JOURNAL OF GREEN COMPLEX ENGINEERING, 2026, Vol.4, No.1, 69~78
https://doi.org/10.59810/greenplexresearch.v4i1.291
e-ISSN 3025-9673

Irrigation Serviceability under Seasonal Scarcity: Digital Water Balances and Canal Deterioration in Pamukkulu

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ABSTRACT

This study evaluates whether Irrigation Service Agreement (ISA) commitments remain physically deliverable under seasonal water scarcity and canal deterioration in the Pamukkulu Irrigation Area, South Sulawesi, Indonesia. A descriptive quantitative design combined farmer questionnaires, field observations, and a 72-period five-day SIPASI water-balance series across six SCADA-supported secondary-canal service units covering 2,885 ha; the September–October 2026 periods were treated as planning projections rather than realized observations. Service performance was assessed through equity, adequacy, and reliability, while principal survey proportions were summarized with Wilson 95% confidence intervals. Mean intake requirement was 4,796.8 L s−1, whereas mean available discharge was 2,380.6 L s−1, equivalent to 49.6% of requirement. The mean K factor was 0.47; full-service conditions were identified in 19 of 72 periods, while severe-deficit conditions were identified in 31 periods. For the projected 1–11 September 2026 periods, available flow covered only 1.4–2.0% of intake demand. Farmers identified leakage as the dominant loss mechanism (72.7%), secondary canals as the highest-loss segment (60.6%), and downstream shortage as the main consequence (51.5%). The results support K-triggered scarcity rules, targeted secondary-canal maintenance, and tighter operational linkage among ISA, SIPASI, SCADA, and P3A.

ARTICLE HISTORY

Received June 22, 2026
Received in revised form July 25, 2026
Accepted August 20, 2026
Available online August 28, 2026.

KEYWORDS

Irrigation Service Agreement; irrigation performance; water scarcity; SIPASI; canal conveyance loss

1. Introduction

Irrigation performance is increasingly judged by the service received by water users rather than by the presence of canals, gates, and control structures alone. This distinction is important in large gravity systems because adequate upstream capacity does not guarantee adequate farm-level delivery when source availability fluctuates, conveyance losses accumulate, or allocation is poorly timed. Recent service assessments in other water systems show the same separation between infrastructure provision and delivered performance: expanding production or coverage can coexist with user dissatisfaction and unreliable service when limited water availability, ageing assets, and management constraints persist [1,2]. Infrastructure-condition studies similarly associate better asset condition with higher quantity and reliability of delivered service [3], while resilience frameworks increasingly treat water availability, infrastructure operation, and quality of service as interacting but distinct performance dimensions [4]. A performance-based perspective is therefore useful because it tests what users actually receive rather than inferring service from the existence of assets [5].

The distribution stage is where this service problem becomes most visible. Water released at an intake must pass through primary, secondary, and tertiary networks before reaching crops. Hydraulic losses and damaged canal sections increase the gross discharge required upstream to satisfy a fixed field requirement. Canal-command studies have linked underused irrigation potential to conveyance loss and insufficient maintenance [6]. At system scale, dynamic reservoir rules and demand assessment can improve supply reliability or clarify when demand cannot be fully met [7]. Scarcity management also involves allocation choices: agricultural water policies may alter cropping responses and water demand [8], while hydro-economic analysis makes explicit the trade-offs among water savings, production, and income [9]. Reservoir optimization studies likewise show that irrigation reliability depends on the operating rules used when demands compete for limited water [10]. Seasonal storage variability further means that a service target feasible in one period may become infeasible in another [11].

In Indonesia, irrigation modernization has introduced the Irrigation Service Agreement (ISA) as a mechanism for clarifying service expectations, responsibilities, and coordination between irrigation managers and farmer organizations. The institutional benefit is clear: allocation rules can be communicated more consistently, obligations become visible, and performance can be reviewed against agreed expectations. The more difficult question is whether those expectations remain hydraulically feasible when water availability is low or the conveyance network is impaired. Evidence from stressed distribution systems indicates that water shortage, physical loss, weak institutions, and operational constraints often occur together rather than independently [12]. Integrated performance assessment therefore needs to distinguish procedural performance from physical service achievement [13]. The same distinction matters for equity. Uniform rules can still produce unequal

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outcomes when users occupy different hydraulic positions or experience different levels of loss [14,15].

Digital monitoring can make the gap between commitment and deliverability observable. In Pamukkulu, SIPASI organizes irrigation requirements, availability, allocation, and the K factor, while SCADA-supported monitoring provides an operational architecture for observing conditions at selected structures. The wider digital-water literature emphasizes that technology is most useful when information changes operational decisions rather than merely generating additional data. Utility studies identify data integration, organizational readiness, and decision processes as key conditions for digital transformation [16,17]. Case studies also show that digitalization may remain incremental when information is weakly connected to strategic management [18,19]. Digital-water-service and digital-twin approaches therefore seek to connect monitoring, network representation, and asset decisions [20-22], while early-warning and proactive-management studies emphasize shortening the interval between observation and response [23,24]. In an Indonesian setting, a web-based GIS framework has similarly been proposed to combine spatial risk information with a monitoring interface for government and communities [25].

