

Reliability, Availability, Maintainability, and Dependability analysis of Tube-wells Integrated with Underground Pipelines in agricultural fields for irrigation

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Abstract

Reliability, Availability, Maintainability, and Dependability (RAMD) study of Tube-wells Integrated with Underground Pipelines (TIUP) is crucial as they are the backbone of the irrigation system. This study is carried out with an objective to perform RAMD analysis, and Failure Modes and Effects Analysis (FMEA) unified with the development of a novel stochastic model using Markovian approach to estimate the Steady-State Availability (SSA) of the TIUP. A real case study of a conventional TIUP system has been performed to validate theoretical and practical results of the proposed model. The failure and repair rates of all subsystems followed exponential distribution, and their impact on system/subsystem's availability and other reliability measures has been investigated. All the repairs are perfect and random variables associated with failure and repair rates are statistically independent. The centrifugal pump and power supply units are the most critical components as far as reliability and maintainability aspects. The labor also plays a critical role in the operation of the TIUP system.

Keywords

Reliability, Availability, Maintainability and Dependability, failure modes and effects analysis, Markovian Approach, Tube-wells Integrated with Underground Pipelines

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Introduction

Agriculture is one of the oldest professions done by human beings after the inception of civilization. In the current age, a large portion of the population is involved in agricultural activities either directly or indirectly. The production of any crop depends upon irrigation, fertilizers, and improved varieties of seeds. The irrigation component is one that influences most the whole yield of the crop. Irrigation to crops in India is done from ancient times through wells, ponds, etc. In 1912, the first attempt was made in Punjab to draw water with the help of a

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tube-well.¹ During the last three decades, tube-well engineering emerges rapidly and now in northern part of India including Punjab, Haryana, etc., most of the farmers have their own tube-wells for irrigation. Tube-wells are installed in the fields, and then through the underground pipelines, water is transported to the fields. In this process, many components are involved that makes tube-wells integrated with underground pipelines (TIUP) a complex system.

The Tube-well with Integrated Underground Pipeline (TIUP) is a prominent source of irrigation in agricultural fields. Underground water is withdrawn and transported through the pipelines for irrigation purpose, as shown in Figure 1. The TIUP system comprises five main subsystems, they are: power supply unit, borewell unit, centrifugal pump, pipeline, and labor. All these units can be considered as series structure as failure of anyone causes the complete system failure, while at component level various type redundancies also utilized to increase the reliability and availability of the system.

Kaneda and Ghaffar² presented some empirical results on the effects of tube-wells on the agriculture of Punjab. The operation of TIUP with high reliability is highly required as failure of its cause's crucial economic effects on farmers including loss of income. Lack of irrigation can spoil the crops either partially or completely.

Several studies have been carried out to estimate the reliability of agricultural machinery. For instance, Najafi et al.³ conducted a study on reliability investigation of agricultural machinery, namely sugarcane chopper harvester. Durczak et al.⁴ established a mathematical model for reliability analysis of farm tractors based on actual failures data collected from a manufacturer. Soltanali et al.⁵ proposed a sustainable production process in automotive manufacturing through reliability, availability, and maintainability methodologies. Da Silva et al.⁶ proposed a

methodology to diagnose the failure in the transmission system of agriculture tractors. This approach is based upon predictive maintenance-based software.

Hashimoto et al.⁷ developed a criterion based upon reliability, resiliency, and vulnerability for water resource systems for performance evaluation. Feng et al.⁸ used Markov Chain to forecast the agricultural water trajectory. Li et al.⁹ estimated the reliability of village-level supply facility of groundwater irrigation in rural China. Mazumder et al.¹⁰ performed reliability estimation of water distribution systems incorporating physical probabilistic pipe failure approach. Afsharnia et al.¹¹ suggested a model for the optimization of sugarcane harvester machine based on fault tolerance Bayesian network reliability by applying the concept of preventive maintenance. Alsharqawi et al.¹² suggested a model for water distribution network's reliability prediction. Darvini et al.¹³ carried out the performance estimation of water distribution systems by incorporating the leakage and temporal variability of water demand. Masciopinto et al.¹⁴ discovered the applications of quantitative microbial risk assessment (QMRA) for safe agricultural water reuses in coastal areas. Elshaboury et al.¹⁵ adopted a minimal cut set approach for the reliability estimation of water distribution networks.

Failure Mode and Effect Analysis (FMEA) is a well-known methodology for risk assessment and is rapidly used in complex systems. Stamatis¹⁶ explained FMEA from theory to execution. Smaranda et al.¹⁷ used FMEA in water supply systems. Arabian-Hoseynabadi et al.¹⁸ used FMEA for wind turbine's reliability evaluation. Hwang et al.¹⁹ proposed resilience-based Failure Mode Effects and Criticality Analysis (FMECA) for regional water supply system. Patil and Kothavale²⁰ conducted FMEA analysis of CNC Turning Center. Kumar et al.²¹ performed Reliability, Availability, Maintainability, and

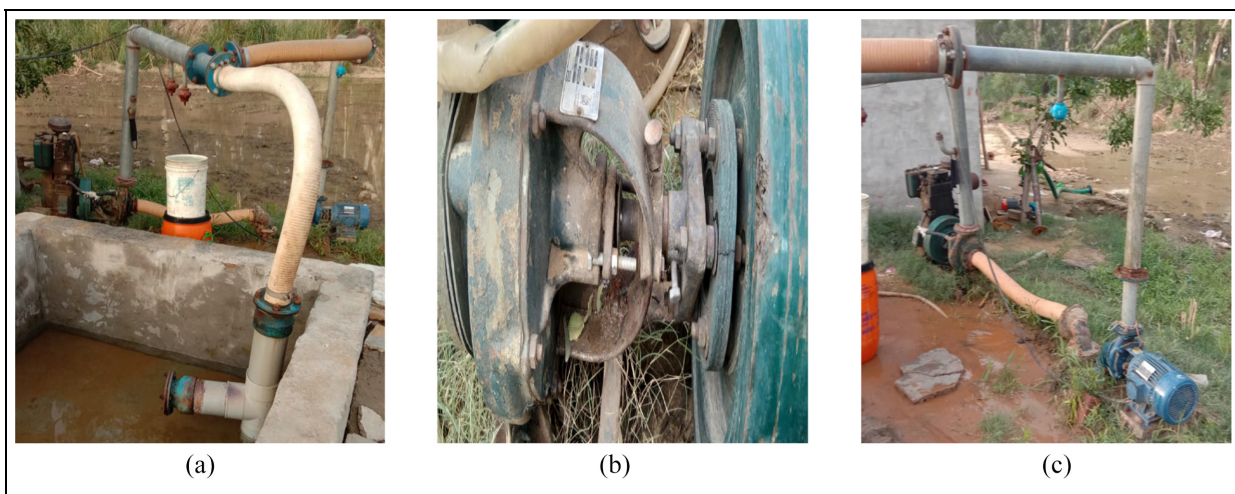


Figure 1. TIUP system under consideration: (a) TIUP line, (b) shaft of TIUP, and (c) redundant energy units.

Dependability (RAMD) analysis and FMEA analysis of soft water treatment and supply plant.

Another popular approach for reliability evaluation of industrial systems when failure and repair rates follow memoryless property is the Markovian approach. Chiquet et al.²² developed a mathematical model for a stochastic dynamic system and estimated the reliability with Markovian approach. Barak et al.²³ proposed a stochastic model for reliability analysis of a single-unit system with inspection subject to different weather conditions. Barak and Barak²⁴ studied the impact of abnormal weather conditions on various reliability measures of a repairable system with inspection. Adumene and Okoro²⁵ proposed a Markov model for reliability evaluation of offshore wind energy system under harsh environments. Aggarwal and Kumar²⁶ proposed a stochastic model for availability optimization of a crushing system of a sugar plant and optimized it using the Particle Swarm Optimization (PSO) algorithm.

