DOI 10.52260/2304-7216.2026.2(63).34
UDC 631.67:338.43
SRSTI 06.54.31

B. Kair*, PhD student[1]
B. Beisengaliyev, d.e.s., professor[2]
Ye. Oskenbayev, d.e.s., professor[1]
A. Imashev, PhD[2]
Narxoz University, Almaty, Kazakhstan[1]
Esil University, Astana, Kazakhstan[2]
* – main author (author for correspondence)
e-mail: bekbolat.kair@narxoz.kz

ECONOMIC APPRAISAL OF DIGITAL IRRIGATION UNDER DATA AND INSTITUTIONAL CONSTRAINTS

Digital irrigation technologies — soil-moisture sensors, smart water meters, remote sensing, geographic information systems (GIS), decision-support systems, telemetry, automated drip systems, and water-accounting platforms — are conventionally justified by the volume of water they are projected to save. This criterion is economically insufficient because higher field-level technical efficiency does not automatically translate into farm profitability, lower governance costs, or reduced basin-level depletion. The article develops a methodological framework for the economic appraisal of digital irrigation under the data and institutional constraints characteristic of transition economies, with Kazakhstan as the contextual case. The study is conceptual-methodological in design, grounded in a structured synthesis of peer-reviewed economic literature and contextual interpretation of national irrigation-modernization materials, and does not produce empirical estimates. The framework comprises four components: a taxonomy distinguishing technical, economic, accounting, and conservation notions of efficiency and value; a three-level appraisal structure separating farm-level private profitability, irrigation-system accounting and governance value, and basin-level social conservation value; a data-availability tier system linking each appraisal method to the data it actually requires; and a method-selection matrix connecting technology class, water-management function, minimum data tier, recommended method, institutional precondition, and dominant appraisal risk, with explicit safeguards against the most common evaluation errors. In practical terms, the architecture can guide farm survey design, subsidy targeting, and investment prioritization before costly data collection begins. The framework's limitation follows from its design: it organizes future empirical work rather than generating causal or quantified findings.

Keywords: *digital irrigation; economic appraisal; water accounting; irrigation efficiency paradox; value of information; transaction costs; agricultural water management, Kazakhstan.*

Кілт сөздер: *цифрлық суару; экономикалық бағалау; суды есепке алу; суару тиімділігінің парадоксы; ақпараттың құндылығы; транзакциялық шығындар; ауыл шаруашылығындағы суды басқару, Қазақстан.*

Ключевые слова: *цифровое орошение; экономическая оценка; учет воды; парадокс эффективности орошения; ценность информации; транзакционные издержки; управление водными ресурсами в сельском хозяйстве, Казахстан.*

JEL classification: Q25; Q16; O33

Introduction. In water-scarce economies, irrigated agriculture accounts for a disproportionately large share of total withdrawals, which makes water a scarce economic resource rather than a purely hydraulic one. The allocation problem is well defined: a cubic metre delivered to one field cannot be delivered to another; the marginal value of water differs across crops, seasons, and locations; and farmers and water administrators routinely lack the information needed to direct water where it yields the most. Digital irrigation matters economically because it addresses this informational core of the allocation problem.

The instruments involved serve distinct economic functions. Soil-moisture sensors and weather telemetry convert calendar-based scheduling into a data-driven activity, reducing the cost of determining when and how much to irrigate [1]. Smart water meters make volumetric abstraction measurable, which is a precondition for volumetric pricing, abstraction caps, and performance-based subsidies. Remote sensing and GIS perform the same function at landscape scale, lowering the cost of independent verification and enabling spatially targeted investment. Decision-support systems and automated drip installations convert the resulting data into irrigation decisions. Treating these instruments as information infrastructure, rather than as water-saving hardware, is the starting point for their proper economic valuation [2].

Appraisal based on field-level efficiency is flawed because the term efficiency covers several distinct concepts that behave differently at different scales. A drip retrofit may raise application efficiency and reduce pumping costs while leaving basin depletion unchanged or even increasing it, because the drainage that previously recharged groundwater or supplied downstream users is reduced. This mechanism, known as the irrigation efficiency paradox, means that higher on-farm efficiency can increase net water consumption at the basin scale unless abstraction is governed independently [3, 4]. The economic value of sensors and satellite products therefore depends not on the devices themselves but on the quality of the decisions those devices inform. The Kazakhstani context makes this problem concrete. Southern Kazakhstan combines physical water scarcity, Soviet-era conveyance infrastructure, dependence on transboundary river flows, and a growing portfolio of monitoring technologies [5]. The data these systems generate are predominantly administrative and technical in character — equipped area, suitability classifications, monitoring outputs — and do not include the cost, volume, price, and yield information that economic appraisal requires. In the terms developed below, the country is relatively well supplied with low-tier data and poorly supplied with high-tier data.

The article addresses one question: how should digital irrigation technologies be appraised economically when field-level technical efficiency does not guarantee farm profitability, system-level water accounting, or basin-level conservation? The answer takes the form of a four-component appraisal framework comprising an efficiency and value taxonomy, a three-level appraisal structure, a data-availability tier system, and a method-selection matrix. Each component is developed in the sections that follow, with reference to Kazakhstan throughout.

Literature review. The literature relevant to this article organises into four strands, each well developed internally but rarely connected to the others.

The first strand treats digital irrigation instruments as measurement and information infrastructure. García et al. document a mature IoT sensing architecture combining soil-moisture sensors, wireless networks, and cloud platforms, and identify hardware cost and connectivity as the binding adoption constraints for smallholders. Wolfert et al. establish that the economic success of data-driven farming depends on data ownership, interoperability, and business models rather than on the devices themselves, which means that the same sensor can create or destroy value depending on the institutional and commercial environment in which it operates. The persistent challenge across this strand is that most agricultural water remains unmetered and therefore cannot be priced, capped, or audited. Foster et al. demonstrate that measurement errors in satellite-based water-use monitoring are large enough to alter welfare conclusions and weaken abstraction caps when left unreported, so remote sensing addresses the metering gap only partially and under specific validation conditions [6]. Zipper et al. confirm that accuracy improves with spatial aggregation but remains insufficient for field-level enforcement without ground-truth calibration [7]. Zhai et al., surveying decision-support systems for Agriculture 4.0, find that most are task-specific and operationally oriented, with limited explicit treatment of economic optimisation in their architecture [8].