The Pamukkulu Irrigation Area in Takalar Regency, South Sulawesi, provides a useful setting for examining this interaction. The scheme serves approximately 6,430 ha. This study focuses on six secondary-canal service units associated with Kulantobengisi (BP.1), Jenematallasa (BP.2), Bontoloe (BP.4), Lantang (BP.5), Cakura (BP.8), and Surulangi (BP.13), covering 2,885 ha across two planting groups. Distribution is organized through scheduling and P3A coordination, yet the SIPASI water balance shows large temporal differences between required and available flow, while farmer reports repeatedly identify leakage and secondary-canal deterioration. The case therefore represents a hydro-institutional service problem: an agreement can organize distribution, but actual performance still depends on how much water is available, how much survives conveyance, and how quickly operations adapt to changing conditions.

The research gap lies in the limited integration of these dimensions within a single service diagnosis. Studies commonly examine water availability, infrastructure deterioration, farmer participation, or digital monitoring separately; fewer ask whether an agreed service remains physically deliverable when these factors interact. The present study addresses that gap by combining farmer-reported service experience, a 72-period SIPASI-based water-balance series combining operational information and planning projections, field observations, and the ISA dimensions of equity, adequacy, and reliability. The objectives are to quantify the temporal structure of the supply–demand gap, identify the network segments and loss mechanisms most strongly associated with deteriorating service, evaluate the implications for ISA performance, and derive operational rules for linking SIPASI and SCADA information to allocation and maintenance. The central proposition is that performance-based irrigation should be evaluated through serviceability: the extent to which agreed service can be delivered under the evaluated hydrologic states and network conditions.

2. Methods

2.1 Study area and service units

The study was conducted in the Pamukkulu Irrigation Area, located in Kale Ko'Mara Village, North Polongbangkeng District, Takalar Regency, South Sulawesi Province, Indonesia. The overall irrigation system serves approximately 6,430 ha. The analytical sample comprised six secondary-canal service units associated with division structures BP.1, BP.2, BP.4, BP.5, BP.8, and BP.13. These units were selected because they represented operational areas in which ISA implementation was being assessed and where SCADA-supported monitoring had been introduced.

The six units covered a total of 2,885.0 ha. Planting Group I comprised Kulantobengisi/BP.1 (763.5 ha), Jenematallasa/BP.2 (223.5 ha), Bontoloe/BP.4 (117.7 ha), and Lantang/BP.5 (670.3 ha), totaling 1,775.0 ha. Planting Group II was represented by Cakura/BP.8 (655.2 ha) and Surulangi/BP.13 (454.8 ha), totaling 1,110.0 ha. The sampled service area therefore represented approximately 44.9% of the total Pamukkulu command area. Distribution in the scheme follows a planting-group arrangement intended to support rotational and scheduled water delivery when water availability is limited. Table 1 summarizes the six service units, planting groups, control structures, and sampled command areas.

Table 1. Study service units and sampled command area.

Planting group	Service unit	Structure	Area (ha)
I	Kulantobengisi	BP.1	763.5
I	Jenematallasa	BP.2	223.5
I	Bontoloe	BP.4	117.7
I	Lantang	BP.5	670.3
II	Cakura	BP.8	655.2
II	Surulangi	BP.13	454.8
	Total sampled area		2,885.0

Note: Sampled area = 2,885.0 ha, approximately 44.9% of the 6,430-ha Pamukkulu irrigation service area.

2.2 Study design and evidence streams

The study used a descriptive quantitative design combining farmer questionnaires, field observations, and secondary operational data. These materials were organized into three complementary evidence streams (Figure 1). The first stream was user-reported service experience from P3A respondents. The questionnaire captured perceived water-loss magnitude and mechanism, location and cause of network damage, the effect of damage on water distribution, and farmer-level consequences such as downstream shortage, planting delay, and yield reduction.

The second stream was the SIPASI water-balance series for 72 five-day periods (panca) from November 2025 through October 2026. The series combines operational water-balance information with planning projections. In particular, the September–October 2026 periods represent SIPASI-derived planning projections rather than realized field observations. Accordingly, the projected available discharge, K factor, and derived service-deficit metrics for these future periods were interpreted as planning indicators of expected irrigation serviceability. SIPASI outputs reported effective rainfall, reference evapotranspiration (ET0), net field water requirement, turnout requirement, intake requirement, predicted available discharge, K factor, and discharge released at the intake. The analysis emphasized intake requirement, available discharge, delivered discharge, conveyance-loss adjustments, and K because these variables directly characterize the physical feasibility of the irrigation service.