RAMD analysis approach used extensively by researchers on time to repair and time to between failures data. Aggarwal et al.²⁷ carried out performance modeling of the skim milk powder production system of a dairy plant using RAMD analysis. Aggarwal et al.²⁸ performed mathematical modeling of the serial processes in refining system of a sugar plant using RAMD analysis. Saini and Kumar²⁹ conducted RAMD analysis for performance analysis of evaporation system in the sugar industry. Choudhary et al.³⁰ proposed RAM methodology for the cement industry and discovered the most sensitive component. Goyal et al.³¹ evaluated the reliability, maintainability, and sensitivity of the sewage treatment plant's physical processing unit to investigate the plant's performance. Gupta et al.³² carried out the analysis of cooling tower in steam turbine power plant using RAMD investigation. Patil et al.³³ used Markov chains in RAM analysis of a Computerized Numerical Control Turning Center. Velmurugan et al.³⁴ used RAMD approach for performance Analysis of Tyre Manufacturing System in the Small and Medium Enterprises (SMEs). Recently, Saini et al.³⁵ performed the availability optimization of condenser of STPP using metaheuristic methodologies. Kumar et al.³⁶ suggested an efficient model for operational availability optimization of cooling towers. Kumar et al.³⁷ suggested an efficient computational model for performance optimization of e-waste management plants (Table 1).

The extensive literature review reveals that the reliability evaluation of tube-wells integrated with underground pipelines has not been explored so far. There is also a need to study the effects caused by failures of such systems. Therefore, the objective of this work is to perform RAMD analysis, and FMEA unified with the development of a stochastic model using Markovian approach to estimate the long-run availability of the TIUP system. The effectiveness and adequacy of the

proposed model is assessed and compared with a case study of a conventional TIUP system.

The remainder of this paper is structured as follows. In Section 2, material and methods are presented and illustrated. Specifically, RAMD and their statistical measures are described. In Section 3, the real TIUP case study is discussed in terms of system description, subsystems, notations, and assumptions. In Sections 4 and 5, the RAMD and the availability analysis are stated, respectively. In Section 6, system level FMEA is described and applied to the system under study. In Section 7, the overall analysis results are reported and discussed. Finally, some conclusions are drawn in Section 8.

Material and methods

Reliability

According to Billinton and Allan,³⁸ "reliability is the probability of an equipment performing its task adequately for a specified period intended under specified operating conditions." Reliability can be calculated by using the following formula:

$$R(t) = 1 - \int_0^t f(t).dt = \int_t^{\infty} f(t).dt \quad (1)$$

where $R(t)$ is the reliability (i.e. survivor) at time t , and $f(t)$ is the failure Probability Density Function (PDF) at time t .

If the failure PDF is exponentially distributed, then:

$$R(t) = e^{-\lambda t} \quad (2)$$

where λ is the rate parameter related to the failure rate.

Availability

According to Billinton and Allan,³⁸ "availability is defined as the probability that a component or system is performing its required function at a given time when it is used under stated operating conditions." In simple words, availability is the probability of finding any product in operating state. It is classified as point, steady-state, and interval availability. Mathematically, the availability function is given by:

$$A = \frac{MTBF}{MTBF + MTTR} \quad (3)$$

where A is the steady state or long-run availability, $MTBF$ is the Mean-Time Between Failure, and $MTTR$ is the Mean-Time To Repair.

Maintainability

"Maintainability is defined to be the probability that a failed component or system will be restored to a specified condition within a period of time when maintenance is performed in accordance with prescribed

Table 1. Review of system reliability evaluation techniques.

Reliability evaluation techniques Authors	Markov Chain	Minimal cut set approach	Reliability block diagram	Semi-Markovian Approach	Markovian Approach	FMEA Analysis	RAMD/RAM Analysis	Particle Swarm Optimization	FT-Bayesian Network
Afsharnia et al. ¹¹					✓				✓
Aggarwal and Kumar ²⁶					✓			✓	
Aggarwal et al. ²⁷					✓		✓		
Arabian-Hoseynabadi et al. ¹⁸					✓	✓			
Adumene and Okoro ²⁵					✓				
Alsharqawi et al. ¹²				✓	✓				
Barak et al. ²³				✓	✓				
Barak and Barak ²⁴				✓	✓				
Billinton and Allan ³⁸				✓	✓				
Billinton and Allan ³⁸				✓	✓				
Choudhary et al. ³⁰			✓	✓	✓		✓		
Chiquet et al. ²²				✓	✓				
Durczak et al. ⁴				✓	✓				
Da Silva et al. ⁶				✓	✓		✓		
Da Silva et al. ⁶				✓	✓		✓		
Dhillon ³⁹				✓	✓				
Elsahaboury et al. ¹⁵		✓			✓				
Feng et al. ⁸	✓				✓				
Goyal et al. ³¹					✓				
Goyal et al. ³¹					✓				
Gupta et al. ³²					✓				
Hashimoto et al. ⁷					✓				
Hwang et al. ¹⁹					✓				
Hwang et al. ¹⁹					✓				
Kumar et al. ²¹					✓				
Kumar et al. ²¹					✓				
Mazumder et al. ¹⁰					✓				
Mazumder et al. ¹⁰					✓				
Najafi et al. ³				✓	✓				
Najafi et al. ³				✓	✓				
Patil et al. ³³					✓				
Patil et al. ³³					✓				
Patil and Kothavale ²⁰					✓				
Patil and Kothavale ²⁰					✓				
Soltanali et al. ⁵					✓				
Soltanali et al. ⁵					✓				
Smaranda et al. ¹⁷					✓				
Smaranda et al. ¹⁷					✓				
Stamatis ¹⁶					✓				
Stamatis ¹⁶					✓				
Saini and Kumar ²⁹					✓				
Saini and Kumar ²⁹					✓				
Velmurugan et al. ³⁴					✓				
Velmurugan et al. ³⁴					✓				
Saini et al. ³⁵					✓				
Saini et al. ³⁵					✓				
Kumar et al. ³⁶				✓	✓			✓	
Kumar et al. ³⁶				✓	✓			✓	
Kumar et al. ³⁷					✓				
Kumar et al. ³⁷					✓				

procedures” Billinton and Allan.³⁸ In simple words, it is the probability that the failed system will be repaired to its working state. Maintainability function for exponential distribution is given by:

$$M(t) = \int_0^t \mu e^{-\mu t} .dt = 1 - e^{-\mu t} \quad (4)$$

where $M(t)$ is the maintainability at time t , and μ is the repair rate of the component or the system.

Dependability

It is a measure of the degree of consistency of performance. It provides a single measurement to assess the performance based on reliability and maintainability. If failure and repair rates followed exponential distribution, then dependability is the ratio of failure and repair rates. Mathematically, the dependability ratio is given by:

$$d = \frac{\mu}{\lambda} \quad (5)$$

Availability function can be expressed in terms of dependability as $A = d/1 + d$. The value of dependability will be high if the availability is larger than 0.9. The minimum value of dependability can be calculated using the following expression:

$$D_{min} = 1 - \left(\frac{1}{d-1} \right) \left(e^{-\frac{\ln(d)}{d-1}} - e^{-\frac{d \ln(d)}{d-1}} \right) \quad (6)$$

where d is the dependability ratio, and D_{min} is its minimum value Aggarwal et al.²⁸.

Mean-Time Between Failure (MTBF)

The average of the times between failures is called the Mean-Time Between Failures (MTBF) Aggarwal et al.²⁸. Mathematically, it can be found by:

$$MTBF = \int_0^t tf(t) .dt = \frac{1}{\lambda} \quad (7)$$

Mean-Time To Repair (MTTR)

The average of the repair times is called the Mean-Time To Repair (MTTR) Aggarwal et al.²⁸. Mathematically, it can be found by:

$$MTTR = \int_0^t tg(t) .dt = \frac{1}{\mu} \quad (8)$$

where $g(t)$ is the repair function.

Real case study: System description, assumptions, notations, and flow chart

System description

The configuration and working procedure of the components of TIUP system is described here. Figure 2 presents the configuration (i.e. the Reliability Block Diagram (RBD)) of the TIUP system. The failure and repair data required for the analysis are collected from the owner of the TIUP system. It is reported that all the repair facilities are available within 5 km range of the system. The information is given on following heads: subsystems, type of failures, number of failures, time to failure, time to repair and component failed for a period of 2 years.

