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Integrated Evaluation of LULC, Soil and Irrigation Water Suitability Analysis for sustainable land and water resource management

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Introduction

With global pressures on land resources, agricultural suitability assessment (ASA) has become crucial for maximizing productivity and promoting sustainable land use. ASA provides a structured methodology to evaluate the physical and socio-economic potential of land for agricultural use. Traditional and modern frameworks use a wide range of criteria, including soil properties, water availability, and LULC data. This review synthesizes existing methodological frameworks for ASA, emphasizing the integration of soil suitability, water suitability, and LULC, and detailing the testing parameters used in each category. It also evaluates key tools and decision-support systems that enhance the effectiveness of suitability analysis. Agricultural land suitability assessment (ASA) is essential for sustainable land management and agricultural planning. This paper reviews methodological frameworks for assessing land suitability, focusing on key components: soil characteristics, water resources, and land use/land cover (LULC). It outlines commonly used approaches, including the FAO Land Evaluation Framework, GIS-based models, and Remote Sensing. Special attention is given to testing parameters used for evaluating soil (pH, texture, organic matter), water (quality, availability), and LULC (vegetation index, land cover classification). The paper concludes by recommending integrated frameworks that incorporate geospatial technology, stakeholder input, and machine learning for robust agricultural planning. Key factors such as soil texture, fertility, pH, drainage characteristics, land slope, elevation, groundwater availability, and climatic conditions were considered. These parameters were analysed and integrated using Geographic Information System (GIS) and Remote Sensing (RS) tools, along with Multi-Criteria Decision Analysis (MCDA) to create a detailed land suitability map. The study employed the FAO land evaluation framework, classifying land into highly suitable, moderately suitable, marginally suitable, and unsuitable categories for cultivation.

Since the beginning of time, India has been primarily an agricultural nation. For people who live in rural areas, agriculture is not a profession but rather a way of life. Undoubtedly, India's primary industry for employment is agriculture, especially in the vast rural portions of the nation. Since the Neolithic age, India has practiced agriculture. India's agricultural output ranks second worldwide. About 18.8% of India's GDP (gross domestic product), or more than

$400 billion, was generated by agriculture in the years 2021-2022. Half of India's workforce is employed there as well. In rural India, agriculture supports about three-fourths of the population. India is a significant global player in agriculture. Around 195 million ha are under cultivation in the nation, with 125 million ha (or around 63%) being rainfed and 37% irrigated. In addition, woods cover 65 million hectares of India's land. The ICAR states that India is fortunate to have large areas of arable land that are separated into 15 agro-climatic zones with a variety of soil types, weather patterns, and crop-growing potential. India is the leading producer of many fresh fruits and vegetables, such as bananas, mangoes, guavas, papayas, and lemons, as well as significant spices like chilli pepper and ginger, as well as fibre crops like millets and castor oil seed. India is the world's second-largest producer of two major food staples: rice and wheat. The items India produces that are currently ranked second in the world include several dry fruits, agriculturally based textile raw materials, roots, and tuber crops, pulses, farmed fish, eggs, coconut, sugarcane, and a range of vegetables.

SOIL SUITABILITY ANALYSIS REVIEW

The ability of soil to fulfil ecological activities, offer ecosystem services to preserve biological production and environmental quality, and improve plant and animal health is known as soil quality. All of the physical, chemical and biological parameters in soil play an important role in the soil’s critical functioning. Any changes to the soils physical (soil texture, bulk density, etc) chemical (pH, salinity, organic carbon, etc) or biological (microbes and enzymes) parameters will have an impact on the soil. These biological chemical and physical factors can be used to gauge the soil’s quality (Maurya, et.al, 2000).

Indicator	Good Value Range	Medium Value range	Poor Value Range
Soil ph	6.5-7.0	6.4 - 4.0	<4.0 or >7.0
Soil Texture (Clay%)	<25% (Loamy/Sandy Loam)	Intermediate	Very Clayey or Sandy
Organic Matter (%)	>3.5%	1.0 - 3.5	<1.0
Soil Depth (m)	>0.30	0.10 - 0.30	<0.10
Electrical Conductivity (dS/m)	<2.0	2.0 - 4.0	>4.0
Cation Exchange Capacity (CEC)	>20	(10-20)	<10
Calcium Carbonate (CaCO3, %)	<10	(10-25)	>25
Water Holding Capacity	High	Medium Value range	Low
Bulk Density (g/cm3)	1.1 - 1.4	1.4 - 1.6	>1.6
Soil Protection Class	classes I, II	III, IV	V
Soil Drainage	Well Drained	Moderately Drained	Poorly Drained