The second strand appraises irrigation investments economically. Borrego-Marín and Berbel's cost-benefit analysis of the Guadalquivir basin modernisation programme documents net benefits attributable to land and labour productivity gains and cropping changes, and provides the most directly applicable CBA methodology for investment-level appraisal in a water-scarce context [9]. Galioto et al. take a different angle, treating precision scheduling through the lens of the value of information: their comparative analysis shows that the payoff of sensor-based scheduling is conditional on pedo-climatic conditions, crop value, and the farmer's prior information environment, so net-benefit estimates cannot be transferred across settings without re-estimation [10]. Jaafar et al. operationalise economic water productivity using earth-observation data to inform allocation decisions in a water-scarce basin, demonstrating how remote-sensing outputs can be converted into policy-relevant indicators when governance conditions permit [11]. These methods are individually mature, yet they are applied one tool and one case at a time, with no structure connecting method choice to the data and institutions actually available.

The third strand severs field-level technical efficiency from basin-level conservation. Grafton et al. establish that raising on-farm efficiency frequently fails to reduce, and can increase, basin depletion, because saved water is re-applied to expand irrigated area and because higher efficiency shrinks the return flows on which downstream users and aquifers depend. Pérez-Blanco et al. confirm in a review of the theory and evidence that conservation from efficiency improvements is conditional, not automatic, and depends on binding abstraction caps and credible water accounting. Törnqvist and Jarsjö quantify this conditionality in a semi-arid basin directly comparable to Central Asia: basin-scale water savings from improved irrigation techniques were approximately 60% lower than on-farm application reductions, because return flows and groundwater recharge fell when less water was applied [12]. Because basin-scale verification itself rests on remotely sensed estimates, the measurement errors documented by Foster et al. and Zipper et al. re-enter at this level, so conservation claims require consumptive-use accounting and error-bounded estimates rather than field-level efficiency ratios.

The fourth strand addresses why economic effects may or may not materialise. Pronti et al., in a structured review of econometric studies on adoption determinants, find that farm size, education, extension access, and credit are the most consistent predictors, but their direction and magnitude vary across technologies and institutional settings, and cross-sectional estimates carry selection bias because larger and better-resourced farms adopt first [13]. Ruzzante et al., drawing on a meta-analysis covering 63 developing countries, confirm that adoption of agricultural technology is driven by economic incentives and institutional support rather than by technology features alone, and that returns to adoption are heterogeneous across farm types [14]. Barrett et al. document that in southeast Kazakhstan, water-user associations cannot sustain or modernise deteriorated systems because farm margins are thin, fee collection is weak, and district agencies override local decisions [15]. Across these settings, administrative and monitoring records are comparatively abundant while farm-operational and basin-accounting data remain scarce, a data profile that directly limits which appraisal methods are feasible. Taken together, the four strands document the technologies, the economic mechanisms, the conservation caveat, and the institutional conditions in detail, yet they remain disconnected. The methods of economic appraisal are mature but deployed one tool and one case at a time; the efficiency paradox is well established but seldom built into appraisal design; and adoption and governance constraints are studied separately from the choice of evaluation method. No existing study offers a unified method-selection framework that specifies which appraisal method is feasible and defensible for a given digital-irrigation technology under a given level of data availability and institutional capacity. This gap is what the present article addresses.

The present framework differs from each of these in three respects: it is specific to digital irrigation instruments rather than to irrigation investment in general; it conditions method choice on data availability rather than assuming a uniform data environment; and it incorporates the efficiency paradox as a structural constraint rather than as a caveat (Table 1).

Table – 1

Positioning of the present framework against related appraisal guidance

Framework	Coverage	What it lacks relative to this article
FAO water productivity guidelines	Crop and system water productivity measurement	Method selection by instrument type and data tier
OECD irrigation investment appraisal	CBA, pricing reform, infrastructure	Digital-specific methods; data-tier conditioning; efficiency paradox
World Bank project appraisal procedures	ERR, shadow pricing, social CBA	Assumes Tier 2–3 data; no remote-sensing error treatment
This article	All of the above, integrated	Limitation: conceptual only; no empirical estimates

**Compiled by the authors*

The architecture developed in this article responds to all three gaps identified in the comparison. The sections that follow present each component in turn: the taxonomy of efficiency and value concepts, the three-level appraisal framework, the data-tier system, and the method-selection matrix with its safeguards. Kazakhstan serves throughout as the contextual reference against which the framework's diagnostic logic is demonstrated.

Materials and Methods. This study is conceptual-methodological in design, grounded in structured literature synthesis and contextual interpretation of national irrigation materials. Its purpose is to construct an appraisal framework that can guide future empirical work rather than to estimate the effect of digital irrigation on water use or farm income. The study is not a systematic or PRISMA review, not an econometric analysis, and not a regional diagnostic assessment; no causal claim is made and no benefit is quantified. Source selection followed relevance to the economic analysis of digital and water-saving irrigation systems. Peer-reviewed papers published between 2017 and 2025 and indexed in Scopus or Web of Science were prioritised; foundational works published before this window were cited only where methodologically necessary. Sources were organised by economic concept rather than by irrigation technology, covering six thematic clusters: economic analysis, cost-benefit analysis, and water productivity; measurement, remote sensing, and the value of information; the irrigation efficiency paradox and rebound effects; adoption determinants and behavioural and institutional barriers; governance, water pricing, and transaction costs; and the Kazakhstan and Central Asia context. Engineering literature was used solely to establish the technical foundation for each instrument. Sources without verifiable bibliographic data were excluded.

The framework was constructed in five sequential stages, each anchored to digital irrigation rather than to investment appraisal in general.

Stage 1 — Problem identification. Four notions that are frequently conflated in practice were separated: technical field efficiency, defined as the share of applied water reaching the root zone; farm-level economic value, expressed as profit per unit of cost and water; system-level water-accounting value, understood as the cost of governing water; and basin-level conservation, meaning the actual change in consumptive use. A single water-saved metric performs differently across these four dimensions and is therefore an unreliable appraisal criterion on its own.

Stage 2 — Mechanism extraction. The economic mechanisms through which digital irrigation generates or destroys value were identified from the literature: cost-benefit and net-present-value logic, payback period, economic water productivity, the value of information, transaction-cost reduction, information-asymmetry reduction, adoption constraints, water pricing and governance, the shadow value of water, rebound effects, and return-flow and depletion effects.

Stage 3 — Mechanism-to-technology mapping. Each mechanism was mapped to the specific instruments that activate it: soil-moisture sensors, smart water meters, remote sensing, GIS, telemetry, decision-support systems, automated drip irrigation, and water-accounting platforms. This step ensures that no appraisal method is discussed in abstraction from the technology and problem it is meant to address.