The system mainly suffers due to electrical and mechanical failures. The subsystem’s description is given as follows:

Power supply unit (PSU). PSU is a significant component to operate the TIUP system. Farmers have various options of power, such as electricity (EL), diesel engine (ES), and tractor (TR). The economic condition of the farmer decides the number of power sources that can use to run the

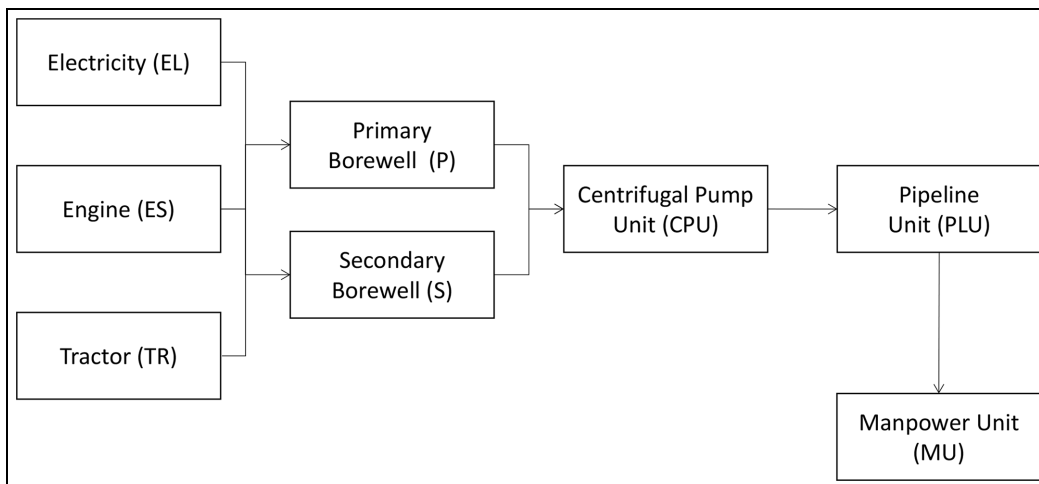


Figure 2. Flowchart of TIUP system.

TIUP system. In the presented case, the farmer has all three sources of power to operate the TIUP system and can be used on standby as and when required. As the power supply from the state electricity board is very irregular, and it is generally available between 6:00 P.M. and 6:00 A.M. So, for the rest of the time, the electric power generated by the diesel engine or the tractor are used.

Borewell unit (BU). In most of the TIUP systems, only one pipe is dragged into land up to water level. But in the considered system, two non-identical systems have been hauled into the ground at different depths. The primary pipe (P) is hauled up to 80 ft, while the secondary pipe (S) is dragged up to 35 ft approximately. Both of the pipes are connected through flanges. After that, a single pipe appears on the ground, and on its upper part, a T-type socket is fixed. On the one-part, an electric motor is fixed, while the end is fixed for the tractor/engine. In practice, the usage of two non-identical pipes would increase the amount of water.

Centrifugal pump unit (CPU). It is the main component in tube-wells. It has several components, such as glen, router, shaft, bush, and bearing. Failure of any of these components causes the failure of the complete system. In practice, the centrifugal pump faces the highest number of failures and, thus, without a proper maintenance intervention, it will be very difficult to effectively operate it. In the present analysis, TIUP system have a SWV440C nominal head model centrifugal pump is used by the farmer. Its prime mover rate is 7 HP, speed

1500 rpm, and efficiency at 75%. It is connected to a power supply unit with a shaft.

Pipeline unit (PLU). It is the underground line of PVC pipes buried below 3 ft of the surface. It connects the tube-well source point, and at a terminal point, there is a valve to release the water into the fields.

Labor unit (MU). To operate the whole system successfully, a dedicated person (called labor) is required. Sometimes, in the absence of labor, or if the farmer stays far from the system, there is a chance that the pump runs dry due to the unavailability of the water in the well, and due to this, the electrical/ mechanical failures may take place.

Assumptions

The following assumptions have been made to carry out the analysis of the present work:

- more than one failure will not occur at a time;
- failure and repair rates of all components are exponentially distributed;
- switch devices are perfect;
- unit works as-good-as-new after every repair action.

Notations

The following notations have been utilized to develop the models:

S. no.	Sub-system	Code		Failure rate/h (λ_i)	Repair rate/h μ_i
		Operative mode	Failed mode		
1	Electricity & electric motor (EL)	A	a	λ_1	μ_1
2	Standby diesel engine (ES)	B	b	λ_2	μ_2
3	Standby tractor (TR)	C	c	λ_3	μ_3
4	Primary Borewell (P)	D	d	λ_4	μ_4
5	Secondary Borewell (S)	E	e	λ_5	μ_5
6	Pipeline Unit (PU)	F	f	λ_6	μ_6
7	Centrifugal Pump Unit (CPU)	G	g	λ_7	μ_7
8	Labor Unit (MU)	H	h	λ_8	μ_8

$\psi_i, i = 0, 1, 2, \dots, 7$: Probability that system is in i^{th} state

$\psi_0(t)$: At time t, the system at 0 state

○: Operative state

□: Failed state

$\eta/(1 - \eta)$ Repaired by ordinary/ expert repairman

$\gamma/(1 - \gamma)$ Repaired by ordinary/ expert repairman

μ_9 : Repair rate of both borewell units simultaneous

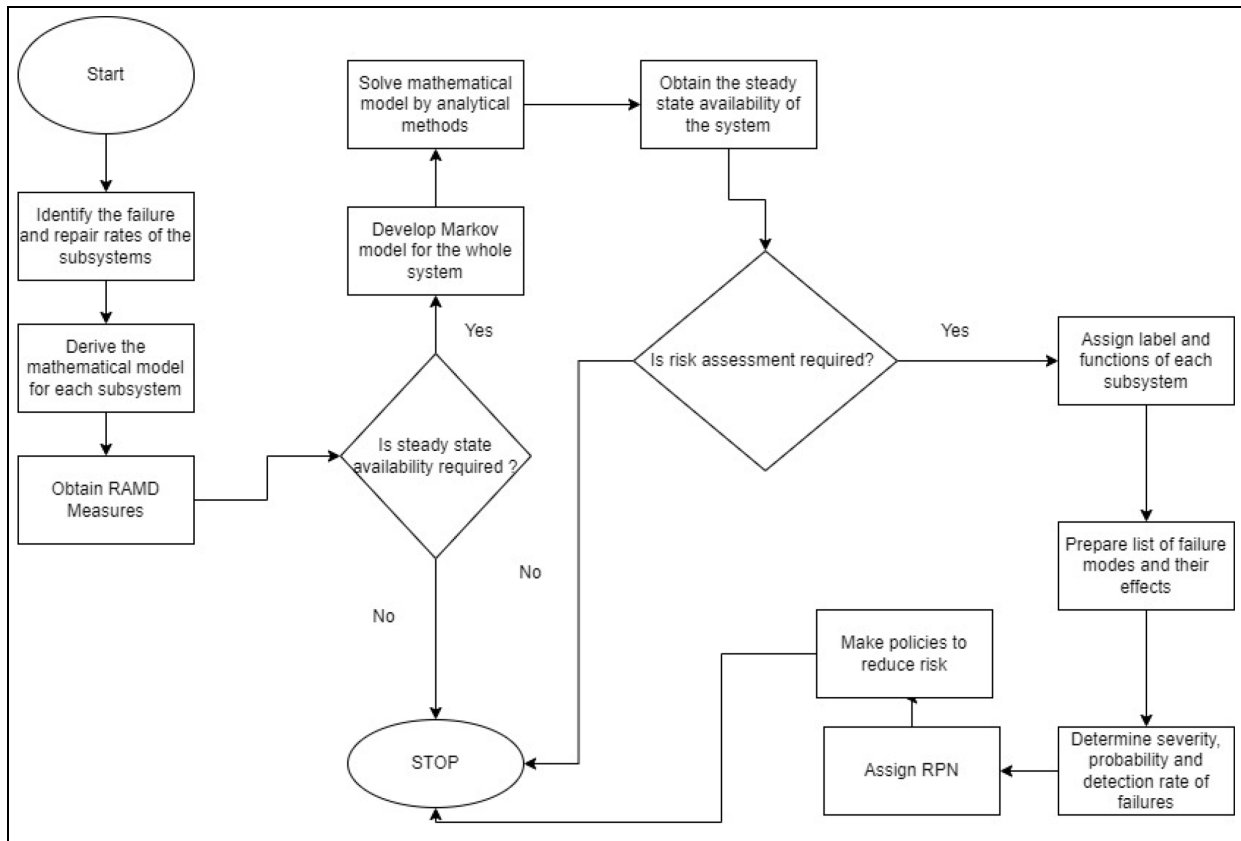


Figure 3. Flow chart of reliability evaluation procedure.