Table 1: Soil Indicators

Soil Health Indicators for its health are meant to help smallholder farmers understand the chain of events and how it affects everything from decisions to the health of plants and animals. Another factor that may have an impact on the sustainability and productivity of land usage is soil quality. It interferes with soil conservations and maintenance procedure and is regulated by the soil's physical, chemical and biological elements and connections. The Physical Indicators: When organic matter is added to soil's, the entire physical properties advance. As a result, one of soil's distinguishing physical characteristics is its potential to sustain biological activity and plant growth (Structure, porosity, and water holding capacity). These are approximations based on soil texture, bulk density, soil porosity and water holding capacity. Chemical Indicators: - Chemical soil quality indicators, depending on the pH of the soil, give information on the soil's capacity to transfer minerals and nutrients. By measuring the pH of the soil, one can determine the activity of hydrogen ions in the soil solution.

Biological Indicators:- Micro-biological intervention dynamically influences soil quality. Mineralizable nitrogen, respiration, soil organic matter and microbial biomass (total bacteria and fungus) are among the biological indicators of the soil quantity (Katiyar, et.al, 2022).

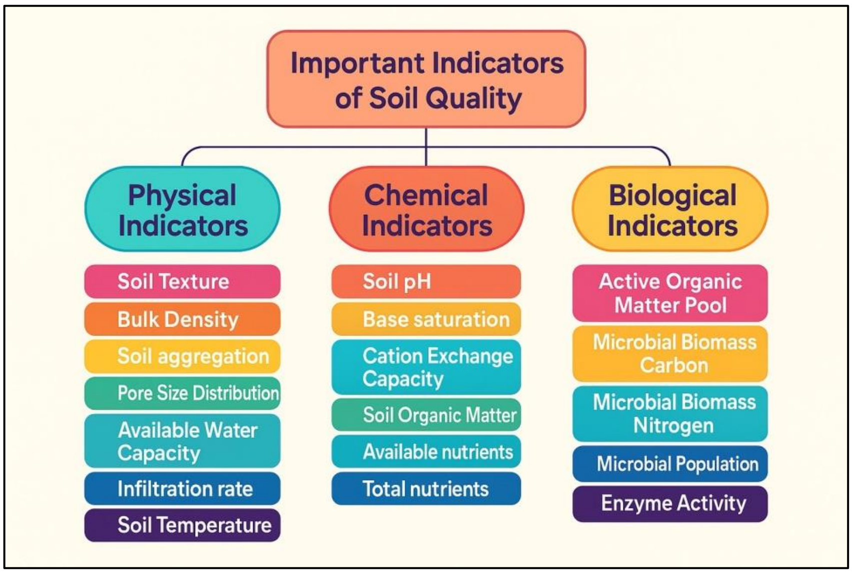

Figure 1: Prusty, et.al, 2022

To choose indicators that are appropriate for the smallest dataset in this step, four guidelines must be adhered to:-

1. The assessment must include chemical, physical, and biological characteristics of soils, as well as their physical and chemical changes;
2. The indicators must be sensitive to soil changes and represent the functions of the soil;
3. The sampling must be accurate, with practical methodologies, easy to assess and interpret, low cost, and available for study on a time scale whenever necessary; and the diagnosis, through the indicators chosen, must assist the decision-makers in maximizing the use of environmental, health, and other resources.

(Simon,et.al,2022)

The indicators of soil quality vary widely depending on the states of the land and the methods used for categorised into three groups, namely soil chemical, physical and physical processes. The ability of soil to produce healthy crops, cycle and retain them to roots for efficient plant production, store carbon in soil and release it to the atmosphere in a dynamic balance that stabilize atmospheric concentration of CO_2, and provide plants with water, nutrients and compounds that promote plant growth should all be reflected in indicators of soil quality.

Computation of Soil Quality Index:

The physical, chemical, and biological characteristics of soils were described statistically. Principal component analysis (PCA) and Expert Opinion (EO) were used to establish the minimal data set for computing the soil quality index (SQI) based on soil parameters. The relative soil quality index (RSQI) was developed to categorize the soils from various regions.

Relative Soil Quality Index: The RSQI was established utilizing 20 significant and well-known physical, chemical, and biological markers with uniform weighting and scoring values in order to compare soils from various sites. Each indication was given a grade, which was then separated into four classes: Class I, Class II, Class III, and Class IV. The grades were 4, 3, 2, and 1, respectively. The following equation was used to determine the SQI in this situation.