Stage 4 — Data-tier classification. The data required to operationalise each method were sorted into four tiers. Tier 0 covers administrative aggregates and records of technology presence. Tier 1 covers monitoring and spatial data, including GIS layers, remote-sensing indices, and suitability classifications. Tier 2 covers farm operational data: sensor and meter logs, energy use, input costs, and yields. Tier 3 covers farm panels joined to basin-level accounting, encompassing evapotranspiration estimates, withdrawals, return flows, and allocation records.

Stage 5 — Matrix and safeguards. The mechanisms, technologies, and data tiers were assembled into a method-selection matrix linking each technology class to its water-management problem, economic function, minimum data tier, recommended appraisal method, necessary institutional condition, and dominant appraisal risk. Explicit safeguards against recurrent appraisal errors were incorporated into the matrix structure.

Kazakhstan's national irrigation-modernisation and monitoring materials were used solely to characterise the data and institutional environment the framework must navigate: ageing conveyance systems, water-saving technologies, space-ground monitoring infrastructure, GIS mapping, and limited farm-operational data. These materials were not used as a dataset from which regional adoption statistics or comparative figures are drawn.

The main part. Each digital instrument is more accurately characterised as an economic device that removes a specific friction in the allocation and governance of water than as a water-saving appliance. Soil-moisture sensors and weather telemetry address the scheduling problem: they convert calendar-based decisions into data-driven ones, generating a payoff defined by reductions in water and energy waste and by lower yield risk. That payoff materialises only when the farmer can act on the data and when crop value justifies the cost of subscription, calibration, and maintenance. Smart water meters address the measurement problem: without metered volumes there is no basis for volumetric pricing, abstraction caps, or compliance auditing, so the meter functions as accounting infrastructure rather than as farm equipment. Remote sensing and GIS reduce the cost of two otherwise expensive operations: independent verification of land and water use, and spatially targeted placement of investments. Both, however, introduce measurement error that must be reported and bounded rather than treated as precise observation.

This characterisation has a direct implication for appraisal. The value of a sensor or a satellite output is not a property of the device; it is a function of the decisions the device enables. The same instrument is economically significant when its outputs feed into a binding abstraction restriction and carries little value when its outputs affect no decision at all.

At least seven distinct concepts circulate under the single word efficiency, each answering a different question and requiring different data (Table 2). Application efficiency measures the share of applied water that reaches the root zone. Physical water productivity measures output per unit of water applied. Economic water productivity measures the value of output per unit of water. Private profitability asks whether adoption pays the individual farmer. System-level accounting value asks whether measurement lowers the cost of governing water. Basin-level conservation asks whether consumptive use actually falls across the watershed. Social welfare asks whether net benefits, including externalities and distributional effects, are positive.

The taxonomy is not a terminological exercise. A drip retrofit that improves application efficiency and private profitability can leave basin-level conservation unchanged or worsen it through reduced return flows, because the drainage that previously recharged groundwater or reached downstream users is eliminated. Labelling a field-level efficiency gain as water saved is therefore a category error, and one with direct fiscal consequences when public subsidies are attached to it.

Table – 2

Efficiency and value concepts in digital irrigation

Concept	**Question it answers**	**Illustrative indicator**	**Main data need**	**Risk if confused**
Application (technical) efficiency	How much applied water reaches the root zone?	Application efficiency ratio (%)	Volumes applied vs. delivered (sensor / meter logs)	Read as proof of water "saved," ignoring withdrawals and return flows
Physical water productivity	Output per unit of water applied	kg or t per m³ applied	Yields plus applied volumes	Crop or price change mistaken for a technology effect
Economic water productivity	Value of output per unit of water	USD per m³ (applied or consumed)	Yields, prices, costs, volumes	High-value crops credited to the device, not agronomy or markets
Private profitability	Does adoption pay the farmer?	NPV, IRR, payback of the sensor / drip / DSS package	CAPEX, OPEX, energy, labour, yield, prices	Engineering water savings assumed to equal financial returns
System / accounting value	Does measurement lower the cost of governing water?	Value of information; transaction-cost reduction	Metering coverage, monitoring / inspection costs	Information assumed useful even when no decision uses it
Basin-level conservation	Does depletion actually fall basin-wide?	Change in consumptive use and return flows	ET, return flows, withdrawals, allocations	Field efficiency credited as basin saving (the paradox)
Social welfare	Do net social benefits exceed costs, with externalities?	Shadow price of water; net social benefit	Above plus externalities and distribution	Private gains mistaken for social gains

**Compiled by the author*

The taxonomy resolves into three appraisal levels, each with its own object, mechanism, methods, and policy use (Table 3). The levels are nested but not substitutable: a favourable result at one carries no guarantee at another, which is why they must be appraised separately.

At Level 1, the object is the farmer's adoption decision for on-farm tools: sensors, controllers, drip automation, and farm decision-support systems. Cheaper information and more precise application alter the farm production function, generating water and energy cost savings, possible yield or quality gains, and lower production risk. Standard cost-benefit methods apply, but only when anchored to the specific device. A net-present-value calculation for an automated drip system is defensible only if its capital expenditure, operating costs including subscriptions, calibration, maintenance, and digital labour, energy use, yield response, and water cost can be observed directly. Cost-effectiveness is best expressed as cost per cubic metre saved or per hectare equipped. Net-benefit estimates derived in other countries depend on local pedo-climatic and informational conditions and must be re-derived rather than transferred.

At Level 2, the object is the measurement-and-information stack: smart meters, telemetry, remote sensing, GIS, and water-accounting platforms, read as governance infrastructure. Its economic value lies in reduced information asymmetry and lower transaction costs. Verifiable, plot-level measurement substitutes for costly field inspection and makes allocation, volumetric pricing, and compliance auditing administrable at the system level. The appropriate methods at this level are value-of-information analysis and a transaction-cost comparison of monitoring and enforcement with and without the digital stack, not a farm-level net present value. This value materialises only where an authority or water-user association is empowered to act on the data.

At Level 3, the same data stack is read at basin scale, drawing on remote-sensing evapotranspiration estimates, return-flow accounting, and GIS, to ask whether efficiency gains translate into real conservation and positive net social benefit. The relevant quantities here are the shadow value of water, consumptive-use and return-flow effects, rebound, externalities, and distributional incidence. The applicable methods are social cost-benefit analysis with shadow pricing, consumptive-use water accounting, and explicit rebound assessment. Level 3 is where the efficiency paradox is most consequential and the level most frequently omitted from practical appraisal.

