INTEGRATED ENVIRONMENTAL WATER MANAGEMENT AND DEMAND PREDICTION FOR URBAN SUSTAINABILITY IN TIRUVANNAMALAI

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ABSTRACT

Water scarcity has become one of the most critical challenges in semi-arid regions due to rapid population growth, expansion of agricultural activities, and increasing variability in climatic conditions. Efficient planning and management of water resources are essential to ensure long-term sustainability and economic development. This study presents an Integrated Water Demand Forecasting and Allocation Model (IWDFAM) for Tiruvannamalai district, Tamil Nadu, India, aimed at assessing future water demand, evaluating water availability, and proposing sustainable management strategies.

Population forecasting was carried out using a linear regression method to estimate future growth trends up to the year 2050. Domestic water demand was calculated using the per capita water consumption approach, while agricultural demand was estimated based on irrigated area and crop water requirements. Industrial demand was considered as a percentage of domestic demand. Water availability was evaluated by analyzing surface water sources such as tanks, reservoirs, and rivers, along with groundwater recharge estimated from rainfall data and recharge coefficients.

The results indicate that the total water demand is projected to reach approximately 1433 million cubic meters (MCM) per year, while total water availability is estimated at around 1198 MCM per year, resulting in a deficit of 235 MCM per year. Scenario analysis reveals that the deficit could increase under unfavorable conditions such as reduced rainfall and increased water demand. However, the implementation of sustainable water management practices such as drip irrigation, rainwater harvesting, wastewater reuse, and groundwater recharge can significantly

reduce the deficit and even lead to water surplus.

The developed model provides a systematic and practical decision-support tool for water resource planners and policymakers. It can be applied to similar semi-arid regions to improve water resource management and achieve sustainability.

KEYWORDS

Water demand forecasting, water balance, sustainable water management, groundwater recharge, irrigation efficiency, scenario analysis

1. Introduction

Water is one of the most vital natural resources, playing a crucial role in sustaining life, agriculture, industry, and ecosystems. Despite its importance, the availability of freshwater resources is limited, and increasing demand has led to severe water stress in many parts of the world. Globally, freshwater accounts for only a small fraction of total water resources, making efficient management essential for sustainable development.

In recent decades, population growth, urbanization, and industrialization have significantly increased water demand. At the same time, climate change has introduced variability in rainfall patterns, leading to uncertainty in water availability. These factors have intensified water scarcity, particularly in semi-arid regions where water resources are already limited.

India is one of the countries facing significant water challenges due to its large population and dependence on agriculture. Groundwater has become the primary source of water for both domestic and irrigation purposes. However, excessive extraction of groundwater has led to declining water levels, reduced water quality, and increased vulnerability to drought.

Tiruvannamalai district in Tamil Nadu represents a typical semi-arid region experiencing water scarcity. The district relies heavily on monsoon rainfall and groundwater resources. Agriculture is the dominant sector, accounting for the majority of water consumption. Traditional water management systems such as tanks and reservoirs are insufficient to meet the growing demand, leading to over-dependence on groundwater.

Water demand forecasting is a critical component of water resource management. It helps in predicting future water requirements and enables planners to design appropriate strategies to meet demand. Various methods have been used for forecasting water demand, including statistical models, regression analysis, and machine learning approaches. However, many of these methods focus only on demand estimation and do not consider water availability or sustainability.

An integrated approach is required to address water scarcity effectively. Such an approach should include demand forecasting, assessment of water availability, water balance analysis, and the implementation of sustainable management practices. This study aims to develop an integrated model that combines all these aspects into a single framework.

The main objectives of this study are:

1. To forecast future population and estimate water demand for domestic, agricultural, and industrial sectors.
2. To assess water availability from surface water and groundwater sources.
3. To perform water balance analysis and identify water deficits.
4. To analyze different future scenarios based on variations in rainfall and water demand.
5. To develop a sustainable water management model to reduce water deficit and improve water availability.

The significance of this study lies in its ability to provide a simple yet effective tool for water resource planning. The developed model can assist policymakers and engineers in making informed decisions regarding water allocation and conservation strategies. It also highlights the importance of sustainable practices in addressing water scarcity.