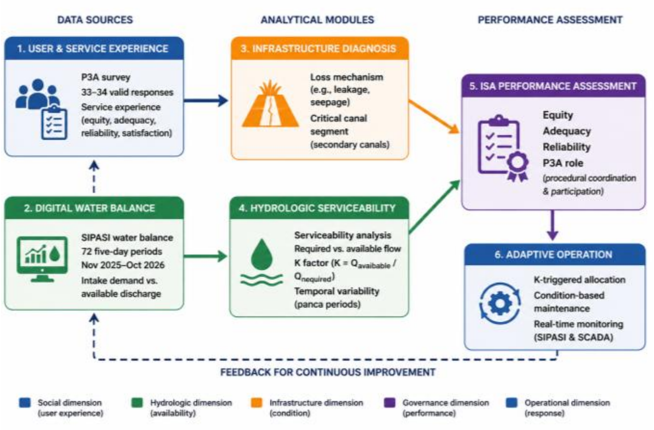

Figure 1. Integrated analytical framework linking user-reported service experience, digital water balance, infrastructure diagnosis, and ISA performance

Source: Authors' analysis.

The third stream comprised field observations and the operational context of SCADA. Field records indicated that the selected secondary canals were included in a modernization setting in which sensor and control information can support monitoring of discharge, water level, and gate operation. Continuous SCADA records were not available as an independent time series for statistical analysis; SCADA was therefore treated as the monitoring architecture supporting service management rather than as a separate quantitative evidence stream. This distinction avoids attributing numerical effects to SCADA that were not measured in the study.

2.3 Irrigation Service Agreement performance framework

ISA performance was evaluated through three primary service dimensions: equity, adequacy, and reliability. Equity was defined as the extent to which allocation procedures and delivery outcomes support proportionate access among service areas, including downstream users. Adequacy was defined as the ability of available discharge to satisfy calculated irrigation requirement. Reliability was defined as the consistency with which the required level of service can be provided across successive analyzed periods. P3A participation was assessed as an enabling institutional condition because the farmer organization communicates demand, supports tertiary-level allocation, and participates in resolving distribution problems.

The analytical logic distinguished procedural performance from physical performance. Procedural equity is indicated by the existence of planting groups, allocation schedules, and P3A coordination. Physical equity requires evidence that comparable service is actually delivered across locations. Likewise, an ISA may be administratively implemented even when adequacy and reliability deteriorate because water availability is insufficient. This distinction is central to the study because it prevents the existence of a service mechanism from being interpreted automatically as proof of service achievement.

2.4 Water-balance and conveyance metrics

The SIPASI analysis uses gross-up calculations to account for conveyance losses between the field, turnout, and intake. The SIPASI calculations report a tertiary-network loss rate of 14.66% and a primary/secondary-network loss rate of 2.84%. If the net field requirement is Q_{field}, the turnout requirement can be represented as:

$$Q_{turnout} = Q_{field} / (1 - L_{tertiary})$$

where $L_{tertiary}$ is the tertiary loss fraction. The intake requirement is then:

$$Q_{intake} = Q_{turnout} / (1 - L_{primary-secondary})$$

These equations explain why the gross discharge required upstream is larger than the net water requirement at the field. For example, in the projected panca 62 planning state, the field requirement was 8,552.4 $L\ s^{-1}$, the turnout requirement increased to 10,021.3 $L\ s^{-1}$, and the intake requirement increased further to 10,314.4 $L\ s^{-1}$. The gross intake requirement was therefore 20.6% higher than the net field requirement.

Operational adequacy was summarized using the K factor:

$$K = \min(1, Q_{available} / Q_{intake})$$

where $Q_{available}$ is the predicted discharge available to the irrigation system and Q_{intake} is the discharge required at the intake. K = 1 indicates that the calculated requirement can be fully satisfied. Values below 1 indicate partial service, with progressively lower values representing increasing scarcity. For interpretation, periods were classified into three service states: full service (K = 1.00), partial service ($0.25 \leq K < 1.00$), and severe deficit ($K < 0.25$). The threshold of 0.25 was used because the study records explicitly distinguished periods below this value as periods of very low fulfillment.

For selected critical periods, an availability coverage ratio was also calculated as $Q_{available} / Q_{intake} \times 100$, and the absolute service gap was calculated as $Q_{intake} - Q_{available}$. These derived metrics were used to express the magnitude of shortage in physically interpretable units.

2.5 Questionnaire and statistical analysis

The questionnaire records indicate 34 participants, but several displayed percentage distributions correspond exactly to 33 valid responses. For example, the reported counts for perceived water-loss severity (15 moderate, 10 large, 5 small, and 3 very large) sum to 33; the same denominator is implied by 24 of 33 respondents identifying leakage as the dominant loss mechanism. Other items, including dominant physical damage and infrastructure age, are consistent with a denominator of 34. The most conservative interpretation is therefore that 34 respondents participated, with one missing or non-valid response on several items. Statistical calculations in this manuscript use the denominator implied by the reported count and percentage for each item rather than forcing a single denominator.