A method is only as defensible as the data behind it, and in transition economies the binding constraint is data availability rather than method choice in principle. Table 4 pairs each appraisal ambition with the tier of data it requires. With Tier 0 administrative aggregates, such as equipped area by technology of the kind found in modernisation reporting, only diagnostic interpretation is honest. Neither a net present value nor a water-productivity figure can be defended at this tier because no costs or volumes are observed; the data support contextual framing and nothing more.

Table – 3

Three-level economic appraisal framework for digital irrigation

Appraisal level	Object and main technologies	Core economic mechanism	Applicable methods	Key indicators and policy use
Level 1 — Farm-level private profitability	Soil-moisture sensors, controllers, drip automation, on-farm DSS	Cheaper information and precise application change the production function; water, energy, labour savings; risk reduction	CBA, NPV, IRR, payback; cost-effectiveness (cost per m^3 saved or per ha)	CAPEX / OPEX, energy and labour savings, yield, water cost, payback; whether and where adoption needs subsidy
Level 2 — System / institutional accounting value	Smart meters, telemetry, remote sensing, GIS, water-accounting platforms	Reduced information asymmetry and transaction costs; verifiable measurement enabling allocation, pricing, compliance	Value-of-information analysis; transaction-cost comparison (monitoring / enforcement with vs. without digital tools)	Metering coverage, monitoring and inspection cost, allocation / compliance accuracy; basis for volumetric pricing
Level 3 — Basin / regional social value	Same data stack at basin scale (RS-ET, return-flow accounting, GIS)	Shadow value of water; consumptive-use and return-flow effects; rebound; externalities and distribution	Social CBA with shadow pricing; consumptive-use water accounting; rebound assessment	Change in consumptive use, return flows, depletion; net social benefit; distribution; design of caps and enforcement

**Compiled by the author.*

Tier 1 monitoring and spatial data, covering remote-sensing indices, GIS layers, suitability classifications, and plot attributes, support Level-2 reasoning about the value of information and spatial investment targeting and allow measurement-error bounds to be stated. They cannot, however, yield farm-level financial returns because operational costs and volumes remain unobserved.

Tier 2 farm operational data, comprising sensor and meter logs of applied and withdrawn volumes, energy use, and on-farm costs, unlock Level-1 cost-benefit analysis and partial economic water productivity. At this tier the analyst can construct a defensible net present value or payback estimate for a specific on-farm technology, provided yields and prices are also available.

Only Tier 3, which joins multi-year farm panels with prices and costs to basin-level withdrawals, evapotranspiration estimates, return flows, and allocation records, supports causal adoption effects, full economic water productivity, basin-level conservation assessment, and welfare analysis. This is the data environment that the efficiency paradox makes non-negotiable for any conservation claim, and it is the tier least available in Kazakhstan and comparable transition economies.

Table – 4

Data-availability tiers and feasible appraisal methods

Data tier	**Typical data available (digital-irrigation context)**	**What can be credibly appraised**	**Feasible methods**	**Methods not yet justified**
Tier 0 — Administrative aggregates	Equipped area by technology / region; modernization reports	Direction and context only; the need for appraisal	Qualitative / diagnostic interpretation; conceptual framing	CBA, NPV, water-productivity estimation (no costs or volumes)
Tier 1 — Monitoring and spatial	Remote sensing (NDVI, ET), GIS layers, suitability classes, plot attributes	System-level information value; spatial targeting; measurement-error bounds	Value-of-information analysis; GIS-based prioritization; error assessment	Farm financial returns; basin consumptive-use balances
Tier 2 — Farm operational	Sensor / meter logs of applied and withdrawn volumes; energy use; on-farm costs	Farm-level profitability; physical and partial economic water productivity	CBA, NPV, IRR, payback; cost-effectiveness	Basin conservation (return flows still unobserved)
Tier 3 — Panel plus basin accounting	Multi-year farm panels with prices and costs; basin withdrawals, ET, return flows, allocations	Causal adoption effects; economic water productivity; basin conservation; welfare	Econometric estimation; social CBA with shadow pricing; full water accounting	— (enables the full framework)

**Compiled by the author.*

Table 5 constitutes the operational core of the framework. It reads each technology class against the water-management problem it addresses, its economic function, the minimum data tier needed to appraise it credibly, the recommended method, the institutional condition without which the economic effect cannot materialise, and the dominant appraisal risk.

The matrix is specific to digital irrigation by design. The same appraisal method takes a different form depending on the instrument to which it is applied. Cost-effectiveness for a soil-moisture sensor is expressed as cost per cubic metre saved at the farm level; for a metering network, the same concept becomes cost per unit of monitoring or compliance achieved at the system level. The data requirements and institutional preconditions differ accordingly, which is why a single generic cost-benefit template applied across all digital-irrigation instruments produces results that are neither comparable nor defensible.

The matrix therefore does not recommend methods in the abstract. Each row specifies what the technology actually does in economic terms, what data are needed to observe that effect, what institution must be in place for the effect to materialise, and what the analyst risks if the method is applied without meeting those preconditions. A decision-support system appraised as if it were continuously and effectively used when adoption rates are low and training is absent will overstate returns. A remote-sensing platform appraised without error bounds will produce conservation estimates that cannot withstand scrutiny. The matrix makes these risks explicit and pairs each with a corresponding safeguard, developed in the following subsection.

Table – 5

Method-selection matrix for the economic appraisal of digital irrigation technologies

Technology class	**Main water-management problem**	**Economic function**	**Min. data tier**	**Recommended appraisal method**	**Necessary institutional condition**	**Main appraisal risk**
Soil-moisture sensors & weather telemetry	Scheduling; input optimization	Lower information cost; cut water / energy use and yield risk	Tier 2	Farm CBA / NPV / payback; cost-effectiveness (cost per m^3 saved)	Farmer liquidity and digital skills; advisory support	Yield or price changes attributed to sensors without controls
Smart water meters	Volumetric measurement; compliance	Reduce information asymmetry; enable pricing and accountability	Tier 1–2	Value-of-information; transaction-cost comparison	An authority empowered to read and act on the data	Data collected but unused; metering without enforcement
Remote sensing & GIS	Monitoring; investment targeting	Cut verification and targeting costs; spatial allocation	Tier 1	GIS-based prioritization; monitoring-cost comparison; error-bounded VoI	Agency to act on maps; data governance	Measurement error mistaken for precise observation
Decision-support systems	Scheduling decisions	Convert information into better input decisions	Tier 2	CBA plus adoption / actual-use analysis	Sustained use and training after installation	Low real use ("shelfware") after installation
Automated drip irrigation	Application precision	Raise field efficiency and economic water productivity	Tier 2–3	CBA + economic water productivity + rebound check	Allocation caps that prevent area expansion	Field savings not realized as basin savings (paradox)
Integrated water-accounting platforms	System governance; allocation	Lower transaction costs; basis for allocation and social appraisal	Tier 1–3	Transaction-cost and social CBA; consumptive-use accounting	Enforcement capacity and inter-agency mandate	Weak enforcement; private gains not equal to social gains

**Compiled by the author. Voi = value of information.*

The matrix is sequenced by the protocol shown in Figure 1. Appraisal begins with the identification of the technology class and moves through an explicit measurement-and-information layer, at which water applied, withdrawn, and consumed are distinguished, to the selection of the appropriate appraisal level.

