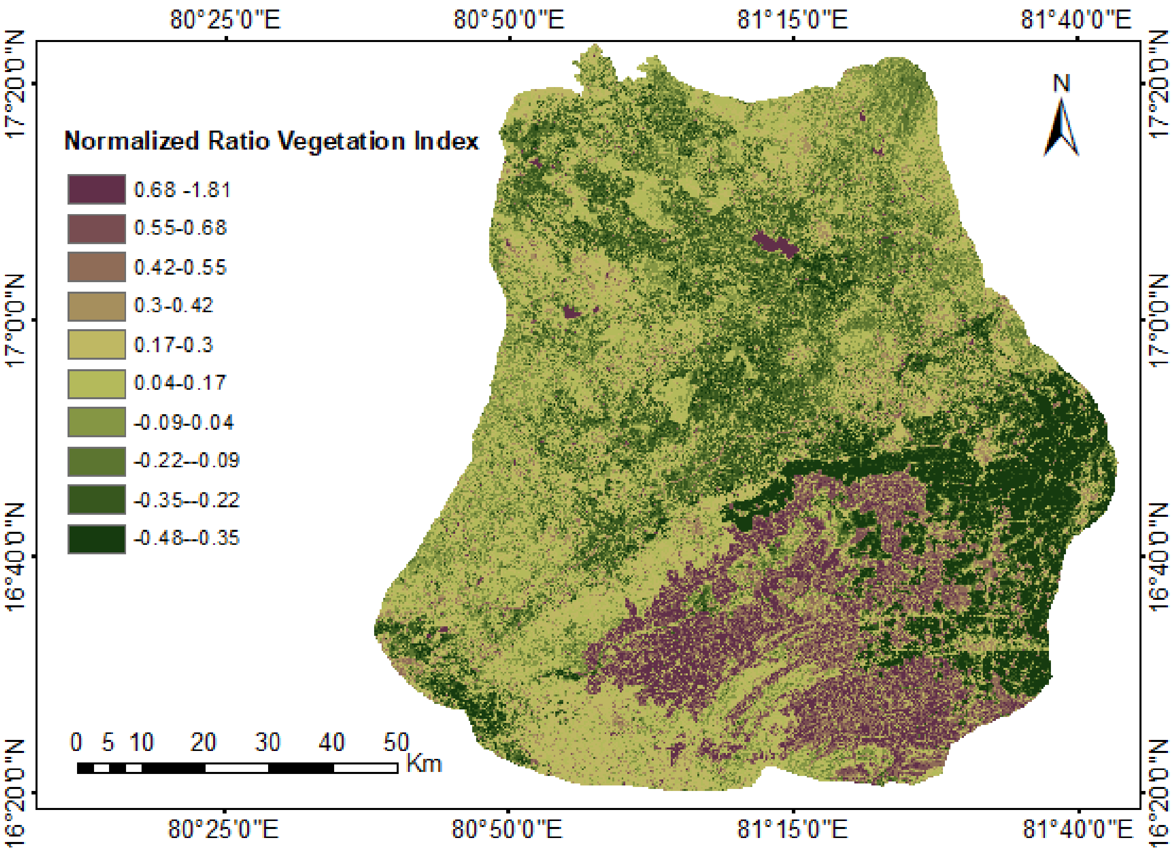

Fig. 4. 7 NDVI (2005) classification of Kolleru Lake catchment

4. 3. 6 Predicting sediment yield

Sediment yield prediction in a catchment embraces, the determination of the amount of soil eroded and transferred from the point of interest at a given period of time. The statistical product between the surface soil erosion (A) and the sediment delivery ratio (D_R) is called sediment yield (S_y). The degree of extent of D_R values for an area are indiscriminately affected by catchment topography, vegetation cover, sediment sources, slope, and the texture of soil material, etc. (Richard 1993, Lin et al. 2002, Fu et al. 2006). However, parameters such as land cover, slope, and catchment area have been mainly used in empirical equations for D_R (Roehl 1962, Hadley et al. 1985, Kothyari & Jain 1997, Fu et al. 2006, Jain & Kothyari 2000).

D_R in grid cells is the main function of the travel time of surface flow within the cell, which was extensively documented by the Ferro & Minacapilli (1995) and Ferro (1997). A conformable grid with 30m × 30m (in this study area, resolution of DEM, 30m) of cell size and a travel time of a surface flow is strongly dependent on land cover and topography characteristics of a catchment. It had been justified the relationship with D_R (Jain & Kothyari 2000). Based on their studies, the land cover and topography has mainly considered in this study, and also assumed that grid cell existing in an overland region of a catchment. The empirical equation as follows:

$$D_{R_i} = exp(-\gamma t_i) \quad (11)$$

Where γ is a constant coefficient for a given catchment and t_i is the travel time (hr) of surface flow from the i_{th} grid to the nearest channel grid. The travel time of each grid in a channel can be estimated with the flow path if one knows lengths and velocities. In GIS (ESRI 1994) analysis, the eight-direction (D8) flow model can be achieved with the flow direction from one cell to a neighboring cell. In a given grid cell, there are eight valid output directions relating to the eight adjacent cells into which the flow could take place. The flow direction is determined by the direction of steepest descent, or maximum drop, from each cell.

$$S_y = \sum_{i=1}^{N} D_{R_i} A_i \quad (12)$$

Where S_y is the sediment yield concentration, A_i is the soil erosion over the catchment, and D_{R_i} is the sediment delivery ratio.

4. 4 Results and Discussions

Maps for values of the RUSLE parameters, such as rainfall erosivity factor (R), soil erodability factor (K), length and slope inclination factor (LS), crop factor (C), and support practice factor (P), were overlaid to form a composite map of soil erosion (A). The results discussed here based on the complete analysis of field and remote sensing data to estimate the soil erosion (A), sediment delivery ratio (D_{R_i}), and sediment yield concentration (S_y) in the Kolleru Lake catchment. The results provide a general understanding of erosion risk levels and the rate of sediment yield concentrations in the catchment.

4. 4. 1 Soil loss

Fig. 4. 8 illustrates the spatial distribution of potential soil erosion risk map of Kolleru lake catchment. The annual average soil loss of the whole catchment was grouped into different classes, as suggested by Singh et al. (1992). About 38% of the area is encountered with slight soil loss (<5 t/ha/yr). Whereas 29% of the area was prone to moderate soil loss (5-10 t/ha/yr), 17% of the area was identified as strong soil loss (10-20 t/ha/yr), while 9% of the area severe soil loss (20-40 t/ha/yr), and 5.5% area was under very severe soil loss (>40 t/ha/yr) respectively. The observation of extreme soil loss areas are more than 5.5% was already gone severe erosion due to its higher elevation slopes. The maximum soil loss areas are mainly concentrated in higher LS factor and conservation practice factors, where a large percent of the area still not covered by conservation measures. Meanwhile, the catchment area consists of less than 12% of vegetation cover that caused high erosion risk where forestland

has the maximum water-retaining capacity while reducing the potential soil loss up to a certain extent. In addition, the studied soils are clayey in texture and non-porous in nature, which is more provision to runoff leading to more soil loss. In the Kolleru Lake catchment, topographic characteristics play a significant role in soil exports, whereas the proportion of the deltaic part is comprised of less than 22% relatively balanced in the downstream region.

Moreover, the study area belongs to the regions of maximum degradation of vegetation cover and changing weather parameters in Andhra Pradesh. However, frequent vegetation changes can promote erosion rates, especially in semi-arid regions (Kumar et al. 2012). According to Patil (2005), about 35.6 million tonnes of surface soil was eroded every year in Andhra Pradesh. Similar data were reported in other parts of the world (Civeira et al., 2016; Rodriguez-Iruretagoiena et al., 2016; Sanchís et al., 2015; Arenas-Lago et al., 2014; Silva et al., 2013), demonstrating the importance of this study.

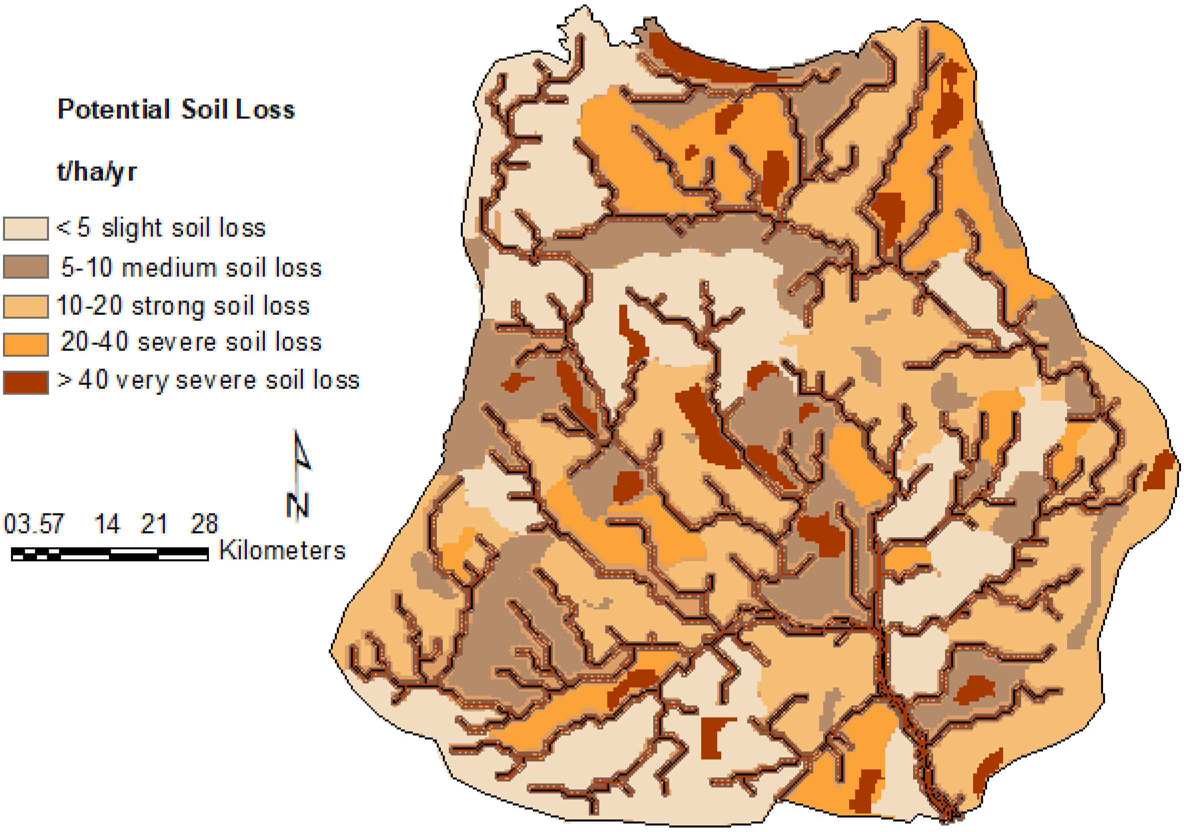

Fig. 4. 8 Soil erosion risk map of Kolleru Lake catchment by using RUSLE method

4. 4. 2 Sediment delivery ratio

The sediment delivery ratio (D_R) showed a strong relationship between cell size and the nearest channel (Fig. 4. 9). SDR assumes that it has an inverse relationship with travel time, which is a function of travel length and velocity (Equation 11). Because of the surface roughness and slope features, the same distance does not imply to all the cell values have the same SDR with different travel times (Fu et al. 2006). The spatial distribution of SDR is extremely important for identifying the potential soil loss areas and their respective sediment delivery sources (Jain & Kothyari 2000, Fu et al. 2006).

Unlike soil loss, the SDR values obtained for the Kolleru lake catchment did not show a strong relation with land uses, while it more likely tends to be affected by the catchment drainage system (Richard 1993). It can be explained in Fig. 4. 9, those large D_R values are associated with the steep headwater areas, which are likely to be stream network channels, while smaller D_R values are found in overland regions, that was surrounded by the channel networks. The steep channel areas had the highest SDR between 0.85 and 1. The average SDR for the Kolleru lake catchment founded is 0.75.

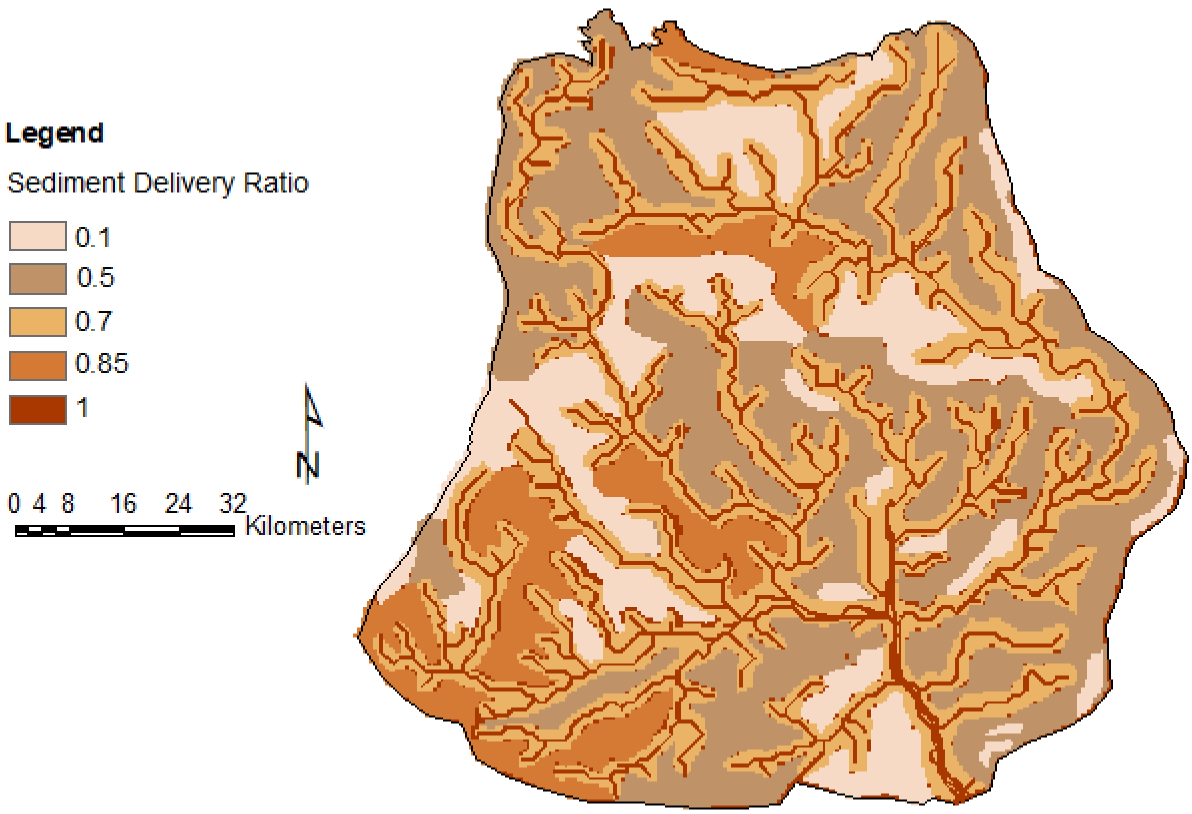

Fig. 4. 9 Spatial distribution of sediment delivery ratio at Kolleru Lake catchment

4. 4. 3 Sediment yield

The factors affecting the sediment yield concentrations mainly from surface runoff, erosion, vegetation type, soil and water conservation practices, and topographic factor. Fig. 4. 10 depicted the sediment yield distribution was classified into five categories according to their proportion of distribution. The average annual sediment yield concentration in the Kolleru Lake catchment is found to be 7.61 t/ha/yr.

Whereas 27% of the area has encountered with slight sediment yield (<1 t/ha/yr), 32% of the area has prone to moderate sediment yield (1-7 t/ha/yr), 22% of the area has identified as strong sediment yield (7-19 t/ha/yr), while 13% of the area severe sediment yield (19-40 t/ha/yr), and 4.5% of the area very severe sediment yield (>40 t/ha/yr). The sediment yield distribution from the entire catchment was followed by the same pattern of soil erosion (Fig. 4. 8); thereby, it was modified with the stream patterns similar to that of SDR (Fig. 4. 9). The sediment yield concentration was relatively high in croplands, particularly from paddy fields. Meanwhile, the cultivation on higher elevation slopes caused great soil erosion in the Kolleru catchment. In addition, the areas with high sediment yields are also concentrated in wastelands, and there the erosion rate is higher in uncovered areas. In the catchment area, red soils and sandy clay soils exported most sediment, and this is much referenced to the soil properties while indicating the depth, slope, texture pattern, erosion, and drainage.