SQI = S Wi x Mi

RSQI = x 100 Observed SQI of the given site/ Maximum value Soil Quality Index (i.e., 400)

Mean percent relative yield computation:

Mean % relative yield = x 100 Observed rice yield of a given site /Maximum yield among the sites

The principal component analysis (PCA) was performed utilizing principal components ((PCs) possessing Eigen value) to identify the minimum data set (MDS) (Brejda et al., 2000) Finally, SQI was determined using accepted approaches (Romanuik et al., 2011; Andrews et al., 2002). (Gayan, et.al, 2020) The gravimetric method was used to calculate the water holding capacity. Using the core approach, bulk density was calculated. Using the wet oxidation method, the total organic carbon in the soil was calculated. The hydrometer method was used to calculate the amounts of clay, sand, and silt. Following the instructions provided a combination electrode for EC and pH was used to measure the electrical conductivity and reactivity of soil samples in a 1:2.5 soil: water ratio (w/v). The Alkaline Permanganate Method was used to calculate the available N. The extraction of the available phosphorus was carried out using Olsen's extractant, 0.5 M $NaHCO_3^-$ (pH 8.5). Using a spectrophotometer and the ammonium molybdate blue color method, the amount of phosphorus in the extract was measured color metrically at 760 nm. With the aid of a flame photometer, the amount of available K in the neutral, normal ammonium acetate extract of soil was determined. The S in the extract was quantified turbidity metrically, and the available Sulphur was evaluated using 0.15% CaCl2solution. By titrating with EDTA, the amount of exchangeable calcium and magnesium in the soil's ammonium acetate extract was calculated. The Cation Exchange

Capacity (CEC) was calculated using Jackson's technique. The scores of all the indicators analyzed were added together to create the unscreened additive index, which was then divided by the total number of indicators used (Mir,et.al,2022).

Soil quality index (SQI) = $\sum_{i=1}^{n} \frac{S_i}{n}$

Where, S denotes linear score of observed soil quality indicator and

N is the number of indicators included in the index.

A soil quality indicator (SQUID) uses the Delphi expert approach to aggregate a st of 10 distinct soil functions into several ecosystem services. The contributions of soil functions to ecosystem services are identified using the findings of a Delphi survey in this index. The weighted factors recommended by the experts are multiplies by the estimated soil function (OPE and SFA) that contributes to each ecosystem service. A SQUID index is created by averaging the derived ecological service values. The soil has a minimum overall score of a 0, which means it has no impact at all ecosystem services. On the other hand, the maximum total result, which is equal to 5, indicates that the soil considerably contributes to the ecosystem service. The formula used to determine the SQUID index id ad follows:-

SQUID = $\sum_{i=1}^{n} ES_i$ (Janku,et.al, 2022)

BOKS index mentions the six attributes that are used to describe the soil quality are added together to create this index. BOKS, in contrast to many other soil quality indices, takes into account both natural and anthropogenic elements when determining the final soil quality index. The ability to produce natural vegetation and crops, control the water cycle, filter out and absorb toxins, and preserve cultural and natural heritage are the four of these six traits that are categorized as natural factors. Contaminated sites and the soil sealing level make up the final two features, which are anthropogenic. Each of these characteristics is scaled from 0 (non-existent) to 5 (very good). The procedures entail defining standards and parameters to direct the evaluation, such as setting indicator value ranges suitable for the particular soils and figuring out the relative weight or relevance that should be assigned to each indicator. Following is a summary of the specific information for each step of the SQI assessment. First, a minimal data set (MDS) of chemical (pH, EC, and SOC) and physical (pb, texture, AWC, and Ksat) indicators was chosen for assessing the management goal. None of the biological indicators mentioned in earlier papers that were suggested were measured. The indicators chosen were based on a review of the literature as well as discussion and agreement amongst the cooperating farmers and researchers who have experience in Ohio and Michigan. The criteria were used to convert the MDS indicators into unitless scores between 1 and 5 for the second stage. Typically, scoring functions come in three different formats. A "the more is better" curve is employed when soil quality improves as an indicator's level rises. A "less is better" curve, on the other hand, is appropriate if soil quality declines as the indicator value increases. The indicators that have an increasingly positive correlation with soil quality up to an optimal level but beyond which soil quality diminishes are then given a "optimum" curve. The unitless values can then be included in a single, overall SQI value with suitable weighting of various indicators, after the selection of the appropriate curve type and scoring of individual indicators (Nakajima,et.al,2016). The granulometric analyses were performed by the Bouyoucos densimeter method, described in EMBRAPA (1997), using NaOH 0,1 N and water as dispersant to determine natural clay and degree of flocculation,

