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ARTICLE

Transient analysis of a smart stochastic model for tube-wells integrated with underground pipeline for sustainable agriculture[1]

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Abstract
The consistent supply of water for irrigation is essential in agriculture to enhance production. There are many methods of irrigation, but using tube-wells along with underground pipelines has become a useful way to deal with water scarcity and provide a steady supply of water for farming. This research studies the factors that affect reliability and availability, with the aim of finding ways to improve the performance of these components and support the long-term sustainability of agricultural water supply systems. This research studies the factors that affect reliability and availability, with the aim of finding ways to improve the performance of these components and support the long-term sustainability of agricultural water supply systems. This paper proposed a smart model for the availability enhancement of tube-wells integrated with underground pipelines (TIUP). The study focuses on key components, including tube-wells, pump sets, sensors, control units, Raspberry Pi units, centrifugal pumps, pipelines, and human resources. A mathematical framework has been formulated employing the birth-death stochastic process, integrated with Chapman-Kolmogorov differential equations to model the system dynamics. The failure and repair rates are assumed to adhere to an exponential distribution, with repair processes considered ideal and fully restorative. To obtain an optimal numerical solution, the fourth-order Runge-Kutta method is utilized. A comprehensive analysis is conducted to examine the impact of the coverage factor on system availability by systematically varying failure and repair rates. The analysis showed that the TIUP system achieved high availability of 0.9966 at $\tau = 0.8$, which further improved to 0.9974 with enhanced repair rates. In contrast, availability decline from 0.9915 at $\tau = 0.5$ to 0.9865 at $\tau = 0.2$, emphasizing the importance of repair efficiency and redundancy in sustaining system reliability. The insights derived from this study provide valuable guidance for agriculture system engineers and policymakers, facilitating strategic planning for enhancing the reliability and sustainability of TIUPs, thereby ensuring an uninterrupted water supply for agricultural applications.

Keywords: Availability; Markov birth-death process; Tube-well integrated underground pipeline (TIUP); Chapman-Kolmogorov differential equations; Runge-Kutta method.

1. Introduction

The agriculture sector stands at a crucial juncture, where the demand for food is rapidly rising due to global population growth, while the resources like needed to meet this demand, particularly water, are steadily declining. Water scarcity is no longer an isolated issue but has become one of the defining challenges of our time. Since agriculture accounts for a major share of global water consumption, optimizing its use has become essential. Traditional irrigation methods have lost favor because of their inefficiencies, often resulting in significant water wastage through evaporation, runoff, and uneven distribution.

In this context, tube-wells integrated with underground pipelines (TIUPs) have emerged as a promising solution, not only reducing water wastage but also improving the precision and control of water delivery in farming. These pipelines, supported by a complex network of components, play a vital role in ensuring a reliable and continuous water supply for crop cultivation. The reliability and availability of TIUPs depend on the performance of each individual component, which collectively determines the system's overall effectiveness. The smooth functioning of tube-wells, pump sets, sensors, control units, Raspberry Pi units, centrifugal pumps, pipelines, and human intervention is crucial for maintaining uninterrupted water supply. Each of these components presents its own challenges and opportunities, making component-level analysis both essential and highly relevant for optimizing system performance.

This study focuses on the detailed assessment of availability at the component level, offering meaningful insights into the sustainability of agricultural water delivery systems. Within the domain of performance analysis, numerous techniques for evaluating availability have already been proposed by researchers, providing a strong foundation for this investigation. Elshaboury *et al.* (2021) introduced a framework that assessed the mechanical and hydraulic reliabilities of water networks to address worldwide challenges of structural deterioration and insufficient investment. It enabled ranking and prioritization based on these reliabilities by evaluating components through a fuzzy analytical network process and minimum cut set analysis. Jawwad *et al.* (2021) proposed a cost-effective IoT solution named smart tube-well for water grid management, featuring sensor nodes and an AWS application layer. A comparison with SCADA highlighted smart tubewell's cost-effectiveness. Saini *et al.* (2023) analyzed the reliability of a cloud infrastructure with five subsystems by applying cold standby redundancy to enhance tolerance. Hussainy and Shabeer (2021) examined stochastic processes for modeling repairable system reliability and focused on point processes, presenting them as examples for supporting maintenance decisions. Das *et al.* (2020) introduced an advanced reliability function to refine reliability estimation, incorporating diverse design parameters to enhance multi-state computational grid efficiency. Kumar and Saini (2018) conducted a stochastic analysis of computing systems, integrating imperfect fault detection and specialized repair mechanism by utilizing semi-Markov process and regenerative point techniques. Park *et al.* (2020) developed a decision-making framework for underground pipeline management, addressing the trade-offs between risk mitigation and maintenance expenses. The proposed model factored in target reliability, consequences, and cost parameters to optimize operational strategies. Maan *et al.* (2022) explored fuzzy reliability metrics within a semi-Markovian framework, accounting for partial system failures, inspections, and adverse environmental conditions. Saini *et al.* (2022) proposed an Efficient and Intelligent Irrigation System (EIIS), designed with a series configuration of five components with additional units in cold standby and optimize the availability of system by applying Grey Wolf Optimization (GWO) and dragonfly algorithm (DA). Kumar *et al.* (2022) developed a stochastic optimization model for sludge digestion processing system (SDPS) by using Genetic Algorithm (GA). Saini *et al.* (2021) proposed a fuzzy reliability model to improve reliability assessment for highly intricate systems like configuration of data centers. Orojloo *et al.* (2018) introduced a comprehensive risk management framework for irrigation canal networks, employing a fuzzy hierarchical approach. Saad and Gamatie (2020) conducted a systematic survey on water management and monitoring in agriculture, exploring cutting-edge technologies such as IoT, WSN, and Cloud Computing to revolutionize agricultural water resource management. The key objective was to explore how these technologies optimized water usage, enhanced crop quality and quantity, and minimized human intervention, while addressing challenges such as water pollution, reuse, and distribution network monitoring.