Survey results were summarized as proportions. For the principal binary reconstructions—such as the proportion identifying leakage, secondary canals, infrastructure age, or downstream shortage—95% Wilson confidence intervals were calculated. Wilson intervals were selected because the sample is modest and several proportions are far from 0.5, conditions under which the conventional normal approximation can perform poorly. The intervals quantify sampling uncertainty around the reported proportions but should not be interpreted as evidence of population representativeness beyond the sampled P3A respondents.

The SIPASI series was summarized using the reported mean, minimum, maximum, and frequency of K service states. The mean intake requirement (4,796.8 L s−1) and mean available discharge (2,380.6 L s−1) were used to calculate the ratio of mean availability to mean requirement and the mean absolute gap. Frequencies of full-service and severe-deficit periods were also expressed as proportions with Wilson 95% confidence intervals. Respondent-level covariance and reach-specific hydraulic measurements were not available; consequently, cross-item regression, time-series modeling, and causal attribution were not attempted.

2.6 Evidence integration and triangulation

The final analysis triangulated the three evidence streams. A physical bottleneck was considered important when the survey consistently identified a damage mechanism and network segment and when the SIPASI results showed a service deficit that such losses could plausibly aggravate. ISA performance was then interpreted by asking whether procedural mechanisms—planting groups, P3A coordination, SIPASI planning, and SCADA-enabled monitoring—were sufficient to maintain equity, adequacy, and reliability under the analyzed hydrologic conditions, including the projected September–October planning states. This integrated design was intended to reveal not only whether ISA was implemented, but whether the system had the hydraulic and institutional capacity to honor the service it was intended to organize.

3. Results and Discussion

3.1 Secondary-canal deterioration and downstream service loss

The questionnaire results show a consistent chain linking physical deterioration to water loss and downstream service effects. On the item describing the magnitude of water loss associated with network damage, 45.5% of respondents classified the loss as moderate and 30.3% as large, while 9.1% considered it very large. Thus, a substantial majority perceived network losses as operationally important rather than negligible. More specifically, 72.7% (24/33; 95% CI 55.8–84.9%) identified canal leakage as the dominant form of water loss. This response was much more frequent than reported theft, seepage, or other loss mechanisms.

The physical diagnosis was even more concentrated. Cracks and leakage were identified as the most common type of damage by 85.3% of respondents (29/34; 95% CI 69.9–93.6%). Infrastructure age was identified as the main cause of damage by 76.5% (26/34; 95% CI 60.0–87.6%), with sedimentation and other causes selected much less frequently. These findings suggest that the observed service problem is not primarily perceived as an isolated operational mistake; it is associated with progressive deterioration of the conveyance system.

The location of the problem is also non-random from a service perspective. The secondary canal was identified as the network segment with the greatest water loss by 60.6% of respondents (20/33; 95% CI 43.7–75.3%). The survey separately showed that 54.5% identified the secondary canal as the segment most frequently damaged, followed by the tertiary network. The convergence of these two items is important: the same network level is perceived both as the most damaged and as the location of the greatest loss. Because the secondary system sits between the main conveyance network and multiple tertiary service areas, losses at this level can propagate to several downstream groups simultaneously.

Respondents also linked network condition to service outcomes. A combined 69.7% (23/33; 95% CI 52.7–82.6%) rated the effect of canal damage on distribution as large or very large. The same combined proportion rated water loss caused by network damage as large or very large. At the user level, 51.5% (17/33; 95% CI 35.2–67.5%) identified downstream water shortage as the principal consequence, followed by yield reduction (30.3%), planting delay (12.1%), and farmer conflict (6.1%). The dominant pathway emerging from the survey can therefore be summarized as: ageing infrastructure → cracks/leakage → secondary-canal losses → reduced downstream supply. Figure 2 consolidates the principal survey indicators supporting this pathway.

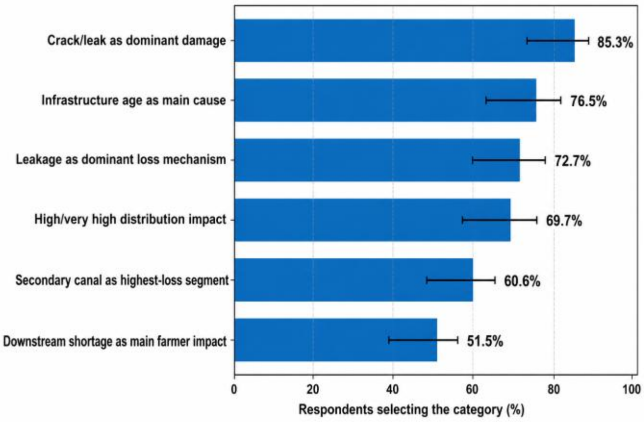

Figure 2. Principal farmer-reported infrastructure and service diagnostics. Error bars show Wilson 95% confidence intervals; item-specific valid denominators were 33 or 34.
Source: Authors' analysis.