A first gate checks whether the available data tier can support the chosen level and method. If it cannot, the analyst restricts the claim to what the data permit and initiates higher-tier data collection rather than forcing an unsupported net present value or conservation estimate. Stating that a method is premature is a legitimate and necessary analytical output; proceeding without the required data produces figures that are indefensible under scrutiny and may misdirect investment or subsidy design.

A second, institutional gate determines whether basin-level conservation may be credited at all. The gate opens only where measurement is coupled to enforceable allocation rules: only under that condition does the protocol advance to the integrated decision, which may be to adopt, subsidise, pilot, scale, regulate, or redesign the instrument or the incentive structure around it. Where the institutional condition is not met, field-level efficiency gains must not be recorded as basin water savings. The appropriate response in that case is to pilot or redesign the governance and incentive arrangements rather than to scale the hardware, because scaling technology without the institutional preconditions in place does not produce the conservation effect and may accelerate depletion through rebound. Because the costly mistakes in this field are systematic rather than random, the matrix is paired with six explicit safeguards. The first guards against the efficiency-conservation conflation. A gain in field efficiency from drip automation or precision scheduling is credited as conservation only after consumptive-use accounting confirms that basin depletion has fallen, and only where abstraction is capped and enforced. The second addresses measurement error. Remote-sensing estimates of irrigation water use carry errors large enough to overturn welfare conclusions, so appraisals are required to report error bounds, ground-truth estimates against test sites, and work with ranges rather than point estimates. The third forbids treating equipped area as a proxy for water use. Tier-0 figures are confined to contextual framing; Tier-2 or Tier-3 volumes are required before any economic claim is advanced.

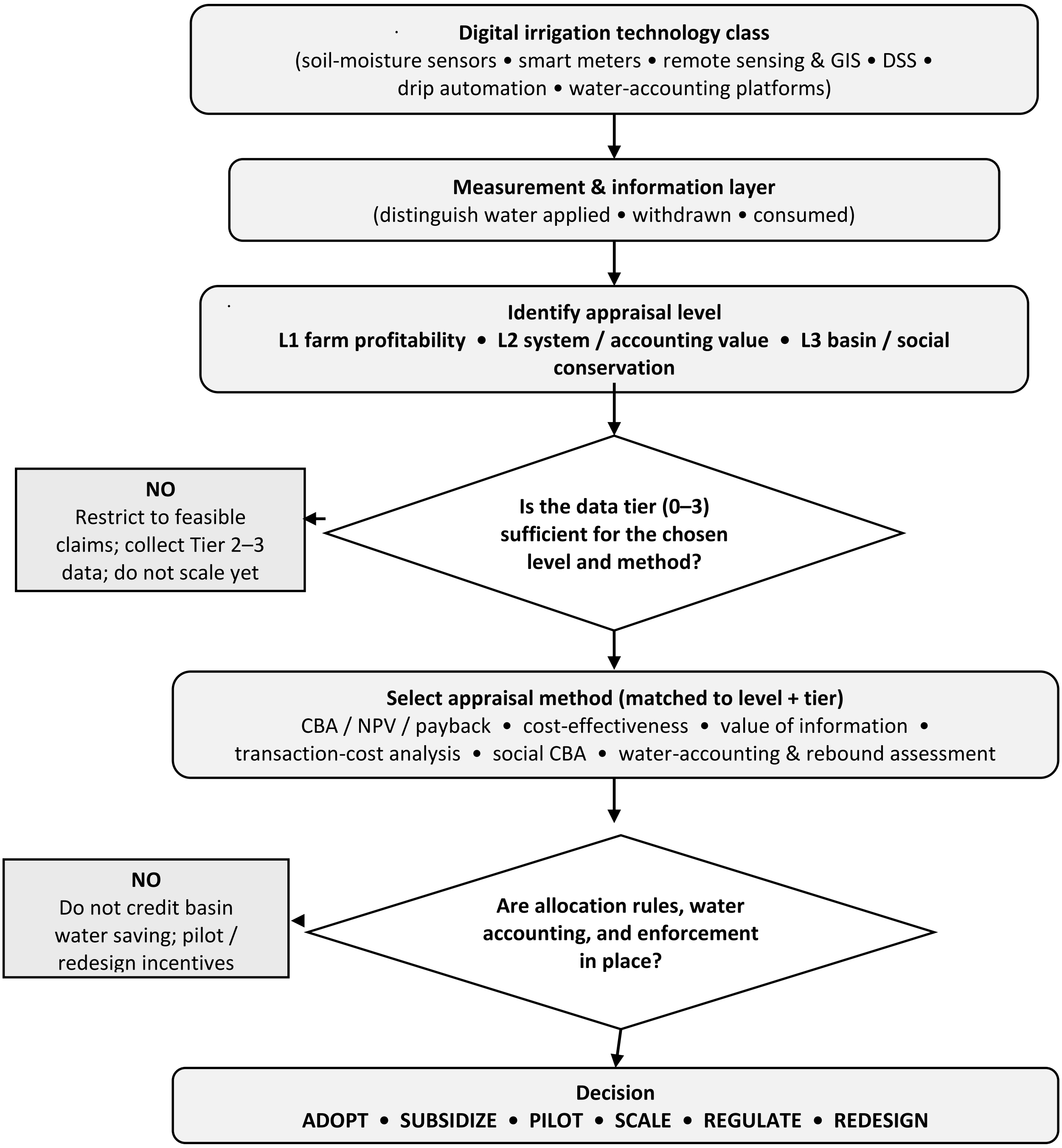

Figure – 1. **Step-by-step protocol for the economic appraisal of digital irrigation**

**Compiled by the author. Basin-level water saving is credited only when measurement is linked to enforceable allocation rules and consumptive-use accounting.*

The fourth separates adoption from benefit. Larger and better-resourced farms adopt sensors and decision-support systems first, so cross-sectional comparisons of adopters and non-adopters carry selection bias. Panel or quasi-experimental designs are required to discipline causal inference.