Rashid and Hossain (2019) developed a sequential irrigation management system for the drought-prone area in Bangladesh. This included enhancing groundwater resources, augmenting surface water, rainwater harvesting, and efficient water distribution. Sikka *et al.* (2022) addressed the impact of climate change on water and agriculture through science-based agriculture water management (AWM) practices. Two methods were discussed to prioritize location-specific AWM practices one is stakeholder analysis and a water balance-based method. Sidhu *et al.* (2021) addressed the challenges posed by water scarcity in agriculture by examining efficient water management methods, with a specific focus on drip irrigation. The study systematically synthesized recent advancements in precision water management and automation of drip irrigation systems, offering valuable insights for researchers and policymakers. Goyal *et al.* (2019) employed reliability, availability, maintainability, and dependability (RAMD) analysis to ensure efficient performance of sewage treatment plant. This study filled a literature gap, providing insight into the RAMD analysis of sewage treatment plant physical processing units, aiding plant designers. Kumar *et al.* (2017) presented a mathematical model that considered an essential aspect of switching, accounting for actual failures in adjacent transitions through two distinct failure types. The evaluation utilized the Gumbel-Hougaard family of copula to enhance applicability and accuracy. Singh *et al.* (2020) focused on analyzing the reliability of a complex system composed of two subsystems, each configured differently. The influence of different failures and repair rate distributions was explored, and specific cases involving the switching device were examined and graphically presented. Kumar *et al.* (2022) conducted a comprehensive RAMD analysis and Failure Modes and Effects Analysis (FMEA) for Tube-wells Integrated with Underground Pipelines (TIUP). Shah (2020) discussed the evolving challenges in irrigation management in South Asian countries. It highlighted the need for a paradigm shift in water policy, considering the changing landscape of groundwater usage and climate change impacts on hydro-climatic patterns and aquifer systems.

By keeping above facts in mind, the present study proposed a smart model for availability enhancement of tube-wells integrated with underground pipelines. The study focuses on key components including tube-wells, pump sets, sensors, control units, Raspberry Pi units, centrifugal pumps, pipelines, and human resources. A mathematical model is proposed using birth-death process and Chapman-Kolmogorov differential equations derived. The findings are helpful for agricultural system designers and policy makers to make the provision for consistent water supply through providing reliable TIUPs. The present analysis has been developed under the assumption that both failure and repair times of system components follow an exponential distribution. This assumption provides mathematical tractability due to the memoryless property of the exponential law and its straightforward integration with the birth–death process. However, in real-world applications, this simplification may not fully capture the behavior of mechanical and electronic components. For instance, pumps and motors often experience wear-out failures, which are more accurately represented by the Weibull distribution commonly used in reliability engineering studies. Similarly, repair processes involving human intervention or spare part availability may follow Lognormal or Normal distributions rather than the exponential. Future extensions of the proposed model could incorporate these alternative lifetime distributions through generalized stochastic processes or simulation-based approaches, thereby enhancing the novelty and applicability of the TIUP availability analysis. The numerical solution of the proposed model is derived using Runge-Kutta 4^{th} order. The effect of coverage factor on availability of system is analyzed by changing the coverage factor, failure rates and repair rates.

The entire manuscript is organized into comprehensive structure comprising five distinct sections. The initial section, denoted as Section 1, serves as a platform for introducing the subject matter and providing an insightful review of the relevant literature. Section 2 seamlessly integrates an elaborate presentation of the materials employed in the study, notations and system description. Section 3 concludes a sophisticated stochastic model development and analysis. The analytical journey advances in Section 4, where the compilation of numerical findings is thoughtfully exhibited. Finally, Section 5 contains the conclusion part.

2. Materials and Methods

In this section, the useful material and techniques are incorporated for the investigation of TIUPs.

2.1 Notations

The following notations are used to develop the state transition diagram and mathematical model corresponding to TIUP system.

Table 1. Notations for the TIUP system

Sr. no.	Sub-systems and configuration	Notations of different states		Failure rates (α_i)	Repair rates (β_j)
		Operative state/Standby state	Complete failed state		
1	Electric pump/motor	P	p	α_1	β_1
2	Diesel pump operative /Standby	Q/Q$_1$	q	α_2	β_2
3	Sensor unit 1	R	r	α_3	β_3
4	Sensor unit 2 operative /Standby	S/S$_1$	s	α_3	β_3
5	Control unit	T	t	α_4	β_4
6	Tube-well 1	U	u	α_5	β_5
7	Tube-well 2 operative /Standby	V/V$_1$	v	α_6	β_6
8	Centrifugal pump unit	W	w	α_7	β_7
9	Pipe-line	X	x	α_8	β_8
7	Manpower	Y	y	α_9	β_9

2.2 System Description

The proposed TIUP system is composed of a several integrated subsystems, namely the power generation unit, sensor module, control units (based on Raspberry Pi technology), tube-wells, centrifugal pumps, underground pipelines, and dedicated manpower for supervision and maintenance. Together, these seven subsystems form the backbone of the TIUP configuration. The functioning of each subsystem is interdependent, meaning that the performance of one directly influences the overall system. For example, pump failure results in water unavailability even if tube-wells and sensors remain functional, whereas control unit malfunction can disrupt coordinated operation despite the availability of other components. These interdependencies are mathematically represented in the birth–death process through state transitions, where the failure of a single unit moves the system into a degraded state with reduced availability. The coverage factor in the model further captures redundancy by allowing operational tube-wells to partially compensate for failed ones.

These sub-systems are organized in a series configuration. The breakdown of subsystems T, W, X, and Y results in the failure of the entire system. However, the power generation unit, sensor unit and tube-wells are structured as a 1-out-of-2: G configuration. A comprehensive illustration detailing the flowchart and the operational role of each component is presented in Figure 1.

2.2.1 *Power Generation Unit (Subsystem P and Q)*

The power generation unit is pivotal in the integrated underground pipeline system for agriculture, driven by electric motors and diesel pumps. It supplies the energy required to lift water from underground sources for irrigation. Electric motors are efficient and eco-friendly, while diesel pumps act as backups during power shortages. This synergy ensures a constant water supply, supporting seamless irrigation and sustainable farming. Electric motors serve as the primary power source (P), while diesel pumps function as standby units. Their distinct failure and repair rates are considered, and this dynamic combination ensures reliable water distribution, helping farmers optimize yields and strengthen food production resilience.

2.2.2 Sensor Unit (Subsystem R and S)

The sensor unit also plays a pivotal role in the integrated underground pipeline system for agriculture. It gathers vital data on temperature, humidity, and soil conditions to enable precision farming. Real-time monitoring supports informed irrigation decisions, thereby optimizing water use and crop yields. The proposed system includes two sensor units, one operational and the other on standby. This configuration enhances overall system availability and reinforces the impact of TIUPs on agricultural practices.

2.2.3 Control Unit (Subsystem T)

The control unit is a compact computer device, the Raspberry Pi, which assumes a vital role in the TIUP system for agriculture. Acting as the central hub, it coordinates all system components. Its main function is to collect data from distributed sensors, enabling precise actions for efficient irrigation and resource allocation. Real-time decisions based on sensor data improve water distribution. By interfacing sensors and enacting timely responses, the control unit boosts system intelligence, ensuring effective water management and enhancing agricultural productivity within the TIUP framework.