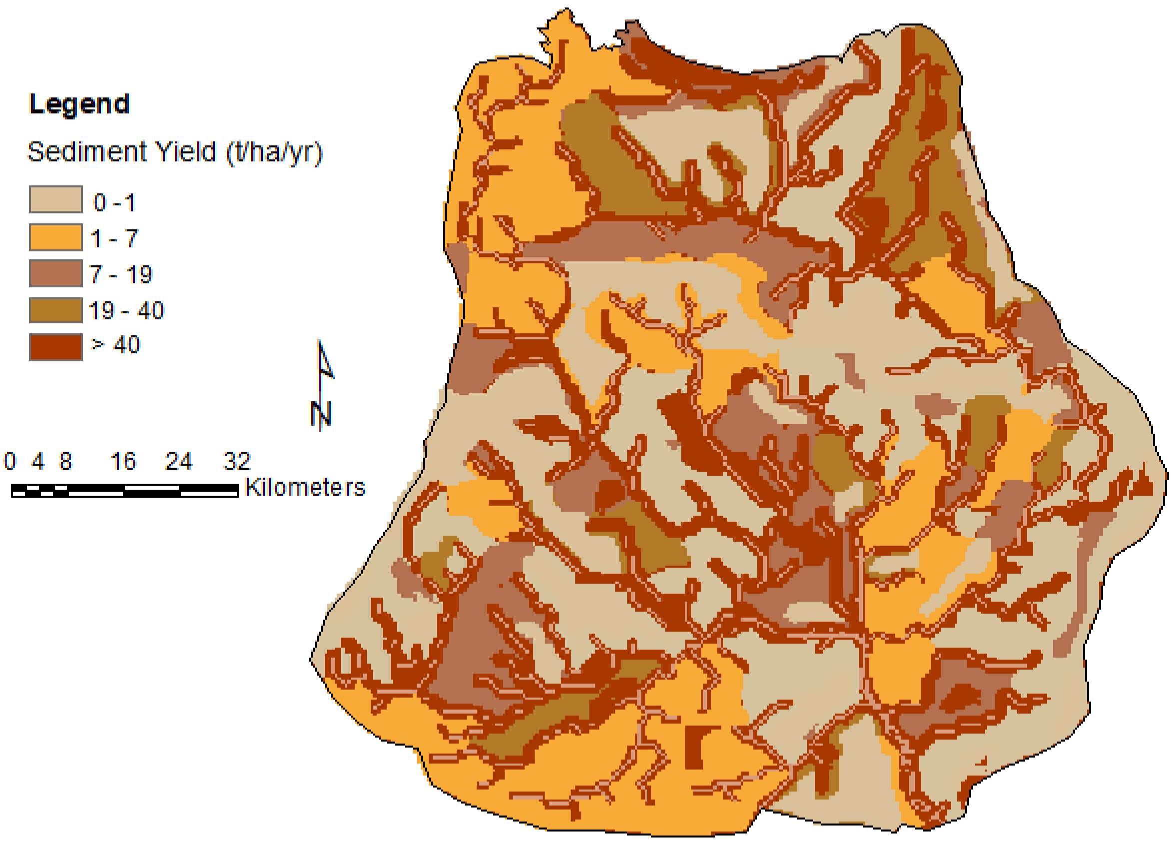

Fig. 4. 10 Sediment yield (t/ha/yr) at Kolleru Lake catchment

Furthermore, agricultural and industrial activities are the major sources of surface erosion and, consequently, sedimentation and siltation within the Kolleru lake catchment (Azeez et al. 2011). According to Narender (1993), eight major industries were located nearby the lake contributing about 7.2 million liters of industrial effluents containing suspended solids, organic acids, colloids, etc. led into the lake. Besides, the perennial rivers of Krishna and Godavari drift down to the lake about

68,000 tons of sediments (Azeez et al. 2011). As it was mentioned by own on-site observations, a substantial proportion of suspended sediments to the Kolleru lake comes from the river banks. Moreover, fishponds cultivation around the lake contains a high organic load, fertilizers, and pesticides (Narender 1993). The catchment confronts several other threats of which siltation, eutrophication, and water circulation are significantly affect the lake ecosystem (Rao & Pillala 2001, Sekhar et al. 2004, Rao et al. 2006). This study presents compiled RUSLE and GIS data and its analyses in different areas of the world previously reported (Sánchiz et al., 2013; Cerqueir et al., 2011; Ribeiro et al., 2012; Quispe et al., 2012).

4. 5 Conclusions

This model helps to identify the susceptible erosion-prone areas where the uncertainty of the data is available that should be targeted for the agricultural management plans. The coupling of GIS and RUSLE models was used in an efficient procedure for the estimation of soil erosion and sediment yield concentration using and collecting the existing data of the Kolleru Lake basin with remote sensing images. The overall results are presented on a pixel-wise spatial distribution of the soil erosion and sediment yield rate in the Kolleru Lake basin. Upland areas exhibited much greater erosion rates to the stream channels than plain areas. The average annual soil loss was estimated at about 13.6 t/ha/yr classifying the basin into a very high soil erosion category. About 31 % of the basin found to be under strong, severe, and very severe erosion rates, while about 67 % of the basin has moderate and slightly moderate erosion risks. Agricultural and industrial activities were found as major sources of soil erosion and sedimentation. The average annual sediment yield of the basin was found to be 7.61 t/ha/yr. About 39 % of the basin found to be strong, severe, and extremely severe sediment yield concentrations, while about 59 % of the basin has moderate and slightly moderate sediment yield concentrations at risk. It was identified that soil loss and sediment yield patterns are spatially connected, and the sediment yield was highly modified with the sediment delivery ratio. This study has found that tributaries and streamlines of the catchment carry high sediment loads to the lake. In this area, the priority attention must be given to the adjacent streamlines, either application of buffer strips has been suggested to prevent more soil losses. The areas under the potential erosion soil losses need immediate attention from the agriculture management point of view, in combination with both detailed investigations of the vegetation maps, soil texture, rainfall intensity, and topographic features and by using remote sensing and GIS techniques the estimation of soil erosion losses and sediment loads accurately.

Answer for working question 4

RUSLE model is best adapted to the developing countries where the application of other complex models could be limited to the lack of input data. Each factor has a significancant influence on estimating erosion and sedimentation. The RUSLE equation is a function of rainfall erosivity, soil erodability, slope length, crop management factor, and conservation practice. It is a simple and convenient method that is suitable for any type of catchment.

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CHAPTER 5

SWAT modeling – an integrated approach for the identification of critical diffuse pollution sources in the Kolleru Lake catchment, India

Abstract

Freshwater ecosystems are facing severe threats from human activities. As a consequence of this, they can get disturbed. In developing countries, like India, freshwater lakes are endangered primarily by agricultural activities, which often accelerate erosion and the runoff. The massive application of pesticides and chemical fertilizers to agricultural lands is one reason for eutrophication in the Kolleru Lake. Industrial pollution causes deteriorating water quality and makes them unfit for drinking water to the inhabitants of the villages around the Kolleru Lake. Besides, the indiscriminate rise of fishponds across the lake is another source of pollution in the lake. The different natural and anthropogenic influences increase the highly complex ecosystem of the lake. Managing these ecosystems is a challenging task. Due to the lack of an integrated approach and comprehensive environmental policy, Kolleru Lake has become an ecological crisis area. Diffuse pollution sources are still remaining. Together with the inadequate management planning and actions, they are contributing to the deterioration of the water body of the Kolleru Lake. Therefore, the objectives of this study are to ascertain the priority control areas, aiming at socio-economic development for the long turn protection of the lake water quality by applying the Best Management Practices (BMPs). For this purpose, the Soil and Water Assessment Tool (SWAT) was used to identify the critical areas of the lake's catchment in terms of pollution from agricultural runoff into the tributaries of the Kolleru Lake and the lake itself. Further, suggestions were provided for the implementation of agricultural management practices to minimize pollution levels.

Keywords: Kolleru Lake, eutrophication, diffuse pollution, water quality, hydrological model, BMPs.

5. 1 Introduction

In recent decades the effective pollution abatement measures to the water quality are sizeable (Parker 2011; Barton et al. 2005; Hettige et al. 1996) But, in developing countries like India, the water quality pollution levels are so high, creating existential threats to biodiversity, thus lead to decreasing economic progress as well as costs of human lives (World Economic Forum 2019). India is one of the foremost agriculture-based economies in the world, with high fertilizer applications and the excessive nutrients from agricultural lands, leading to prominent diffuse pollution to the surface water quality (Central Pollution Control Board 2016; Bassi et al. 2014). The high alarming rate of increasing pollutant load of surface water from industrial accompanies is known from the concentration based discharge control of point sources, which is already an important task to control and to achieve water quality targets (Wang et al. 2004). Additionally, the reduction of diffuse pollution sources is required.

Although urbanization and demographic changes are substantial influences within the lake's catchment, land-use changes cause extreme disturbances of the catchment's ecosystems and the lake itself. Most studies demonstrate that land-use changes (Fang et al. 2019; Tu 2009; Zampella et al. 2007) as a driving factor for the environmental, including the physical and chemical characteristics of surface water bodies and their internal structure. Improper management of natural resources, coupled with an ever-increasing population, is responsible for introducing many impairments of water quality threats. Most of the freshwater resources are under stress caused by urbanization, and large-scale industrialization processes are a worldwide concern (Hoyer & Chang 2014; Holopainen et al. 2016; Liao et al. 2012).

The complexity exist in several ecosystem functions of the surface water bodies adversely affected foremost water quality in freshwater lakes which, in turn, and among others, influence ponds, rivers, streams and slowly enter into the groundwater (Gilboa et al. 2014; Banadda et al. 2010; Rees et al. 2009). Diffuse pollution caused by agricultural activities can be carried into adjacent water bodies by surface runoff and erosion (Taylor et al. 2016; Guo et al. 2010). Such excess of nutrients accelerates eutrophication and algae blooming in freshwater ecosystems. Besides, point sources are another significant reason for the deteriorating water quality in surface water bodies. However, the spatial and temporal distribution of diffuse pollutants is a challenge. It is important to monitor these distributions even for a large catchment area, due to changing climate, land-use, and strong relations to anthropogenic activities (Shen et al. 2013; Randhir and Tsvetkova 2011). Therefore, it is essential to determine the severe diffuse pollution sources of a catchment and to apply the best management practices (BMPs) to protect lake water quality.

The Kolleru Lake catchment in India has been taken as a case study for understanding and modeling of the Spatio-temporal variability in the pollutant loads, which will be a prerequisite for better management of agricultural, industrial, and water resources.

In recent decades, many studies have used the Soil and Water Assessment Tool (SWAT) (Arnold et al., 1998) to model the management of agricultural catchments for identifying polluted areas (Izydorczyk et al., 2019). SWAT is a useful tool for the estimation of both nitrogen and phosphorus (N & P) emissions and the degree of eutrophication. Both information a necessary prerequisite for the selection of BMPs from small scale areas (Coffey et al. 2013; Shang et al. 2012; Kang et al. 2006) to large scale catchments (Abbaspour et al. 2015; Yalew et al. 2013). The U.S.

Environmental Protection Agency (EPA) recognized the SWAT model and incorporated it into the EPA's BASINS (Better Assessment Science Integrating Point and Non-point Sources) (Abbaspour et al. 2015). Apart from that, several studies were extended into the SWAT-based optimization tool for obtaining cost-effective strategies for sustainable management (Liu et al., 2019; Wallace et al. 2017). However, due to continuous simulations and operations on a daily time step, it is an essential tool for the identification of pollutant sources.

The main objective of this study serves a better understanding of diffuse pollution sources in the Kolleru Lake catchment, a typical flood balancing catchment between the Krishna and the Godavari basins. Here the first study is conducted to estimate diffuse pollution in Kolleru Lake for the catchment level. Further, the study assimilated the critical sub-basin measures on the Hydrological Response Unit (HRU) level priority areas, to conclude the planning of BMPs. Furthermore, suggestions are provided for the implementation of better lake management practices in the catchment.

5. 2 Study area

The catchment area is one of the most developed agricultural regions of Andhra Pradesh state, as well as the state, which is historically called the "Rice Bowl of India." With a massive fertilizer application and a high crop yield production, the Kolleru lake catchment accounts for 22.7% of chemical fertilizer consumption in the Andhra Pradesh state. According to the Andhra Pradesh Pollution Control Board (APPCB), reports that in excess of 17,000 tons/yr of fertilizers enter into the lake. Because of the high proportion of agricultural land and diverse agro-climatic conditions in this region, encourage the cultivation of different crops, a large number of chemical fertilizers considerably replaced the traditional organic fertilizer. In recent decades, besides the sewage inflow from nearby towns, diffuse agricultural pollution was accounted for a significant pollution source. In most cases, adding more quantities of N & P fertilizers to the soils does not result in increased crop yields and significantly led to proliferating eutrophication of the lake (Vijayalakshmi & Brahmaji 2017; Krishna et al. 2016; Bassi et al. 2014).

Kolleru lake is one of the most polluted lakes (Kolleru Lake, Pulicat Lake, Chilika Lake) in India. Therefore it is under the control of the Ministry of Environment, Forest and Climate Change (MoEF & CC), along with Central Pollution Control Board (CPCB) and State Pollution Control Boards (SPCBs). These organizations are responsible for the legal and regulatory framework for environmental protection in India (CPCB 2005; MoEF 2007). MoEF is accountable for the preparation of environmental policies through the Central Empowered Committee (CEC) in coordination with the Kolleru Lake Development Committee (KLDC), whereas the "Operation Kolleru" was implemented. The main objective of this voluntary program was to minimize the pollution from fishponds across the lake, the Supreme Court of India initiated the "Operation Kolleru" in 2006 to clear all encroachments and their water pollutants. It divided into three phases between 16 February 2006 and 13 June 2006. As a result, approximately 1,776 fish ponds became destroyed, and further 89.08 lakh cubic meters of natural earth forming embankments were removed (Azeez et al. 2011).

5. 3 Significance of the study

It is generally acknowledged that the following essential criteria are prerequisites for the Kolleru Lake pollution control measures and implement the adequate BMPs between point and diffuse sources:

- In the catchment, point source pollution is distinguishable. They substantially contribute to water pollution. The reduction of pollution sources should be feasible and cost-effective;
- The rise of illegal fishponds within the lake area should be controlled and monitored;
- For reducing diffuse pollution, sources must be identified, and the usage of chemical fertilizers in croplands should be replaced by traditional organic methods.

Due to the lack of a comprehensive environmental policy, the Kolleru lake is still facing severe threats by, firstly, agricultural runoff. In the catchment area, paddy cultivation carried two times every year, the first crop cultivated between July and September is known as a summer crop, whereas the second crop grown between October and March is a winter crop (Azeez et al. 2011). According to Rao (2005), the usage of chemical fertilizers significantly varied between these two seasons, and the first crop uses less amount of fertilizers is about 40 kg/ha, and that of a second crop uses more than a half amount of 120 kg/ha to the first crop. Besides, around the catchment area, approximately used of 1,16, 800 tons/yr inorganic fertilizers, and one-fourth of them end up in the lake through run-off and leaching (Sreenivas and Kumar 2013). The level of chemical fertilizer application is far beyond the maximum trend in this region, and the decrease of fertilizer application would be beneficial.

Secondly, the water quality of the lake is deteriorated by point sources; thus, untreated industrial effluents released into the lake from nearby cities (Azeez et al. 2011). According to the list of critical pollution industries of the Kolleru Lake, there are 36 industrial pollutants located in the catchment. The major industries such as rice mills, paper industries, sugar factories, milk factories situated around the lake, alternately sewage sludge from nearby cities have contributed to its depletion and pollution. The pollution sources of the lake have highlighted by several studies and still continuous effort on point source pollution control not yet implemented – the management of the Kolleru Lake wetland ecosystem has received inadequate attention in the Central Water Commission (CWC) agenda. Thereby, it is subjected to severe anthropogenic pressure.

As more and more studies conducted on the Kolleru Lake ecosystem (Vijayalakshmi & Brahmaji 2017; Azeez et al. 2011; Jayanthi et al. 2006; Rao & Pillala 2001; Narender 1993), it is possible to use the accumulated information for the development of pollution control measures and their responses to environmental changes. Apart from the point and diffuse sources, damages and losses due to massive flooding during the monsoon season, and partly drying out during summertime, as a result of inadequate management planning and action, are seen as areas of improvement (RIS 2002). These natural and anthropogenic processes are influencing the lake. Both local drivers and features originating in the whole catchment of the lake occur. Since the 1990s, the lake has gone through enormous changes; more information about these changes can be found in Azeez et al. (2011). Based on the complexity of the existing threats of the lake, first, it is necessary to identify priority or test areas for applying management practices in the Kolleru Lake catchment, at least for lake protection. This paper reports on the priority control areas aiming at socio-economic development linking with the "Operation Kolleru for demolishing the fish ponds to reestablish the past glory of the lake" (hereafter the "Operation Kolleru scheme") and in the long turn protection of the lake water quality by applying the Best Management Practices (BMPs).