$$GH(AT-AN/AT)*100$$

Where, AT = total clay (dispersed in NaOH), AN = natural clay (dispersed in water). The determination of erodibility (K), used to determine the susceptibility of the soil to erosion, was performed for each horizon of the soil profile, using the model proposed by WISCHMEIER et al. (1971) (Filho, et.al, 2021). Microbial diversity index (Shannon diversity index (H') was determined by the following equation - H' = S pi x Inpi (Lupwayi et al., 2001). A high-quality soil's characteristics are to be qualitatively described using a soil quality model, where soil quality is determined by how well it can carry out specific tasks. Based on modelling results, we may examine the effects of various practices on various soil types or temporal patterns on the same soil type and fully appreciate the importance of dynamic soil quality evaluation. Where Q is the soil quality index (QI), qk represents values for different soil quality indicators, and wt is the weights applied to each indicator (Li,et.al, 2005).To measure the physical parameters of soil sample, 100mL of water and 10g of soil were added to a funnel for this examination, and the mixture was then sealed with a glass stopper. So that the soil could absorb the most water possible, soil samples were left on a table for 2-4 hours to determine the soil's water holding capacity (WHC). The usual international pippete protocol was used to calculate the soil texture. The pH of soil was measured using double-distilled water in the ratio of 1:2.5 (w/v) soils to water. The organic carbon content (OCC) was investigated using the Walkley and Blake (1947) approach. Applying a standard protocol and the titration approach described by Nelson and Sommers (1996) allowed for the determination of soil organic matter (SOM). In case of heavy metal concentration in soil samples, in a flask, 15 mL of aqua (HNO_3/HCl, 1:3, v/v) was added to 1 gram of processed soil before it was held for 24 hours for examination. The flask was held at a temperature of 120 C for two hours after being heated to 50 C for 30 minutes. 10 mL of 0.25 M HNO3 was added once the flask had cooled. Using Whatman paper No. 542, the solution was filtered, and 0.25 M nitric acid was used to increase the filtrate's volume to 50 ml. Utilizing an atomic absorption spectrophotometer (AAS) model 700 from China, examination of the prepared soil samples was carried out in triplets, with the average value being calculated. Using the international pipette technique (IPM), the soil type or texture was determined. According to the USDA's texture classification system, soil classes were divided and named based on the percentage of sand, silt, and clay in the sample. Utilizing appropriate statistical software, the gathered data was examined (Ishtiaq, et.al, 2022). The soil samples were ground up, air dried, and put through a 2 mm sieve. For laboratory analysis, the fractions smaller than mm were employed. The hydrometer method was used to determine particle size distribution. The core sampler was used to calculate bulk density. Using a glass electrode pH meter, soil pH was determined in water. The dichromate wet oxidation method was used to measure organic carbon. By saturating the soil with normal neutral ammonium acetate solution, the soils cation exchange capacity (CEC) was ascertained. The Kjeldahl method was used to determine the total N. Atomic absorption spectrometer, Ca and Mg were evaluated. Using a flame photometer Sodium and K were evaluated (Yahqub, et.al, 2021). Samples were taken at intervals of 0-15, 15-30, 60-90, 90-120 and 120-150 m depth at each assessment for study. Using a Metrohm 660 Conductometer, the electrical conductivity of the saturated extract, was measured, and a Haakebuchler chloridometer was used to quantify the chloride content. A PerkinElmer 2380 atomic absorption spectrophotometer was used to detect the amounts of sodium (Na), magnesium (Mg), and calcium (Ca) in the saturated extract. By drying the saturated soil paste in an oven at 103°C for 24 hours, the moisture content was determined (Beecher, et.al, 2002).

Using pH meter (Dig-sun electronics) the hydrogen ion was determined . Using flame photometer with standard potassium chloride the electrical conductivity was evaluated. With the help of 0.02 N EDTA Titrimetric method the total hardness was determined. By using stannous chloride method with the phosphate was determined. With the help of standard method water holding capacity and bulk density if soil water were evaluated (Nandini, et.al, 2010). The color of the soil can reveal how a soil will react under specific proposed land uses. Examples include:

- Darker colour of the below layer is connected with organic residues and the consequent improvement to tilt, structure, accessible nutrients, and water holding capacity.