2.2.4 Tube-wells (Subsystem U and V)

Tube-wells are crucial pillars of the integrated underground pipeline system in agriculture. The proposed TIUP system incorporates two tube-wells, one with a depth of 60 metres and the other with a depth of 150 meters. Depending on requirements, either one or both may be used. However, failure of both tube-wells results in complete system shutdown.

2.2.5 Centrifugal Pump (Subsystem W)

The centrifugal pump unit is of pivotal significance within the tube-well–integrated underground pipeline system for agriculture. Serving as the system's workhorse, it efficiently lifts groundwater from underground sources to the fields. Its primary function is to ensure a consistent and reliable water supply for irrigation, which is vital for crop growth. Failure of this unit leads to total system failure.

2.2.6 Pipelines (Subsystem X)

The pipeline unit is an integral part of the tube-well–integrated underground pipeline system for agriculture. Acting as conduits, pipelines transport water seamlessly from tube-wells to fields. This network ensures efficient distribution, minimizes wastage, and optimizes irrigation practices. The pipelines enable controlled water flow, thereby enhancing crop yields and contributing to sustainable farming. Failure of this subsystem can halt the entire TIUP process.

2.2.7 Manpower (Subsystem Y)

Manpower is a critical element in the tube-well–integrated underground pipeline system for agriculture. Skilled individuals are essential for installation, maintenance, and troubleshooting. Their expertise ensures the proper functioning of pumps, regular pipeline inspections, and timely resolution of technical issues. Their contribution guarantees efficient system performance, improving water distribution and supporting sustainable agricultural practices. This subsystem is considered an integral unit, and its failure can result in complete system breakdown.

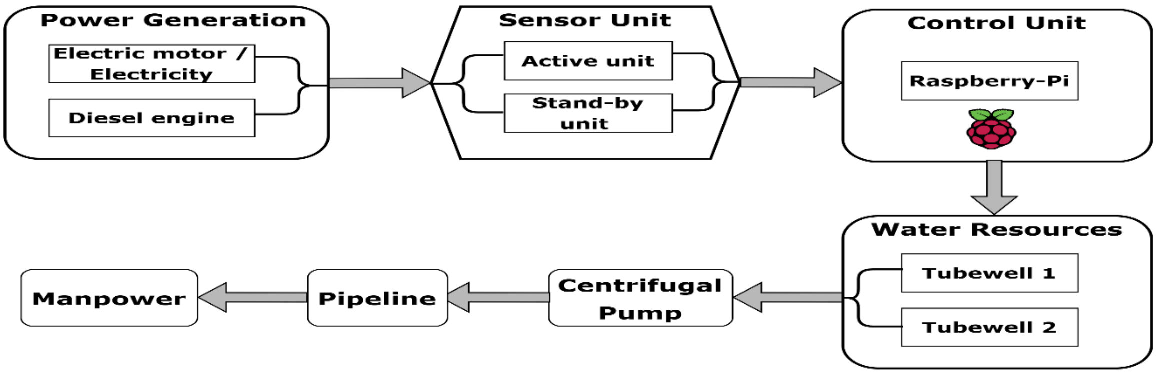

Figure 1. Flow chart of TIUP sub-components.

3. Mathematical Modeling and Analysis

Here In this section, a mathematical model is developed to investigate the reliability and performance behavior of the TIUP system under varying conditions. This model is created by employing the Markovian birth-death process. The Chapman-Kolmogorov differential-difference equations are derived according to the state transition diagram depicted in Figure-2. This combination of approaches enables a full understanding of the TIUP systems.

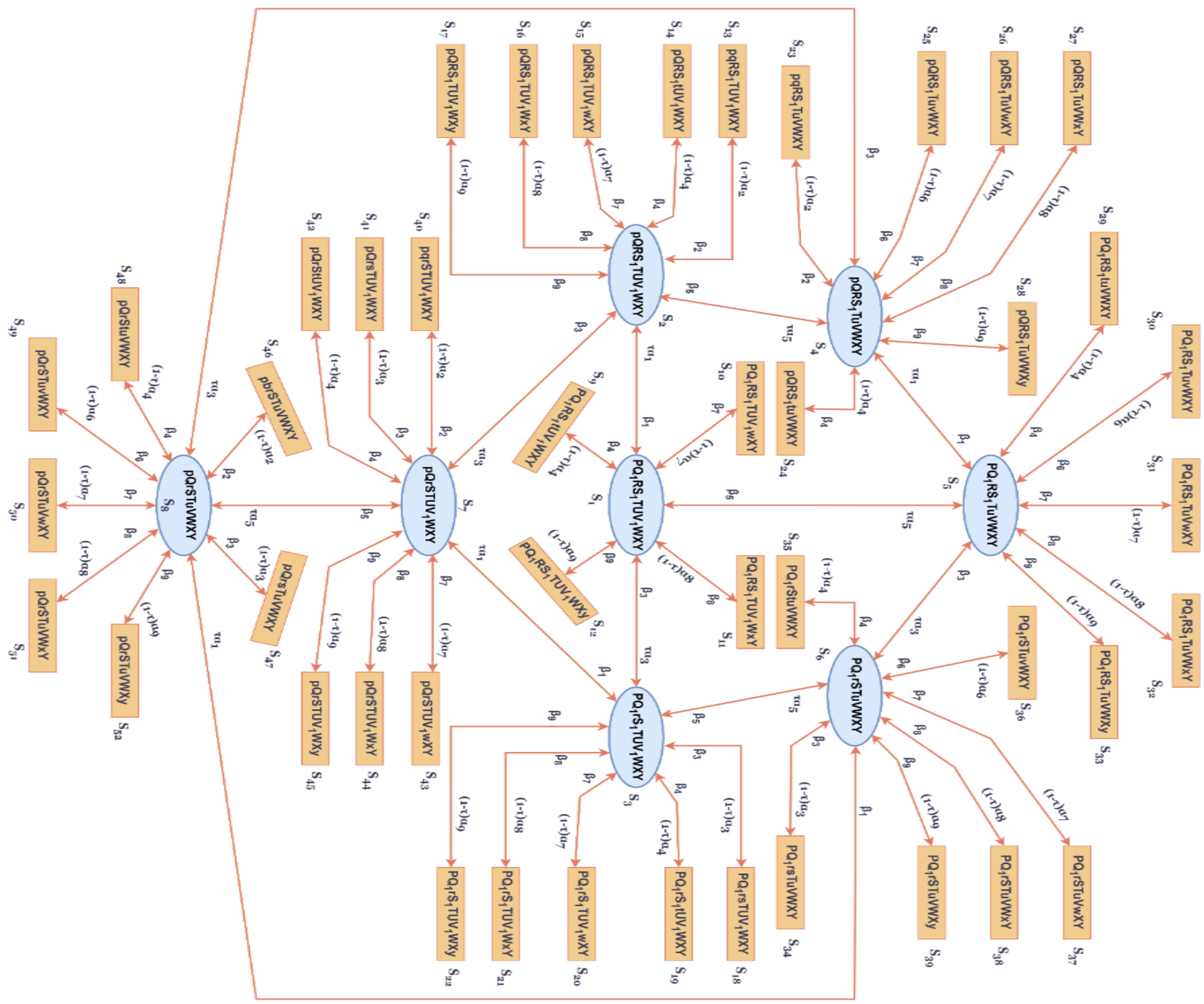

Figure 2. Steady state diagram of TIUP system.