5. 4 Materials and Methods

5. 4. 1 SWAT model setup

The SWAT model was developed by the Agriculture Research Service of the United States Department of Agriculture (Arnold et al., 1998). This approach was adopted to simulate the diffuse pollution load in the Kolleru lake catchment. It is a physically-based and semi-distributed model that operates on a daily step and capable of continuous simulation over long periods (Gassman et al. 2007). In this study, the SCS (Soil Conservation Service) (USDA-SCS 1972) curve number was used to calibrate the surface runoff from daily rainfall data, further potential evapotranspiration from Penman-Monteith, and sedimentation from the Modified Universal Soil Loss Equation (MUSLE) (Williams 1976). The model equations are extensively documented on the official SWAT website (http://swatmodel.tamu.edu).

The data used in the SWAT model are in two different formats, i.e., from a spatial and a temporal database. Table 3. 1 outlines the available data for the SWAT simulation. The spatial data includes the DEM (Digital Elevation Model) generated using stereo images of ASTER DEM with a spatial resolution of 30 m. Land-use data were mainly classified into agricultural land (for paddy cultivation), fishponds, urban, barren land (unused or uncultivated land), and forest areas (Fig. 5. 1a). The soil types were categorized into 38 classes (Fig. 5. 1b). The data provide insights into soil depth, drainage, texture, slope, erosion, salinity, etc. (Table 3. 3). The temporal data include hydrological parameters, such as daily precipitation, maximum & minimum temperature, relative humidity, wind speed, and solar radiation. The mainly used rain gauge stations were Bhimavaram, Eluru, Gudivada, Nuzvid, and

Tadepalligudem. The catchment weather information used from daily monitoring data for the period 2008-2014. Information on crop patterns, fertilizer application, fish farming, social economics, and industrial pollution was based on previous literature and data collected from local statistic yearbooks (Azeez et a.. 2011), and on-field investigations as well.

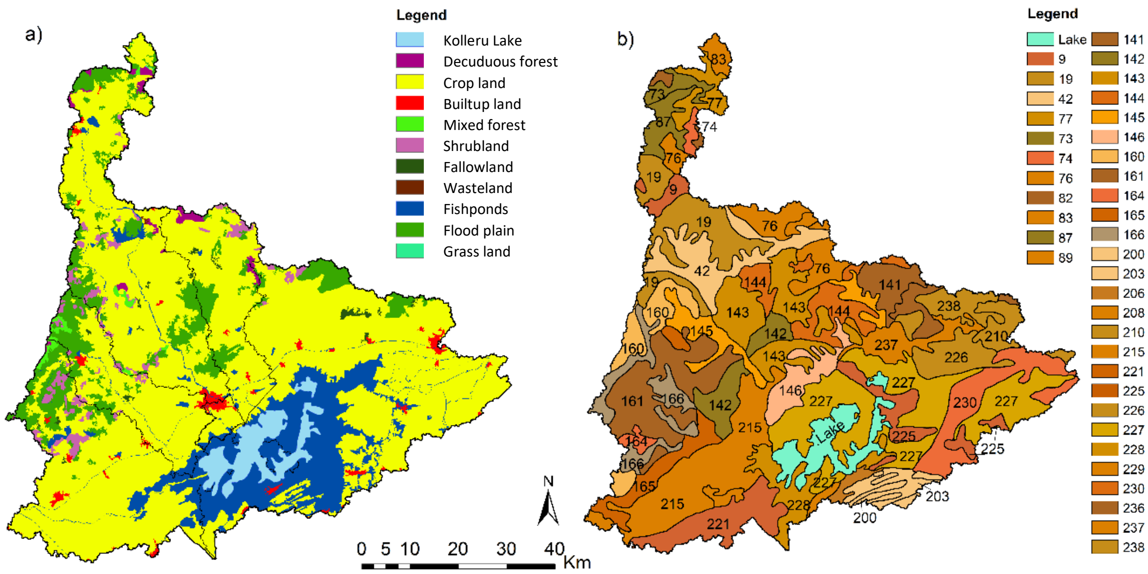

Fig. 5. 1. **a)** Land use and land cover map **b)** Soil classification map of the Kolleru lake catchment (i.e., The reference code of the soil data is presented based on their original data source) [Note: The physical properties of the soil for the whole catchment area is outlined in Table 2].

The catchment area is composed of 38 different soil types, dominantly with clayey texture. According to this data, 46.7 percent of the catchment is largely extended to the well-drained condition, 19.9 percent is moderately well-drained, while 27.8 percent is composed of imperfectly drained, and 2.4 percent is excessively drained. Very deep soils (55 percent) are predominantly identified within the catchment area, with clay dominance in texture and pore in coarse and medium pores. Present up-slope in the headwaters are covered by shrub vegetation and forest areas. The runoff from the upper catchment passes the agricultural fields of the middle part before entering into the lake. Agricultural land is the dominant land use cover (68%) of the catchment, followed by fishponds (16%), mangrove forests on gently sloped areas (10%), and the urban area does not exceed 3% of the total area.

Using a DEM with 30 m spatial resolution, SWAT delineated the catchment into 20 sub-basins depending on the flow direction, stream network, and drainage outlets. Slopes were classified into four gradient categories: <3%, 3-5%, 5-10%, and >10%. Hydrologic Response Units (HRU) obtained from adjusting thresholds of 12% land-use, 15% soil, and 15% slope. There are 1,281 feature classes (HRU) that were delineated, while each HRU is being independent of the SWAT model, with a similar slope, land-use, and soil characteristics. The model was extensively calibrated against daily discharge, nitrate pollution (NO_3_N), and total phosphorus (TP) loads in the Kolleru Lake catchment.

5. 4. 2 Workflow to Action Plan

After the "Operation Kolleru," the lake water still received serious threats by diffuse pollution. Therefore, the state government authorities approved that the lake was not polluted by the fishponds, due to agricultural runoff and urban infrastructure. Kolleru Lake pollution mitigation plans were formulated between 1982 and 2015. The efforts were taken in 2006 to resolve the pollution by fishponds one site. Still, the other sources of pollution left for discussion between researchers, stakeholders, and the state government authorities. Therefore this paper reports about the identification of priority areas of diffuse pollution from 2008 to 2014 (after Operation Kolleru), based on the SWAT model (Fig. 3. 4).

The workflow included four stages: problem definition, preparing a database and SWAT model execution, identification of priority areas, and formulation of pollution mitigation measures. The first stage included the knowledge deficit in this area, discussed with the Kolleru Lake development programs, especially with the Kolleru Lake Forest Department (KLFD), Kolleru Lake Development Committee (KLDC), researchers, and water managers. Researchers and water managers provided the necessary data for understanding and visualizing the pollution levels in the catchment. The second stage devoted to the database preparation and model execution based on the daily time step. The third stage included the identification of priority areas based on the results obtained from the SWAT model. Further, the results and necessary actions will be discussed with the researchers, stakeholders, and state government authorities. The last stage was the implementation of a measures plan protecting lake water against pollution.

5. 4. 3 BMPs setups and stakeholders engagements

The first methodological approach has identified the agricultural management priority areas for applying BMPs to facilitate the relevant information to the stakeholders. The central and state government organizations had formulated the Kolleru Lake development programs and aimed to bring an optimized solution to conserve the lake resources (Azeez et al. 2011). One such program is the Kolleru Lake Development Committee (KLDC), which checks the encroachments, regulating or monitoring the pollution level, and clearing the lake weeds every year. This study considers the agricultural runoff attributes the first time for the Kolleru Lake catchment. Thus promotes the awareness of the decision-makers and stakeholders on values, functions of the stream network, and variables of the Kolleru Lake catchment.

Furthermore, the potential outcome of the "Operation Kolleru" program aimed to reestablished the past glory of the lake. A priority response of an integrated water management plan (IWMP) on the catchment level became possible for an optimal set of the lake ecosystem. However, the IWMP contains an activity to enlighten the stakeholder's perception towards lake degradation. Stakeholders will become able to include Kolleru Lake ecosystem resource users, will be guided about the crucial significance of the lake functions, values, and resources from which they fulfill their needs. Moreover, the state government agencies should incorporate with the stakeholders to adopt sustainable development activities that would need a priority response.

5. 5 Results and discussion

The results will be demonstrated on the sub-basin level (Tab. 5.1). HRUs priority level of management practices is presented below. Further, suggestions were discussed to achieve the best conservation of the lake ecosystem.

5. 5. 1 Sub-basin level BMPs

Table 5. 1 Diffuse pollution in a tributary level

Tributary River Basin	**Sub-basins included**	**Ranked sub-basins for (NO_3-N)**	**NO_3-N** (kg/ha)	**Ranked sub-basins for (TP)**	**TP** (kg/ha)
Ramileru River	12,14	1	238.8	3	16.5
Budameru River	15,16,17,18, 19	2	118.3	2	28.1
Thammileru River	5,6,13	3	64.4	1	31.2
Minor Drain	1,2,3,4,8,9,11,20	4	19.5	4	7.43
Gunderu River	7,10	5	8.5	5	2.85

The SWAT model quantified the spatial distribution of N and P emissions in the Kolleru Lake catchment. This study examined that the diffuse pollution from agricultural runoff is an essential contribution to the total loads of nitrate-nitrogen (NO_3-N) and total phosphorus (TP). According to Fig. 5. 2a, the amount of NO_3-N is extremely different in each sub-basin ranged from 3.5 kg/ha/yr to 429 kg/ha/yr, respectively. Among the five river sub-basins, the NO_3-N was the highest in the Ramileru basin, with up to 429 kg/ha/yr in some sub-basins, and the lowest in the Gunderu basin, with less than 8.5 kg/ha/yr in each sub-basin. The average range of each tributary river basin ranked from high to low based on the load intensities is outlined in Table 5. 1. However, the annual average load of NO_3-N in the Ramileru basin is 238.8 kg/ha/yr. The amount is larger than 40 kg/ha/yr in most sub-basins of Budameru and Thammileru. For example, 55.6% of the NO_3-N export from the entire catchment came from sub-basins No. 19, 14, 16, 13, 12, 5, 17, and 8, each contributing >28.7 kg/ha/yr of the areal NO_3-N export. NO_3-N in the lake mainly originates from the chemical fertilizers used in the Kolleru Lake catchment, where the agricultural land majorly accounts for paddy cultivation.

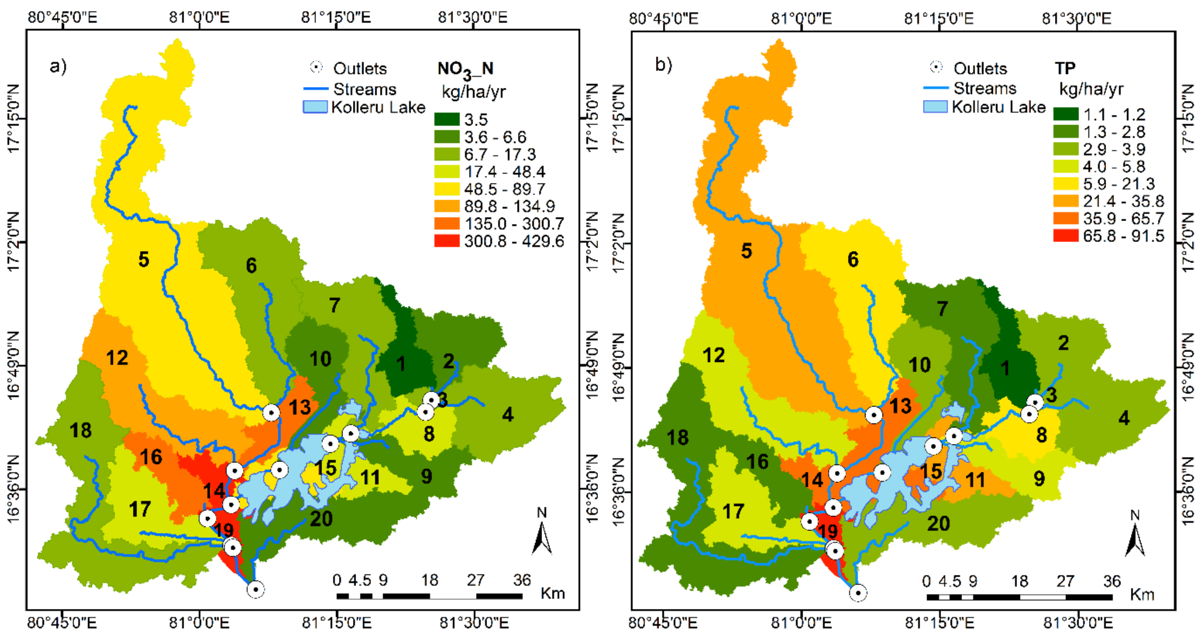

Fig. 5. 2 Spatial distribution of **a)** nitrate-nitrogen **b)** and total phosphorus load in the Kolleru Lake catchment (2008-2014).

According to Fig. 5. 2b, the spatial distribution of mean annual TP in the Kolleru Lake catchment varied from one sub-basin to another, ranging from 1.1 kg/ha/yr to 91.5 kg/ha/yr respectively. The highest TP load was established in the Thammileru basin, with up to 45 kg/ha/yr in some sub-basins, and the corresponding lowest values within the Gunderu basin, with less than 5.5 kg/ha/yr in each sub-basin. The Thammileru basin is accounted for the highest annual precipitation, which enabled the large wet deposition of P. Similar to the NO_3-N, the highest contribution of TP origin from the sub-basins No. 19, 14, 13, 11, 15, 5, 6, and 8, accounted >16.5 kg/ha/yr annually. The cause of the difference in sub-basin loads was observed in the Kolleru lake catchment related to human activities. Additionally, the soil data obtained from the National Bureau of Soil Survey identified that N and P distribution in the soil types do have close spatial interaction with diffuse pollution. The higher intensity load of these soils is associated with higher export amounts of pollutants from sub-basins. Therefore, this must be considered for conservation practices. Moreover, the agricultural land was disturbed by the frequent cropping and harvesting as well as by fertilizer application. The TP load from medium to maximum variation of the sub-basins is similar to the NO_3-N, which is accounted onto the mainstream channel.

The high proportion of agricultural land use has a crucial factor in NO_3-N and TP exports. Many catchments worldwide show an explicit positive correlation between N & P loss and cropland percentages (Li et al., 2018; Chen et al., 2017; Harrison et al., 2009). In the Kolleru Lake catchment medium to maximum variations of NO_3-N and TP loads in each sub-basin level was observed, following the percentage of land uses (Fig. 5. 3). Sub-basins with a higher percentage of paddy fields result in higher N and P exports in the Ramileru and the Thammileru basins. Li et al. (2018) also show a low percentage of paddy fields, resulting in less amount of TN. However, the intensity of frequent fertilizer applications significantly impacts the sub-basins nutrient level exports and catchment characteristics as well.

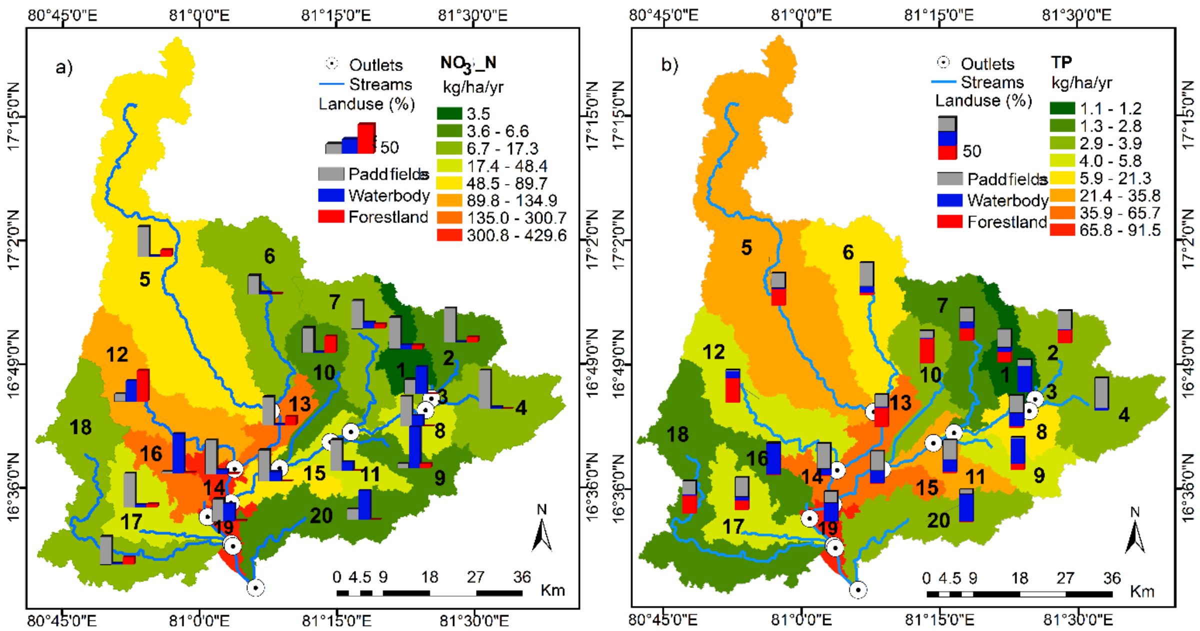

Fig. 5. 3 Spatial distribution of NO_3_N and TP, and percentage of land-use types in sub-basins

5. 5. 2 Determination of HRU level BMPs

The BMPs priority areas were identified following the methodology of Izydorczyk et al., 2019, Piniewski et al. 2015) by SWAT on the HRU level as paddy cultivated lands where the amounts of NO_3-N and TP emissions are the highest. Here, the priority levels were divided into two types according to the area, which is under net irrigated, gross irrigated, and the rain-fed regions. The first BMPs priority level is the area cultivated more than once a year; emission in selected HRUs ranged from 10.5 to 28.3 kg/ha for NO_3-N, while for TP, the emission level ranged from 3.2 to 9.8 kg/ha. The second BMPs priority level is where the cropping intensity is higher than 50 % under gross cropped areas ranged from 1.2 to 10.5 kg/ha for NO_3-N, while for TP ranged from 0.5 to 3.2 kg/ha (Fig. 5. 4a and 4b).