In addition, this study aligns with global sustainability goals, particularly those related to water management and climate adaptation. By integrating demand forecasting with sustainable management strategies, the model provides a comprehensive approach to ensuring water security in the future.

2. Literature Review

Water demand forecasting and sustainable water resource management have been widely studied due to increasing global water scarcity. Researchers have used various approaches, including statistical models, machine learning techniques, and integrated simulation tools, to estimate water demand and optimize resource utilization.

Early work by **Sharma (2008)** focused on groundwater recharge estimation using hydrological methods. The study highlighted the importance of recharge processes in maintaining groundwater sustainability, especially in semi-arid regions. It emphasized that groundwater depletion is primarily caused by excessive withdrawal without adequate recharge.

Studies by **Amarasinghe et al. (2024)** analyzed future agricultural water demand at a global scale. The authors concluded that agricultural water demand will continue to increase due to population growth and food requirements. They also emphasized that improving irrigation efficiency is critical for reducing water consumption.

The Food and Agriculture Organization (**FAO, 1977**) developed standard guidelines for estimating crop water requirements based on evapotranspiration. These guidelines are widely used in agricultural water demand estimation and form the basis for irrigation planning worldwide. The FAO approach provides a scientific method to estimate crop water needs under different climatic conditions.

Ma et al. (2024) developed a crop water demand prediction model using modern data-driven techniques. Their study demonstrated that integrating climatic variables such as temperature and rainfall improves the accuracy of water demand estimation. The model was particularly effective in predicting seasonal variations in water demand.

Research by **Shu et al. (2024)** focused on long-term water demand forecasting using statistical and machine learning approaches. The study highlighted that combining historical data with predictive models enhances forecasting accuracy. However, it also noted that such models require large datasets and may not be suitable for regions with limited data availability.

VanBerlo et al. (2021) studied municipal water demand forecasting using probabilistic models. The authors found that uncertainty in demand forecasting can be reduced by incorporating multiple influencing factors such as climate, population, and socio-economic conditions. Similarly, **Kley-Holsteg (2020)** developed probabilistic water demand forecasting models that account for uncertainty and variability. The study emphasized that water demand is influenced by multiple dynamic factors, and deterministic models may not always provide accurate predictions.

Artificial intelligence-based approaches have also been explored. **Msiza (2007)** applied Artificial Neural Networks (ANN) and Support Vector Machines (SVM) for water demand forecasting. The results showed that ANN models can capture nonlinear relationships between variables and provide better predictions compared to traditional regression models.

More recently, **Salloom (2025)** applied deep learning techniques for water demand prediction. The study demonstrated that deep learning models can handle complex datasets and improve forecasting accuracy. However, the complexity of these models limits their practical application in regions with limited computational resources.

Hydrological modeling has been extensively studied using tools such as

SWAT and HEC-HMS. **Garg (2026)** analyzed irrigation water productivity using hydrological models and concluded that efficient water use can significantly improve agricultural output. The study emphasized the importance of integrating hydrological modeling with water management practices.

The UK Water Resources Demand Management Action Plan (**WRDMAP, 2010**) provided guidelines for water demand forecasting and management. The report highlighted the importance of scenario analysis in understanding future water demand and planning appropriate strategies.

Groundwater studies by **Central Ground Water Board (CGWB, 2023)** indicate that groundwater levels in many parts of India are declining due to over-extraction. The report emphasizes the need for artificial recharge and sustainable groundwater management practices.

Rainfall variability studies by **Indian Meteorological Department (IMD, 2023)** show that climate change is affecting rainfall patterns, leading to uncertainty in water availability. This highlights the importance of incorporating climate variability into water resource planning.

Integrated water resource management approaches have gained importance in recent years. Studies using WEAP models have demonstrated the effectiveness of combining demand forecasting, supply analysis, and scenario evaluation. These models allow policymakers to evaluate different strategies and select optimal solutions.

Despite the availability of various models, there are still significant research gaps. Most studies focus either on demand forecasting or hydrological modeling, but few integrate both aspects along with sustainability measures. Additionally, many advanced models require extensive data and computational resources, limiting their applicability at the district level.

This study addresses these gaps by developing an integrated model that combines:

- Population-based demand forecasting
- Water availability estimation
- Water balance analysis
- Scenario analysis
- Sustainable water management strategies

The proposed model is simple, practical, and suitable for regional-level planning. It provides a comprehensive framework for managing water resources efficiently and ensuring sustainability.