As an illustration the Chapman-Kolmogorov differential-difference equation at state S_1 is shown below and similar methodology is adopted for the other states.
By simple probabilistic arguments:

$$\boldsymbol{P_1(t+\Delta t) = (1-\tau\alpha_1\Delta t-\tau\alpha_3\Delta t-(1-\tau)\alpha_4\Delta t-\tau\alpha_5\Delta t-(1-\tau)\alpha_7\Delta t-(1-\tau)\alpha_8\Delta t-(1-\tau)\alpha_9\Delta t)P_1(t)+\beta_1P_2(t)\Delta t+\beta_3P_3(t)\Delta t+\beta_4P_9(t)\Delta t+\beta_5P_5(t)\Delta t+\beta_7P_{10}(t)\Delta t+\beta_8P_{11}(t)\Delta t+\beta_9P_{12}(t)\Delta t} \quad (1)$$

Solving (1) by taking limit $\lim_{t\to\infty}$, we get

$$\boldsymbol{(\tau\alpha_1+\tau\alpha_3+(1-\tau)\alpha_4+\tau\alpha_5+(1-\tau)\alpha_7+(1-\tau)\alpha_8+(1-\tau)\alpha_9)P_1 = \beta_1P_2+\beta_3P_3+\beta_4P_9+\beta_5P_5+\beta_7P_{10}+\beta_8P_{11}+\beta_9P_{12}} \quad (2)$$

Similarly,

$$\boldsymbol{(\beta_1+(1-\tau)\alpha_2+\tau\alpha_3+(1-\tau)\alpha_4+\tau\alpha_5+(1-\tau)\alpha_7+(1-\tau)\alpha_8+(1-\tau)\alpha_9)P_2 = \tau\alpha_1P_1+\beta_2P_{13}+\beta_3P_7+\beta_4P_{14}+\beta_5P_4+\beta_7P_{15}+\beta_8P_{16}+\beta_9P_{17}} \quad (3)$$

$$\boldsymbol{(\tau\alpha_1+\beta_3+(1-\tau)\alpha_3+(1-\tau)\alpha_4+\tau\alpha_5+(1-\tau)\alpha_7+(1-\tau)\alpha_8+(1-\tau)\alpha_9)P_3 = \beta_1P_7+\tau\alpha_3P_1+\beta_3P_{18}+\beta_4P_{19}+\beta_5P_6+\beta_7P_{20}+\beta_8P_{21}+\beta_9P_{22}} \quad (4)$$

$$(\beta_1+(1-\tau)\alpha_2+\tau\alpha_3+(1-\tau)\alpha_4+\beta_5+(1-\tau)\alpha_6+(1-\tau)\alpha_7+(1-\tau)\alpha_8+(1-\tau)\alpha_9)P_4 = \tau\alpha_1P_5+\beta_2P_{23}+\beta_3P_8+\beta_4P_{24}+\tau\alpha_5P_2+\beta_6P_{25}+\beta_7P_{26}+\beta_8P_{27}+\beta_9P_{28} \quad (5)$$

$$(\tau\alpha_1+\tau\alpha_3+(1-\tau)\alpha_4+\beta_5+(1-\tau)\alpha_6+(1-\tau)\alpha_7+(1-\tau)\alpha_8+(1-\tau)\alpha_9)P_5 = \beta_1P_4+\beta_3P_6+\beta_4P_{29}+\tau\alpha_5P_1+\beta_6P_{30}+\beta_7P_{31}+\beta_8P_{32}+\beta_9P_{33} \quad (6)$$

$$(\tau\alpha_1+\beta_3+(1-\tau)\alpha_3+(1-\tau)\alpha_4+\beta_5+(1-\tau)\alpha_6+(1-\tau)\alpha_7+(1-\tau)\alpha_8+(1-\tau)\alpha_9)P_6 = \beta_1P_8+\tau\alpha_3P_5+\beta_3P_{34}+\beta_4P_{35}+\tau\alpha_5P_3+\beta_6P_{36}+\beta_7P_{37}+\beta_8P_{38}+\beta_9P_{39} \quad (7)$$

$$(\beta_1+(1-\tau)\alpha_2+(1-\tau)\alpha_3+\beta_3+(1-\tau)\alpha_4+\tau\alpha_5+(1-\tau)\alpha_7+(1-\tau)\alpha_8+(1-\tau)\alpha_9)P_7 = \tau\alpha_1P_3+\beta_2P_{40}+\beta_3P_{41}+\tau\alpha_3P_2+\beta_4P_{42}+\beta_5P_8+\beta_7P_{43}+\beta_8P_{44}+\beta_9P_{45} \quad (8)$$

$$(\beta_1+(1-\tau)\alpha_2+\beta_3+(1-\tau)\alpha_3+(1-\tau)\alpha_4+\beta_5+(1-\tau)\alpha_6+(1-\tau)\alpha_7+(1-\tau)\alpha_8+(1-\tau)\alpha_9)P_8 = \tau\alpha_1P_6+\beta_2P_{46}+\tau\alpha_3P_4+\beta_3P_{47}+\beta_4P_{48}+\tau\alpha_5P_7+\beta_6P_{49}+\beta_7P_{50}+\beta_8P_{51}+\beta_9P_{52} \quad (9)$$

$$\alpha_4P_1 = \beta_4P_9 \quad (10)$$

$$\textstyle\sum_{a=7}^{9}\alpha_aP_1 = \sum_{b=7}^{9}\beta_bP_{b+3} \quad (11)$$

$$\alpha_2P_2 = \beta_2P_{13} \quad (12)$$

$$\alpha_4P_2 = \beta_4P_{14} \quad (13)$$

$$\textstyle\sum_{c=7}^{9}\alpha_cP_2 = \sum_{d=7}^{9}\beta_dP_{d+8} \quad (14)$$

$$\alpha_3P_3 = \beta_3P_{18} \quad (15)$$

$$\alpha_4P_3 = \beta_4P_{19} \quad (16)$$

$$\textstyle\sum_{e=7}^{9}\alpha_eP_3 = \sum_{f=7}^{9}\beta_fP_{f+13} \quad (17)$$