According to Fig. 5. 4a, the majority of selected HRUs of NO_3-N were clustered around the lake area. Subsequently, they cause the eutrophication of the lake and led to increasing weed distribution. On the priority of HRUs distribution, higher NO_3-N load contributing areas were concentrated in the northern and middle-western villages of the catchment. Among them, the outstanding villages were located in the Ramileru and the Thammileru basins. In these two sub-basins, specific topographic features play an essential role in the highest NO_3-N emission. Besides, the main inflow rivers contributing the water to the lake run through these villages, are the Budameru River (5.5% of total NO_3-N in 2010), the Thammileru River (22.7% of total

NO_3-N in 2010), and partially the Ramileru River (19.2% of total NO_3-N in 2010). Moreover, the diversified irrigation network canals connected to the mainstream of the river can easily extract the nutrient onto the river and nitrate loads into the lake. In contrast, the flow contribution of NO_3-N from the eastern villages are low, because of the migration ability of pollutants are limited there.

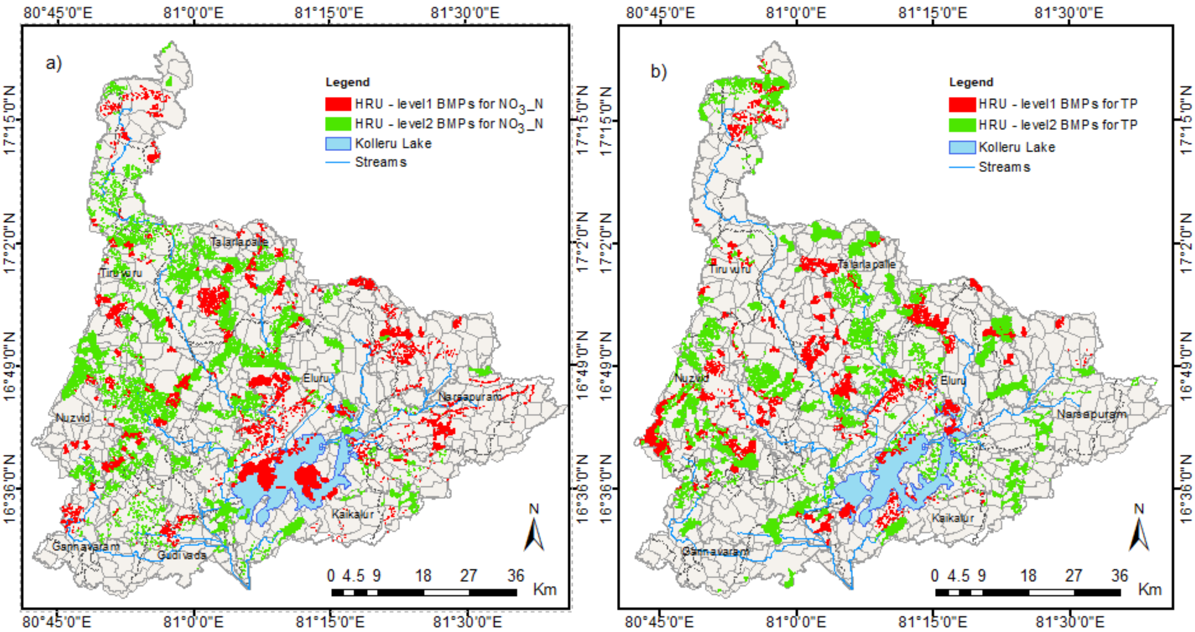

Fig. 5. 4 Spatial distribution of HRU priority levels for BMPs of **a)** nitrate-nitrogen and **b)** total phosphorus in the Kolleru Lake catchment against village level division

According to Fig. 5. 4b, the TP emissions are spatially distributed and partially overlapped with the regions of NO_3-N. The majority of TP emissions are primarily concentrated in the middle reaches of the catchment. Approximately 534 village communities were located in the catchment area. Most of the regions are under gross irrigated. At certain stages, early-season drought changed the behavior of the farmers to apply the water-soluble fertilizers (NPK-nitrogen, phosphorus, and potassium), the ratio of 19-19-19, 20-20-20, and 21-21-21 to supplement nutrition. During the time, the soil absorbs the N and P to enrich the plant growth, and unleash the soluble compounds during the flooding period by surface runoff. In the catchment, topographic properties play a key role, because of moderate slopes as well as more than >46.7% of the catchment area is mostly extended to the well-drained condition, hence, nonporous in nature, contributed to high NO_3-N and TP emissions as a result of surface water runoff.

5. 5. 3 Temporal characteristics of diffuse pollutants

The annual amount of NO_3-N and TP, including streamflow, were simulated. Fig. 5. 5a illustrates the annual distribution of diffuse pollution from 2008 to 2014 in the Kolleru Lake catchment. The distribution of the NO_3-N was very uneven between different years. During wet years higher peak values van be observed than in the dry years. The NO_3-N was relatively consistent with the runoff. Therefore, to assess the possible relation between the NO_3-N and the runoff, a simple Pearson's correlation analysis was performed. The results show a strong correlation between the NO_3-N and the streamflow ($r=0.89$, $p<0.01$), which means that the NO_3-N was primarily governed by the runoff (Fig. 5. 5b). Hence, the result was justified with other studies (Qin et al., 2018; Navarro et al., 2014; Helmreich et al., 2010). The correlation between the TP and the runoff (Fig. 5. 5c) is also high ($r=0.84$, $p<0.01$), but lower than the NO_3-N and the runoff. This can be attributed to the agricultural water diversion system, and a mode of severe nutrient transport. However, during the wet period (July 2010, August 2011), the runoff is relatively high and subsequently resulted in a high nutrient export, which can be transported by a stream network and accumulated near to the downstream area of the Lake. NO_3-N sources are the chemical fertilizers used in agricultural fields, especially for paddy cultivation followed by Cotton, Maize, and Chillies, in the Kolleru Lake catchment. The upward trend of NO_3-N load in June 2010, resulting from the heavy precipitation recorded during that month, according to the data derived from the Indian Meteorological Department, might be responsible for the higher nitrate export load. Industrial pollution, excessive fertilizer application, and chemical usage of fishponds to enrich the fish growth contribute in significant quantities to the nutrient loads. The primary reasons for high nutrient flow in the catchment are both frequent land-use changes, intensive paddy cultivation, and the two large rivers Krishna and Godavari.

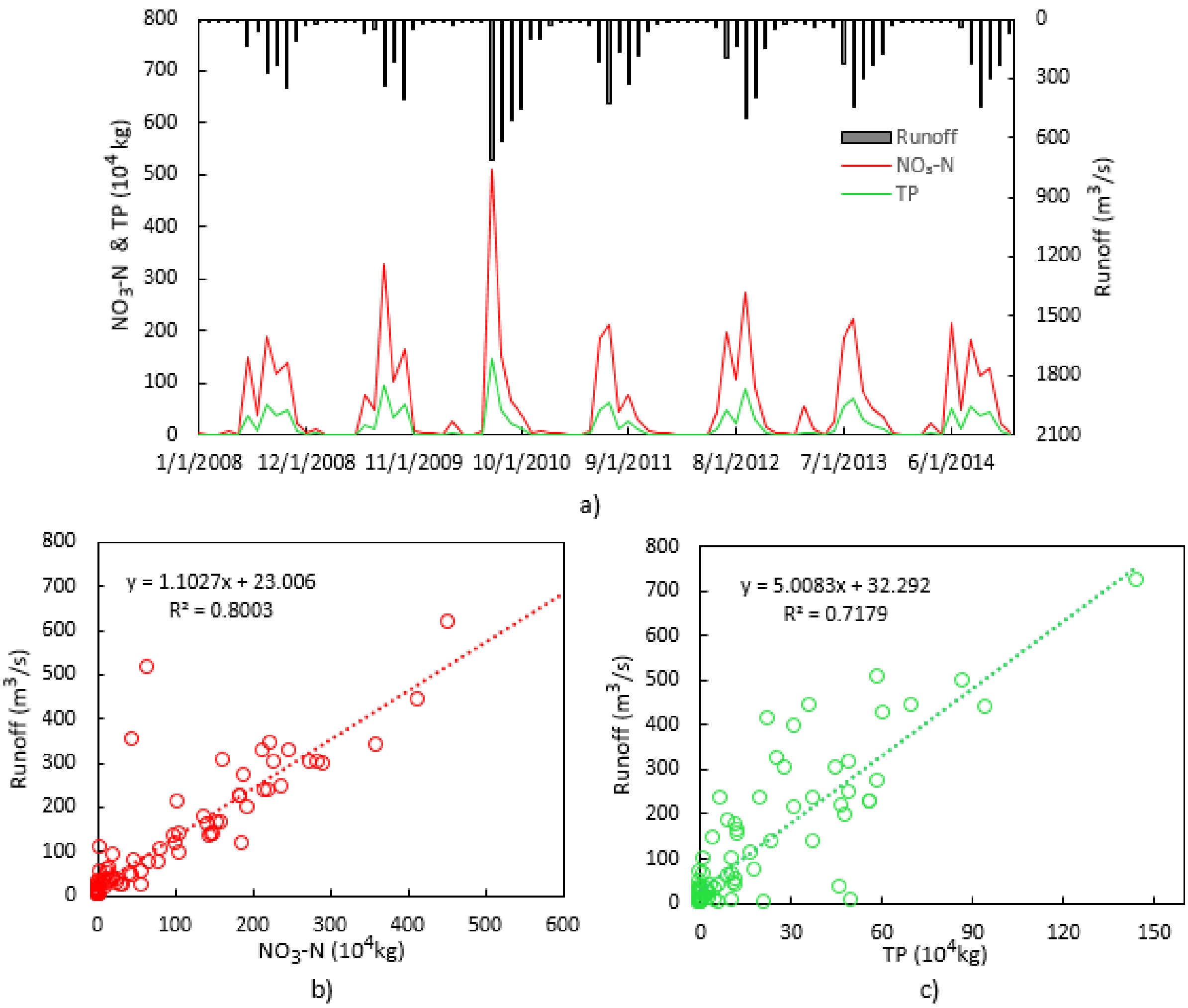

Fig. 5. 5 Relation between **a)** runoff and nutrient fluxes in the Kolleru Lake catchment **b)** runoff and NO_3-N **c)** runoff and TP from 2008-2014.

5. 5. 4 Suggestions for pollution mitigation measures

Suggestions for adequate pollution mitigation measures can be drawn from the results of critical sub-basins and the HRU priority areas as well. This study emphasized that improved agricultural management practices are necessary for the whole catchment area. There are numerous methods to improve the agricultural practices that can be adopted by farmers to prevent nutrient losses from croplands (Izydorczyk et al. 2018). However, management practices can be targeted on agricultural lands and the development of proper land use planning and zoning practices in sub-basins. Furthermore, the implementation of buffer strips and the management of water margins to reduce surface runoff from fields are essential measures to achieve environmental improvements (Izydorczyk et al., 2018; McCracken et al. 2012, Zhang et al. 2010; Anbumozhi et al. 2005). The buffer width, the slope gradient, and the vegetation type are difficult to site conditions for designing an adequate buffer. However, an increasing buffer width would increase sediment removal efficiency (Zhang et al. 2010). Mainly, vegetated buffers are widely used for good agricultural practices to reduce diffuse source pollution from runoff (Balestrini et al. 2011). However, these effective mitigation buffer measures of nutrient losses are still rarely implemented in India (Anbumozhi et al. 2005; Bhojvaid et al. 1996).

To reduce the chemical pesticide consumption in Andhra Pradesh state, between 1999 and 2005, the European Union had conducted the “Non-Pesticide Management in Andhra Pradesh, India” in the cooperative project of the German Council for Sustainable Development and Centre for Sustainable Agriculture (CSA). The potential outcome of this program was to enlighten the farmers to use natural pesticides, such as neem (*Azadirachta indica*) and chili-garlic extracts, rather than intensive use of chemical fertilizers. Therefore, the positive results caused increased biodiversity, no adverse environmental effects, preventing soil erosion, and improving soil fertility. This study further suggests the implementation of the "Non-pesticide management” practices in the Kolleru Lake catchment. However, this kind of institutional practice for empowering rural people, imparting training to farmers, and laying demonstrations are essential for sustainable management growth. Besides, the catchment comprises of 534 villages, and not even more than >20% adopted the conventional irrigation methods. Moreover, this study identified the HRUs level priority areas along with critical sub-basin measures, which should be analyzed and implemented. For minimizing the environmental crisis, also a forest area has suggested around the 3ft contour level of the lake. Thus, it provides shelters for the 20 million immigrant, international birds as well as to conserve the environmental lake ecosystem.

Additionally, the Government of India notified that only the conventional method of fishing activities should allow around the lake, following the law of G.O.Ms.No.120, dated 4.10.1999. For this purpose, the Kolleru Fisherman Cooperative Society (KFCS) should follow the standards laid down by the Ministry of Environment, Government of India, to bring back the Kolleru Lake to its near-pristine condition. Moreover, adequate steps should be taken for stoppage and regulation of industrial pollutants from nearby towns. Furthermore, the villages surrounded by the lake must be classified as zones for BMPs.

5. 5. 5 Limitations

Because the Kolleru Lake catchment is an ungauged type, sufficient calibration, and validation of the SWAT model are limited. Unfortunately, there exists still a lack of observed data for nutrient load, especially for the discharge depending on nutrient load. However, the study was conducted based on original data, acquired from Indian Organizations, promising the results obtained from the SWAT model. This is the first study conducted for the whole Kolleru Lake catchment level, regards certain assumptions that were made in terms of catchment delineation boundaries and the crop fertilization period. Field investigations on the interaction of pollutant loads with the runoff should be taken into consideration for a better calculation of the pollutant load.

5. 5. 6 Summary

From the above-mentioned suggestions, it can be concluded that the management of agricultural practices is required to adapt to the whole catchment region. The essential features of nutrient runoff from croplands should take into consideration the protection of the lake water quality. Pollution abatement methods, continuous monitoring of point sources pollution, and laying demonstrations to enlighten the public perception towards lake degradation would be beneficial.

This paper serves as an initial discussion of the diffuse pollution in the Kolleru Lake catchment. The results of SWAT modeling showed that 28% of the highest NO_3-N load contributed from the Ramileru basin, and 32% of TP load from the Thammileru basin, which make them to the critical river basins of diffuse pollution. Among them, the average load of individual sub-basins is estimated. This study indicated that diffuse pollutions are mainly governed by agricultural runoff. Apart from that, HRU priority level critical sources of NO_3-N and TP were identified against the village communities. Besides, the first and second priority levels of BMPs of diffuse sources were highlighted. These results improve the understanding of pollution levels and targeting control measures of critical priority areas in the Kolleru Lake catchment. The communication between the stakeholders and water quality managers are required for knowledge exchange. This is a basis for a profound understanding of the ecological crisis of lake degradation levels, and a prerequisite for the development of further implementation measures.

Answer for working question 1

Here in the case of Lake Kolleru, agricultural runoff is the driving factor that contributes to deterioration by releasing major pollutants that are NO_3_N and TP into the lake. These are the most fertilizer compounds that intensively used by the farmers into their paddy fields. Two major rivers and 68 minor irrigation canals flow into the lake, carrying a massive amount of agricultural pollutants that significantly lead to proliferating weeds in the lake area. By implementation of buffer strips and the management of water margins to reduce surface runoff from fields are essential measures to protect the lake water.

Answer for working question 2

The government is already implemented “Operation Kolleru” for dismantling the fishponds across the lake that causing the biological magnification diseases to the local inhabitants. However, the government has failed to justify the local people who depend on the lake sources such extent by suddenly implementing “Operation Kolleru” that made agitations among the fisher community. Moreover, involve the inhabitants in designing the policy and let them contribute the local knowledge, which proved to be very beneficial in designing and also in the efficient implementation of the policy.