Flow chart

In this section, the methodology used for reliability evaluation of TIUP is presented with the help of flow chart appended in Figure 3. Initially, the configuration of the TIUP system is investigated. The failure and repair rates of various sub systems is derived from the collected failure and repair data. The reliability, availability, maintainability, and dependability measures of all the subsystems are derived through developing the time dependent mathematical model for each subsystem. By using probabilistic arguments, the transient behavior of RAMD measures for whole system is derived. After that, to identify the steady state availability and most sensitive component of the TIUP system Markov analysis is performed. The Chapman-Kolmogorov differential-difference equations derived and simplified using algebraic methods for above stated rate of parameters. The risk assessment of the system is performed by using failure mode and effect analysis. The labels and function of all the components defined initially. The type of failures and their impact on system is analyzed. The severity, probability and detection frequency of the failures determined and RPN number is obtained. On the basis of RPN number, the policies are formulated to reduce the risk of failures.

RAMD analysis

The required data for RAMD analysis has been obtained with the help of the TIUP system owner. The data has been collected for the following questions: (i) Number of subsystems, (ii) number of failures of each subsystem, (iii) time to failures, (iv) time to repair, (v) type of failure, and (vi) name of the failed subsystem, for 2 years. The major failure faced by farmers are electrical, mechanical (related to router, bearing), and human. Based on the given information, the values of the various parameters are obtained and summarized in Table 2. By incorporating the above-stated assumptions and notations, changeover diagrams associated with each subsystem have been prepared and shown in Figure 4(a) to (c). By applying the Markovian birth-death process, Chapman-Kolmogorov differential equations Saini and Kumar²⁹ have been derived to obtain the RAMD measures of these systems.

Power supply unit (PSU)

PSU has three units EL (i.e. Electricity and equipment), ES (i.e. Diesel engine), and TR (i.e. Tractor). Initially, the EL unit is operative while ES and TR are kept in cold standby. In practice, the failure of all three units

Table 2. Failure and repair rates of various subsystems.

Subsystem name	Failure rate	Repair rate
Electricity and equipment (EL)	$\lambda_1 = 0.1$	$\mu_1 = 0.0625$
Diesel engine (ES)	$\lambda_2 = 0.000457$	$\mu_2 = 0.5$
Tractor (TR)	$\lambda_3 = 0.00001142$	$\mu_3 = 1$
Primary borewell (P)	$\lambda_4 = 0.00001427$	$\mu_4 = 0.0208$
Secondary borewell (S)	$\lambda_5 = 0.0000381$	$\mu_5 = 0.125$
Pipeline (PU)	$\lambda_6 = 0.0001142$	$\mu_6 = 0.1667$
Centrifugal pump unit (CPU)	$\lambda_7 = 0.0002283$	$\mu_7 = 0.1667$
Labor unit (MU)	$\lambda_8 = 0.001142$	$\mu_8 = 0.5$
Complete borewell system		$\mu_9 = 0.1458$
Repair probability: $\eta = 0.6, \lambda = 0.7$		

causes a complete system failure. The state changeover diagram of the PSU system is appended in Figure 4(a). The differential equations associated with the state changeover diagram are given as follows:

$$\begin{aligned}
 \psi'_0(t) &= -\lambda_1\psi_0(t) + \eta\mu_2\psi_2(t) + \mu_1\psi_1(t) + \gamma\mu_3\psi_3(t) \\
 \psi'_1(t) &= -(\mu_1 + \lambda_2)\psi_1(t) + \lambda_1\psi_0(t) + (1 - \eta)\mu_2\psi_2(t) \\
 \psi'_2(t) &= -(\mu_2 + \lambda_3)\psi_2(t) + \lambda_2\psi_1(t) + (1 - \gamma)\mu_3\psi_3(t) \\
 \psi'_3(t) &= -\mu_3\psi_3(t) + \lambda_3\psi_2(t)
 \end{aligned} \tag{9}$$

Letting $t \rightarrow \infty$ and applying initial conditions, equation (9) shown above become:

$$\begin{aligned}
 -\lambda_1\Psi_0 + \eta\mu_2\Psi_2 + \mu_1\Psi_1 + \gamma\mu_3\Psi_3 &= 0 \\
 -(\mu_1 + \lambda_2)\Psi_1 + \lambda_1\Psi_0 + (1 - \eta)\mu_2\Psi_2 &= 0 \\
 -(\lambda_3 + \mu_2)\Psi_2 + \lambda_2\Psi_1 + (1 - \gamma)\mu_3\Psi_3 &= 0 \\
 -\mu_3\Psi_3 + \lambda_3\Psi_2 &= 0
 \end{aligned} \tag{10}$$

Since $\psi_0 + \psi_1 + \psi_2 + \psi_3 = 1$, solving equation (10), one can get:

$$\Psi_0 = \left[1 + k + \frac{\lambda_2 k}{(\lambda_3 + \mu_2) - (1 - \gamma)\lambda_3} + \frac{\lambda_3 \lambda_2 k}{\mu_3 \{(\lambda_3 + \mu_2) - (1 - \gamma)\lambda_3\}} \right]^{-1}$$

where $k = \lambda_1 \left((\lambda_2 + \mu_1) - \frac{\mu_2 \lambda_2 (1 - \eta)}{(\lambda_3 + \mu_2) - (1 - \gamma)\lambda_3} \right)^{-1}$

Similarly, expressions ψ_1 and ψ_2 have been derived. Based on the state changeover diagram, the availability of the system model is $A_{PSU} = \psi_0 + \psi_1 + \psi_2 = 0.97086$.

Other measures of system effectiveness are appended below in Table 3.

Borewell unit (BU)

BU has two non-identical units, P (i.e. primary borewell) and S (i.e. secondary borewell). Initially, both units are

in operative mode. In practice, the failure of both units causes a complete system failure. The state changeover diagram of the BU system is appended in Figure 4(b). The differential equations associated with the state changeover diagram are:

$$\begin{aligned}
 \psi'_0(t) &= -(\lambda_4 + \lambda_5)\psi_0(t) + \mu_4\psi_1(t) + \mu_5\psi_2(t) + \mu_9\psi_3(t) \\
 \psi'_1(t) &= -(\mu_4 + \lambda_5)\psi_1(t) + \lambda_4\psi_0(t) \\
 \psi'_2(t) &= -(\mu_5 + \lambda_4)\psi_2(t) + \lambda_5\psi_0(t) \\
 \psi'_3(t) &= -\mu_9\psi_3(t) + \lambda_5\psi_1(t) + \lambda_4\psi_2(t)
 \end{aligned} \tag{11}$$

Letting $t \rightarrow \infty$ and applying initial conditions, equation (11) shown above become:

$$\begin{aligned}
 -(\lambda_4 + \lambda_5)\psi_0(t) + \mu_4\psi_1(t) + \mu_5\psi_2(t) + \mu_9\psi_3(t) &= 0 \\
 -(\mu_4 + \lambda_5)\psi_1(t) + \lambda_4\psi_0(t) &= 0 \\
 -(\mu_5 + \lambda_4)\psi_2(t) + \lambda_5\psi_0(t) &= 0 \\
 -\mu_9\psi_3(t) + \lambda_5\psi_1(t) + \lambda_4\psi_2(t) &= 0
 \end{aligned} \tag{12}$$

Since $\psi_0 + \psi_1 + \psi_2 + \psi_3 = 1$, solving equation (12), one can get:

$$\psi_0 = \left[1 + \frac{\lambda_4}{(\mu_4 + \lambda_5)} + \frac{\lambda_5}{(\mu_5 + \lambda_4)} + \frac{\lambda_4 \lambda_5}{\mu_9} \left\{ \frac{1}{(\mu_4 + \lambda_5)} + \frac{1}{(\mu_5 + \lambda_4)} \right\} \right]^{-1}$$

Similarly, expressions ψ_1 and ψ_2 have been derived. Based on the state changeover diagram, the availability of the system model is $A_{BU} = \psi_0 + \psi_1 + \psi_2 = 0.99991$.

Other measures of system effectiveness are appended in Table 3.