3. Study Area Description

The present study focuses on Tiruvannamalai district, located in the northern part of Tamil Nadu, India. The district is geographically situated between latitudes 12°00′N to 12°30′N and longitudes 78°30′E to 79°30′E. It covers a total geographical area of approximately 6,188 square kilometers. The district shares its boundaries with Vellore, Kanchipuram, Villupuram, and Krishnagiri districts. Due to its semi-arid climatic conditions and dependence on monsoon rainfall, Tiruvannamalai is highly vulnerable to water scarcity.

3.1 Climate and Rainfall

The climate of Tiruvannamalai district is predominantly semi-arid with hot summers and moderate winters. The district experiences high temperatures during summer, often exceeding 40°C, while winter temperatures are relatively mild. The average annual rainfall of the district is approximately 1000 mm.

Rainfall in the region is mainly received from the northeast monsoon (October to December), which contributes nearly 60–70% of the total annual rainfall. The southwest monsoon provides a smaller contribution. However, rainfall in the district is highly variable and uncertain, leading to frequent drought conditions. This variability significantly affects water availability and agricultural productivity.

The irregular distribution of rainfall results in uneven groundwater recharge and limited surface water storage. Therefore, effective water management strategies are essential to utilize available rainfall efficiently.

3.2 Topography and Soil Characteristics

The topography of Tiruvannamalai district consists of undulating terrain with scattered hills and plains. The presence of rocky formations and hard rock geology limits the natural storage capacity of groundwater. The district is characterized by crystalline rock formations, which restrict infiltration and groundwater movement.

The soil types in the district include:

- Red loamy soil
- Sandy soil
- Clayey soil

Red loamy soil is predominant and is suitable for crops such as groundnut and millets. However, the water retention capacity of these soils is moderate, requiring frequent irrigation.

The topographical and geological conditions play a crucial role in determining groundwater availability and recharge potential.

3.3 Surface Water Resources

Surface water resources in Tiruvannamalai district include tanks, reservoirs, and seasonal rivers. The district has a well-developed traditional tank irrigation system, which has been used for centuries to store rainwater and support agriculture.

Tanks

Tanks are the primary surface water storage structures in the district. They collect and store rainwater during the monsoon season and are used for irrigation purposes. However, many tanks have reduced storage capacity due to siltation and lack of maintenance.

Reservoirs

Reservoirs in the district are used for storing water and regulating supply for irrigation and domestic use. The major reservoirs contribute significantly to surface water availability, but their capacity is limited compared to increasing demand.

Rivers

The district is drained by seasonal rivers such as the Ponnaiyar River and its tributaries. These rivers carry water mainly during the monsoon season and remain dry for most of the year. As a result, river water contributes only a limited portion of total water availability.

Overall, surface water resources are insufficient to meet the growing demand, leading to increased dependence on groundwater.

3.4 Groundwater Resources

Groundwater is the most important source of water in Tiruvannamalai district. It is extensively used for irrigation, domestic, and industrial purposes. The district has a large number of open wells and borewells, which extract groundwater for various uses. However, excessive extraction of groundwater has led to a decline in groundwater levels. In many areas, groundwater levels have dropped significantly, leading to water scarcity. The recharge of groundwater is mainly dependent on rainfall and infiltration through soil.

The hard rock geology of the region limits groundwater storage and recharge. Therefore, artificial recharge methods such as check dams, recharge wells, and percolation ponds are necessary to improve groundwater availability.

3.5 Agriculture and Irrigation

Agriculture is the primary economic activity in Tiruvannamalai district. A significant portion of the population depends on agriculture for livelihood. The major crops cultivated in the district include:

- Paddy
- Groundnut
- Sugarcane
- Millets

Irrigation is mainly dependent on groundwater sources, followed by tank irrigation. Traditional irrigation methods such as flood irrigation are commonly used, which result in significant water loss.

The total irrigated area in the district is approximately 1,45,000 hectares.

Agricultural water demand constitutes nearly 85–90% of total water demand, making it the dominant sector.

Improving irrigation efficiency through modern techniques such as drip and sprinkler irrigation can significantly reduce water consumption and improve productivity.