$$\alpha_2 P_4 = \beta_2 P_{23} \tag{18}$$

$$\alpha_4 P_4 = \beta_4 P_{24} \tag{19}$$

$$\alpha_6 P_4 = \beta_6 P_{25} \tag{20}$$

$$\sum_{g=7}^{9} \alpha_g P_4 = \sum_{h=7}^{9} \beta_h P_{h+19} \tag{21}$$

$$\alpha_4 P_5 = \beta_4 P_{29} \tag{22}$$

$$\alpha_6 P_5 = \beta_6 P_{30} \tag{23}$$

$$\sum_{i=7}^{9} \alpha_i P_5 = \sum_{j=7}^{9} \beta_j P_{j+24} \tag{24}$$

$$\alpha_3 P_6 = \beta_3 P_{34} \tag{25}$$

$$\alpha_4 P_6 = \beta_4 P_{35} \tag{26}$$

$$\alpha_6 P_6 = \beta_6 P_{36} \tag{27}$$

$$\sum_{k=7}^{9} \alpha_k P_6 = \sum_{l=7}^{9} \beta_l P_{l+30} \tag{28}$$

$$\sum_{m=2}^{4} \alpha_m P_7 = \sum_{n=2}^{4} \beta_n P_{n+38} \tag{29}$$

$$\sum_{o=7}^{9} \alpha_o P_7 = \sum_{\mathrm{p}=7}^{9} \beta_{\mathrm{p}} P_{\mathrm{p}+36} \tag{30}$$

$$\sum_{\mathrm{q}=2}^{4} \alpha_{\mathrm{q}} P_8 = \sum_{\mathrm{r}=2}^{4} \beta_{\mathrm{r}} P_{\mathrm{r}+44} \tag{31}$$

$$\alpha_6 P_8 = \beta_6 P_{49} \tag{32}$$

$$\sum_{\mathrm{s}=7}^{9} \alpha_{\mathrm{s}} P_8 = \sum_{\mathrm{t}=7}^{9} \beta_{\mathrm{t}} P_{\mathrm{t}+43} \tag{33}$$

The initial conditions for the system are as below

$$P_\xi(0) = \begin{cases} 1 & if \quad \xi = 0 \\ 0 & if \quad \xi \neq 0 \end{cases} \tag{34}$$

Using normalizing condition $\sum_{\xi=1}^{52} P_\xi = 1$, that is, the sum of all the transition probabilities is equal to 1. The availability expression of TIUP system is given as follows:

$$A_\theta = P_1 + P_2 + P_3 + P_4 + P_5 + P_6 + P_7 + P_8 \tag{35}$$

As the above mathematical model and availability expression mentioned in (35), is very complex and its algebraical solution is very tedious. So, here an effort is made to derive the transient availability of the system using Runge-Kutta method of 4th order with the help of MATLAB software.

4. Numerical Results and Discussion

In this section, the availability of TIUP system is derived for a particular case by using Runge-Kutta method of 4th order with help of MATLAB software. The arbitrary values of repair and failure rates of subsystems collected with the help of farmers, literature, and TIUP plant personals are given in table-2.

Table-2. Failure and repair rates for all the subsystems of TIUPs.

Sr. no.	Sub-systems	Failure rates (α_i)	Repair rates (β_i)
1	Electric pump/motor (P)	α_1= 0.0032	β_1= 1.06
2	Standby diesel pump (Q)	α_2= 0.0026	β_2= 0.72
3	Sensors unit (R)	α_3= 0.0018	β_3= 0.96
4	Standby sensor unit (S)	α_3= 0.0018	β_3= 0.96
5	Control unit (T)	α_4= 0.0028	β_4= 1.18
6	Tube-well 1 (U)	α_5= 0.00094	β_5= 0.82
7	Tube-well 2 (V)	α_6= 0.00098	β_6= 0.76
8	Centrifugal pump unit (W)	α_7= 0.0048	β_7= 0.98
9	Pipe-line (X)	α_8= 0.0022	β_8= 1.12
10	Manpower (Y)	α_9= 0.0066	β_9= 0.84

Table 3. Impact of variation failure rates on the availability of TIUP system with respect to at coverage factor τ=0.8

Time (In days)	Base value	α_1+10% α_1	α_2+10% α_2	α_3+10% α_3	α_4+10% α_4	α_5+10% α_5	α_6+10% α_6	α_7+10% α_7	α_8+10% α_8	α_9+10% α_9
0	1	1	1	1	1	1	1	1	1	1
5	0.996624	0.996623	0.996623	0.996623	0.996577	0.996624	0.996624	0.996527	0.996585	0.996470
10	0.996590	0.996590	0.996590	0.996590	0.996543	0.996590	0.996590	0.996493	0.996551	0.996434
15	0.996590	0.996590	0.996590	0.996590	0.996543	0.996590	0.996590	0.996493	0.996551	0.996434
20	0.996590	0.996590	0.996590	0.996590	0.996543	0.996590	0.996590	0.996493	0.996551	0.996434
25	0.996590	0.996590	0.996590	0.996590	0.996543	0.996590	0.996590	0.996493	0.996551	0.996434

Time	Base value	α_1+50% α_1	α_2+50% α_2	α_3+50% α_3	α_4+50% α_4	α_5+50% α_5	α_6+50% α_6	α_7+50% α_7	α_8+50% α_8	α_9+50% α_9
0	1	1	1	1	1	1	1	1	1	1
5	0.996624	0.996623	0.996623	0.996623	0.996389	0.996623	0.996623	0.996141	0.996429	0.995855
10	0.996590	0.996590	0.996590	0.996590	0.996355	0.996590	0.996590	0.996104	0.996395	0.995811
15	0.996590	0.996589	0.996589	0.996589	0.996355	0.996590	0.996590	0.996104	0.996395	0.995810
20	0.996590	0.996589	0.996589	0.996589	0.996355	0.996590	0.996590	0.996104	0.996395	0.995810
25	0.996590	0.996589	0.996589	0.996589	0.996355	0.996590	0.996590	0.996104	0.996395	0.995810