Pipeline unit (PLU)

PLU has only one unit, and its failure causes the complete system failure. The state changeover diagram of the PLU system is appended in Figure 4(c). The differential equations associated with the state changeover diagram are:

$$\begin{aligned}
 \psi'_0(t) &= -\lambda_6\psi_0(t) + \mu_6\psi_1(t) \\
 \psi'_1(t) &= -\mu_6\psi_1(t) + \lambda_6\psi_0(t)
 \end{aligned} \tag{13}$$

Letting $t \rightarrow \infty$ and applying initial conditions, equation (13) shown above becomes:

$$\begin{aligned}
 -\lambda_6\psi_0 + \mu_6\psi_1 &= 0 \\
 -\mu_6\psi_1 + \lambda_6\psi_0 &= 0
 \end{aligned} \tag{14}$$

Since $\psi_0 + \psi_1 = 1$, solving equation (14), one can get:

$$\psi_0 = \left[1 + \frac{\lambda_6}{\mu_6} \right]^{-1}$$

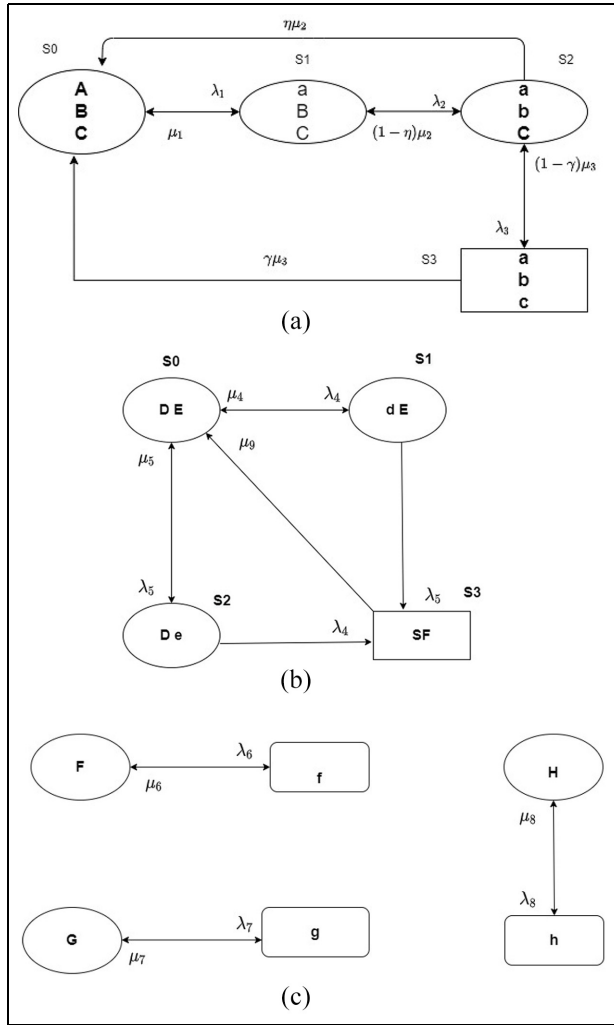


Figure 4. (a) Changeover diagram of PSU, (b) changeover diagram of BU, and (c) changeover diagram of PU, CPU, and MU.

Based on the state changeover diagram, the availability of the system model is $A_{PLU} = \psi_0 = 0.998632$.

Other measures of system effectiveness are appended in Table 3.

Centrifugal pump unit (CPU)

CPU has only one unit, and its failure causes the complete system failure. The state changeover diagram of the CPU system is appended in Figure 4(c). The differential equations associated with the state changeover diagram are:

$$\begin{aligned}\psi'_0(t) &= -\lambda_7\psi_0(t) + \mu_7\psi_1(t) \\ \psi'_1(t) &= -\mu_7\psi_1(t) + \lambda_7\psi_0(t)\end{aligned}\quad (15)$$

Letting $t \rightarrow \infty$ and applying initial conditions, equation (15) shown above become:

$$\begin{aligned}-\lambda_7\psi_0 + \mu_7\psi_1 &= 0 \\ -\mu_7\psi_1 + \lambda_7\psi_0 &= 0\end{aligned}\quad (16)$$

Since $\psi_0 + \psi_1 = 1$, solving equation (16), one can get:

$$\psi_0 = \left[1 + \frac{\lambda_7}{\mu_7}\right]^{-1}$$

Based on the state changeover diagram, the availability of the system model is $A_{CPU} = \psi_0 = 0.998632$.

Other measures of system effectiveness are appended in Table 3.

Labor unit (MU)

Labor is a very critical component in the irrigation system, and its failure causes complete system failure. The state changeover diagram of the MU system is appended in Figure 4(c). The differential equations associated with the state changeover diagram are:

$$\begin{aligned}\psi'_0(t) &= -\lambda_8\psi_0(t) + \mu_8\psi_1(t) \\ \psi'_1(t) &= -\lambda_8\psi_1(t) + \mu_8\psi_0(t)\end{aligned}\quad (17)$$

Letting $t \rightarrow \infty$ and applying initial conditions, equation (17) shown above becomes:

$$\begin{aligned}-\lambda_8\psi_0 + \mu_8\psi_1 &= 0 \\ -\lambda_8\psi_1 + \mu_8\psi_0 &= 0\end{aligned}\quad (18)$$

Since $\psi_0 + \psi_1 = 1$, solving equation (18), one can get:

$$\psi_0 = \left[1 + \frac{\lambda_8}{\mu_8}\right]^{-1}$$

Based on the state changeover diagram, the availability of the system model is $A_{MU} = \psi_0 = 0.997721$.

Other measures of system effectiveness are appended in Table 3.

TIUP system time dependent system availability analysis

Among the RAMD measures, availability is a characteristic that can be used to identify the most sensitive components of the TIUP system. The operational procedure of TIUP is highly influenced by failure and repair rates. Thus, the impact of failure and repair rates on time dependent system availability has been investigated by mathematically analyzing the system. Using the assumptions and notations described above, a changeover diagram has been prepared and appended in Figure 5. It is observed that transition from one state to another state with some rate parameter. Here, $\psi_i(t)$ is transition probability from state i at time t and $\psi'_i(t)$ is the derivate with respect to time. Using simple probabilistic arguments and changeover

Table 3. Important reliability characteristics of various subsystems.

System characteristics	Power supply unit (PSU)	Borewell unit (BU)	Pipeline unit (PLU)	Centrifugal pump unit (CPU)	Labor unit (MU)
$R(t)$	$e^{-0.10046842t}$	$e^{-0.00005237t}$	$e^{-0.0001142t}$	$e^{-0.0002283t}$	$e^{-0.001142t}$
$M(t)$	$1 - e^{-3.34t}$	$1 - e^{-0.5818t}$	$1 - e^{-0.1667t}$	$1 - e^{-0.1667t}$	$1 - e^{-0.5t}$
MTBF	9.95338 hrs.	19094.902hrs.	8756.567hrs	4380.2015hrs	876.657hrs
MTTR	0.2994 hrs	1.7187 hrs	5.9988 hrs	5.9988 hrs	2 hrs
D	33.244	11109.4137	1459.7198	730.18	437.828
D_{min}	0.973017	0.99991	0.999318	0.998643	0.997748