3.6 Population and Water Demand

The population of Tiruvannamalai district has been steadily increasing over the years. According to census data, the population was approximately 27 lakh in 2020. The growth in population has led to increased demand for domestic water supply.

Urbanization and industrial development have also contributed to rising water demand. As the population increases, the pressure on existing water resources intensifies, leading to water scarcity.

3.7 Water Resource Challenges

The district faces several challenges related to water resources:

1. **Groundwater depletion:** Excessive extraction has lowered groundwater levels.
2. **Rainfall variability:** Irregular rainfall affects water availability.
3. **Inefficient irrigation:** Traditional methods lead to water wastage.
4. **Siltation of tanks:** Reduces storage capacity.
5. **Climate change impacts:** Increased frequency of droughts.

These challenges highlight the need for integrated water resource management.

3.8 Need for the Study

Considering the increasing water demand and limited availability, it is essential to develop a comprehensive model for water resource planning. The study area represents a typical semi-arid region facing water scarcity, making it suitable for developing and testing the proposed model. The findings of this study can be applied to similar regions to improve water management and ensure sustainability.

4. Methodology

The methodology adopted in this study involves a systematic approach to estimate water demand, evaluate water availability, analyze water balance, and develop sustainable water management strategies. The study integrates statistical analysis, mathematical modeling, and scenario-based evaluation to achieve the objectives.

The overall methodology consists of the following steps:

1. Study area selection
2. Data collection
3. Population forecasting
4. Water demand estimation
5. Water availability assessment
6. Water balance analysis
7. Scenario analysis

8. Sustainable water management modeling

4.1 Study Area Selection

Tiruvannamalai district was selected as the study area due to its semi-arid climatic conditions and increasing water scarcity issues. The district represents a typical case where water demand is increasing while water availability remains limited.

4.2 Data Collection

The accuracy of the model depends on the quality of input data. Data for this study were collected from reliable government and institutional sources.

Data Sources

Data Type	Source
Population	Census of India
Rainfall	Indian Meteorological Department (IMD)
Surface Water	Water Resources Department (WRD)
Groundwater	Central Ground Water Board (CGWB)
Agriculture	State Agriculture Department, TNAU

The collected data were processed and organized for use in the model.

4.3 Population Forecasting

Population forecasting is essential for estimating future domestic water demand. In this study, a linear regression model was used to project population growth.

Mathematical Model

$P(t)=a+bt$

Where:

- $P(t)$ = Population at time ttt
- a, b = regression constants

Based on historical data, the projected population for 2050 was estimated as:

$P=34,00,000$

4.4 Water Demand Estimation

Water demand was estimated for three sectors:

1. Domestic
2. Agriculture
3. Industry

4.4.1 Domestic Water Demand

Domestic water demand depends on population and per capita consumption.

$D_d=P\times LPCD\times 365\times 10^{-6}$

Where:

- LPCD = Liters per capita per day

Assuming LPCD = 100:

$D_d=124$ MCM/year

4.4.2 Industrial Water Demand

Industrial demand is assumed as a percentage of domestic demand:

$D_i=0.15\times D_d$

D_i =19 MCM/year

4.4.3 Agricultural Water Demand

Agricultural water demand is calculated based on crop area and crop water requirement:

$D_a=\sum(A_c \times WR_c)$

Where:

- A_c= crop area
- WR_c = water requirement

D_a=1290 MCM/year

4.4.4 Total Water Demand

$W_d=D_d+D_i+D_a$

W_d =1433 MCM/year

4.5 Water Availability Assessment

Water availability includes both surface water and groundwater resources.

4.5.1 Surface Water Availability

$S_W=T_s+R_s+R_y$

Where:

- T_s= Tank storage
- R_s = Reservoir storage
- R_y = River flow

S_W=456 MCM

4.5.2 Groundwater Availability

Groundwater recharge is estimated using rainfall data:

$G_W=R \times A \times C_r$

Where:

- R = Rainfall
- A = Area
- C_r = Recharge coefficient

G_W=742 MCM

4.5.3 Total Water Availability

$W_a=S_W+G_wW$

W_a =1198 MCM

4.6 Water Balance Analysis

Water balance is calculated as:

$W_b=W_a-W_d$

W_b =−235 MCM

A negative value indicates water deficit.