Time	Base value	α_1+100% α_1	α_2+100% α_2	α_3+100% α_3	α_4+100% α_4	α_5+100% α_5	α_6+100% α_6	α_7+100% α_7	α_8+100% α_8	α_9+100% α_9
0	1	1	1	1	1	1	1	1	1	1
5	0.996624	0.996622	0.996622	0.996622	0.996154	0.996623	0.996623	0.995659	0.996235	0.995088
10	0.996590	0.996589	0.996589	0.996589	0.996119	0.996590	0.996590	0.995619	0.996200	0.995032
15	0.996590	0.996588	0.996588	0.996589	0.996119	0.996590	0.996590	0.995618	0.996200	0.995032
20	0.996590	0.996588	0.996588	0.996589	0.996119	0.996590	0.996590	0.995618	0.996200	0.995032
25	0.996590	0.996588	0.996588	0.996589	0.996119	0.996590	0.996590	0.995618	0.996200	0.995032

The effect of the change in the failure rates at the coverage factor τ = 0.8 on the TIUP system availability is observed based on numerical results appended in table 3. It is observed that availability of TIUP system decreases with respect to time as well as with the increase in failure rates of the subsystems of TIUP. It is observed that system availability at any specific time point is declined rapidly with the increase in the failure rate of any subsystem. The availability is rapidly decline after making 100% variation in the failure rate of manpower. The effect of variation at 10%, 50%, and 100% in failure rate is investigated on system availability. From table 4, it is observed that how system availability changes over time as we increase the repair rates of different subsystems while keeping a coverage factor of 0.8 constant. As repair rates rise, the availability of TIUP and its subsystems increase. This means that as we focus on faster repairs, the system becomes more reliable and accessible, ensuring smoother operation and better performance for the integrated system. When repair rates increase the availability of subsystem manpower (Y) and centrifugal pump (W) affected more among all others. It is observed that availability of subsystems increases with the increment in repair rates.

Table 4. Impact of variation repair rates on the availability of TIUP system with respect to at coverage factor $\tau = 0.8$

Time (in days)	Base value	β_1+10% β_1	β_2+10% β_2	β_3+10% β_3	β_4+10% β_4	β_5+10% β_5	B_6+10% β_6	β_7+10% β_7	β_8+10% β_8	β_9+10% β_9
0	1	1	1	1	1	1	1	1	1	1
5	0.996624	0.996624	0.996624	0.996624	0.996666	0.996624	0.996624	0.996709	0.996658	0.996756
10	0.996590	0.996591	0.996591	0.996591	0.996633	0.996591	0.996591	0.996679	0.996626	0.996732
15	0.996590	0.996590	0.996590	0.996590	0.996633	0.996590	0.996590	0.996679	0.996626	0.996732
20	0.996590	0.996590	0.996590	0.996590	0.996633	0.996590	0.996590	0.996679	0.996626	0.996732
25	0.996590	0.996590	0.996590	0.996590	0.996633	0.996590	0.996590	0.996679	0.996626	0.996732

Time	Base value	β_1+50% β_1	β_2+50% β_2	β_3+50% β_3	β_4+50% β_4	β_5+50% β_5	B_6+50% β_6	β_7+50% β_7	β_8+50% β_8	β_9+50% β_9
0	1	1	1	1	1	1	1	1	1	1
5	0.996624	0.996624	0.996624	0.996623	0.996779	0.996624	0.996624	0.996941	0.996752	0.997123
10	0.996590	0.996591	0.996591	0.996591	0.996748	0.996591	0.996591	0.996915	0.996720	0.997111
15	0.996590	0.996591	0.996591	0.996590	0.996747	0.996590	0.996590	0.996915	0.996720	0.997111
20	0.996590	0.996591	0.996591	0.996590	0.996747	0.996590	0.996590	0.996915	0.996720	0.997111
25	0.996590	0.996591	0.996591	0.996590	0.996747	0.996590	0.996590	0.996915	0.996720	0.997111

Time	Base value	β_1+100% β_1	β_2+100% β_2	β_3+100% β_3	β_4+100% β_4	β_5+100% β_5	B_6+100% β_6	β_7+100% β_7	β_8+100% β_8	β_9+100% β_9
0	1	1	1	1	1	1	1	1	1	1
5	0.996624	0.996624	0.996624	0.996624	0.996779	0.996623	0.996624	0.997103	0.996817	0.997381
10	0.996590	0.996591	0.996591	0.996591	0.996748	0.996591	0.996591	0.997077	0.996785	0.997371
15	0.996590	0.996591	0.996591	0.996591	0.996747	0.996590	0.996590	0.997077	0.996786	0.997371
20	0.996590	0.996591	0.996591	0.996591	0.996747	0.996590	0.996590	0.997077	0.996785	0.997371
25	0.996590	0.996591	0.996591	0.996591	0.996747	0.996590	0.996590	0.997077	0.996785	0.997371

Table 5. Impact of variation failure rates on the availability of TIUP system with respect to at coverage factor $\tau = 0.5$

Time (in days)	Base value	α_1+10% α_1	α_2+10% α_2	α_3+10% α_3	α_4+10% α_4	α_5+10% α_5	α_6+10% α_6	α_7+10% α_7	α_8+10% α_8	α_9+10% α_9
0	1	1	1	1	1	1	1	1	1	1
5	0.991602	0.991602	0.991602	0.991602	0.991486	0.991602	0.991602	0.991363	0.991506	0.991222
10	0.991523	0.991523	0.991523	0.991523	0.991407	0.991523	0.991523	0.991282	0.991427	0.991137
15	0.991522	0.991522	0.991522	0.991522	0.991405	0.991522	0.991522	0.991281	0.991425	0.991136
20	0.991522	0.991522	0.991522	0.991522	0.991405	0.991522	0.991522	0.991281	0.991425	0.991136
25	0.991522	0.991522	0.991522	0.991522	0.991405	0.991522	0.991522	0.991281	0.991425	0.991136

Time	Base value	α_1+50% α_1	α_2+50% α_2	α_3+50% α_3	α_4+50% α_4	α_5+50% α_5	α_6+50% α_6	α_7+50% α_7	α_8+50% α_8	α_9+50% α_9
0	1	1	1	1	1	1	1	1	1	1
5	0.991602	0.991601	0.991601	0.991601	0.991021	0.991602	0.991602	0.990408	0.991121	0.989702

10	0.991523	0.991522	0.991522	0.991522	0.990941	0.991523	0.991523	0.990321	0.991041	0.989597
15	0.991522	0.991521	0.991521	0.991521	0.990939	0.991522	0.991522	0.990320	0.991039	0.989595
20	0.991522	0.991521	0.991521	0.991521	0.990939	0.991522	0.991522	0.990320	0.991039	0.989595
25	0.991522	0.991521	0.991521	0.991521	0.990939	0.991522	0.991522	0.990320	0.991039	0.989595