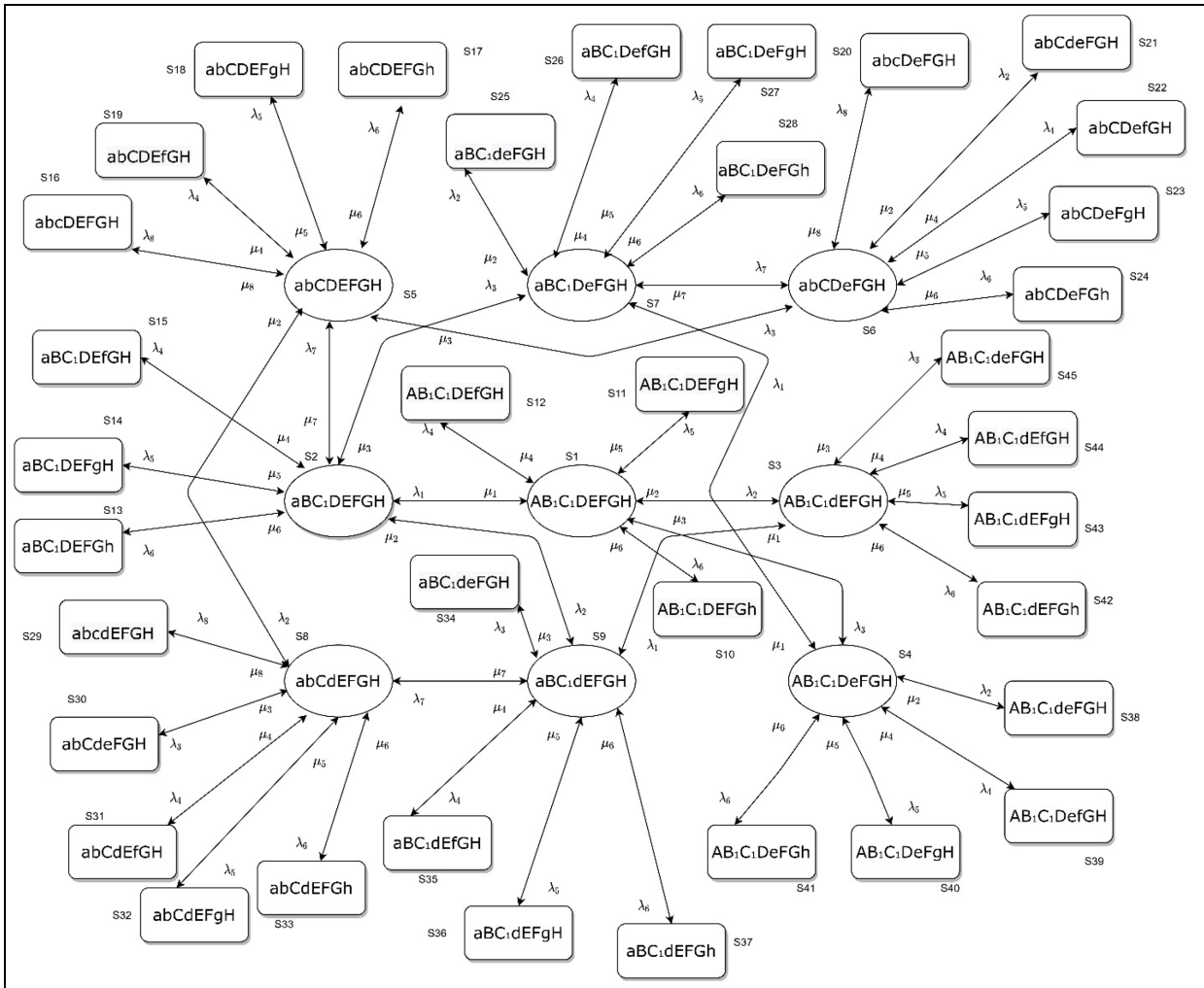


Figure 5. Changeover diagram of TIUP system.

diagram, the mathematical model has been developed. The differential equations have been described as follows:

$$\psi'_1(t) + \left\{ \sum_{i=1}^6 \lambda_i \right\} \psi_1(t) = \mu_1 \psi_2(t) + \mu_2 \psi_3(t) + \mu_3 \psi_4(t) + \mu_4 \psi_{12}(t) + \mu_5 \psi_{11}(t) + \mu_6 \psi_{10}(t) \tag{19}$$

$$\psi'_2(t) + \left\{ \mu_1 + \sum_{i=2}^7 \lambda_i \right\} \psi_2(t) = \lambda_1 \psi_1(t) + \mu_7 \psi_5(t) + \mu_2 \psi_9(t) + \mu_3 \psi_7(t) + \mu_4 \psi_{15}(t) + \mu_5 \psi_{14}(t) + \mu_6 \psi_{13}(t) \tag{20}$$

$$\psi'_3(t) + \left\{ \mu_2 + \sum_{i=1,3}^6 \lambda_i \right\} \psi_3(t) = \lambda_2 \psi_1(t) + \mu_1 \psi_9(t) + \mu_3 \psi_{45}(t) + \mu_4 \psi_{44}(t) + \mu_5 \psi_{43}(t) + \mu_6 \psi_{42}(t) \tag{21}$$

$$\begin{aligned} \psi'_4(t) + \left\{ \mu_3 + \sum_{i=1,2,4}^6 \lambda_i \right\} \psi_4(t) &= \lambda_3 \psi_1(t) + \mu_1 \psi_7(t) \\ &+ \mu_2 \psi_{38}(t) + \mu_4 \psi_{39}(t) + \mu_5 \psi_{40}(t) + \mu_6 \psi_{41}(t) \end{aligned} \quad (22)$$

$$\begin{aligned} \psi'_5(t) + \left\{ \mu_7 + \sum_{i=2}^{6,8} \lambda_i \right\} \psi_5(t) &= \lambda_7 \psi_2(t) + \mu_3 \psi_6(t) \\ &+ \mu_2 \psi_8(t) + \mu_4 \psi_{19}(t) + \mu_5 \psi_{18}(t) + \mu_6 \psi_{17}(t) \\ &+ \mu_8 \psi_{16}(t) \end{aligned} \quad (23)$$

$$\begin{aligned} \psi'_6(t) + \left\{ \mu_3 + \sum_{i=2,4}^8 \lambda_i \right\} \psi_6(t) &= \lambda_3 \psi_5(t) + \lambda_7 \psi_7(t) \\ &+ \mu_8 \psi_{20}(t) + \mu_2 \psi_{21}(t) + \mu_4 \psi_{22}(t) + \mu_5 \psi_{23}(t) \\ &+ \mu_6 \psi_{24}(t) \end{aligned} \quad (24)$$

$$\begin{aligned} \psi'_7(t) + \left\{ \mu_1 + \mu_3 + \sum_{i=2,4}^7 \lambda_i \right\} \psi_7(t) &= \lambda_1 \psi_4(t) \\ &+ \lambda_7 \psi_7(t) + \mu_8 \psi_{20}(t) + \mu_2 \psi_{21}(t) + \mu_4 \psi_{22}(t) \\ &+ \mu_5 \psi_{23}(t) + \mu_6 \psi_{24}(t) \end{aligned} \quad (25)$$

$$\begin{aligned} \psi'_8(t) + \left\{ \mu_2 + \mu_7 + \sum_{i=3}^{6,8} \lambda_i \right\} \psi_8(t) &= \lambda_8 \psi_9(t) \\ &+ \lambda_2 \psi_5(t) + \mu_8 \psi_{29}(t) + \mu_3 \psi_{30}(t) + \mu_4 \psi_{31}(t) \\ &+ \mu_5 \psi_{32}(t) + \mu_6 \psi_{33}(t) \end{aligned} \quad (26)$$

$$\begin{aligned} \psi'_9(t) + \left\{ \mu_2 + \mu_1 + \sum_{i=3}^7 \lambda_i \right\} \psi_9(t) &= \lambda_1 \psi_3(t) \\ &+ \lambda_2 \psi_2(t) + \mu_7 \psi_8(t) + \mu_3 \psi_{34}(t) + \mu_4 \psi_{35}(t) \\ &+ \mu_5 \psi_{36}(t) + \mu_6 \psi_{37}(t) \end{aligned} \quad (27)$$