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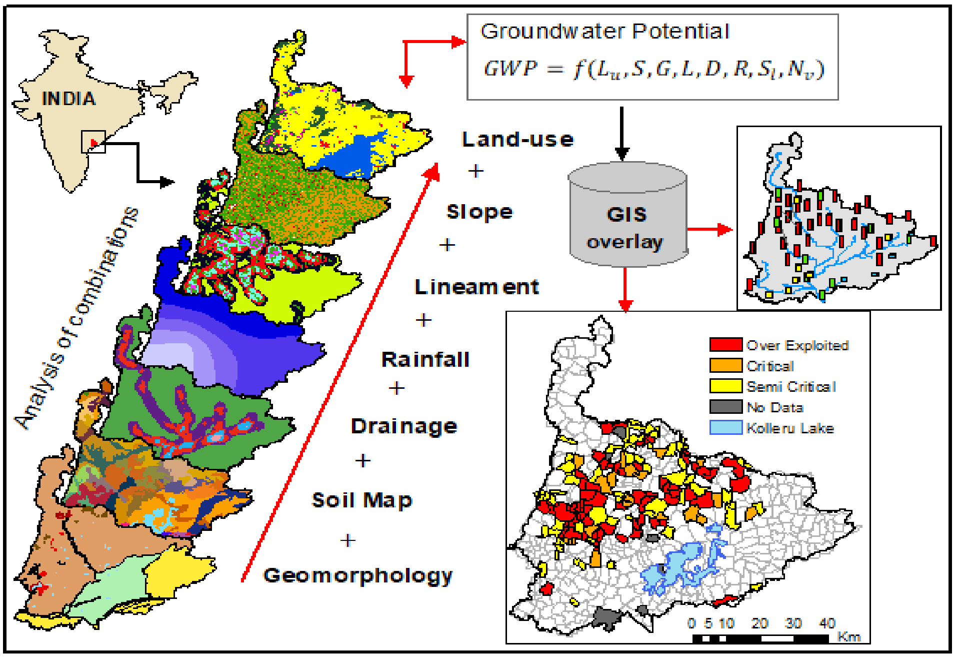
CHAPTER 6

Mapping of Potential Groundwater Recharge Zones in the Kolleru Lake Catchment, India, by Using Remote Sensing and GIS Techniques

Graphical abstract



Abstract

Water scarcity is the major problem in India where the population has been tremendously increasing, which results in invading natural resources, thus effect on hydrological processes. Because of this, significant surface water bodies have been disappearing continuously. Therefore more pressure on groundwater resources is a consequence of that. The integration of remote sensing and geographical information system (GIS), which helps in groundwater research for the investigation of potential groundwater availability is essential to assess, monitor, and conserve groundwater resources. This analysis reports on the mapping of various potential groundwater resources in the Kolleru Lake catchment, India, by using remote sensing and GIS techniques. For this, a Survey of India toposheets and IRC-1C satellite imageries were used to prepare thematic layers of geomorphology, drainage density, lineament, slope, land-use, soil, rainfall, and NDVI converted into raster format in ArcGIS. The raster maps of these thematic layers were assigned to a weight-based factor depending on the catchment characteristics and its topographic

influence. The results demonstrated that about 7% of the area is under excellent groundwater potential recharge. Good, moderate, and lower potential conditions are 42%, 38%, and 13%, respectively. The results indicated that the management of groundwater potential zones should be targeted on the middle-catchment region. Further, the results were validated with the borehole data obtained from the Government of Andhra Pradesh – Groundwater Department. These results are useful for better both planning and groundwater management sources in the Kolleru Lake catchment.

Keywords: Groundwater potential zones, Kolleru Lake catchment, India, remote sensing, GIS, weighted overlay analysis.

6. 1 Introduction

Groundwater is a hidden natural resource that serves many purposes for living beings. There is always a second choice of the available groundwater next to the surface water bodies. Rainfall is the primary source of groundwater recharge through infiltration (Jordan & Weber 1995). However, different physiographic, geomorphic, and geologic properties, play a significant role in infiltration rates, like elevation and slope extended to climatic conditions that confront the potential groundwater sources (Barzegar et al. 2018; Saidi et al. 2011; Sener et al. 2005; Zabet 2002). In recent years, rapid industrialization and urban infrastructure exploit groundwater resources, resulting in adverse impacts. During the dry season, the groundwater is reaching its maximum depth, and it is difficult to extract it. In this situation, water scarcity is a common phenomenon in India.

There are numerous methods to explore groundwater resources. However, conventional ground survey methods are the most reliable and standard methods for determining the location of boreholes and aquifer thickness (Jha et al. 2010). Such approaches need skilled persons, and they are time-consuming and cost-effective (Fetter 1994; Roscoe 1990). Many spatial problems give rise to GIS-based multi-criteria decision analysis (Graymore et al., 2009). With the introduction of remote sensing and Geographical Information System (GIS) techniques, an easy procedure to estimate the spatial distribution of groundwater sources from very high to low levels became possible (Golla et al., 2018; Yeh et al. 2016; Adiat et al. 2012; Abdalla 2012; Lee et al. 2012; Magesh et al. 2011; Oh et al. 2011; Ozdemir 2011; Rahman 2008). A GIS framework was developed and analyzed by Das et al. (1997) for the investigation of potential groundwater resources. Many researchers have been used GIS methods to explore potential groundwater zones, further, demonstrated that different topographic, physiographic, and geologic terrains cause in different depths of water levels (Bathis & Ahmed 2016; Oikonomidis et al. 2015; Mohammady et al. 2012; Dar et al. 2010; Ghose et al. 2010; Adiat et al. 2009). Surface phenomena not always control both the occurrence and the movement of groundwater by porosity and permeability (Magesh et al. 2012). But many sub-surface aquifers are governed by surface features like elevation, slope, drainage density, rainfall, soil textural properties, lineament density, land-use patterns, lithology, water bodies, etc. For example, higher elevation and steeper slopes increase surface runoff and while the presence of depressions strives to increase infiltration rates, thus optimizing the groundwater recharge potential.

Various types of information can be extracted from remote sensing data, i.e., hydrologic, geologic, surface features, etc. extended to the below ground level (Harini et al. 2018; Kumar et al. 2011; Chowdhury et al. 2010). However, a lack of precision in in-situ analysis requires validation with borehole data (Scanion et al. 2002). This study was conducted to develop a digital database of groundwater availability in the Kolleru Lake catchment, India, by using geological, hydrological, structural information and remote sensing data as well for the rough estimation of crop patterns. The data was collected from various Indian organizations and prepared in a GIS database for overlay analysis to achieve the objective of this study. To further analyze, the results were validated with the borehole data obtained from the Government of Andhra Pradesh – Ground Water Department.

6. 2 Study area

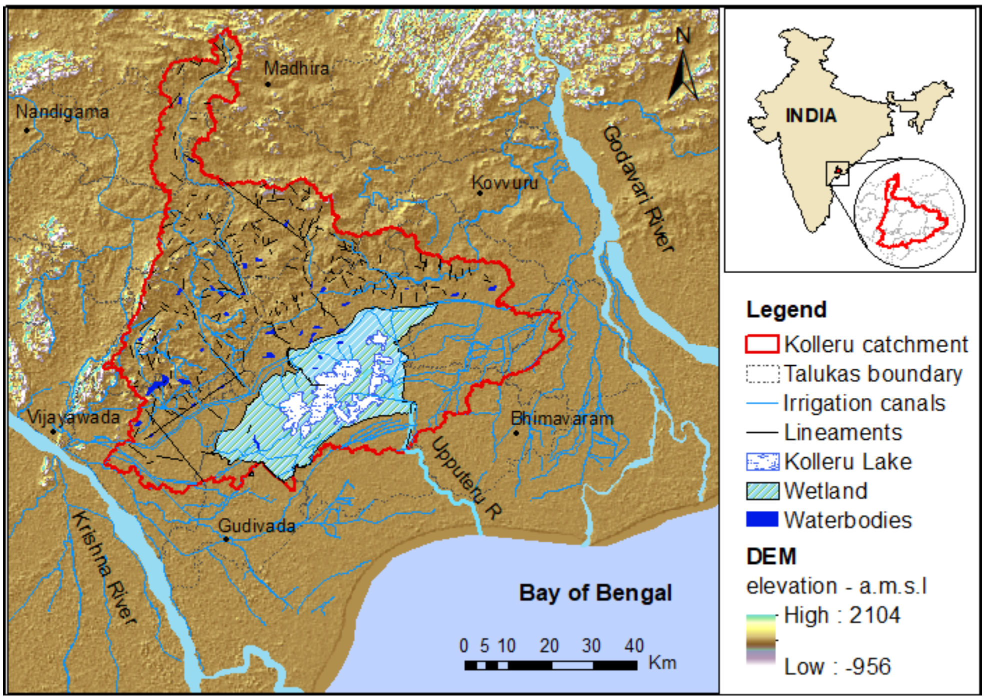


Fig. 6. 1 Location of the Kolleru Lake catchment in South India

The Kolleru Lake has situated between 16º 24′ 10″ and 17º 23′ 44″ North latitude, and 80º 41′ 5.5″ and 81º 39′ 27.5″ East longitude in the south-eastern part of India (Fig. 6.1). It is the largest freshwater lake in India located in the state of Andhra Pradesh and forms the largest shallow freshwater lake in Asia, with a catchment area of 5,052 km^2, a water surface area of 901 km^2 at +10 MSL (mean sea level) (Barman 2004). The average temperature of 28 ^{o}C and the annual mean precipitation is 1,094 mm (Azeez et al. 2011). More than >70% of the annual rainfall occurs between June and September by South-West monsoons, and the North-East monsoons bring one-third of rainfall in October (Azeez et al., 2011). Sixty-eight minor irrigation channels are flowing into the lake. It has only one outlet river, the Upputeru River, which connects the Kolleru Lake to the Bay of Bengal (Sekhar et al., 2004; Rao 2003). The lake has a rich biodiversity, and thereby, the international Ramsar Convention declared it as a wetland of international importance in November 2002 (Rao & Pillala 2001).

Two perennial rivers, the Krishna and the Godavari, formed its catchment, which gives the lake a unique characteristic and has led to its role as a natural flood-balancing reservoir between these two river basins. The catchment is served with both surface water and groundwater sources. The Government of Andhra Pradesh Ground Water Department (2016) reported that the catchment area holds deep water levels of more than 20 m depth to the water table. However, the quality of water is good and suitable for both drinking and irrigation purposes, except for the southern part of the deltaic region. Salinity and waterlogging are the major problems in the deltaic aquifers. The Kolleru Lake catchment is characterized by much abundance in the surface runoff, with many irrigation canals and a high sediment transport capacity. The whole catchment water resources are mainly used for agriculture and industrial purposes. Despite the high amount of surface water provided by the Kolleru Lake wetland ecosystem, the surface water levels always fluctuated by seasonal variations, thus massive flooding during the monsoon period, and partial drying out during the dry season.

6. 3 Database and methods

The data used in this study obtained from various Indian organizations are summarised in Table 6. 1 The base map of the Kolleru Lake was prepared based on the Survey of India topographic maps (65H/2, 5, 6) on a 1:50,000 scale. The drainage network for the study area was extracted from DEM (Digital Elevation Model), depending on flow direction and flow accumulation from Arc Hydro Tools. The slope map was prepared from DEM in the ArcGIS Spatial Analyst tool. The rainfall map was prepared from the data obtained from the Indian Meteorological Department (IMD) gauge stations, by using Kriging interpolation to prepare the spatial distribution of rainfall maps. The drainage density and lineament density maps were prepared by using the line density analysis tool in the ArcGIS.

Table 6. 1 Description of available data of the Kolleru Lake catchment

Data used	Scale	Spatial resolution	Data description	Data source
DEM	1:12,500	30 m × 30 m	Elevation, slope, streams	National Remote Sensing Centre (NRSC), Hyderabad

Landuse	1:50,000	30 m × 30 m	Landuse types	Indian Space Research Organization (ISRO), Bangalore
Soil map	1:500,000	250 m × 250 m	Soil physical & chemical properties	National Bureau of Soil Survey and Landuse Planning (NBSS&LUP), Nagpur
Weather data	Rain gauge	Monthly records	Rainfall data	Indian Meteorological Department (IMD), Hyderabad
Geomorphology	1:50,000	30 m × 30 m	Landform & topography	National Remote Sensing Centre (NRSC), Hyderabad
Lineament map	1:50,000	30 m × 30 m	Faults, joints, fractures	National Remote Sensing Centre (NRSC), Hyderabad

Satellite images from IRS-1C, LISS-III sensor, on a scale of 1:50,000 were georeferenced into the UTM projected coordinate system, and have been used for delineation of thematic layers of a soil map. Land use, lineament, and geomorphology were converted into a raster format with a 30 m grid resolution. The methodology adopted in this study is shown in Fig. 6. 2 According to the catchment area characteristics, the most sensitive parameters to the groundwater potential recharge are derived in equation 1, where the study area is comprised of the wetland ecosystem, and a maximum of cropland in the northern region, and Lacustrine terrain in the deltaic region.

$$GWP = f(L_u, S, G, L, D, R, S_l, N_v) \qquad (1)$$

Where GWP refers to the groundwater potential, L_u is the land-use classification, S is the soil type, G is the geomorphology, L is the lineament density, D is the drainage density, R is the mean annual rainfall, S_l is the slope classification and N_v is the normalized difference vegetation index (NDVI).

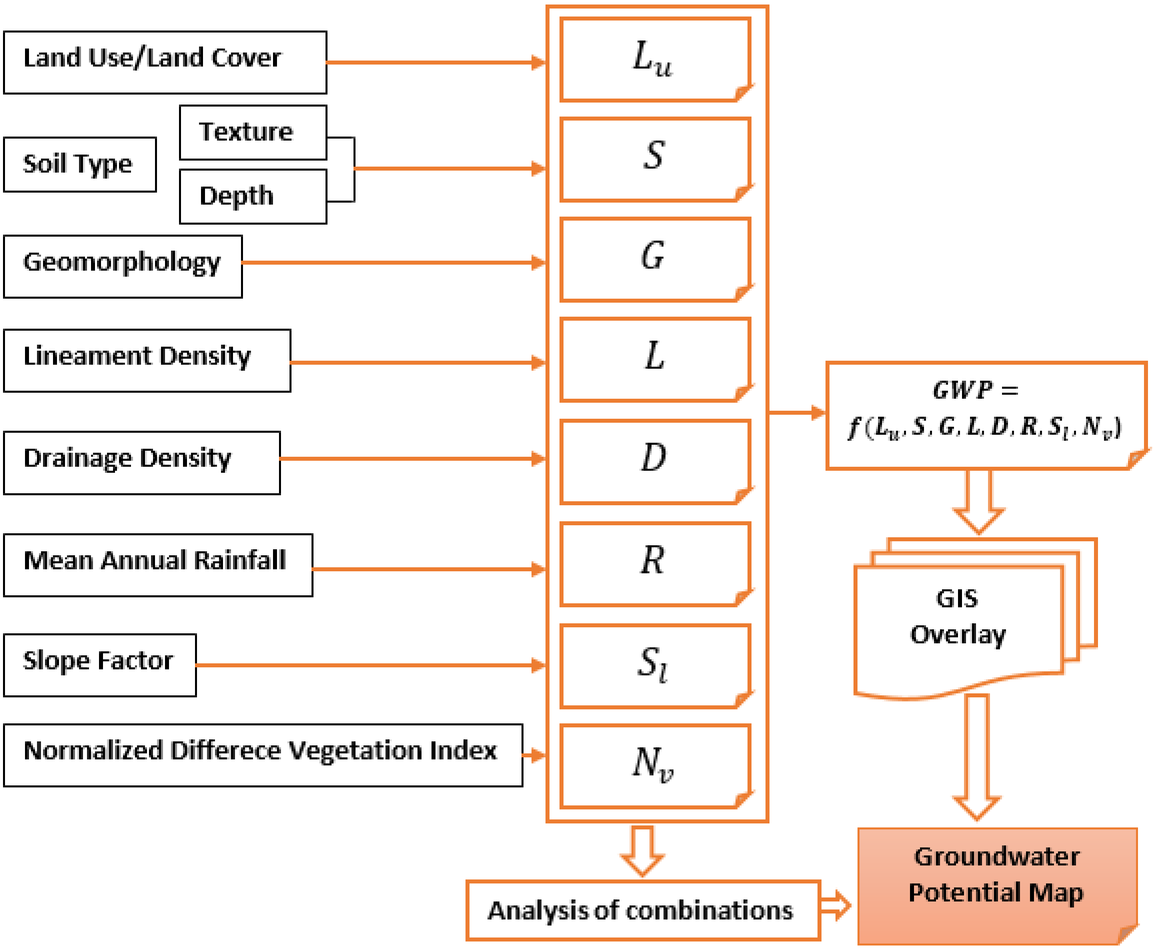


Fig. 6. 2 Methodology flowchart used for deriving potential groundwater zones

During the delineation of potential groundwater zones, each factor has its own characteristic influence on groundwater recharge, and every factor was independent (Shaban et al. 2006). The catchment characteristics were analyzed and based on the previous literature sources, and the thematic weight was assigned to evaluate potential groundwater zones is outlined in Table 6. 2.