Time	**Base value**	**α_1+100% α_1**	**α_2+100% α_2**	**α_3+100% α_3**	**α_4+100% α_4**	**α_5+100% α_5**	**α_6+100% α_6**	**α_7+100% α_7**	**α_8+100% α_8**	**α_9+100% α_9**
0	1	1	1	1	1	1	1	1	1	1
5	0.991602	0.991600	0.991600	0.991600	0.990440	0.991602	0.991602	0.989216	0.990641	0.994658
10	0.991523	0.991521	0.991520	0.991520	0.990358	0.991523	0.991523	0.989122	0.990559	0.994622
15	0.991522	0.991519	0.991519	0.991519	0.990357	0.991522	0.991522	0.989120	0.990557	0.994621
20	0.991522	0.991519	0.991519	0.991519	0.990357	0.991522	0.991522	0.989120	0.990557	0.994621
25	0.991522	0.991519	0.991519	0.991519	0.990357	0.991522	0.991522	0.989120	0.990557	0.994621

Table 6. Impact of variation repair rates on the availability of TIUP system with respect to coverage factor τ=0.5

Time (in days)	**Base value**	**β_1+10% β_1**	**β_2+10% β_2**	**β_3+10% β_3**	**β_4+10% β_4**	**β_5+10% β_5**	**B_6+10% β_6**	**β_7+10% β_7**	**β_8+10% β_8**	**β_9+10% β_9**
0	1	1	1	1	1	1	1	1	1	1
5	0.991602	0.991602	0.991603	0.991603	0.991707	0.991602	0.991602	0.991814	0.991689	0.991931
10	0.991523	0.991523	0.991523	0.991523	0.991629	0.991523	0.991523	0.991742	0.991611	0.991874
15	0.991522	0.991522	0.991522	0.991522	0.991628	0.991522	0.991522	0.991741	0.991610	0.991873
20	0.991522	0.991522	0.991522	0.991522	0.991628	0.991522	0.991522	0.991741	0.991610	0.991873
25	0.991522	0.991522	0.991522	0.991522	0.991628	0.991522	0.991522	0.991741	0.991610	0.991873

Time	**Base value**	**β_1+50% β_1**	**β_2+50% β_2**	**β_3+50% β_3**	**β_4+50% β_4**	**β_5+50% β_5**	**B_6+50% β_6**	**β_7+50% β_7**	**β_8+50% β_8**	**β_9+50% β_9**
0	1	1	1	1	1	1	1	1	1	1
5	0.991602	0.991603	0.991603	0.991602	0.991989	0.991602	0.991602	0.992390	0.991921	0.992840
10	0.991523	0.991524	0.991524	0.991524	0.991912	0.991523	0.991523	0.992326	0.991844	0.992811
15	0.991522	0.991523	0.991523	0.991522	0.991911	0.991522	0.991522	0.992325	0.991844	0.992811
20	0.991522	0.991523	0.991523	0.991522	0.991911	0.991522	0.991522	0.992325	0.991844	0.992811
25	0.991522	0.991523	0.991523	0.991522	0.991911	0.991522	0.991522	0.992325	0.991844	0.992811

Time	**Base value**	**β_1+100% β_1**	**β_2+100% β_2**	**β_3+100% β_3**	**β_4+100% β_4**	**β_5+100% β_5**	**B_6+100% β_6**	**β_7+100% β_7**	**β_8+100% β_8**	**β_9+100% β_9**
0	1	1	1	1	1	1	1	1	1	1
5	0.991602	0.991603	0.991604	0.991603	0.992183	0.991602	0.991603	0.992791	0.992082	0.993481
10	0.991523	0.991524	0.991524	0.991524	0.992107	0.991523	0.991523	0.992728	0.992006	0.993458
15	0.991522	0.991523	0.991523	0.991523	0.992105	0.991522	0.991522	0.992726	0.992005	0.993457
20	0.991522	0.991523	0.991523	0.991523	0.992106	0.991522	0.991522	0.992727	0.992005	0.993457
25	0.991522	0.991523	0.991523	0.991523	0.992105	0.991522	0.991522	0.992727	0.992005	0.993457

Table 5-6, briefed about the impact of variation in failure rates on the availability with respect to time and constant coverage factor τ = 0.5. The same pattern of availability is observed with respect to failure rates and repair rates. This is because higher failure rates lead to more frequent breakdowns and longer periods of non-operation, reducing the overall reliability of the system. The decrease in subsystem availability underscores the importance of managing failure rates to maintain a dependable and efficient integrated system. As repair rates rise, subsystem availability improves. Quicker repairs lead to shorter downtime periods, enhancing the overall reliability and performance of the system. This increase in availability highlights the significance of timely and efficient repairs to ensure that the integrated system operates optimally. By prioritizing swift and effective repairs, the system becomes more dependable and capable of maintaining high availability levels, leading to enhanced functionality and productivity over time. It is observed that with respect to the imperfect coverage, that is, in situation of incomplete fault coverage, the availability of the TIUP decreases.

Table 7. Impact of variation failure rates on the availability of TIUP system with respect to at coverage factor $\tau = 0.2$

Time (in days	Base value	α_1+10% α_1	α_2+10% α_2	α_3+10% α_3	α_4+10% α_4	α_5+10% α_5	α_6+10% α_6	α_7+10% α_7	α_8+10% α_8	α_9+10% α_9
0	1	1	1	1	1	1	1	1	1	1
5	0.986632	0.986632	0.986632	0.986632	0.986448	0.986632	0.986632	0.986253	0.986480	0.986029
10	0.986510	0.986509	0.986509	0.986509	0.986325	0.986510	0.986510	0.986128	0.986357	0.985898
15	0.986508	0.986508	0.986508	0.986508	0.986323	0.986508	0.986508	0.986127	0.986355	0.985896
20	0.986508	0.986507	0.986507	0.986508	0.986323	0.986508	0.986508	0.986126	0.986355	0.985896
25	0.986508	0.986507	0.986507	0.986508	0.986323	0.986508	0.986508	0.986126	0.986355	0.985896

Time	Base value	α_1+50% α_1	α_2+50% α_2	α_3+50% α_3	α_4+50% α_4	α_5+50% α_5	α_6+50% α_6	α_7+50% α_7	α_8+50% α_8	α_9+50% α_9
0	1	1	1	1	1	1	1	1	1	1
5	0.986632	0.986631	0.986631	0.986631	0.985711	0.986632	0.986632	0.984741	0.985870	0.983624
10	0.986510	0.986509	0.986509	0.986509	0.985587	0.986509	0.986509	0.984607	0.985746	0.983461
15	0.986508	0.986507	0.986507	0.986507	0.985585	0.986508	0.986508	0.984605	0.985744	0.983459
20	0.986508	0.986507	0.986507	0.986507	0.985585	0.986508	0.986508	0.984605	0.985744	0.983458
25	0.986508	0.986507	0.986507	0.986507	0.985585	0.986508	0.986508	0.984605	0.985744	0.983458