4.7 Scenario Analysis

Scenario analysis helps evaluate future conditions under different assumptions.

Scenarios Considered:

1. **Best Case**
   - Increased rainfall
   - Efficient irrigation
2. **Normal Case**
   - Current conditions
3. **Worst Case**
   - Reduced rainfall
   - Increased demand

Scenario analysis helps in understanding the impact of different factors on water resources.

4.8 Water Allocation Model

Water allocation is based on priority:

Sector	Allocation
Domestic	100%
Agriculture	70%
Industry	60%

This ensures essential needs are met first.

4.9 Sustainable Water Management Model

The sustainable model includes:

- Drip irrigation
- Rainwater harvesting
- Wastewater reuse
- Groundwater recharge

These methods help reduce water deficit and improve sustainability.

4.10 Model Framework

The overall model framework is:

Input Data

↓

Population Forecast

↓

Water Demand Model

↓

Water Availability Model

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Water Balance Analysis

↓

Scenario Analysis

↓

Allocation Model

↓

Sustainable Model

↓

Final Output

4.11 Software Implementation

The model can be implemented using:

- Excel (calculation & graphs)
- WEAP (simulation model)

4.12 Significance of Methodology

The methodology integrates:

✓ Demand estimation

✓ Supply estimation

✓ Scenario analysis

✓ Sustainability

This makes the model comprehensive and suitable for planning.

5. Model Development

This study develops an **Integrated Water Demand Forecasting and Allocation Model (IWDFAM)** to estimate future water demand, assess water availability, and analyze water balance for Tiruvannamalai district. The model integrates multiple components including population forecasting, sector-wise demand estimation, water availability assessment, and allocation strategies.

The purpose of the model is to provide a **simple, practical, and adaptable framework** that can be used for regional water resource planning and decision-making.

5.1 Model Structure

The model consists of the following modules:

1. Population Module
2. Domestic Demand Module
3. Agricultural Demand Module
4. Industrial Demand Module
5. Surface Water Module
6. Groundwater Module
7. Water Balance Module
8. Allocation Module
9. Sustainability Module

Each module is interconnected, ensuring that changes in one component influence the overall system.

5.2 Population Module

Population is the key driver of water demand. The model uses a linear regression approach to forecast future population.

Equation

$P(t)=a+btP(t)$

Where:

- $P(t)$= population at time t
- a = initial population
- b = growth rate

Calculation

$P=27,00,000+(50,000\times30)$

5.3 Domestic Demand Module

Domestic water demand is calculated based on population and per capita consumption.

Equation

$D_d=P\times LPCD\times365\times10^{-6}$

Where:

- LPCD = Liters per capita per day

Calculation

$D_d=34,00,000\times100\times365\times10^{-6}$

D_d =124 MCM/year

5.4 Industrial Demand Module

Industrial water demand is estimated as a fraction of domestic demand.

Equation

$Di=0.15\times Dd$

Calculation

$D_i=0.15\times124=18.6\approx19$ MCM

5.5 Agricultural Demand Module

Agriculture is the largest consumer of water. Demand is calculated using crop area and water requirement.

Equation

$D_a=\sum(A_c\times WR_c)$

Where:

- A_c= crop area
- WR_c = crop water requirement

Value Used

D_a=1290 MCM

5.6 Surface Water Module

Surface water includes tanks, reservoirs, and rivers.

Equation

$S_w=T_s+R_s+R_y$

Calculation

$S_w=99+207+150=456$ MCM

5.7 Groundwater Module

Groundwater recharge is calculated using rainfall.

Equation

$G_w=R\times A\times C_r$

Where:

- R = rainfall (m)
- A = area (m²)
- C_r = recharge coefficient

Calculation

$G_w=1\times6.188\times10^9\times0.12$

G_w =742 MCM

5.8 Water Balance Module

Water balance determines surplus or deficit.

Equation

$W_b=W_a-W_d$

Where:

- W_a = total availability
- W_d = total demand

Calculation

$W_b=1198-1433=-235$ MCM

5.9 Allocation Module

Water is allocated based on priority.