The fifth refuses to value information that no institution is empowered to use. Level-2 value is conditional on water-user-association or authority capacity and on data governance arrangements that connect measurement to decision-making.

The sixth keeps private and social value distinct. The shadow price of water and distributional incidence are added at Level 3 wherever adoption may shift water costs onto downstream users or third parties.

Kazakhstan illustrates why an appraisal framework, rather than another technology census, is the more pressing need. National materials document a genuine and expanding digital capacity: water-saving irrigation technologies, a space-ground monitoring structure, GIS mapping of irrigated and prospective lands, and remote-sensing processing of vegetation and moisture indices verified on test sites. In the terms of Table 4, what these materials supply is predominantly Tier-0 and Tier-1 information: administrative aggregates, records of technology presence, modernisation reporting, suitability classifications, and monitoring outputs. What they do not supply is the Tier-2 and Tier-3 information that economic appraisal requires: farm-level applied and withdrawn volumes, consumptive use, return flows, crop yields, output prices, energy and labour costs, maintenance and calibration expenditures, subsidy and adoption-timing records, water-user-association capacity indicators, longitudinal observation, and basin accounting. Placed against the framework, this profile yields a precise diagnostic. The existing evidence supports Level-2 reasoning about the value of monitoring and about where to target investment, and it justifies the conceptual case for constructing an appraisal architecture; it cannot yet support robust farm net present values, causal adoption effects, or basin-level conservation estimates. The binding constraint is not the absence of measurement technology but its limited linkage to economic decision-making and to enforceable allocation, which is precisely the institutional condition that the efficiency paradox makes non-negotiable. Importing net-benefit figures from mature water economies would compound rather than solve the problem, because Kazakhstan has neither the pricing and enforcement arrangements those figures presuppose nor the panel data that econometric transfer requires, and its institutional setting differs substantially from the regional cases documented in the literature. The framework converts a general call for digitalisation into a tier-by-tier, level-by-level appraisal and data-collection agenda.

Against engineering appraisal, the architecture refuses to equate physical water savings with economic value and forces attention to cost, profitability, and institutional fit. Against descriptive adoption studies, it separates adoption from benefit and incorporates a selection safeguard. Against generic cost-benefit analysis, it anchors every method to a named digital-irrigation technology and to the specific water-management problem that technology addresses: measurement, scheduling, allocation, monitoring, compliance, productivity, or basin conservation. Irrigation is not treated as an interchangeable capital project. Against technology inventories, it supplies the analytical structure that converts a list of installed equipment into an evaluable object.

Conclusion. This article addresses the question of how digital irrigation technologies should be appraised economically when field-level technical efficiency does not guarantee farm profitability, system-level water accounting, or basin-level conservation. The response takes the form of a four-component appraisal architecture: a taxonomy of efficiency and value concepts, a three-level appraisal framework, a data-availability tier system, and a method-selection matrix with explicit safeguards. The architecture is operationalised through a two-gate protocol that defers conservation credits until both data sufficiency and institutional preconditions are confirmed.

The contribution of the article lies in the construction of the architecture itself. Rather than surveying the literature or cataloguing technologies, the study integrates a fragmented evidence base into a single, internally consistent methodology for the economic appraisal of digital irrigation. Each appraisal method is anchored to a named technology, a specific water-management problem, a minimum data tier, and a necessary institutional condition, so that the framework produces structured analytical guidance rather than generic recommendations.

For Kazakhstan, the contribution is diagnostic and programmatic. The framework locates the country within the data-tier system: it is relatively well supplied with monitoring and spatial data at Tiers 0 and 1, and poorly supplied with the farm-financial and basin-accounting data at Tiers 2 and 3 that economic appraisal requires. This diagnosis identifies what can and cannot be credibly appraised at present and redirects attention from hardware procurement toward strengthening the measurement-institution links without which no economic value from digital irrigation can be demonstrated or sustained. The limitations of the study follow from its design. The article is conceptual-methodological: it does not estimate the causal effect of any digital-irrigation technology, does not quantify benefits, and uses Kazakhstan as contextual background rather than as an empirical subject. The architecture is scaffolding for measurement and estimation, not a substitute for it.

The research agenda implied by the framework is specific. It includes farm panel studies linking digital irrigation to water use, yields, costs, and profit at field level; cost-benefit analyses and economic water productivity estimates disaggregated by crop; adoption modelling with selection correction; evaluation of subsidy and pricing instruments; GIS-based investment prioritisation; and integration of remote-sensing measurement with farm-level economic data. Each of these tasks corresponds to a tier and level within the framework and can be initiated as the requisite data become available.

The article was prepared within the framework of the research project entitled "Systemic Effects of Reforming the Quasi-Public Sector: Towards a New Model of Public Governance in Kazakhstan" (supported by a grant from the Science Committee of the Ministry of Education and Science of the Republic of Kazakhstan; IRN AP26104777).

REFERENCES

1. García L., Parra L., Jimenez J.M., Lloret J., Lorenz P. IoT-Based Smart Irrigation Systems: An Overview on the Recent Trends on Sensors and IoT Systems for Irrigation in Precision Agriculture // Sensors. – 2020. – №4(20). – 1042 p. – DOI: 10.3390/s20041042.

2. Wolfert S., Ge L., Verdouw C., Bogaardt M.-J. Big Data in Smart Farming – A Review // Agricultural Systems. – 2017. – №153. – P. 69–80. – DOI: 10.1016/j.agsy.2017.01.023.

3. Grafton R.Q., Williams J., Perry C.J., Molle F., Ringler C., Steduto P., Udall B., Wheeler S.A., Wang Y., Garrick D., Allen R.G. The Paradox of Irrigation Efficiency // Science. – 2018. – №6404(361). – P. 748–750. – DOI: 10.1126/science.aat9314.

4. Pérez-Blanco C.D., Hrast-Essenfelder A., Perry C. Irrigation Technology and Water Conservation: A Review of the Theory and Evidence // Review of Environmental Economics and Policy. – 2020. – №2(14). – P. 216–239. – DOI: 10.1093/reep/reaa004.

5. Казахский научно-исследовательский институт водного хозяйства. Технологии и технические средства орошения при вводе новых земель орошения, реконструкции и модернизации существующих оросительных систем: заключительный отчет о научно-исследовательской работе. Рег. № 0121РК00747. – Тараз. – 2023.

6. Foster T., Mieno T., Brozović N. Satellite-Based Monitoring of Irrigation Water Use: Assessing Measurement Errors and Their Implications for Agricultural Water Management Policy // Water Resources Research. – 2020. – №56. – DOI: 10.1029/2020WR028378.