Time	Base value	α_1+100% α_1	α_2+100% α_2	α_3+100% α_3	α_4+100% α_4	α_5+100% α_5	α_6+100% α_6	α_7+100% α_7	α_8+100% α_8	α_9+100% α_9
0	1	1	1	1	1	1	1	1	1	1
5	0.986632	0.986631	0.986631	0.986631	0.984792	0.986632	0.986632	0.982858	0.952219	0.9480259
10	0.986510	0.986508	0.986508	0.986508	0.984665	0.986509	0.986509	0.982710	0.951916	0.9476648
15	0.986508	0.986506	0.986506	0.986506	0.984664	0.986507	0.986507	0.982709	0.951916	0.9476632
20	0.986508	0.986506	0.986506	0.986506	0.984664	0.986507	0.986507	0.982709	0.951915	0.9476630
25	0.986508	0.986506	0.986506	0.986506	0.984664	0.986507	0.986507	0.982709	0.951915	0.947663

Table 8. Impact of variation repair rates on the availability of TIUP system with respect to at coverage factor $\tau = 0.2$

Time (in days)	Base value	β_1+10% β_1	β_2+10% β_2	β_3+10% β_3	β_4+10% β_4	β_5+10% β_5	B_6+10% β_6	β_7+10% β_7	β_8+10% β_8	β_9+10% β_9
0	1	1	1	1	1	1	1	1	1	1
5	0.986632	0.953643	0.953643	0.953643	0.953799	0.953643	0.953643	0.956798	0.953772	0.954133
10	0.986510	0.953343	0.953343	0.953343	0.953500	0.953343	0.953343	0.956590	0.953472	0.953862
15	0.986508	0.953342	0.953342	0.953342	0.953498	0.953341	0.953342	0.956590	0.953471	0.953861
20	0.986508	0.953342	0.953342	0.953341	0.953498	0.953341	0.953341	0.956590	0.953471	0.953861
25	0.986508	0.953342	0.953342	0.953341	0.953498	0.953341	0.953341	0.956590	0.953471	0.953861

Time	Base value	β_1+50% β_1	β_2+50% β_2	β_3+50% β_3	β_4+50% β_4	β_5+50% β_5	B_6+50% β_6	β_7+50% β_7	β_8+50% β_8	β_9+50% β_9
0	1	1	1	1	1	1	1	1	1	1
5	0.986632	0.953645	0.953644	0.953644	0.954217	0.953643	0.953643	0.965463	0.954115	0.955487
10	0.986510	0.953343	0.953343	0.953343	0.953917	0.953343	0.953343	0.965360	0.953819	0.955251
15	0.986508	0.953342	0.953342	0.953342	0.953917	0.953342	0.953342	0.965367	0.953818	0.955250
20	0.986508	0.953342	0.953342	0.953342	0.953917	0.953341	0.953341	0.965362	0.953818	0.955249
25	0.986508	0.953342	0.953342	0.953342	0.953917	0.953341	0.953341	0.965362	0.953818	0.955249

Time	Base value	β_1+100% β_1	β_2+100% β_2	β_3+100% β_3	β_4+100% β_4	β_5+100% β_5	B_6+100% β_6	β_7+100% β_7	β_8+100% β_8	β_9+100% β_9
0	1	1	1	1	1	1	1	1	1	1
5	0.986632	0.953640	0.953644	0.953644	0.954502	0.953643	0.953643	0.971579	0.954352	0.956441
10	0.986510	0.953345	0.953343	0.953345	0.954208	0.953345	0.953343	0.971490	0.954058	0.956206
15	0.986508	0.953342	0.953342	0.953342	0.954205	0.953341	0.953342	0.971472	0.954056	0.956207

20	0.986508	0.953342	0.953342	0.953342	0.954205	0.953341	0.953341	0.971487	0.954056	0.956206
25	0.986508	0.953342	0.953342	0.953342	0.954205	0.953341	0.953341	0.971487	0.954056	0.956206

Tables 7-8 contains the transient availability of TIUP system with respect to time at various levels of failure rate and coverage factor at $\tau = 0.2$. It is observed that availability of the system decreases with an increase in the failure rate and increase with respect to repair rate.

5. Conclusion

This study presented a stochastic availability analysis of tube-wells integrated with underground pipelines (TIUP), a critical infrastructure for sustainable agriculture irrigation. By modeling the system using the birth-death process and solving the Chapman-Kolmogorov equations with the fourth-order Runge-Kutta method, we quantified the influence of subsystem failure and repair rates, along with varying coverage factor. The numerical analysis revealed that TIUP availability decreases over time with higher subsystem failure rates, particularly when the coverage factor is low. For instance, at coverage factor $\tau = 0.8$, the system maintained a high availability of 0.9966.

The manpower unit (Y) and centrifugal pump unit (W) exhibited the most significant reductions in availability, underscoring their pivotal role in overall system reliability. Notably, improvement in repair rates were shown to enhance availability from 0.9966 to 0.9974, clearly demonstrating the tangible benefits efficient maintenance practices in sustaining system performance. Fault coverage also emerged as a decisive factor influencing system resilience. When coverage factor decreased from $\tau = 0.5$ to $\tau = 0.2$, availability dropped from 0.9915 to 0.9865, highlighting the critical necessity of incorporating redundancy in sensors, tube-wells and pumps. Higher fault coverage thus directly translates into improved operational continuity and robustness of TIUP system.

In conclusion, the findings establish manpower reliability, centrifugal pump performance, and sensor redundancy as the most influential determinants of TIPU availability. Strengthening repair processes, implementing redundancy strategies, and leveraging advanced monitoring technologies such as IoT enabled sensors, can significantly enhance the reliability guidance for agriculture engineers and policymakers to design resilient TIUP infrastructures that ensure uninterrupted irrigation, thereby contribution to food security and sustainable water resource management.

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Conflicts of Interest

The authors declare no conflict of interest.

Author Contributions

Conceptualization: KUMAR, A.; MAAN, V.S. **Data curation:** KUMAR, A. **Formal analysis:** MAAN, V.S. **Funding acquisition:** NIL; **Investigation:** MAAN, V.S.; SAINI, M. **Methodology:** MAAN, V.S.; SAINI, M. **Project administration:** KUMAR, A.; MAAN, V.S. **Software:** MAAN, V.S. **Resources:** MAAN, V.S. **Supervision:** KUMAR, A. **Validation:** KUMAR, A.; SAINI, M. **Visualization:** MAAN, V.S. **Writing - original draft:** MAAN, V.S. **Writing - review and editing:** KUMAR, A.; MAAN, V.S.

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