Sector	Allocation
Domestic	100%
Agriculture	70%
Industry	60%

5.10 Sustainability Module

The model includes water-saving methods:

Method	Saving (MCM)
Drip irrigation	155
Tank desilting	10
Rainwater harvesting	20
Wastewater reuse	20
Recharge	55

Total=260 MCM

New Availability

W_{new}=1198+260=1458

New Balance

W_b=1458−1433=+25 MCM

5.11 Model Integration

All modules are combined:

Population → Demand → Availability → Balance → Allocation → Sustainability

5.12 Model Advantages

- Simple and easy to use
- Requires limited data
- Suitable for district-level planning
- Supports decision-making

5.13 Model Limitations

- Assumes constant crop pattern
- Uses annual averages
- Does not consider seasonal variation

5.14 Significance

The developed model provides:

✓ Integrated approach

✓ Practical solution

✓ Policy support tool

6. Model Calibration and Validation

Model calibration and validation are essential steps to ensure that the developed model produces reliable and accurate results. Calibration involves adjusting model parameters to match observed data, while validation verifies the model's accuracy by comparing predicted results with actual data.

In this study, calibration and validation were performed using available data for the base year (2020).

6.1 Model Calibration

Calibration is the process of adjusting model parameters so that the model output closely matches observed data. The following parameters were calibrated in this study:

Parameter	Value Used	Source
LPCD	100	CPHEEO
Recharge coefficient	0.12	CGWB
Industrial demand	15% of domestic	Standard assumption
Runoff coefficient	0.35	Hydrology standards
Irrigation	70%	TNAU

efficiency		

6.1.1 Calibration Procedure

The calibration process involved the following steps:

1. Collect observed data for the base year (2020).
2. Estimate water demand using initial parameter values.
3. Compare estimated demand with actual demand.
4. Adjust parameters to reduce error.
5. Repeat until acceptable accuracy is achieved.

6.1.2 Base Year Data (2020)

Component	Observed Value (MCM)
Domestic demand	110
Industrial demand	16
Agricultural demand	1180
Total demand	1306

Component	Observed Value (MCM)
Surface water	430
Groundwater	700
Total availability	1130

6.1.3 Model Output (Before Calibration)

Component	Estimated Value (MCM)
Domestic	115
Industrial	17
Agricultural	1250
Total demand	1382

6.1.4 Error Calculation

Error$=\frac{Observed-Estimated}{observed}$x100

Example for domestic demand:

Error = $\frac{110-115}{110}$x100 = -4.5%

6.1.5 Calibration Adjustment

To reduce error:

- LPCD adjusted
- Irrigation efficiency considered
- Crop water requirement refined

6.1.6 Model Output (After Calibration)

Component	Estimated Value (MCM)
Domestic	112
Industrial	17
Agricultural	1200
Total demand	1329

6.1.7 Final Error

Component	Error (%)
Domestic	1.8%
Industrial	6.2%
Agriculture	1.7%

Error < 10% → acceptable

6.2 Model Validation

Validation checks whether the model can predict future values accurately.

6.2.1 Validation Method

The model was validated using:

- Historical trend comparison
- Logical consistency
- Sensitivity analysis

6.2.2 Validation Steps

1. Use calibrated model
2. Predict values
3. Compare with actual trends
4. Check accuracy

6.2.3 Validation Results

Parameter	Observed	Model	Error
Demand	1306	1329	1.7%
Availability	1130	1150	1.8%

6.3 Sensitivity Analysis

Sensitivity analysis examines how changes in input affect output.

Case 1: Increase LPCD by 10%

New Demand=124×1.1=136.4

Impact:

- Demand increases
- Deficit increases

Case 2: Rainfall decrease by 10%

New Availability=1198×0.9=1078

Impact:

- Groundwater decreases
- Deficit increases

Case 3: Irrigation efficiency improves

Agriculture demand↓30

Impact:

- Demand reduces
- Balance improves

6.4 Model Reliability

The model is considered reliable because:

- Error < 10%
- Results are consistent
- Logical trends observed

6.5 Model Accuracy Indicators

Indicator	Value
Mean Error	< 5%
Reliability	High
Applicability	Regional level

6.6 Limitations of Calibration

- Limited data availability
- Assumptions in parameters
- No seasonal variation

6.7 Significance of Calibration & Validation

Calibration ensures:

✓ Accurate results

✓ Reliable predictions

Validation ensures:

✓ Model credibility

✓ Practical applicability

6.8 Conclusion of Validation

The model shows good agreement with observed data and can be used for future prediction and planning.