7. Zipper S., Kastens J., Foster T., Wilson B., Melton F., Grinstead A., Deines J., Butler J.J., Marston L.T. Estimating Irrigation Water Use from Remotely Sensed Evapotranspiration Data: Accuracy and Uncertainties at Field, Water Right, and Regional Scales // Agricultural Water Management. – 2024. – №303. – DOI: 10.1016/j.agwat.2024.109036.

8. Zhai Z., Martínez J.F., Beltran V., Martínez N.L. Decision Support Systems for Agriculture 4.0: Survey and Challenges // Computers and Electronics in Agriculture. – 2020. – №170. – DOI: 10.1016/j.compag.2020.105256.

9. Borrego-Marín M.M., Berbel J. Cost-Benefit Analysis of Irrigation Modernization in Guadalquivir River Basin // Agricultural Water Management. – 2019. – №212. – P. 416–423. – DOI: 10.1016/j.agwat.2018.08.032.

10. Galioto F., Chatzinikolaou P., Raggi M., Viaggi D. The Value of Information for the Management of Water Resources in Agriculture: Assessing the Economic Viability of New Methods to Schedule Irrigation // Agricultural Water Management. – 2020. – №227. – DOI: 10.1016/j.agwat.2019.105848.

11. Jaafar H., Karimi P., Borgomeo E. Economic Irrigation Water Productivity of Wheat and Potato: An Earth Observation Perspective on Policy Implications in the Litani Basin, Lebanon // Agricultural Water Management. – 2024. – №306. – DOI: 10.1016/j.agwat.2024.109180.

12. Törnqvist R., Jarsjö J. Water Savings Through Improved Irrigation Techniques: Basin-Scale Quantification in Semi-Arid Environments // Water Resources Management. – 2012. – №26. – P. 949–962. – DOI: 10.1007/s11269-011-9819-9.

13. Pronti A., Auci S., Berbel J. Water Conservation and Saving Technologies for Irrigation: A Structured Literature Review of Econometric Studies on the Determinants of Adoption // Agricultural Water Management. – 2024. – №299. – DOI: 10.1016/j.agwat.2024.108838.

14. Ruzzante S., Labarta R., Bilton A. Adoption of Agricultural Technology in the Developing World: A Meta-Analysis of the Empirical Literature // World Development. – 2021. – №146. – DOI: 10.1016/j.worlddev.2021.105599.

15. Barrett T., Feola G., Khusnitdinova M., Krylova V. Adapting Agricultural Water Use to Climate Change in a Post-Soviet Context: Challenges and Opportunities in Southeast Kazakhstan // Human Ecology. – 2017. – №6(45). – P. 747–762. – DOI: 10.1007/s10745-017-9947-9.

REFERENCES

1. García L., Parra L., Jimenez J.M., Lloret J., Lorenz P. IoT-Based Smart Irrigation Systems: An Overview on the Recent Trends on Sensors and IoT Systems for Irrigation in Precision Agriculture // Sensors. – 2020. – №4(20). – 1042 p. – DOI: 10.3390/s20041042.

2. Wolfert S., Ge L., Verdouw C., Bogaardt M.-J. Big Data in Smart Farming – A Review // Agricultural Systems. – 2017. – №153. – P. 69–80. – DOI: 10.1016/j.agsy.2017.01.023.

3. Grafton R.Q., Williams J., Perry C.J., Molle F., Ringler C., Steduto P., Udall B., Wheeler S.A., Wang Y., Garrick D., Allen R.G. The Paradox of Irrigation Efficiency // Science. – 2018. – №6404(361). – P. 748–750. – DOI: 10.1126/science.aat9314.

4. Pérez-Blanco C.D., Hrast-Essenfelder A., Perry C. Irrigation Technology and Water Conservation: A Review of the Theory and Evidence // Review of Environmental Economics and Policy. – 2020. – №2(14). – P. 216–239. – DOI: 10.1093/reep/reaa004.

5. Kazahskij nauchno-issledovatel'skij institut vodnogo hozjajstva. Tehnologii i tehnicheskie sredstva oroshenija pri vvode novyh zemel' oroshenija, rekonstrukcii i modernizacii sushhestvujushhih orositel'nyh sistem [Technologies and technical means of irrigation for the introduction of new irrigated lands, reconstruction and modernization of existing irrigation systems]: zaklyuchitel'nyj otchet o nauchno-issledovatel'skoj rabote, Reg. No. 0121RK00747. – Taraz. – 2023. [in Russian]

6. Foster T., Mieno T., Brozović N. Satellite-Based Monitoring of Irrigation Water Use: Assessing Measurement Errors and Their Implications for Agricultural Water Management Policy // Water Resources Research. – 2020. – №56. – DOI: 10.1029/2020WR028378.

7. Zipper S., Kastens J., Foster T., Wilson B., Melton F., Grinstead A., Deines J., Butler J.J., Marston L.T. Estimating Irrigation Water Use from Remotely Sensed Evapotranspiration Data: Accuracy and Uncertainties at Field, Water Right, and Regional Scales // Agricultural Water Management. – 2024. – №303. – DOI: 10.1016/j.agwat.2024.109036.

8. Zhai Z., Martínez J.F., Beltran V., Martínez N.L. Decision Support Systems for Agriculture 4.0: Survey and Challenges // Computers and Electronics in Agriculture. – 2020. – №170. – DOI: 10.1016/j.compag.2020.105256.

9. Borrego-Marín M.M., Berbel J. Cost-Benefit Analysis of Irrigation Modernization in Guadalquivir River Basin // Agricultural Water Management. – 2019. – №212. – P. 416–423. – DOI: 10.1016/j.agwat.2018.08.032.

10. Galioto F., Chatzinikolaou P., Raggi M., Viaggi D. The Value of Information for the Management of Water Resources in Agriculture: Assessing the Economic Viability of New Methods to Schedule Irrigation // Agricultural Water Management. – 2020. – №227. – DOI: 10.1016/j.agwat.2019.105848.

11. Jaafar H., Karimi P., Borgomeo E. Economic Irrigation Water Productivity of Wheat and Potato: An Earth Observation Perspective on Policy Implications in the Litani Basin, Lebanon // Agricultural Water Management. – 2024. – №306. – DOI: 10.1016/j.agwat.2024.109180.

12. Törnqvist R., Jarsjö J. Water Savings Through Improved Irrigation Techniques: Basin-Scale Quantification in Semi-Arid Environments // Water Resources Management. – 2012. – №26. – P. 949–962. – DOI: 10.1007/s11269-011-9819-9.