$$\psi'_{10}(t) + \mu_6 \psi_{10}(t) = \lambda_6 \psi_1(t) \quad (28)$$

$$\psi'_{11}(t) + \mu_5 \psi_{11}(t) = \lambda_5 \psi_1(t) \quad (29)$$

$$\psi'_{12}(t) + \mu_4 \psi_{12}(t) = \lambda_4 \psi_1(t) \quad (30)$$

$$\psi'_{13}(t) + \mu_6 \psi_{13}(t) = \lambda_6 \psi_2(t) \quad (31)$$

$$\psi'_{14}(t) + \mu_5 \psi_{14}(t) = \lambda_5 \psi_2(t) \quad (32)$$

$$\psi'_{15}(t) + \mu_4 \psi_{15}(t) = \lambda_4 \psi_2(t) \quad (33)$$

$$\psi'_{16}(t) + \mu_8 \psi_{16}(t) = \lambda_8 \psi_5(t) \quad (34)$$

$$\psi'_{17}(t) + \mu_6 \psi_{17}(t) = \lambda_6 \psi_5(t) \quad (35)$$

$$\psi'_{18}(t) + \mu_5 \psi_{18}(t) = \lambda_5 \psi_5(t) \quad (36)$$

$$\psi'_{19}(t) + \mu_4 \psi_{19}(t) = \lambda_4 \psi_5(t) \quad (37)$$

$$\psi'_{20}(t) + \mu_8 \psi_{20}(t) = \lambda_8 \psi_6(t) \quad (38)$$

$$\psi'_{21}(t) + \mu_2 \psi_{21}(t) = \lambda_2 \psi_6(t) \quad (39)$$

$$\psi'_{22}(t) + \mu_4 \psi_{22}(t) = \lambda_4 \psi_6(t) \quad (40)$$

$$\psi'_{23}(t) + \mu_5 \psi_{23}(t) = \lambda_5 \psi_6(t) \quad (41)$$

$$\psi'_{24}(t) + \mu_6 \psi_{24}(t) = \lambda_6 \psi_6(t) \quad (42)$$

$$\psi'_{25}(t) + \mu_2 \psi_{25}(t) = \lambda_2 \psi_7(t) \quad (43)$$

$$\psi'_{26}(t) + \mu_4 \psi_{26}(t) = \lambda_4 \psi_7(t) \quad (44)$$

$$\psi'_{27}(t) + \mu_5 \psi_{27}(t) = \lambda_5 \psi_7(t) \quad (45)$$

$$\psi'_{28}(t) + \mu_6 \psi_{28}(t) = \lambda_6 \psi_7(t) \quad (46)$$

$$\psi'_{29}(t) + \mu_8 \psi_{28}(t) = \lambda_8 \psi_8(t) \quad (47)$$

$$\psi'_{30}(t) + \mu_3 \psi_{30}(t) = \lambda_3 \psi_8(t) \quad (48)$$

$$\psi'_{31}(t) + \mu_4 \psi_{31}(t) = \lambda_4 \psi_8(t) \quad (49)$$

$$\psi'_{32}(t) + \mu_5 \psi_{32}(t) = \lambda_5 \psi_8(t) \quad (50)$$

$$\psi'_{33}(t) + \mu_6 \psi_{33}(t) = \lambda_6 \psi_8(t) \quad (51)$$

$$\psi'_{34}(t) + \mu_3 \psi_{34}(t) = \lambda_3 \psi_9(t) \quad (52)$$

$$\psi'_{35}(t) + \mu_4 \psi_{35}(t) = \lambda_4 \psi_9(t) \quad (53)$$

$$\psi'_{36}(t) + \mu_5 \psi_{36}(t) = \lambda_5 \psi_9(t) \quad (54)$$

$$\psi'_{37}(t) + \mu_6 \psi_{37}(t) = \lambda_6 \psi_9(t) \quad (55)$$

$$\psi'_{38}(t) + \mu_2 \psi_{38}(t) = \lambda_2 \psi_4(t) \quad (56)$$

$$\psi'_{39}(t) + \mu_4 \psi_{39}(t) = \lambda_4 \psi_4(t) \quad (57)$$

$$\psi'_{40}(t) + \mu_5 \psi_{40}(t) = \lambda_5 \psi_4(t) \quad (58)$$

$$\psi'_{41}(t) + \mu_6 \psi_{41}(t) = \lambda_6 \psi_4(t) \quad (59)$$

$$\psi'_{42}(t) + \mu_6 \psi_{42}(t) = \lambda_6 \psi_3(t) \quad (60)$$

$$\psi'_{43}(t) + \mu_5 \psi_{43}(t) = \lambda_5 \psi_3(t) \quad (61)$$

$$\psi'_{44}(t) + \mu_4 \psi_{44}(t) = \lambda_4 \psi_3(t) \quad (62)$$

$$\psi'_{45}(t) + \mu_3 \psi_{45}(t) = \lambda_3 \psi_3(t) \quad (63)$$

The initial conditions associated with the model are:

$$\prod_i(t=0) = \begin{cases} 1 & \text{if } i = 1 \\ 0 & \text{if } i \neq 1 \end{cases} \quad (64)$$

As the mathematical model of the TIUP system for time-dependent system availability is a very complex, and analytical solution of it is very difficult to obtain. So, using MATLAB R2019a the Runge-Kutta method of fourth order has been implanted to get the numerical solution.

The following formulation provides the numerical values of SSA for the TIUP system:

Table 4. Severity, occurrence, and detection rating.

Rating	Severity (S)	Occurrence (O)	Detection (D)
1	No damage happened	Inaccessible failure. 1 unit fail in 100,000	Surely detectable
2	Very minor loss	Low. 1 unit fail among 10,000	Very high chance
3	Minor loss		High chance
4	low	Mild. 1 unit fail among 100	Mild
5	Mild		
6			Low
7	High	High. Failures occurs repeatedly. 1 unit fail among 10	Very low
8	Very high		Remote
9	Hazardous loss with cautioning	Very high. Very frequent failures. 1 unit fail out of 2	Inaccessible
10	Hazardous loss without cautioning		Totally uncertain

$$TDSA = \sum_{i=1}^9 \prod_i(t) \quad (65)$$

FMEA analysis

Failure Modes and Effects Analysis (FMEA) is an extensively used methodology in reliability engineering. Generally, FMEA is classified into three categories namely: design FMEA, process FMEA and system FMEA. Because of RAMD and steady state results of TIUP system, system level FMEA is applied here. In practice, it helps in identifying the probable failures, evaluate their effect on the operation of system and suggest solution processes to overcome those effects.³⁹ The FMEA outputs are helpful to rectify the errors in the design and production phase of any item. It involves examination of hardware, software, human and functional components of any system/process. The qualitative measurements of severity, occurrence, and detection are appended in Table 4.

In our investigation, maintainability is the issue of concern as the system operates in different environmental conditions under the open sky. Sometimes the system sinks in water also due to heavy rainfall and high level of seepage in the fields. Therefore, we visited the site of the tube-well and discussed the challenges faced by farmers to operate and maintain such systems. The data is collected from the farmer on the number of failures and time to repair. On the basis of that, FMEA at the system level has been performed as given below:

- i. The system and its components were described carefully, and probable failure modes and their effects were determined. It is observed that the availability of operating equipment's, labor and maintenance scheduling are the key factors affecting the TIUP system;
- ii. The key cause of failure is also identified and appended in FMEA sheet, as shown in Table 4. It

helps in deciding which kind of maintenance is required; On the existing failure modes there is no current control except maintenance planning and detection rate is high in the FMEA matrix;

iii. Risk Priority Number (RPN) has been calculated for each mode by multiplying severity (1–10), occurrence (1–10) and detection (1–10) ranges between 1 and 1000. The smaller value of RPN is better. RPN helps in identification that which problem must be solved on priority basis rather than focusing the whole;

iv. After observing the RPN values an action plan is suggested for the failure modes which have high RPN value.

v. It is observed that the disruption in electricity supply, unavailability of standby units like engine/ tractor, electronic item failure and mechanical failures are the factors responsible for the current maintainability level of TIUP unit.

Results and discussion

The failure of any component causes the complete failure of system that motivated to consider it as a series system. The reliability, availability, maintainability, and dependability expressions of series system can be derived by using the following expressions:

$$R_{TIUP}(t) = \prod_{i=1}^5 R_i(t) = e^{-0.10200529t} \quad (66)$$

$$A_{TIUP}(t) = \prod_{i=1}^5 A_i(t) = 0.965912 \quad (67)$$

$$M_{TIUP}(t) = \prod_{i=1}^5 M_i(t) = 1 - e^{-4.7552t} \quad (68)$$

$$D_{minTIUP}(t) = \prod_{i=1}^5 D_{min_i}(t) = 0.96876 \quad (69)$$

From Table 5, it is revealed that reliability of system decreases with respect to time for all subsystems as well as system. The power supply unit, labor unit and centrifugal pump attain minimum reliability that resulted that after 10h system's reliability is only 0.130015.

Table 5. Reliability of various subsystems with respect to time.

Time (h)	R_{PSU}	R_{BU}	R_{PU}	R_{CPU}	R_{MU}	R_{TIUP}
10	0.36616	0.999476	0.998859	0.99772	0.988645	0.360576
20	0.134073	0.998953	0.997719	0.995444	0.977419	0.130015
30	0.049092	0.99843	0.99658	0.993174	0.96632	0.04688
40	0.017976	0.997907	0.995442	0.99091	0.955348	0.016904
50	0.006582	0.997385	0.994306	0.98865	0.9445	0.006095
60	0.00241	0.996863	0.993171	0.986395	0.933775	0.002198

Table 6. Maintainability of various subsystems with respect to time.