Table 6. 2 Classification of weighted thematic factors influencing potential groundwater zones

Factor	Domain of effect	Assigned weight	Thematic assigned
Landuse	Built-up land	1	4
	Wasteland	2	
	Mangrove forest/dense forest	3	
	Shrubland	4	
	Cropland	5	
	Wetland/lake	6	

Soil type	Very fine, moderately well-drained, clayey soils	1	5
	Imperfectly drained clayey soils	2	
	Excessively drained, sandy soils	3	
	Moderately drained, clays soils	4	
	Deep, well-drained, clayey soils	5	
	Very deep and moderately well-drained, fine loamy soils	6	
	Fine loamy soils	7	
	Well-drained gravelly loam soils	8	
Geomorphology	Denudation origin-pediment, Pedi plain complex	1	2
	Dissected Hills & Valleys	2	
	Lower Plateau	3	
	Lacustrine Terrain	4	
	Deltaic Plain	5	
	Older Coastal Plain	6	
	Fluvial origin active flood plain	7	
Lineament density	Very low	1	3
	Low	2	
	Medium	3	
	High	4	
	Very high	5	
Drainage density	Very low	1	1
	Low	2	
	Medium	3	
	High	4	
	Very high	5	
Mean rainfall	921.5 – 961.2	1	7
	961.2 – 986.4	2	
	986.4 – 1,010.3	3	
	1,010.3 – 1,036.1	4	
	1,036.1 – 1,082.3	5	
Slope	18.4 – 51.4	1	6
	9.89 – 18.3	2	
	5.86 – 9.88	3	
	2.83 – 5.85	4	
	0 – 2.82	5	

6. 4 Results and discussions

The fluctuations of groundwater in the Kolleru Lake catchment are governed by several parameters such as land-use, soil type, lineament density, geomorphology, drainage density, slope, and rainfall, which are discussed below.

6. 4. 1 Landuse map

Landuse plays a significant role in surface runoff and available moisture conditions. Urban areas contribute more surface runoff, whereas agricultural areas contribute to less runoff as compared to the urban area, but not more than forest areas. Where the surface runoff is higher, it implies less influence on the infiltration rate. Landuse map for this study area delineated from IRS LISS-III satellite data based on NRSC (National Remote Sensing Centre) - LULC classification is depicted in Fig. 6. 3a. Land-use data were mainly classified into agricultural land (for paddy cultivation), fishponds, urban, barren land (unused or uncultivated land), and forest areas. Present up-slope in the headwaters are covered by shrub vegetation and forest areas. The runoff from the upper catchment passes the agricultural fields of the middle part before entering into the lake. Agricultural land is the dominant land use cover (68%) of the catchment, followed by fishponds (16%), mangrove forests on gently sloped areas (10%), and the urban area does not exceed 3% of the total area. The high weight assigned for the forest, agricultural land, and waterbody, whereas the low weight assigned for built-up land, shrubland for groundwater delineation.

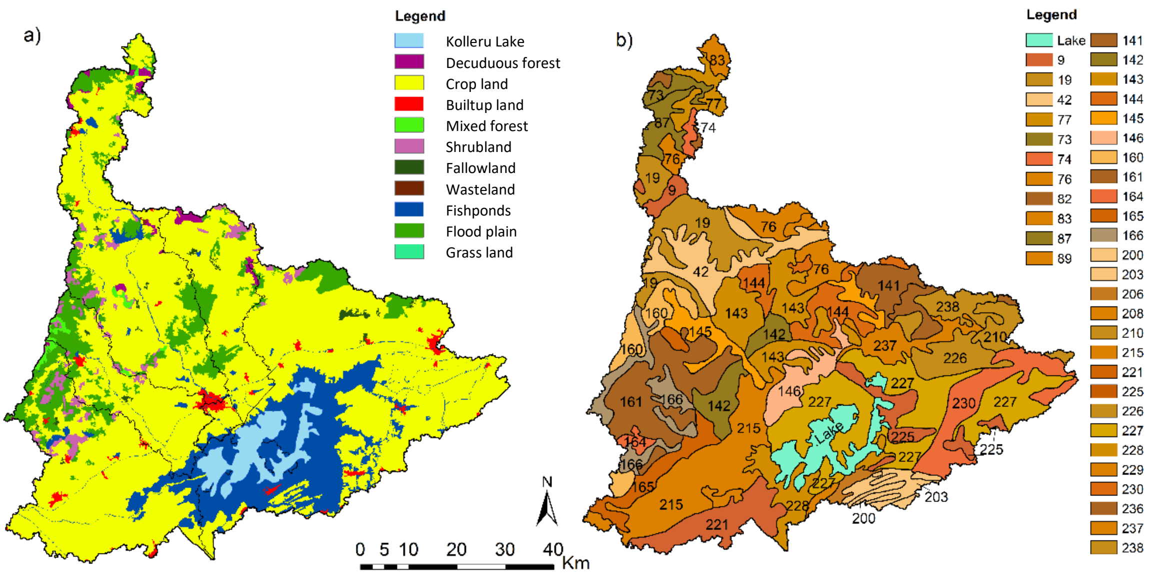


Fig. 6. 3. a) Land use and land cover map **b)** soil classification map of the Kolleru Lake catchment. (i.e., the reference code of the soil data is presented based on their original data source). [Note: the physical properties of the soil for the whole catchment area is outlined in Table 3. 3].

6. 4. 2 Soil map

The soil map was obtained from the ICAR – National Bureau of Soil Survey & Land Use Planning, Nagpur, India (ICAR-NBSS&LUP). It was georeferenced to the UTM projected coordinate system in ArcGIS. Further, the map was precisely geo-coded to each soil profile at different categoric levels in classifying soils. The catchment area is composed of 38 different soil types, dominantly with clayey texture is depicted in Fig. 6. 3b.The insight of data provides soil depth, drainage, texture, erosion, and soil taxonomy is summarised in Table 3. 3 (Sehgal et al. 1987; Soil Survey Division Staff 1995). According to this data, 46.7% of the catchment is largely extended to the well-drained condition, 19% is a moderately well-drained, while 27.8 % is composed of imperfectly drained, and 2.4% is excessively drained. The field capacity of the soil for this catchment is mainly depended upon the soil depth and drainage condition. Very deep soils (55%) are predominantly identified within the catchment area, with clay dominance in texture and pore in coarse and medium pores. The soil type is an essential factor for the amount of water that can infiltrate into the subsurface and influence on groundwater recharge (Das, 2017; Gröngröft 2012). Therefore, the high weight assigned for the excessively drained soil and the low weight assigned for the imperfectly drained.

6. 4. 3 Geomorphology

Geomorphologically the catchment can be divided into five most distinct units; Pediplain complex, Lacustrine Terrain, Active Flood Plain, Coastal Plain, and Deltaic Plain. The major part of the catchment in the northern region underlain by the Pediplain complex consists of hills and ridges, which is overlain by valley-fill sediments. In contrast, the southern part of the area represented by the alluvial plains forming the Krishna and Godavari deltas. The Krishna and Godavari rivers and its tributaries have contributed to the formation of the alluvial plain. The deltaic part is a relatively flat surface. The major course of rivers forms the flood plain deposits. The relief, slope, type of wethering material, thickness of alluvium, nature of the deposited material, and the overall formation of deposits play a vital role in defining the groundwater regime (Sar et al., 2015). The most important of the catchment overlain by the Lacustrine Terrain is the Kolleru Lake wetland ecosystem. The study area consists of a different composition of landforms such as wetlands, floodplain deposits, alluvial plains, and natural terrains, which together form a unique relief characteristic of the catchment (Fig. 6. 4a).

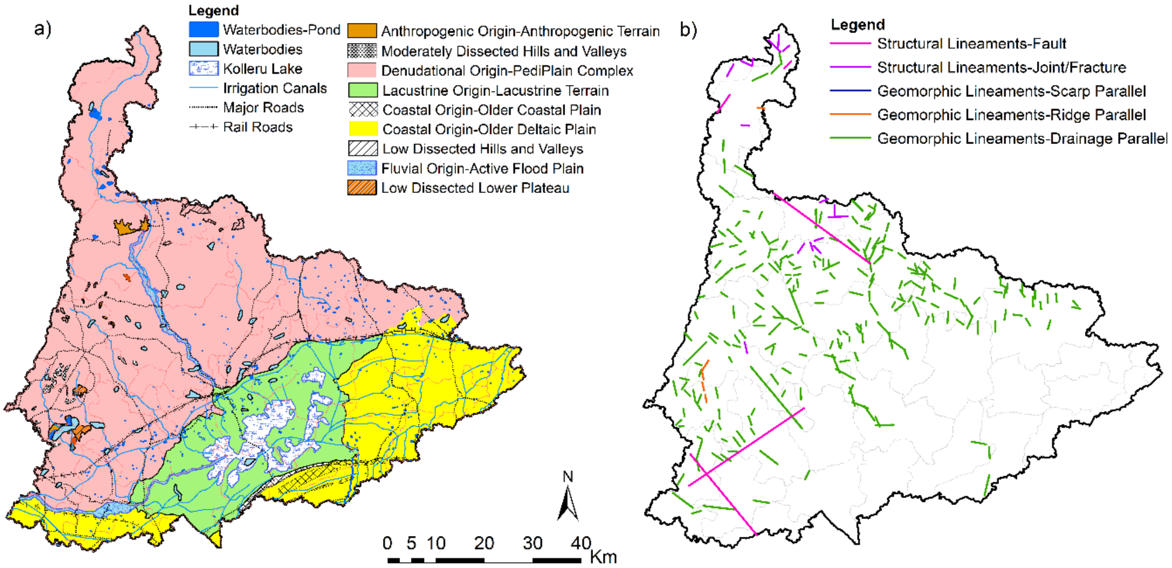


Fig. 6. 4. a) Geomorphology and **b)** Lineament of the Kolleru Lake catchment

6. 4. 4 Lineament

Lineaments are natural faults, joints, and fractures, which can easily be distinguished from satellite images by their relatively linear alignments. Lineaments represent the zones of faulting and fracturing, resulting in increased secondary porosity and permeability (Yeh et al., 2016). Lineaments are the one form of the natural permeable layer directly represent groundwater moment. If there is a presence of lineament, it reveals that there is good groundwater potential. The lineament map of the study was obtained from the National Remote Sensing Centre (NRSC), thereby the lineament density map was prepared in ArcGIS by using the line density tool is depicted in Fig. 6. 4b. The lineament of the study is highly concentrated in northern and western areas of the catchment, because of the southern part its presence of a wetland, since it is already a permeable layer.

6. 4. 5 Rainfall

Rainfall is the major factor of the hydrological cycle that significantly influences surface runoff and infiltration. The high infiltration rate contributes to groundwater recharge, which depends on the very high intensity and the duration of the rainfall. The annual average rainfall of the catchment is 1,094 mm. More than 70% of the annual rainfall occurs between June and September by South-West monsoons, and the North-East monsoons (25%) bring one-third of rain from October to March. For this study, rainfall data of 2018 was used. Further, the Kriging interpolation method applied to generate a spatial distribution of rainfall map is depicted in Fig. 6. 5a. The annual average rainfall range from 921.5 mm to 1,082 mm. For the groundwater potential, high weights are assigned to the high rainfall data.

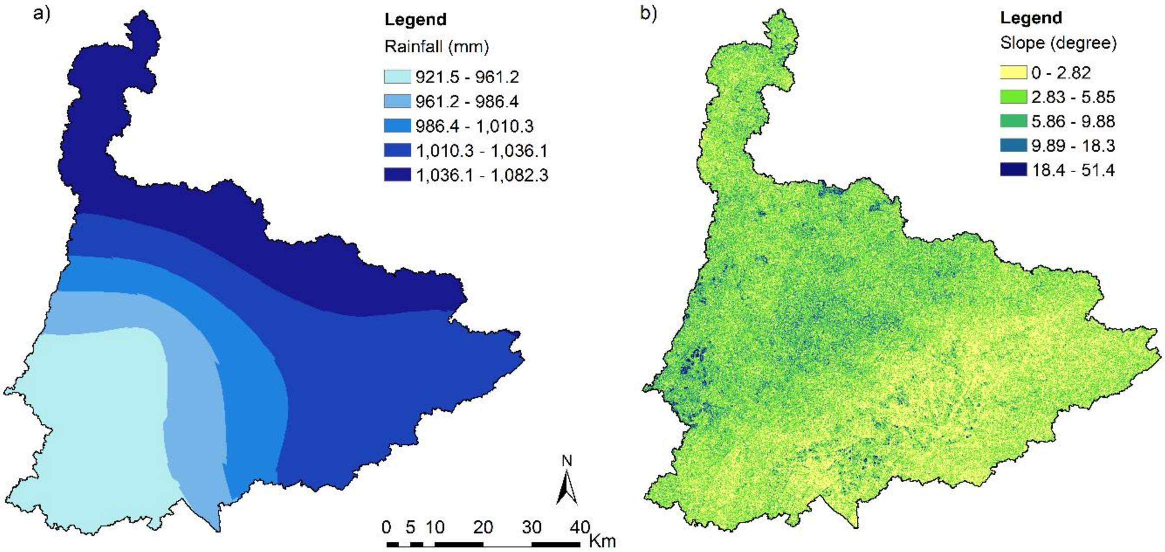


Fig. 6. 5 a) Rainfall distribution map **b)** Slope map of the Kolleru Lake catchment

6. 4. 6 Slope

The slope is an essential factor for the delineation of potential groundwater zones. A higher degree slope indicates a rapid runoff, which might accelerate the erosion rate with feeble recharge potential (Jhariya et al., 2016; Magesh et al., 2011). The slope map of the study area prepared from the DEM using the ArcHydro Tool in ArcGIS. The sloping grid is identified as “the maximum rate of change in value from each cell to its neighbors” (Burrough 1986). A maximum of 45 % of the catchment falls under the 0-2.82^{o} slope classification, which means that the study area has excellent potential for a high infiltration rate. Similarly, 28 % of the areas having a slope of 2.83-5.85^{o} causing significant runoff and considered as a good infiltration rate, and the areas having a slope of 5.86-9.88^{o} cause relatively high runoff as categorized as a moderate infiltration rate. Whereas the areas having a slope of 9.89-18.3^{o} and 18.4-51.4^{o} are considered as a very poor infiltration rate, and the runoff is extremely high, as well as the infiltration rate is very low. Fig. 6. 5b illustrates the slope map of the study area.

6. 4. 7 Drainage density

Drainage density defines the spatial closeness of the stream network (Dingman, 1978). It is a value of the total length of streams and rivers in a catchment divided by the total area of the catchment. The inverse proportion exists between drainage density and permeability; therefore, it is one of the main factors in the delineation of the groundwater potential zone. High drainage density causes less permeability of the soil; hence, it doesn't have much concentration of the groundwater availability (Arulbalaji et al. 2019; Pallard et al. 2009). Similarly, a low drainage density means that the high ability of the infiltration rate increases the groundwater potential. The drainage density of the catchment was calculated based on the stream network, which depicted in Fig. 6. 6a. It was reclassified into five categories, and these classes were assigned into 'Very poor' (0-0.215 km/km^2), 'Poor' (0.215-0.376 km/km2), 'Moderate' (0.376-0.538 km/km^2), 'Good' (0.538-0.735 km/km^2), and 'Very good' (0.735-1.143 km/km^2). For the estimation of potential groundwater zone, the high weight assigned for the low density and low weight for the high density because of its relation with surface runoff and permeability.

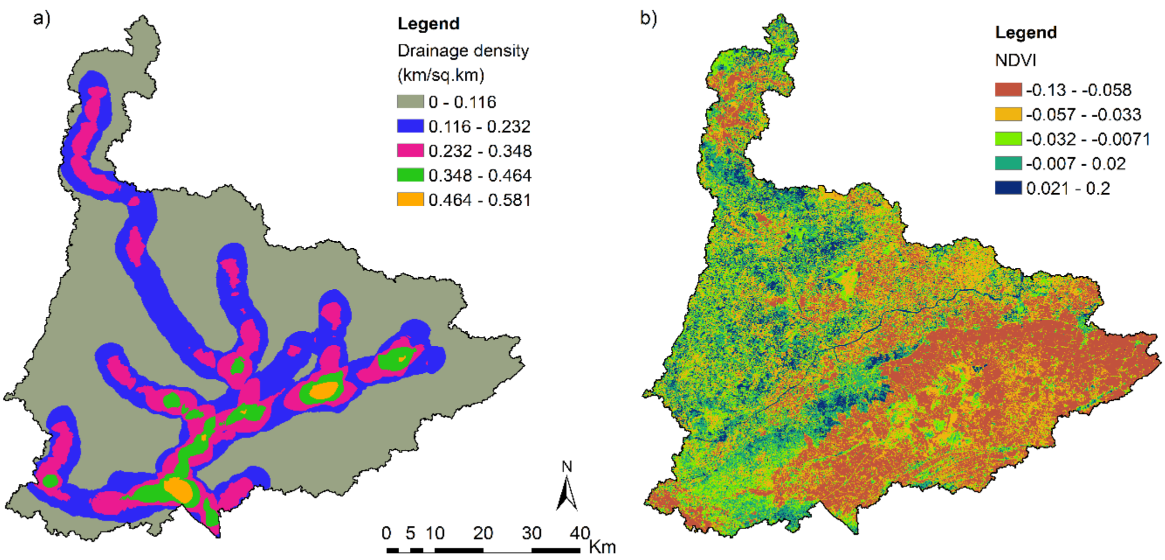


Fig. 6. 6. a) Drainage density **b)** 2018 (September), NDVI of the Kolleru Lake catchment

6. 4. 8 NDVI

Normalized Difference Vegetation Index (NDVI) was extracted from the Landsat-8 satellite image for the rough estimation of crop patterns in the catchment. Crop estimation indicates that available moisture condition in the soil, further reveals the permeability condition. Fig. 6. 6b illustrates the 2018 (September) NDVI classification of the Kolleru Lake catchment. NDVI values range from -0.13 to 0.2, while vegetation represents positive values, and for water bodies, NDVI indicates negative values.