- Bright coloured soils tend to have less drainage issues that would limit their use.

Additionally, colour is utilized to describe other elements critical to comprehending the growth and behaviour of soil (pores, concretions, nodules, castes etc.). A Munsell System is used to determine the soil colour (hue, value, and chroma). Because moisture affects soil colour, the recorded value is labelled as either "wet" or "dry."

Organic matter is important to soil quality because it:-

- Improves the soil's capability for exchanging cations, which allows it to hold vital plant nutrients.
- Offers products for decomposition that bind soil particles into aggregates to improve soil structure, water infiltration, and tilth.
- Provides a food source for a variety of soil organisms that encourage soil air and water flow and nutrient recycling.
- Represents the main sources of N and S (as well as most of the P) for crops.

IRRIGATION WATER SUITABILITY ANALYSIS REVIEW:

Sodium absorption ratio (SAR) is a measure of the water suitability for irrigation usage. The effects of the physicochemical parameters on water quality and SAR, which included Calcium (Ca^{2+}), Magnesium (Mg^{2+}), Sodium (Na^{+}), Potassium(K), Chloride (Cl^{-}), Sulfate (SO_4^{-2}), Carbonates (Co_3^{2-}), Bicarbonate (HCO_3^{-}), Nitrate (NO_3^{-}), Total Hardness (TH), Total Dissolved Salts (TDS), Electrical Conductivity (EC), degree of reaction (DR), Boron(B) and the monthly and annually flow discharge are examined. Sodium absorption ratio is the important parameters to be examined during the suitability of water for use in irrigation and could be used to manage the Sodium affected soils. The high amount of Sodium irrigation water increases the salinity of the water that effects soil structure and conversion from natural to saline water, thereby, the hydraulic conductivity of the soil and the rate of infiltration are reduced.

The value of SAR could be indicated by evaluating the concentration of Na, Mg and Ca.

$$SAR = \frac{Na}{\sqrt{(Na+Mg)/2}}$$ (Khudhair.B.H., et.al, 2020)

The SAR is a water quality index that indicates the percentage of sodium in the water and function of the ratio of sodium to divalent cations such as Ca and Mg. The high amount of sodium in irrigation water may negatively affect the soil structure and decreases the soil hydraulic conductivity in fine-texture soil. The rate to which sodium will be absorbed by a soil is a function of the amount of sodium divalent cations (Ca and Mg) and is regularly depicted by sodium absorption ratio (SAR).

$$SAR = \frac{Na^{+}}{\sqrt{\left[\frac{Ca^{++}+Mg^{++}}{2}\right]}}$$ (Asadollahfardi., et.al, 2013)

There are several irrigation water indices, such as soluble sodium percentage (SSP), sodium acsorption ratio (SAR) magnesium absorption ratio(MAR), residual sodium carbonate (RSC), Kelly's ratio (KR), permeability index (PI) and irrigation water quality (IWQ) index which are applied to evaluate irrigation water quality.

S. No.	Parameter	Abbreviation	Mathematical Expression*	Reference
1	Electrical Conductivity	EC	Measured directly (dS m^{-1} at 25°C)	Wilcox (1948)
2	Sodium Adsorption Ratio	SAR	$SAR = \frac{Na^{+}}{\sqrt{(Ca^{2+}+Mg^{2+})/2}}$	Richards (1954)
3	Kelly's Ratio	KR	$KR = \frac{Na^{+}}{(Ca^{2+}+Mg^{2+})}$	Kelly (1963)
4	Sodium Percentage	Na%	$Na\% = \frac{Na^{+}+K^{+}}{(Na^{+}+Ca^{2+}+Mg^{2+}+K^{+})} \times 100$	Ayers & Westcot (1985)
5	Magnesium Adsorption Ratio	MAR	$MAR = \frac{Mg^{2+}}{(Ca^{2+}+Mg^{2+})} \times 100$	Raghunath (1990)
6	Permeability Index	PI	$PI = \frac{Na^{+}+\sqrt{HCO_3^{-}}}{(Ca^{2+}+Mg^{2+}+Na^{+})} \times 100$	Doneen (1964)
7	Residual Sodium Carbonate	RSC	$RSC = (HCO_3^{-}+CO_3^{2-}) - (Ca^{2+}+Mg^{2+})$	Raghunath (1987)
8	Total Hardness	TH	$TH = 2.497(Ca^{2+}) + 4.11(Mg^{2+})$	Todd (1980); Raghunath (1987)
9	Soluble Sodium Percentage	SSP	$SSP = \frac{Na^{+}+K^{+}}{(Na^{+}+K^{+}+Ca^{2+}+Mg^{2+})} \times 100$	Todd (1980)
10	Potential Salinity	PS	$PS = Cl^{-} + 0.5(SO_4^{2-})$	Doneen (1964)