The survey pattern makes the secondary network the most defensible first target for maintenance. A reach that serves several tertiary units can have a larger service consequence than a more visibly damaged but hydraulically isolated segment. Condition-based rehabilitation studies support this service-criticality approach: asset condition is more useful when combined with downstream consequence and operational risk [26], while GIS-supported maintenance frameworks use condition and failure information to identify sections that require priority intervention [27,28]. Integrated leakage programs also show that monitoring, data analysis, and field intervention are more effective when they are coordinated rather than implemented separately [29]. In Pamukkulu, the available evidence does not quantify loss from each crack, but it is sufficient to justify reach-scale inflow–outflow measurement and targeted repair of secondary canals before generalized rehabilitation. This priority is also consistent with studies linking water loss to operational productivity and reliability [30] and with risk-based infrastructure planning that connects failure information to maintenance decisions [31].

3.2 Seasonal supply–demand mismatch

The SIPASI water-balance results show that the infrastructure problem occurred within a broader hydrologic constraint. Across the 72 five-day periods, mean intake requirement was 4,796.8 L s−1, while mean available discharge was 2,380.6 L s−1. The ratio of these means was 49.63%, leaving a mean gap of 2,416.2 L s−1. This does not imply that every analyzed period represented a 50% deficit, because both demand and availability varied substantially. Instead, it indicates that the annual analysis horizon was structurally tight: on average, the water predicted to be available was only about half of the water required at the intake.

The range of the SIPASI-derived variables illustrates the magnitude of this variability. Intake requirement reached a projected maximum of 10,314.4 L s-1 at panca 62 (6 September), whereas predicted available discharge reached its reported maximum of 9,938.0 L s-1 at panca 20 (6 February) and its projected minimum of 120.0 L s-1 at panca 71 (21 October). The maximum delivered intake discharge was 6,133.3 L s-1 at panca 19, while the projected minimum intake discharge was 101.8 L s-1 at panca 61. These differences show that neither demand nor supply can be represented adequately by a single seasonal average; irrigation serviceability depends on the timing of their intersection.

A period of near-complete service is illustrated by panca 19 (1 February). Required intake discharge was 6,133.3 L s−1 and available discharge was 6,288.0 L s−1, producing a supply margin of 154.7 L s−1, or 2.5% above requirement. Under this condition, K was 1.00 and the delivered discharge matched the requirement. In contrast, the SIPASI planning scenario for early September indicated an extreme scarcity state. At panca 61 (1 September), the projected intake requirement was 10,183.9 L s−1, whereas projected available discharge was only 138.0 L s-1. The resulting projected absolute deficit was 10,045.9 L s-1, with available water covering only 1.36% of the requirement. At panca 62 (6 September), projected intake requirement increased to 10,314.4 L s-1 while projected available discharge was 174.0 L s-1, corresponding to 1.69% coverage. At panca 63 (11 September), projected intake requirement remained 10,085.5 L s-1 and projected available discharge was 206.0 L s−1, or 2.04% coverage. These values represent SIPASI planning projections rather than realized September observations. Figure 3 places these selected SIPASI periods against the 1:1 line of full hydrologic serviceability and illustrates the magnitude of the projected September deficit.

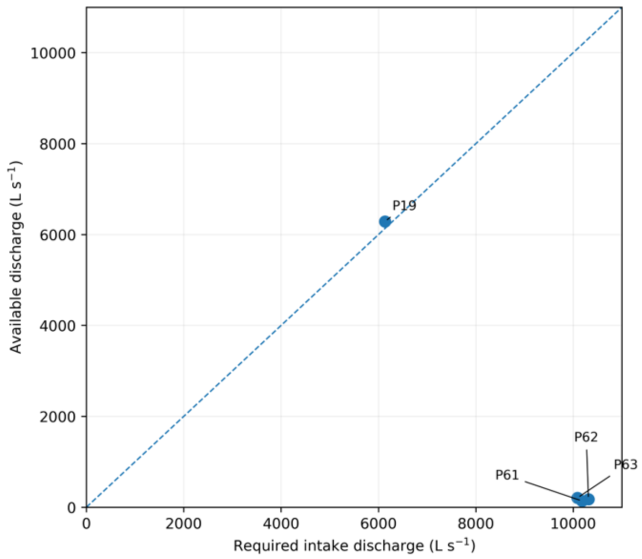

Figure 3. Required versus available intake discharge for selected SIPASI five-day periods. P61–P63 represent planning projections for September 2026. The dashed 1:1 line indicates full hydrologic serviceability; points far below the line indicate severe deficit.
Source: Authors' analysis.

3.3 Conveyance losses amplify scarcity

The SIPASI calculations make clear that canal losses amplify scarcity by increasing the gross discharge that must be supplied at the upstream end of the system. The SIPASI calculations report a tertiary conveyance loss of 14.66% and a primary/secondary loss of 2.84%. Because upstream requirements are calculated by dividing net demand by the remaining conveyance efficiency, the increase in gross requirement is larger than the loss percentage itself.