6. 4. 9 Delineating of Groundwater Potential zone

The potential groundwater zones for the catchment area were delineated by using weighted overlay analysis of various thematic maps, i.e., drainage density, slope, rainfall, soil data, lineament density, land-use, geomorphology, and NDVI using remote sensing and GIS methods. The method of using user-defined ranks based on theoretical concepts of infiltration, runoff, permeability, and available moisture conditions. According to the overlay analysis, potential groundwater zones of this catchment area were classified into five zones, namely very poor, poor, moderate, good, and very good (Fig. 6. 7). The areas with low potential sources are mainly concentrated in the middle and north-western of the catchment. Due to their higher elevation slopes, these areas don't have water-holding capacities. However, the moderate zones are mainly concentrated in the upstream areas and partly focused on the western part of the catchment due to the agricultural land with high infiltration ability, indicates that soil textural properties and slope are important factors for the groundwater augmentation. Furthermore, excellent potential groundwater sources are located in the downstream area of the catchment, because of the Kolleru wetland ecosystem, the average water depth of 1 m and a maximum water depth of 3 m can be monitored during the southwest monsoon period (Barman 2004). Moreover, drainage density and lineament density help the permeability of the accumulated water to the ground. About 13% of the area falls under the poor condition, 38% of the area falls under the moderate condition, 42% of the area under good condition, and about 7% of the area is under excellent condition. The multiple influenced factors of groundwater in weighted overlay analysis based on the GIS model revealed the potential groundwater zones of the Kolleru Lake catchment.

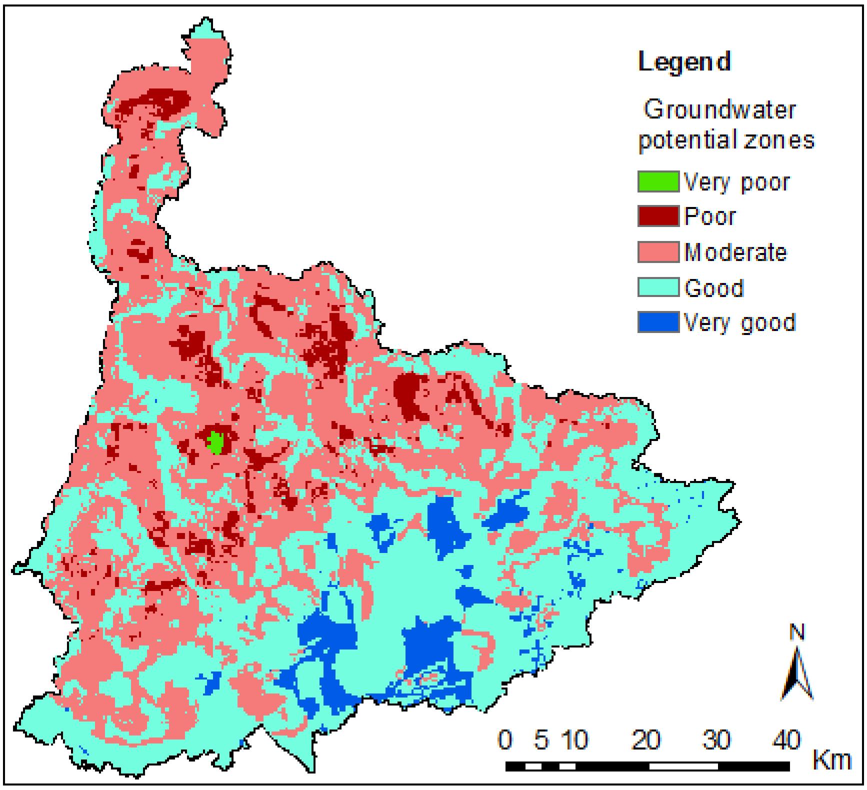


Fig. 6. 7 Groundwater potential zones of the study area

Further, the results were validated with the borehole data obtained from the Government of Andhra Pradesh – Groundwater Department. Fig. 6. 8a illustrates the spatial distribution of village-level groundwater assessment, which was classified into four categories; safe, semi-critical, critical, and overexploited regions. 17.5% of the communities are under the overexploited category and mainly concentrated in the middle-catchment region, because of the high population density as well as the agricultural dominated area there. 9.8% of the communities are under the critical zones, while 15.4% of the regions belonging to the semi-critical zones. The last is concentrated in the middle part of the catchment. However, irrigation canals don't run through these village communities. They are highly dependent on rainfall and groundwater availability. According to Fig. 6. 8b, more communities are falling into the depth of 20m below the groundwater level. However, the groundwater management level should focus on the middle part of the catchment. These results attributed to the assessment, visualization, and understanding of the existing groundwater levels in the Kolleru Lake catchment.

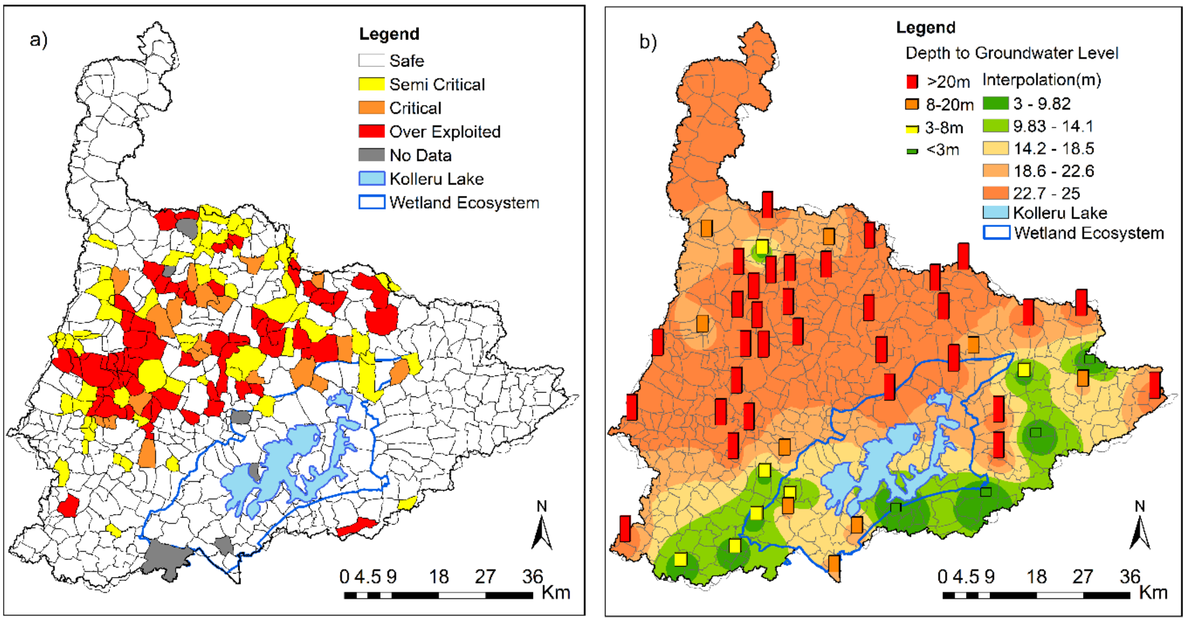


Fig. 6. 8 a) Spatial distribution of village groundwater assessment **b)** depth to groundwater level

6. 5 Conclusions

This study successfully delineated the potential groundwater resources in the Kolleru Lake catchment by using remote sensing, GIS, and weighted overlay techniques to enable quick decision-making for sustainable groundwater management. For this, satellite images, topographic maps, and conventional data sets were used to prepare thematic layers of land-use, soil map, drainage density, slope, rainfall, lineament density, geomorphology, and NDVI. The various thematic layers were assigned a proportional weight through weighted overlay analyses that were integrated into the GIS environment to delineate the potential groundwater map of this study area. According to the results, the potential zone map of Kolleru Lake catchment can be divided into five categories, namely, 'very poor', 'poor', 'moderate', 'good', and 'very good' zones. These results attributed to the future groundwater management projects and artificial recharge plans of the Kolleru Lake catchment to maintain sufficient groundwater levels. The results were validated with the borehole data of

Kolleru Lake catchment showed that most of the areas located in the middle part of the catchment, are under overexploited zones, need immediate integral water management plans. This study established the interrelationship between geology, lithology, and remote sensing data to explore the potential groundwater levels in the Kolleru Lake catchment. The maps obtained by this can be useful for the water policymakers, as a general understanding of the groundwater deficient areas.

Answer for working question 3

Investing the potential groundwater recharge zones for a particular area which depends on the hydrological characteristics, geographic location, and how often the area is overexploited by the community for drinking and irrigation purposes. Remote sensing is the best tool for identifying the potential zones by overlaying various thematic layers in ArcGIS. According to the topographic influence on the area, each factor assigned by weight to join thematic layers to obtain the potential groundwater zones.

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CHAPTER 7

Final Conclusions

7. 1 Conclusions

The world's endangered natural resources are termed wetlands. Since the past decades, the wetlands are facing tremendous changes that are imposed by natural and human activities. Many studies demonstrated that human-induced activities are critical, and they have overexploited wetland sources. Some studies disseminated that wetlands are disappearing by agricultural expansion and rapid industrialization. The major cause of the Government has not paid much attention to natural resources by implementing land-use policies, sustainable management plans, regular monitoring of the wetland areas. Wetlands maintain water regime, hydrology, biodiversity, flood control, and groundwater recharge, and more purposes. If wetlands continue to pose threats, the first damage to the environment can be observed in the countries where poverty exists and also in developing countries. India is the largest demographic country in the world, while 68% of the population is living in rural areas, and a maximum of them are wetlands resource-dependent. It is difficult to patch up the damage that occurred when the wetland area is occupied by other economic purposes, like the Kolleru Lake wetland ecosystem. In the 1990s, the lake sanctuary is maximum occupied by the fishponds, including illegal encroachments into the lake area. The fishpond's growth is proving benefits to the local people; at the same time, it causes pollution to the lake. Because of that, the local community people are not able to use the lake water for drinking. Some migratory birds are not returning after spring to the lake region due to high pollution levels. However, the Supreme Court of India had formed the committee in 2006, to dismantle the illegal encroachments in the lake region, which is called "Operation Kolleru" to regain the past lake glory. Maximum of illegal fishponds were removed, but the local community people lost their job and agitated about the Supreme Court policies. This is because of the lack of awareness, lack of communication between Government and people, lack of understanding of the pollution levels, ecological crisis, and including climate change. There has been much research done in this region, but most studies have only focused on the land cover changes and environmental issues related to the lake. Few studies have published high levels of organic pollutants, aquaculture affects, and sediment load concentration issues. However, the maximum of these studies is limited to the wildlife sanctuary region. This research has been conducted based on the existing pollution levels in the catchment region, erosion and sediment analysis, and investigated the potential groundwater recharges.

Soil erosion is a highly complex process that continues significantly noticed when the area is affected by natural and human activities. The first research objective of the study was the assessment of both soil erosion and sediment yield concentration rate of the Kolleru catchment. The study was conducted using the Revised Universal Soil Loss Equation (RUSLE) model. Upland areas exhibited much greater erosion rates to the stream channels than plain areas. The average annual soil loss was estimated at about 13.6 t/ha/yr classifying the basin into a very high soil erosion category. Agricultural and industrial activities were found as major sources of soil erosion and sedimentation. The maximum soil loss areas are mainly concentrated in higher LS factor and conservation practice factors, where a large percent of the area still not covered by conservation measures. Meanwhile, the catchment area consists of less than 12% of vegetation cover that caused high erosion risk where forestland has the maximum water-retaining capacity while reducing the potential soil loss up to a certain extent. In addition, the studied soils are clayey in texture and non-porous in nature, which is more provision to runoff leading to more soil loss. In the Kolleru Lake catchment, topographic characteristics play a significant role in soil exports, whereas the proportion of the deltaic part is comprised of less than 22% relatively balanced in the downstream region.

The average annual sediment yield of the basin was found to be 7.61 t/ha/yr. This study has found that tributaries and streamlines of the catchment carry high sediment loads to the lake. It was identified that soil loss and sediment yield patterns are spatially connected, and the sediment yield was highly modified with the sediment delivery ratio. In this area, the priority attention must be given to the adjacent streamlines, either application of buffer strips has been suggested to prevent more soil losses. The survey of the lake from 1964 to 1973 has shown that the bed is raised from (-3.0’) to (-1.0’) and (-2.0’) at many places. This works out to a silting rate of 2.5 cm/yr. The raise in the bed level is due to the settlement of silt reinforced with dead weed due to high eutrophic conditions that prevailed in the lake. Thus the water holding capacity of the lake is getting reduced. The sediment yield concentration was relatively high in croplands, particularly from paddy fields. Meanwhile, the cultivation on higher elevation slopes caused great soil erosion in the Kolleru catchment. In addition, the areas with high sediment yields are also concentrated in wastelands, and there the erosion rate is higher as in uncovered areas. Within the catchment areas of red soils and sandy clayey soils are the main source areas of eroded sediments. This is much referenced to such soil properties like erodibility, while indicating the soil depth, slope, texture pattern, erosion, and drainage.

In the last five decades, the use of pesticides has strongly increased the quantity which turn in huge surface nutrient emissions that caused pollution levels in the catchment. However, increased pestcides amounts used, that concerns the adverse effects on nontarget organisms including humanbeings. The rise of pollution levels in the catchment, significantly damage aquatic plants, animals, and biodiversity life. The second research objective aimed at revealing different patterns of diffuse critical sources in tributary river basins for the long turn protection of the lake water quality. Maximum polluted tributary river sub-basins of NO_3-N and TP were estimated. Further, it investigated the sustainable utilization of the lake's resources in different community people across the lake region, and the Government should adopt the devolution mechanism to implement the policy. The management of critical pollutant sources was highlighted for Best Management Practices at the catchment level. In conclusion, certain practices should be considered for diffuse control in some particular areas of the Kolleru Lake catchment. In the catchment, the diffuse pollution exhibited apparent tempo-spatial heterogeneity. SWAT delineated the catchment into 20 sub-basins, and each basin has consisted of the primary and secondary streams. The results of SWAT modeling showed that 28% of the highest NO_3-N load contributed from the Ramileru basin, and 32% of TP load from the Thammileru basin, which make them to the critical river basins of diffuse pollution. Among them, the average load of individual sub-basins is estimated. Runoff is the main driving factor that accelerated the diffuse sources of nitrate-nitrogen (NO_3-N) and total phosphorus (TP) in this catchment. The nutrient load is much higher in cultivated areas. The diffuse pollution occurring within different sub-basins in the catchment varied greatly, and the load intensities of each sub-basin are slightly different. The NO_3-N was the highest in the Ramileru basin, with up to 429 kg/ha/yr, whereas the highest TP load was established in the Thammileru basin, with up to 45 kg/ha/yr. Apart from that, HRU priority level critical sources of NO_3-N and TP were identified against the village communities. On the priority of HRUs distribution, higher NO_3-N load contributing areas were concentrated in the northern and middle-western villages of the catchment. Among them, the outstanding villages were located in the Ramileru and the Thammileru basins. In these two sub-basins, specific topographic features play an essential role in the highest NO_3-N emission. The majority of TP emissions are primarily concentrated in the middle reaches of the catchment.

The pesticides remain in the environment for a longer time period. When they can not keeped absorbed by the soil, they enter into the groundwater. All residues present in the surface water and as well as groudwater remain contaminants by the intensive agriculture. The pesticides which are most likely to bind covalently to soil humic matter have functionalities similar to the components of humus. The different variables that jointly determine the susceptibilty of groundwater to pollution through the soil which includes land use, climate, and hydrogeological conditions and the nature of the pollutants. A mapping concept of “groundwater vulnerability” determination can help to identify vulnerable areas and sites, and therefore it can contribute to groundwater protection.

The third research objective discussed the potential groundwater recharge zones. Particularly in this catchment, the river water from the Krishna and Godavari is diverted into the agricultural lands, besides the water is extracted from downstream.