Figure 2: Irrigation Water Quality Indices and Formulae

Biraj Singh has used, two data-driven model i.e, Gaussian Process (GP) and Support Vector Machine (SVM) to predict the sodium absorption (SAR). A compression was also done with these two data-driven models with Artificial Neural Network (ANN). For this he used the parameters, total dissolved solid, electrical conductivity, Ph values, CO_3, HCO_3, Chlorine(Cl), SO_4, Calcium(Ca), Magnesium(Mg), sodium(Na) and potassium (K) as input variables and SAR as output For SVM and GP regression, two Kernel functions (radial – Based Kernal and Person Kernal function) were used (Singh. B, 2019). The physical and chemical major parameters of ground water like electrical conductivity (EC, Ph, total dissolved solids, Na, K, Ca, Mg, Cl, HCO_3^-, SO_4 and NO_3 were determined. The significant constituents that influence the water quality for irrigation such as sodium absorption ratio, sodium percentage, soluble sodium percentage and residual sodium bi-carbonate and permeability index, magnesium absorption ratio, and Kelly's ratio were calculated. The mineralization of the groundwater is controlled by these two ions (sodium chloride facies) (Bouderbala, A, 2015). Water quality was demonstrated in terms of Water Quality Index, which was determined through summarizing multiple parameters of water results. The application of Water Quality Index was performed with sixteen physicochemical water quality parameters to evaluate quality of Tigris River for drinking usage. These sixteen physicochemical parameters includes : Turbidity, Alkalinity, Total hardness(TH), Calcium(Ca), Magnesium(Mg), Iron(Fe), pH value, electrical conductivity(EC), Sulphate, Chloride, Total Solids(TS), Total Suspended Solids(TSS), Nitrate, Nitrate, Ammonia and arthophosphate. The Water Quality Index (WQT) was calculated using the Weighted Arithmetic Index method. The quality rating scale for each parameter (q1) was calculated by using equation (1):

$$q1 = Ci/Si \times 100$$ (Khudhair,2019)

Water quality is defined in physical, chemical, biological forms in each category and water quality parameters are selected based on their intended use. In general the main objective of water quality assessment is to determine the fulfilment of defined objectives; to describe water quality at regional, national or international level and to examine trends over time so that it can be classified within the relevant regulatory standards for various purposes such as potable water, agricultural, recreational and industrial water uses. For this purpose, concentration ranges have been defined in Indian Standards (IS) and Central Pollution Control Board standards also taking into account the International Standards of the World Health Organization and the European Commission. According to Singh, the general methodology for the development of a water quality index can be summarized in the following four steps:

1. Parameter selection
2. Development of Sub-indices Function - Transformation of concentration of water quality of concentration of water quality parameters into mathematical equation.
3. Assignment of weight - Deciding suitable weights of various selected water quality parameters.

4. Aggregation of Sub-indices to Construct an Overall Index - Construction of an overall all water quality index (OWQI).

In India, Indian Standards (IS 1050:1991) and Central Pollution Control Board (CPCB) standards regulates the quality of water for various uses (Singh, et.al, 2015). Sharma has taken the samples of drinking water in clean polythene bottles from different source viz. tube-well, bore well and hand pump in the pre and post monsoon. Total eleven physico-chemical characteristics were analysed: total dissolved solids, total hardness, chloride, nitrate, electrical conductance, sodium, fluoride and potassium, pH, turbidity, temperature and observed values were compared with standard values recommended by Indian Standard and World Health Organization. TDS is calculated by the evaporation method, Chloride has been determined using spectrophotometry (Sharma,S., et.al, 2015).One of the most commonly used is the water quality index, not only for its ability to generate understandable classifications, but also for its ability to facilitate studied behaviour over time. The WQT provides a single number that represents overall water quality based on a small number of parameters. The idea of the index is to transform complex water quality data into information that is appropriate and quantifiable by the general public. The main disadvantage of WQT is that some information regarding individual variables and their interactions may be lost (Marino, et.al, 2013)

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