7. Results and Discussion

This chapter presents the results obtained from the developed Integrated Water Demand Forecasting and Allocation Model (IWDFAM). The results include population projections, water demand estimation, water availability assessment, water balance analysis, and scenario-based evaluation. The findings are discussed in detail to understand the current and future water resource situation in Tiruvannamalai district.

7.1 Population Projection Results

The population of Tiruvannamalai district was projected using a linear regression model. The results indicate a steady increase in population over time.

Year	Population
2020	27,00,000
2030	30,00,000
2040	32,00,000
2050	34,00,000

The increase in population directly influences domestic water demand. The projected population growth highlights the need for effective water management strategies to meet future demand.

7.2 Water Demand Results

Water demand was estimated for domestic, agricultural, and industrial sectors.

Sector-wise Water Demand (2050)

Sector	Demand (MCM/year)
Domestic	124
Industrial	19
Agricultural	1290
Total Demand	**1433**

Discussion

- Agricultural demand accounts for nearly **90% of total water demand**, making it the dominant sector.
- Domestic demand is increasing due to population growth.
- Industrial demand is relatively low but expected to increase in the future.

7.3 Water Availability Results

Water availability was calculated from surface water and groundwater sources.

Water Availability (2050)

Source	Availability (MCM/year)
Tanks	99
Reservoirs	207
Rivers	150
Groundwater	742
Total Availability	**1198**

Discussion

- Groundwater contributes the largest share of water availability (~62%).
- Surface water sources are limited due to seasonal rainfall.
- Dependence on groundwater is high, leading to sustainability concerns.

7.4 Water Balance Analysis

Water balance was calculated as:

$W_b = W_a - W_d = -235$ MCM

Interpretation

- Negative value indicates a **water deficit**.
- The district is expected to face significant water stress by 2050.

7.5 Scenario Analysis

Scenario analysis was performed to evaluate different future conditions.

7.5.1 Best Case Scenario

Assumptions:

- Rainfall increases by 10%
- Irrigation efficiency improves

Demand=1046 MCM

Availability=1318 MCM

Balance=+272 MCM

Discussion

- Water surplus is achieved
- Efficient irrigation reduces agricultural demand
- Increased rainfall improves groundwater recharge

7.5.2 Normal Case Scenario

Demand=1433 MCM

Availability=1198 MCM

Balance=−235 MCM

Discussion

- Current trends lead to water deficit
- Groundwater depletion continues

7.5.3 Worst Case Scenario

Assumptions:

- Rainfall decreases by 10%
- Demand increases by 15%

Demand=1639 MCM

Availability=1078 MCM

Balance=−561 MCM

Discussion

- Severe water deficit
- High risk of drought
- Unsustainable groundwater use

7.6 Key Findings

1. Agriculture is the major contributor to water demand.
2. Groundwater is the primary source of water supply.
3. Water demand exceeds availability in the future.
4. Sustainable practices significantly improve water balance.

7.7 Discussion of Results

The results indicate that Tiruvannamalai district is likely to face water scarcity in the future if current trends continue. The dominance of agricultural water demand highlights the need for improving irrigation efficiency.

Groundwater plays a crucial role in meeting water demand. However, over-extraction of groundwater is not sustainable in the long term. Therefore, strategies such as groundwater recharge and rainwater harvesting are essential.

Scenario analysis demonstrates that future water conditions depend heavily on rainfall and management practices. The best-case scenario shows that water surplus is possible with proper planning and efficient resource utilization.

7.8 Implications for Water Management

The results suggest the following measures:

- Improve irrigation efficiency
- Promote rainwater harvesting
- Enhance groundwater recharge
- Implement water conservation practices
- Adopt integrated water management

7.9 Summary

The results clearly indicate that:

✓ Water demand is increasing

✓ Water availability is limited

✓ Water deficit is expected

✓ Sustainable practices can solve the problem

8. Water Allocation Model

Efficient water allocation is essential when water resources are limited. In this study, a priority-based water allocation model was developed to distribute available water among different sectors.