The projected panca 62 planning state provides a clear numerical example. Net water requirement at the field was 8,552.4 L s−1. After accounting for the 14.66% tertiary loss, the turnout requirement increased to 10,021.3 L s−1, a 17.2% gross-up relative to field demand. After the additional 2.84% loss in the primary/secondary network, intake requirement increased to 10,314.4 L s−1. The final intake requirement was therefore 20.6% greater than the net field requirement. When available water is abundant, this gross-up can be absorbed by the system. When available discharge collapses, however, each percentage point of avoidable conveyance loss widens an already severe service deficit.

The survey and SIPASI results are therefore mutually reinforcing. The digital water balance quantifies the gross requirement associated with conveyance losses, while the farmer survey identifies leakage and secondary-canal deterioration as the most visible physical mechanisms. The two data streams do not establish a causal coefficient linking a specific crack to a specific discharge loss, because paired hydraulic measurements were not available. They do, however, show that physical deterioration occurs exactly at the level of the system where reducing loss would have the highest operational value during scarcity.

The water balance and the farmer evidence describe two constraints that reinforce one another. Seasonal scarcity determines how much water can enter the system, whereas conveyance condition determines how much of that scarce water reaches downstream users. The 20.6% gross-up between field and intake requirement in the projected panca 62 state illustrates why network efficiency matters most when source water is already limited. Under abundant conditions, some conveyance loss can be absorbed without changing service state. Under extreme scarcity, the same loss reduces an already small deliverable fraction. Dynamic reservoir studies similarly show that reliability depends on operating rules that respond to changing availability [7], and scenario-based basin analysis demonstrates the value of evaluating demand satisfaction together with water-resource variability [32]. Decision-support frameworks for water-scarce systems therefore treat hydrologic information as an input to allocation choices rather than as a reporting endpoint [33].

3.4 Reliability and K-based service states

The 72-period SIPASI K-factor profile provides an integrated summary of irrigation serviceability across the analysis horizon. Because the September–October 2026 portion of the series consists of planning projections, the profile should be interpreted as a combined operational-and-planning assessment rather than as a purely observed annual reliability record. Across the full SIPASI series, the K factor ranged from 0.01 to 1.00, with a mean of 0.47. Full service (K = 1.00) occurred in 19 of 72 five-day periods, equivalent to 26.4% (95% CI 17.6–37.6%). Severe deficit (K < 0.25) occurred in 31 periods, or 43.1% (95% CI 32.3–54.6%). The remaining 22 periods (30.6%) represented partial service between these two states (Figure 4).

This distribution has an important implication for ISA. A SIPASI series in which only about one quarter of the analyzed periods can meet calculated demand fully indicates limited serviceability under the evaluated operating and planning conditions. The mean K across the 72-period SIPASI series (0.47) also indicates substantial temporal variability: periods of full service coexist with periods in which the deliverable fraction of demand approaches zero. The projected September sequence is particularly critical, with K values of approximately 0.01–0.02. Under such conditions, normal allocation rules are insufficient; scarcity has to be managed explicitly through prioritization, rotation, or adjusted service commitments.

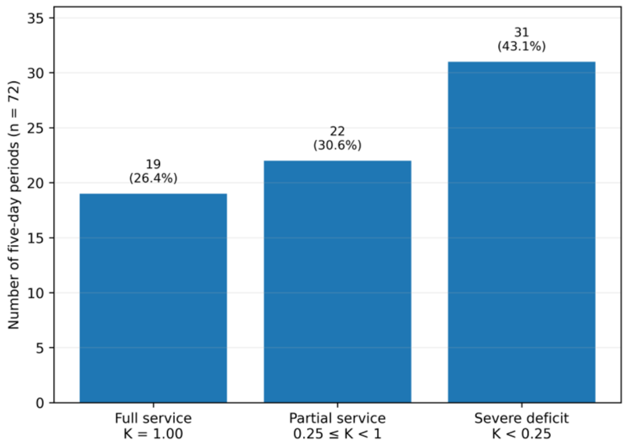

Figure 4. Distribution of K-factor service states across the 72 five-day SIPASI analysis periods. The September–October 2026 periods represent SIPASI planning projections.

Source: authors' SIPASI analysis.

Table 2 consolidates the hydrologic balance, K-factor reliability, conveyance-loss assumptions, and projected supply coverage during the three critical September periods.

For ISA, the K distribution changes the meaning of reliability. A system that can meet calculated demand fully in only about one-quarter of its analyzed periods cannot treat full delivery as an unconditional promise. K offers a practical service-state trigger because it is already produced by SIPASI and directly expresses the ratio between available and required discharge. When K = 1.00, normal scheduled service is physically supportable. When 0.25 ≤ K < 1.00, allocation can move to a partial-service rule based on proportional reduction or rotation. When K < 0.25, a severe-deficit protocol should replace routine service expectations and specify priority rules, notification timing, and verification. Short-horizon forecasting can make such allocation rules more actionable when water availability is nonlinear [34]. The important institutional point is that hydrologically conditional service does not weaken accountability: managers remain responsible for timely shortage declaration, transparent rotation, gate operation, leakage response, and consistent treatment of users within the same scarcity state.