13. Pronti A., Auci S., Berbel J. Water Conservation and Saving Technologies for Irrigation: A Structured Literature Review of Econometric Studies on the Determinants of Adoption // Agricultural Water Management. – 2024. – №299. – DOI: 10.1016/j.agwat.2024.108838.

14. Ruzzante S., Labarta R., Bilton A. Adoption of Agricultural Technology in the Developing World: A Meta-Analysis of the Empirical Literature // World Development. – 2021. – №146. – DOI: 10.1016/j.worlddev.2021.105599.

15. Barrett T., Feola G., Khusnitdinova M., Krylova V. Adapting Agricultural Water Use to Climate Change in a Post-Soviet Context: Challenges and Opportunities in Southeast Kazakhstan // Human Ecology. – 2017. – №6(45). – P. 747–762. – DOI: 10.1007/s10745-017-9947-9.

Каир Б.А., Бейсенгалиев Б.Т., Оскенбаев Е.С., Имашев А.Б.

ДЕРЕКТЕРДІҢ ШЕКТЕУЛІЛІГІ ЖӘНЕ ИНСТИТУЦИОНАЛДЫҚ ШЕКТЕУЛЕР ЖАҒДАЙЫНДА ЦИФРЛЫҚ СУАРУДЫ ЭКОНОМИКАЛЫҚ БАҒАЛАУ

Аңдатпа

Цифрлық суару технологиялары — топырақ ылғалдылығы датчиктері, ақылды су есептегіштері, қашықтықтан зондтау, географиялық ақпараттық жүйелер (ГАЖ), шешім қабылдауды қолдау жүйелері, телеметрия, автоматтандырылған тамшылатып суару жүйелері және суды есепке алу платформалары — дәстүрлі түрде олардың үнемдеуі күтілетін су көлемімен негізделеді. Бұл өлшем экономикалық тұрғыдан жеткіліксіз: егістік деңгейіндегі жоғары техникалық тиімділік фермерлік шаруашылықтың табыстылығының өсуіне, су ресурстарын басқару шығындарының төмендеуіне немесе бассейн деңгейінде су қорының азаюына автоматты түрде әкелмейді. Мақалада Қазақстанды контекстік мысал ретінде пайдалана отырып, өтпелі экономикаларға тән деректердің шектеулілігі мен институционалдық шектеулер жағдайында цифрлық суаруды экономикалық бағалаудың әдіснамалық негізі әзірленеді. Зерттеу тұжырымдамалық-әдіснамалық сипатта болып, рецензияланған экономикалық әдебиетті құрылымдалған синтездеуге және ирригацияны жаңғырту жөніндегі ұлттық материалдарды контекстік түсіндіруге негізделген; эмпирикалық бағалаулар жүргізілмейді. Әзірленген негіз төрт компоненттен тұрады: тиімділік пен құндылықтың техникалық, экономикалық, есептік және табиғатты қорғау ұғымдарын ажырататын таксономия; фермерлік шаруашылық деңгейіндегі жеке табыстылықты, ирригациялық жүйе деңгейіндегі суды есепке алу мен басқару құндылығын және бассейн деңгейіндегі су ресурстарын сақтаудың әлеуметтік құндылығын бөліп қарастыратын үш деңгейлі бағалау құрылымы; әрбір бағалау әдісін нақты қажет деректермен байланыстыратын деректер қолжетімділігінің деңгейлер жүйесі; және технология класын, су ресурстарын басқару функциясын, деректердің ең төменгі деңгейін, ұсынылатын әдісті, институционалдық алдын ала шартты және бағалаудың басым тәуекелін ең жиі кездесетін қателерге қарсы нақты қорғаныс механизмдерімен байланыстыратын әдіс таңдау матрицасы. Практикалық тұрғыдан алғанда, ұсынылған архитектура қымбат деректер жинауға дейін фермерлік шаруашылықтарды зерттеуді, субсидияларды нысаналы бағыттауды және инвестицияларды басымдыққа қоюды құрылымдауға мүмкіндік береді. Негіздің шектеуі оның дизайнынан туындайды: ол болашақ эмпирикалық жұмысты ұйымдастырады, себеп-салдарлық немесе сандық өлшенген нәтижелер бермейді.

Каир Б.А., Бейсенгалиев Б.Т., Оскенбаев Е.С., Имашев А.Б.

ЭКОНОМИЧЕСКАЯ ОЦЕНКА ЦИФРОВОГО ОРОШЕНИЯ В УСЛОВИЯХ ОГРАНИЧЕННОСТИ ДАННЫХ И ИНСТИТУЦИОНАЛЬНЫХ ОГРАНИЧЕНИЙ

Аннотация

Цифровые технологии орошения — датчики влажности почвы, интеллектуальные счётчики воды, дистанционное зондирование, географические информационные системы (ГИС), системы поддержки принятия решений, телеметрия, автоматизированные системы капельного орошения и платформы учёта воды — традиционно обосновываются объёмом воды, который они способны сэкономить. Данный критерий экономически недостаточен: более высокая техническая эффективность на уровне поля не означает автоматического роста прибыльности фермерского хозяйства, снижения затрат на управление водными ресурсами или сокращения истощения водных запасов на уровне бассейна. В статье разрабатывается методологическая рамка экономической оценки цифрового орошения в условиях ограниченности данных и институциональных ограничений, характерных для переходных экономик, с использованием Казахстана в качестве контекстного примера. Дизайн исследования носит концептуально-методологический характер: он основан на структурированном синтезе рецензируемой экономической литературы и контекстной

интерпретации национальных материалов по модернизации ирригации и не предполагает получения эмпирических оценок. Разработанная рамка включает четыре компонента: таксономию, разграничивающую технические, экономические, учётные и природоохранные понятия эффективности и ценности; трёхуровневую структуру оценки, различающую частную прибыльность на уровне фермерского хозяйства, ценность учёта воды и управления на уровне ирригационной системы, а также социальную ценность сохранения водных ресурсов на уровне бассейна; систему уровней доступности данных, связывающую каждый метод оценки с фактически необходимыми данными; и матрицу выбора методов, соотносящую класс технологии, функцию управления водными ресурсами, минимальный уровень данных, рекомендуемый метод, институциональное предварительное условие и доминирующий риск оценки, с явными защитными механизмами против наиболее распространённых ошибок. С практической точки зрения предложенная архитектура позволяет структурировать обследования фермерских хозяйств, таргетирование субсидий и приоритизацию инвестиций до начала дорогостоящего сбора данных. Ограничение рамки вытекает из её дизайна: она организует будущую эмпирическую работу, не производя причинно-следственных или количественно измеренных результатов.

* * *