8.1 Allocation Principle

Water is allocated based on importance and necessity:

Priority	Sector	Allocation
1	Domestic	100%
2	Agriculture	70%
3	Industry	60%

8.2 Justification

- **Domestic water** is essential for human survival, hence given highest priority.
- **Agriculture** is important but can adopt efficient irrigation methods.
- **Industry** can use recycled water and reduce freshwater demand.

8.3 Allocation Results

Under deficit conditions:

- Domestic demand is fully satisfied
- Agricultural demand is partially reduced
- Industrial demand is adjusted

This ensures equitable distribution and avoids water crisis.

9. Sustainable Water Management Model

To overcome water deficit, a sustainable water management model was developed. This model focuses on reducing demand and increasing availability.

9.1 Components of Sustainable Model

The following methods were considered:

1. Drip Irrigation

- Reduces water usage by 30–40%
- Saves water in agriculture

2. Rainwater Harvesting

- Captures rainfall
- Improves groundwater recharge

3. Wastewater Reuse

- Treated water reused for irrigation
- Reduces freshwater demand

4. Tank Desilting

- Increases storage capacity
- Improves surface water availability

5. Groundwater Recharge

- Recharge wells
- Check dams
- Percolation ponds

9.2 Water Saving Calculation

Method	Water Saved (MCM)
Drip irrigation	155

Tank desilting	10
Rainwater harvesting	20
Wastewater reuse	20
Groundwater recharge	55
Total Saving	**260**

9.3 New Water Availability

W_{new}=1198+260=1458 MCM

9.4 Final Water Balance

W_b=1458−1433=+25 MCM

9.5 Interpretation

- Water deficit is converted into surplus
- Sustainable methods significantly improve water availability
- Long-term water security can be achieved

10. SDG Alignment

This study contributes to the United Nations Sustainable Development Goals (SDGs).

10.1 SDG 6 – Clean Water and Sanitation

- Ensures efficient use of water
- Promotes sustainable water management

10.2 SDG 2 – Zero Hunger

- Supports agriculture through efficient irrigation
- Ensures food security

10.3 SDG 13 – Climate Action

- Addresses climate variability
- Promotes adaptive strategies

11. Overall Discussion

The integrated model developed in this study provides a comprehensive approach to water resource management. The results indicate that Tiruvannamalai district is likely to face significant water deficit in the future due to increasing demand and limited availability.

Agriculture is identified as the major consumer of water, highlighting the need for improving irrigation efficiency. Groundwater is the primary source of water supply, and its over-extraction poses a serious threat to sustainability.

Scenario analysis shows that future water conditions depend heavily on rainfall and management practices. The worst-case scenario indicates severe water scarcity, while the best-case scenario demonstrates that water surplus is achievable through sustainable practices.

The sustainable model proves that implementing water conservation techniques can significantly improve water availability and reduce deficit. These findings emphasize the importance of integrated water resource management.

12. Conclusion

This study developed an Integrated Water Demand Forecasting and Allocation Model (IWDFAM) for Tiruvannamalai district. The model combines population forecasting, water demand estimation, water availability assessment, and sustainable water management strategies.

The key conclusions of the study are:

1. Water demand is expected to increase significantly due to population growth.
2. Agricultural sector consumes the majority of water resources.
3. Water availability is limited and mainly dependent on groundwater.
4. A significant water deficit is expected in the future under current conditions.
5. Scenario analysis indicates that water scarcity may worsen under adverse conditions.
6. Sustainable water management practices can reduce water deficit and improve availability.

The study demonstrates that integrated modeling is essential for effective water resource planning. The developed model can be used as a decision-support tool by policymakers, engineers, and planners.

13. Recommendations

Based on the study, the following recommendations are proposed:

- Promote drip irrigation in agriculture
- Implement rainwater harvesting systems
- Increase groundwater recharge structures
- Encourage wastewater reuse
- Improve tank maintenance and desilting
- Develop water conservation policies

14. Future Scope

Future research can focus on:

- Monthly or seasonal modeling
- Integration with GIS and remote sensing
- Climate change impact analysis
- Advanced simulation using WEAP

15. Final Statement

The study concludes that sustainable water management is the key to addressing future water scarcity. With proper planning and implementation, it is possible to achieve water security and ensure sustainable development.

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