Table 2. Integrated irrigation-service performance metrics.

Domain	Indicator	Result
Hydrologic balance	Mean intake requirement	4,796.8 L s−1
Hydrologic balance	Mean available discharge	2,380.6 L s−1
Hydrologic balance	Ratio of mean availability to mean requirement	49.63%
Hydrologic balance	Mean absolute gap	2,416.2 L s−1
K-factor reliability	Mean and range	0.47 (0.01–1.00)
K-factor reliability	Full service (K = 1.00)	19/72 periods; 26.4% (95% CI 17.6–37.6%)
K-factor reliability	Severe deficit (K < 0.25)	31/72 periods; 43.1% (95% CI 32.3–54.6%)
Conveyance	Tertiary loss used in SIPASI	14.66%
Conveyance	Primary/secondary loss used in SIPASI	2.84%
Projected critical period	Panca 61 supply coverage	1.36% of requirement
Projected critical period	Panca 62 supply coverage	1.69% of requirement
Projected critical period	Panca 63 supply coverage	2.04% of requirement

Note: Confidence intervals are Wilson 95% intervals for period proportions. Panca 61–63 represent SIPASI planning projections for September 2026 rather than realized observations.

3.5 Procedural equity and delivered equity

Pamukkulu uses planting groups to organize water distribution, and P3A participates in communicating farmer demand, coordinating tertiary delivery, and mediating distribution problems. These arrangements support procedural equity by creating a shared schedule and a mechanism through which users can participate in allocation. They are consistent with the service-oriented logic of ISA, which seeks clarity in responsibilities and expectations.

The data, however, do not demonstrate outcome equity in the same strong sense. The available records do not contain paired head-versus-tail flow measurements for each service unit, so a quantitative equity coefficient cannot be calculated. Instead, the strongest outcome signal is the farmer response identifying downstream shortage as the most common consequence of water loss. This result, combined with the concentration of reported damage and loss in secondary canals, indicates that physical deterioration can transform an administratively fair schedule into an unequal delivered service.

Accordingly, equity in Pamukkulu should be interpreted as conditional. The scheme has mechanisms that are designed to distribute scarcity fairly, but the actual outcome depends on how much water enters the network and how much survives conveyance to downstream users. ISA therefore appears to provide a useful procedural platform, while SIPASI and SCADA provide the information architecture needed to detect when the physical basis for equal service is deteriorating. The key unresolved requirement is to connect these elements operationally so that service schedules are adjusted before severe deficits and network losses translate into persistent downstream disadvantage.

The distinction between procedural and delivered equity is equally important. Planting groups and P3A coordination provide a fair procedure only if the resulting water reaches users in comparable proportions. Infrastructure-equity research warns that apparently neutral asset and allocation processes can still generate unequal outcomes when distributional effects are not measured directly [14]. Modeling of intermittent supply also shows that aggregate availability can coexist with large node-level differences in demand satisfaction [15]. Future ISA evaluation in Pamukkulu should therefore compare delivered discharge with requirement at representative head, middle, and tail locations. A standardized delivery ratio would allow the procedural claim of fairness to be tested against hydraulic outcomes and would reveal whether a system-wide K masks localized failure.

3.6 Digital monitoring and adaptive service control

The coexistence of ISA, SIPASI, and SCADA gives Pamukkulu the elements of an adaptive service system, but their value depends on operational linkage. SIPASI can quantify requirement, availability, losses, and K; SCADA can verify field conditions and gate behavior; ISA can define the response to each service state; and P3A can communicate and check the resulting allocation. Digital-water research repeatedly shows that data become useful when they are connected to decisions [16,17]. Digital initiatives that are weakly connected to organizational practice often deliver limited strategic change [18,19], whereas digital-water-service and smart-network frameworks emphasize integration among monitoring, models, and asset management [20,22].

A practical operating sequence follows from the Pamukkulu evidence. First, SIPASI should classify each five-day period by K state and publish the corresponding service gap. Second, SCADA observations should verify whether planned releases and gate settings are implemented. Third, ISA should specify the allocation rule for each K state, including rotation, priority, communication, and review. Fourth, P3A should receive the same core information used by the manager so that changes in service can be understood and checked. Early-warning research supports this short observation-to-action cycle [23,24]. Indonesian studies also provide relevant implementation analogies: spatial risk information has been organized through a web-based GIS intended to support monitoring and response [25], while the placement and design of hydrologic measuring structures has been linked to spatial vulnerability to strengthen monitoring and early warning [35]. These examples support a simple principle for Pamukkulu: monitoring points should be located where a measurement can change an allocation or maintenance decision.