Time (h)	M_{PSU}	M_{BU}	M_{PU}	M_{CPU}	M_{MU}	M_{TIUP}
10	1	0.997026	0.811187	0.811187	0.993262	1
20	1	0.999991	0.96435	0.96435	0.999955	1
30	1	1	0.993269	0.993269	1	1
40	1	1	0.998729	0.998729	1	1
50	1	1	0.99976	0.99976	1	1
60	1	1	0.999955	0.999955	1	1

After 60 h reliability of system decreases up to 0.002198 that is very crucial. While Table 6 revealed that borewell unit have lowest maintainability value and it takes maximum time to restore in operational condition after repair. From Table 5, it is revealed that power supply unit is the most sensitive component of the TIUP system and highly influenced the reliability of the whole system. The repair of pipeline and centrifugal pump takes time takes time in repairing.

By making some variation in various failure and repair rates, the impact on time dependent system availability of system has been observed. A constant change of 50% has been made in all parametric values associated in repair rates. From Table 7, it is revealed that with respect to time steady state availability decrease slightly but variation in failure rate of some subsystems like power supply unit, secondary borewell, pipeline, and centrifugal pump influenced the most. Any change in failure rate of any subsystem causes the decline in availability of TIUP system. While Table 8 showed that any increment in repair rate resulted as the enhancement of the system availability. It is revealed by Table 7 that, the availability of the power supply unit is less in comparison of all other units in long run. This validates the results of RAMD analysis.

Conclusions

The key findings of the present study are pointed out as follows:

- Through RAMD analysis, it is observed that steady state system availability of TIUP system is 0.965912 while TDSA is 0.9983249 after 400 h.

- Power supply unit and labor are the less reliable subsystems which reduces the whole system reliability.
- The reliability of TIUP system after 60 h is 0.002198 only.
- The dependability ratio and its minimum value is greater than 0.9 for all subsystems and system that indicates that system availability is high.
- It is revealed that whole system certainly restored in working conditions.
- A constant change of 50% in all failure and repair rates highlighted significant increment of TIUP system reliability and maintainability, respectively.
- Centrifugal pump is the most sensitive component in sense of variation in failure rate.
- The systems which have provision of redundancy are highly reliable and available.
- From FMEA analysis given in Table 9, it is observed that electricity and electric components and maintenance planning are the main factors for system failure with high RPN value 720 and 810 respectively.
- The availability results derived by RAMD, and Markovian approaches shows that power supply unit is the most sensitive unit in TIUP systems and need extra care for successful operation.

Finally, it is concluded that the TIUP system can be made more reliable and available for use by taking care of most sensitive components through proper maintenance or providing spare units. Though, the present model is developed for TIUPs but the same methodology can be applied for other irrigation systems also.

Table 7. Impact of various failure rates on steady state availability of TIUP system.

Time (h)	Base line (Table 1)	$\lambda_1 +$ 50% of λ_1	$\lambda_2 +$ 50% of λ_2	$\lambda_3 +$ 50% of λ_3	$\lambda_4 +$ 50% of λ_4	$\lambda_5 +$ 50% of λ_5	$\lambda_6 +$ 50% of λ_6	$\lambda_7 +$ 50% of λ_7	$\lambda_8 +$ 50% of λ_8
40	0.99862519	0.99862490	0.99862509	0.99862509	0.99843190	0.99847424	0.99828412	0.99862425	0.99862425
80	0.9984542	0.9984539	0.9984541	0.9984541	0.9981769	0.9983023	0.9981128	0.9984532	0.9984532
120	0.998381	0.9983808	0.9983809	0.9983809	0.9980673	0.9982291	0.9980397	0.9983801	0.9983801
160	0.9983492	0.998349	0.9983491	0.9983491	0.9980197	0.9981974	0.9980079	0.9983483	0.9983483
200	0.9983354	0.9983351	0.9983353	0.9983353	0.9979989	0.9981835	0.9979941	0.9983344	0.9983344
240	0.9983294	0.9983291	0.9983293	0.9983293	0.9979899	0.9981775	0.9979881	0.9983284	0.9983284
280	0.9983268	0.9983265	0.9983267	0.9983267	0.997986	0.9981749	0.9979855	0.9983258	0.9983258
320	0.9983256	0.9983254	0.9983255	0.9983255	0.9979843	0.9981738	0.9979844	0.9983247	0.9983247
360	0.9983251	0.9983249	0.998325	0.998325	0.9979836	0.9981733	0.9979839	0.9983242	0.9983242
400	0.9983249	0.9983246	0.9983248	0.9983248	0.9979832	0.9981731	0.9979837	0.998324	0.998324

Table 8. Impact of various repair rates on steady state availability of TIUP system.

Time (h)	Base (Table 1)	$\mu_1 +$ 50% of μ_1	$\mu_2 +$ 50% of μ_2	$\mu_3 +$ 50% of μ_3	$\mu_4 +$ 50% of μ_4	$\mu_5 +$ 50% of μ_5	$\mu_6 +$ 50% of μ_6	$\mu_7 +$ 50% of μ_7	$\mu_7 +$ 50% of μ_7
40	0.99862519	0.99862549	0.99862526	0.99862526	0.99868651	0.99872462	0.99885216	0.99862581	0.99862582
80	0.9984542	0.9984545	0.9984542	0.9984542	0.9985903	0.9985555	0.9986819	0.9984548	0.9984548
120	0.998381	0.9983813	0.9983811	0.9983811	0.9985635	0.9984823	0.9986087	0.9983817	0.9983817
160	0.9983492	0.9983495	0.9983493	0.9983493	0.9985558	0.9984505	0.9985769	0.9983499	0.9983499
200	0.9983354	0.9983357	0.9983355	0.9983355	0.9985536	0.9984367	0.9985631	0.998336	0.998336
240	0.9983294	0.9983297	0.9983295	0.9983295	0.998553	0.9984307	0.998557	0.99833	0.99833
280	0.9983268	0.9983271	0.9983268	0.9983268	0.9985528	0.998428	0.9985544	0.9983274	0.9983274
320	0.9983256	0.9983259	0.9983257	0.9983257	0.9985528	0.9984269	0.9985533	0.9983263	0.9983263
360	0.9983251	0.9983254	0.9983252	0.9983252	0.9985527	0.9984264	0.9985528	0.9983258	0.9983258
400	0.9983249	0.9983252	0.998325	0.998325	0.9985527	0.9984262	0.9985526	0.9983256	0.9983256

Table 9. FMEA of TLUP system.

Procedure function	Key failure mode	Key effect of failure	Sev	Key cause (s) of failure	Occur	Current procedure controls	Detec	RPN	Recommendations	Accountability and aim	Sev	Occ	Det	RPN											
Availability of operating equipment	Disruption in electricity supply, non-availability of Standby units like Engine/Tractor	Irrigation cannot be done and directly affect the crop production	8	Less supply of electricity	9	None	10	720	Purchase special electricity connection, use redundant units in better way	Farmer/person who operates the Tube-well	7	5	7	245											
															Electronic items failure/Mechanical failures	5	Non e	10	400	Use quality items of reputed manufacturers	Farmer	6	5	8	240
Labour	Non availability of spare parts	Purchase water for irrigation from other tube-well or wait until the spare parts available till that system remain idle	6	High Demand	8	None	10	360	Schedule maintenance after a pre specified time	Farmer/Operator	8	5	8	320											
															System fails due to human errors	5	None	10	400	Appoint a skilled operator on pipeline	Farmer	7	5	7	245
Maintenance planning	Farmer have no maintenance planning to avoid future failures	Not prepared for dealing the future failures	9	No proper handling of system	9	Only two times in a year Maintenance is done	10	810	For farmers some TPM workshops should be organized	Agriculture department of state	8	6	8z	384											

The present study is carried out on limited data and in future it can be extended by collecting large amount of data from various sources. Here, labor is only considered in terms of presence or absence only associated with considered system, in future study, competence of the various persons will be considered. The sensitivity analysis of system performance measures can be conducted in future work. As well as an effort can be made to achieve the global solution by applying some advanced metaheuristics, such as genetic algorithm, Gray-wolf optimization, and particle swarm optimization.



Declaration of conflicting interests

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