In addition, the over exploiting of groundwater leads to the severe water crisis during summers in this catchment. The integration of remote sensing and geographical information system (GIS), which helps in groundwater research for the investigation of potential groundwater availability is essential to assess, monitor, and conserve groundwater resources. This analysis reports on the mapping of various potential groundwater resources in the Kolleru Lake catchment, India, by using remote sensing and GIS techniques. Various thematic layers of geomorphology, drainage density, lineament, slope, land-use, soil, rainfall, and NDVI converted into raster format in ArcGIS. The raster maps of these thematic layers were assigned to a weight-based factor depending on the catchment characteristics and its topographic influence. Landuse and soil profiles play a significant role in surface runoff and available moisture conditions. The field capacity of the soils for this catchment is mainly dependent upon the soil depth and drainage condition. According to the overlay analysis, potential groundwater zones of this catchment area were classified into five zones, namely very poor, poor, moderate, good, and very good. The areas with low potential sources are mainly concentrated in the middle and north-western of the catchment. Due to their higher elevation slopes, these areas don’t have water-holding capacities. However, the moderate zones are mainly concentrated in the upstream areas and partly focused on the western part of the catchment due to the agricultural land with high infiltration ability, indicates that soil textural properties and slope are important factors for the groundwater augmentation. The results demonstrated that about 7% of the area is under excellent groundwater potential recharge. Good, moderate, and lower potential conditions are 42%, 38%, and 13%, respectively. These results were validated with the borehole data. The data showed that 17.5% of the communities are under the overexploited category and mainly concentrated in the middle-catchment region. Because of the high population density as well as the agricultural dominated area there. However, the groundwater management level should focus on the middle part of the catchment. These results attributed to the assessment, visualization, and understanding of the existing groundwater levels in the Kolleru Lake catchment.

There are numerous factors that contribute to lake degradation. Industrial pollution studies are limited though they have a large share of pollution to the lake. The Government should implement policies to restore the lake, for example, conservation measures, management plans, awareness arising strategies, and establishment of the field research station in the catchment. The awareness programs and workshops to educate and train the inhabitants to build their capacity.

7. 2 Limit of study

Some recommendations are furnished as follows.

- The research is conducted mainly based on available data. Further investigation can be made through detailed primary data collection. This opens an opportunity for more comprehensive research work. There is an ample scope to include more variables. The more variables will be added to the study, and the more accurate the result will be.

- The results are not cross-checked with the filed investigations; however, this is the first catchment level study; certain assumptions on methods are considered.
- Due to the still existing lack of observed data of the tributaries, i.e., runoff, sediment, water quality parameters, nutrient load, the used methods are limited and suitable just for an estimation.
- Field investigations on the interaction of pollutant loads with the runoff would be advantageous for a better calculation of the pollutant load and its dynamic.
- Because of the limited funding capacity, it is challenging to do a field survey to control every remote sensing and GIS result of this research.

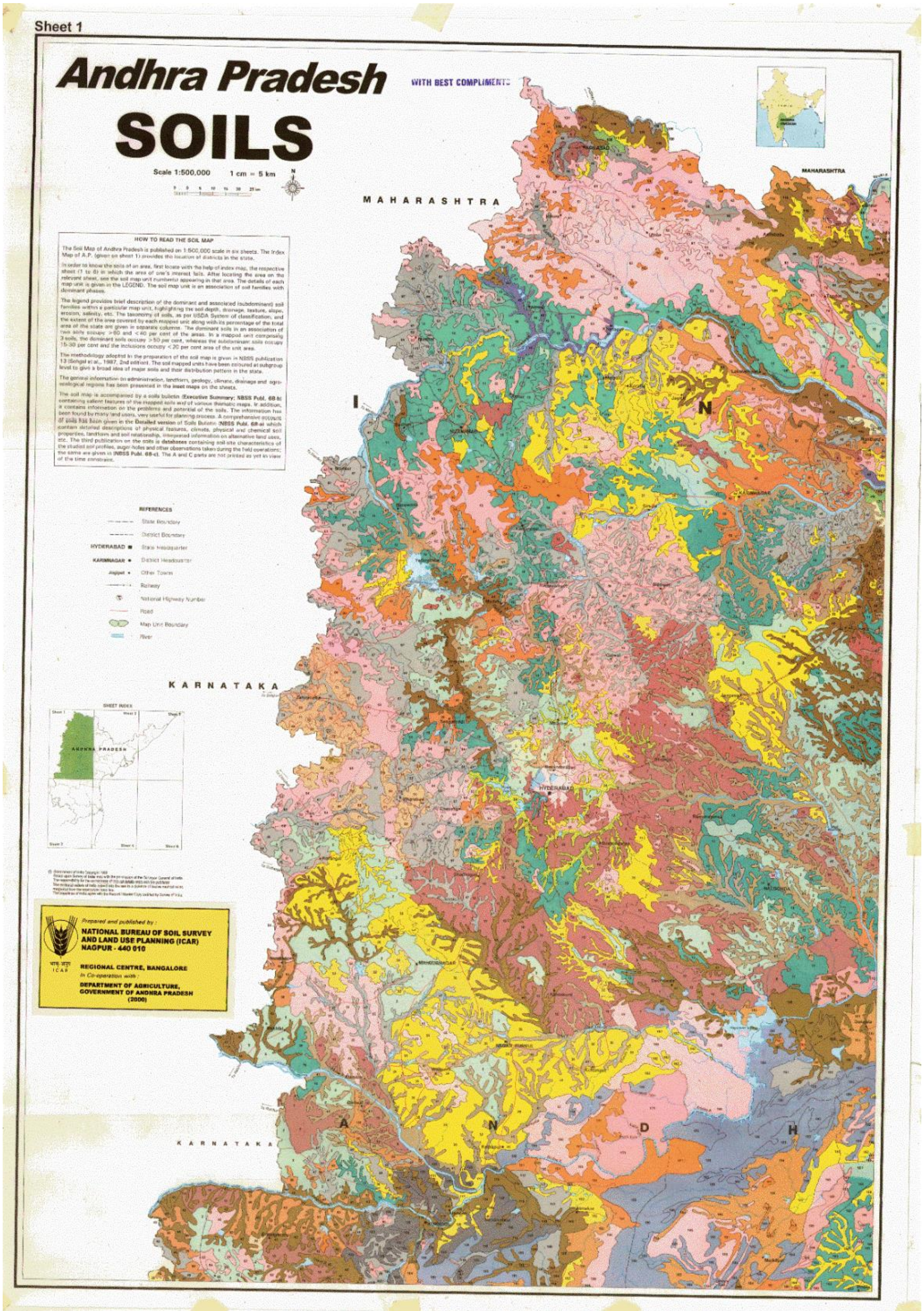
7. 3 Scope of further study

There is some future scope in which the work can be carried out on basic individual parameters that continues to pose severe threats to the lake's water quality. Despite the many factors which need to be considered for management plans, still there is point source studies are remaining for the scientific understanding of how the lake polluted from industrial contaminants is essential. There is some future scope in which work can be carried out:

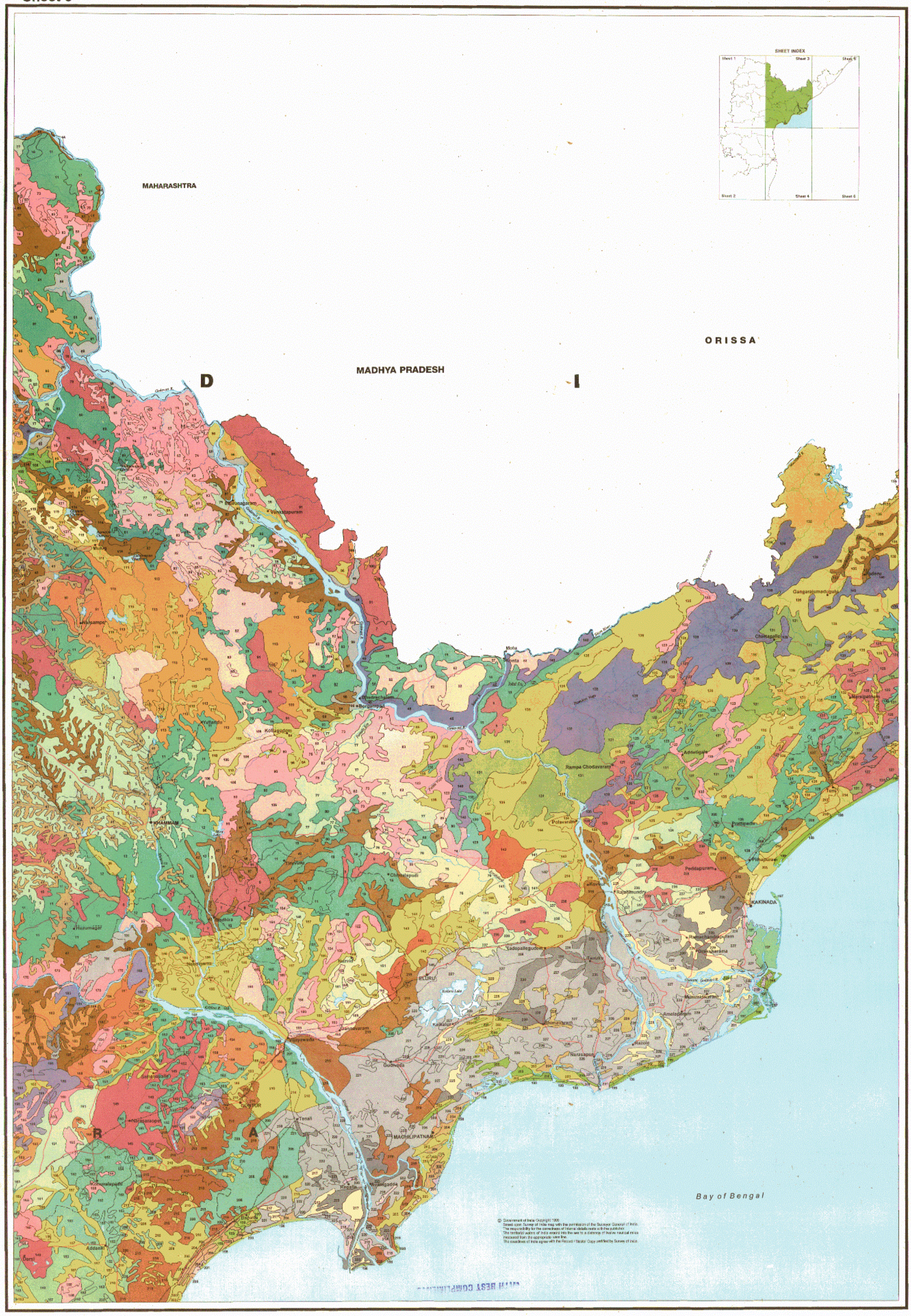
- Further research should focus on individual river basins as they are an integral part of the catchment that will be studied. Therefore, the catchment must be divided into a number of tributary river basins, and each basin should be studied separately to perceive the characteristics of catchment hydrology, climate, land use, soil, and socio-economic factors in a more detail level.
- Further groundwater quality analyses should be realized to estimate the likely presence of problem constituents in the stormwater, their mobility through soils, the type of treatment received before infiltration, and the kind of infiltration.
- Point source pollution studies, threats, discharge capacities should monitor and analyze the pollution levels in the lake.
- Local people and enterprises should become a part of the Best Management Praxis plan with the help of participation algorithms to feel them more responsible for the lake water quality. Such participation algorithms must be adapted to the local and regional situation in South India.

Appendix A:

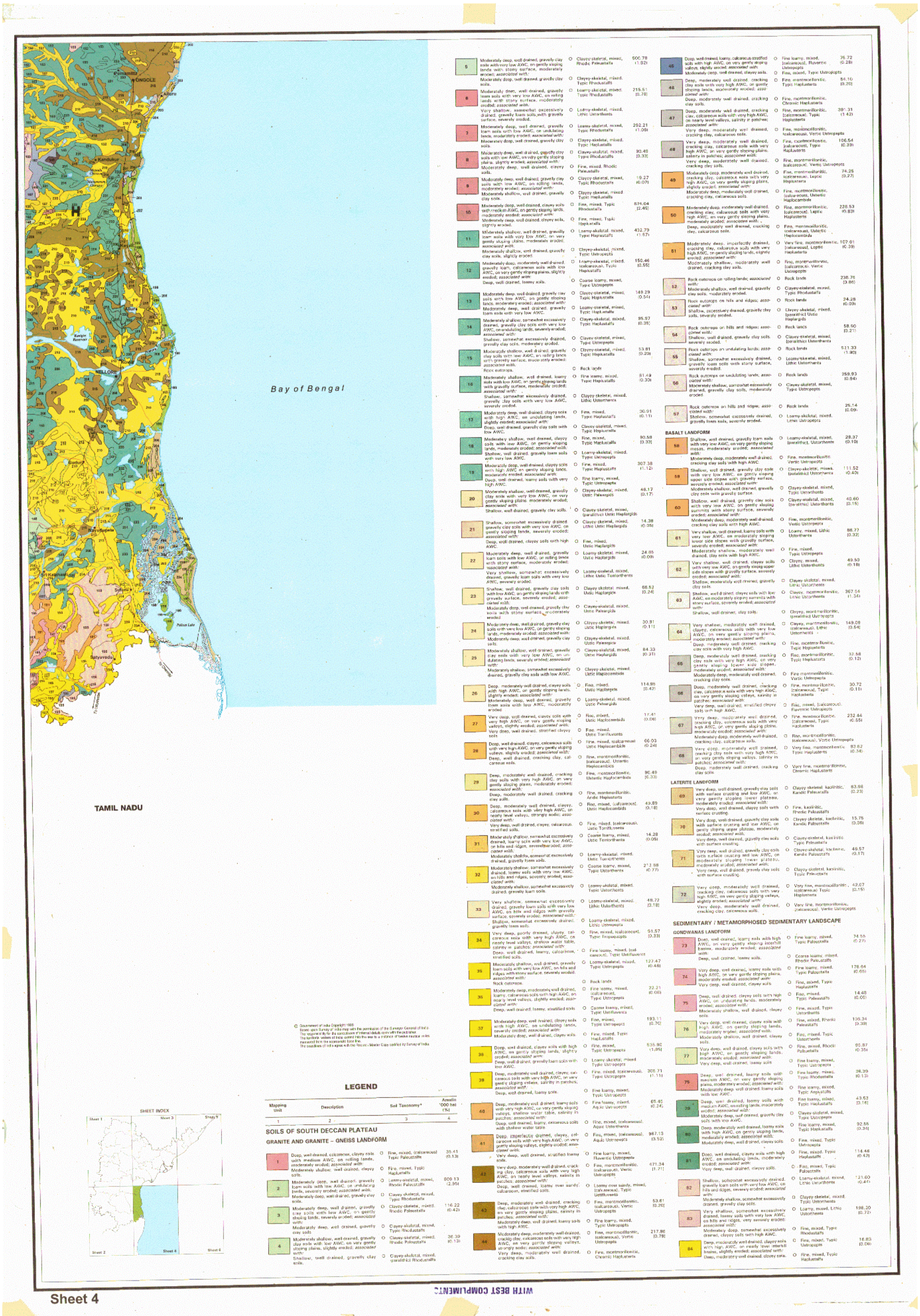
Spatial distribution of soils for Andhra Pradesh state (source: ICAR- National Bureau of Soil Survey and Land Use Planning, Nagpur, Maharashtra).



Sheet 3



MAHARASHTRA
MADHYA PRADESH
ORISSA
D
I
R
A
KHAMMAM
ELURU
KAKINADA
MACHILIPATNAM
Bay of Bengal
SHEET INDEX


ONGOLE
NELLORE
Bay of Bengal
TAMIL NADU
LEGEND
SHEET INDEX
SOILS OF SOUTH DECCAN PLATEAU
GRANITE AND GRANITE - GNEISS LANDFORM
BASALT LANDFORM
LATERITE LANDFORM
SEDIMENTARY / METAMORPHOSED SEDIMENTARY LANDSCAPE
GONDWANAS LANDFORM
Sheet 4


DHARWARS LANDFORM
CUDDAPAHS AND KURNOOLS LANDFORM
SOILS OF EASTERN GHATS (NORTH)
GRANITE AND GRANITE – GNEISS LANDFORM
DHARWARS LANDFORM
SOILS OF EASTERN GHATS (SOUTH)
GRANITE AND GRANITE – GNEISS LANDFORM
CUDDAPAHS AND KURNOOLS LANDFORM
DHARWARS LANDFORM
CUDDAPAHS AND KURNOOLS LANDFORM
SOILS OF COASTAL PLAINS (ANDHRA COAST)
MARINE LANDFORM
INLAND PLAINS LANDFORM
DELTA PLAIN
KRISHNA DELTA LANDFORM
GODAVARI DELTA LANDFORM
LATERITE LANDFORM
SANDSTONE (RAJAHMUNDRY) LANDFORM
SHEET INDEX
Sheet 6