The same logic applies to failure diagnosis. If K is low because source availability collapses, the appropriate response is scarcity allocation. If source availability is adequate but downstream delivery remains poor, attention should shift to leakage, sedimentation, gate operation, or unauthorized abstraction. If calculated and measured delivery are adequate but users still report poor service, timing or local coordination may be limiting. Smart-network studies show how continuous sensing can support adaptive operation [36] and how sensor systems can detect anomalies and infrastructure problems [37,38]. Irrigation-focused monitoring likewise demonstrates the value of combining field information with water-management decisions [39]. Pamukkulu does not yet provide the continuous reach-scale data needed for automated diagnosis; the immediate need is therefore more basic and more consequential: measure critical secondary reaches, verify losses, and connect the result to maintenance and ISA service rules.

3.7 Management implications, policy relevance, and study limitations

Four management priorities follow. First, secondary-canal maintenance should be ranked by expected service recovery using condition surveys and reach-scale flow measurements. Second, K-based scarcity states should be written into ISA so that severe deficit triggers a defined rotation and communication protocol rather than an ad hoc reduction. Third, the same service-state information should be shared with P3A to distinguish unavoidable hydrologic scarcity from avoidable operational failure. Fourth, performance targets should separate controllable attributes—forecast accuracy, notification, gate operation, rotation compliance, maintenance response, and data transparency—from hydrologically conditional attributes such as full volumetric adequacy.

The study also defines clear limits to inference. Questionnaire responses were available in aggregated form, with valid denominators of 33 or 34 depending on the item, so relationships among individual responses could not be tested. Reach-specific inflow–outflow measurements were unavailable, preventing calibration of loss to individual defects. The analysis covers one 72-period irrigation analysis horizon, including September–October planning projections, and six selected secondary-canal units, and outcome equity was not measured directly at head, middle, and tail locations. Future work should combine respondent-level records, continuous discharge measurements, canal-condition scoring, and spatial delivery ratios over multiple seasons. Those data would allow the proposed serviceability framework to be tested against measured equity and to quantify the service recovered through targeted rehabilitation.

4. Conclusion

This study demonstrates that irrigation service performance in Pamukkulu is governed by the interaction between institutional arrangements, hydrologic availability, and physical conveyance condition. ISA provides a useful procedural framework for scheduling, clarifying responsibilities, and involving P3A, while SIPASI and SCADA provide the planning and monitoring architecture needed for performance-based management. Across the full 72-period SIPASI series, which includes planning projections for September–October 2026, mean available discharge was 2,380.6 L s−1, equivalent to 49.6% of the mean intake requirement of 4,796.8 L s−1. The mean K factor was 0.47, full-service conditions were identified in 19 of 72 five-day periods, and severe-deficit conditions were identified in 31 periods. For the projected early-September 2026 periods, available discharge was estimated to cover only 1.4–2.0% of calculated intake demand. These projected values indicate the potential severity of seasonal scarcity under the SIPASI planning scenario rather than documenting realized September observations.

The physical network intensified this constraint. Farmers most frequently identified leakage, cracks, ageing infrastructure, and secondary canals as the dominant loss pathway, and downstream shortage was the most commonly reported farmer-level consequence. These results indicate that the secondary network is a high-leverage point for protecting service during scarcity. They also show why procedural equity should not be equated automatically with delivered equity.

The central implication is that ISA should evolve from a largely fixed service agreement into an adaptive performance framework linked directly to hydrologic state. K can serve as an operational trigger for full-service, partial-service, and severe-deficit protocols; SCADA can verify delivery conditions; SIPASI can quantify the service gap; and P3A can support transparent implementation of shortage rules. In parallel, condition-based maintenance should prioritize secondary-canal reaches with high downstream service consequences.

Accordingly, the novelty of the Pamukkulu case lies in showing that the credibility of performance-based irrigation depends on “serviceability”: the extent to which agreed service is physically deliverable under evaluated water-availability conditions and network efficiency. Future ISA evaluation should therefore measure not only whether agreements and schedules exist, but whether water is delivered equitably, adequately, and reliably at the point of use under changing hydrologic conditions.

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During preparation of this manuscript, the authors used OpenAI ChatGPT to assist with language editing, structural consistency, and reference-format checking. The authors reviewed and revised the resulting text, verified the numerical results and cited sources, and take full responsibility for the final content.

CRediT authorship contribution statement

Nur Hikmah Amelia: Conceptualization, methodology, investigation, data curation, formal analysis, visualization, writing—original draft. Farida Gaffar: Methodology, supervision, validation, writing—review and editing. Indriyanti Azis: Methodology, supervision, validation, writing—review and editing.

Funding

This research received no specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

Data availability

The aggregate survey results and SIPASI-derived water-balance data supporting the findings are available from the corresponding author on reasonable request, subject to permissions governing operational records and respondent confidentiality.

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