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Detecting illegal water abstractions using Earth Observation and artificial intelligence: challenges, research gaps, and future directions

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ABSTRACT

Water scarcity and unsustainable withdrawals are major environmental challenges, particularly in semi arid and Mediterranean regions where agriculture places strong pressure on limited hydrological resources. Illegal or unreported water abstractions intensify these pressures by undermining ecosystem stability, policy compliance, and long term water security. Although Earth Observation (EO) and artificial intelligence (AI) have substantially advanced irrigation monitoring, evapotranspiration estimation, soil moisture retrieval, and agricultural analysis, the detection of potentially unauthorized water use remains insufficiently addressed. Most existing studies focus on describing water use patterns or estimating irrigation related variables rather than identifying suspicious abstraction behaviour in governance settings. This paper presents a structured literature review of recent research relevant to the detection of illegal water abstractions using EO and AI. The review synthesizes evidence across irrigation monitoring, biophysical estimation, anomaly detection, and operational water governance studies, with particular attention to methodological limitations affecting real world deployment. The analysis shows that the field is constrained less by the absence of useful technical components than by the lack of integrated, validated, interpretable, and scalable monitoring frameworks. Key challenges include heterogeneous data integration, limited ground truth validation, weak linkage to administrative and legal context, and the predominance of descriptive rather than predictive approaches. The review identifies a critical research gap: the absence of governance ready systems capable of proactively screening abnormal water use behaviour across heterogeneous agricultural landscapes. It therefore outlines a research agenda centred on EO data fusion, integrated spatiotemporal modelling, and predictive anomaly detection for risk informed monitoring and decision support.

Keywords: Earth Observation, illegal water abstraction, artificial intelligence, water governance, environmental monitoring, water management

1. INTRODUCTION

Water scarcity has become one of the most critical environmental challenges of the twenty-first century. Rapid population growth, expanding agricultural production, and increasing climate variability are placing unprecedented pressure on global freshwater resources. Agriculture accounts for approximately 70% of global freshwater withdrawals, making irrigation practices a key factor in water resource sustainability and environmental resilience.[1] In many semi arid and Mediterranean regions, excessive groundwater extraction and inefficient irrigation practices further intensify water stress, threatening both agricultural productivity and ecosystem stability. Effective monitoring of water use is therefore essential for sustainable water governance and long term environmental balance.[1]

A particularly significant challenge in this context is the occurrence of illegal or unreported water abstractions, including unauthorized groundwater pumping and unregulated irrigation activities. Such practices undermine water management policies, accelerate groundwater depletion, and increase the vulnerability of water systems to drought events. Detecting and managing these activities is therefore essential for enforcing environmental

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regulations and protecting water resources. However, monitoring illegal water abstractions remains technically difficult because irrigation activities are spatially dispersed, ground based monitoring infrastructures are limited, and hydrological systems are inherently complex. European regulatory initiatives and environmental monitoring programmes have therefore emphasized the need for more advanced technological solutions capable of supporting the detection and management of non-authorized water abstractions at regional scales.[2]

Traditional monitoring approaches relying on administrative reporting, field inspections, and *in situ* measurements are often constrained by high operational costs, limited spatial coverage, and delayed data availability, leaving many cases of unauthorized extraction undetected.[3] Recent advances in Earth Observation (EO) technologies and artificial intelligence (AI) have substantially expanded the analytical toolkit for irrigation monitoring, crop water stress, soil moisture (SM) retrieval, evapotranspiration (ET) estimation, and environmental anomaly detection.[1,4–7] Despite these technological developments, detecting illegal water abstractions remains a relatively underexplored research problem. Most EO studies focus on estimating irrigation demand, mapping irrigated areas, or monitoring agricultural productivity rather than explicitly identifying abnormal or unauthorized water use behaviours. In addition, many current approaches do not adequately integrate spatial satellite observations, temporal environmental dynamics, and contextual agricultural information. These limitations reduce the effectiveness of existing monitoring approaches in operational water governance settings and highlight the need for more comprehensive analytical frameworks.

This paper presents a structured literature review of research relevant to the detection of illegal water abstractions using EO and AI. The review synthesizes current methodologies, evaluates their capabilities and limitations, and identifies key research gaps that must be addressed to support the development of intelligent and governance relevant monitoring frameworks for sustainable water resource management.

The remainder of the paper is structured as follows. Section 2 reviews the background and related work, with emphasis on EO for water monitoring, AI in remote sensing (RS), and current approaches to water use detection. Section 3 discusses the principal research challenges and limitations that constrain progress in the field. Section 4 outlines future research directions, focusing on EO data fusion, integrated spatiotemporal modelling, and predictive anomaly detection. Section 5 discusses the broader policy, environmental, and governance implications of the problem. Finally, Section 6 concludes the paper by summarizing the main findings and highlighting the need for more robust and intelligent monitoring systems.

2. BACKGROUND AND RELATED WORK

The literature relevant to the detection of illegal water abstractions using EO and AI spans several overlapping domains, including irrigation monitoring, SM and ET estimation, land surface phenology analysis, environmental anomaly detection, and geospatial decision support. Because the topic lies at the intersection of environmental monitoring and water governance, the available evidence is methodologically diverse and dispersed across RS, hydrology, agricultural water management, and policy oriented sources. This section therefore adopts a structured thematic synthesis rather than a full systematic review.

To strengthen the review character of the paper, the synthesis was informed by Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 reporting principles, particularly with respect to scope definition, thematic grouping, and transparent organization of evidence.[8] The review focused primarily on peer reviewed journal articles, recent review papers, and governance oriented reports relevant to EO based irrigation monitoring, AI and machine learning (ML) methods for environmental analysis, uncertainty and validation issues, and emerging work on suspicious or unauthorized water use detection. Emphasis was placed on recent studies and on contributions that are methodologically or conceptually informative for compliance oriented abstraction monitoring, even when illegal abstraction is not their primary focus. Representative studies were selected for comparative synthesis according to four dimensions: EO monitoring, AI and ML analytics, governance relevance, and methodological quality. These dimensions are summarized in Table 1, which defines the review scope and clarifies the analytical logic used in this study.

A total of 22 sources were identified through this process and form the evidentiary basis of the synthesis presented in Sections 2 through 5; the full bibliographic detail of every reviewed source, together with a one-sentence summary, the variables and topics covered, and an explicit assessment of methodological quality and relevance to illegal water abstraction detection, is provided in Table 4 (Appendix). This review adopts a structured, purposive selection of recent and representative studies, prioritizing methodological depth and governance relevance over exhaustive bibliometric coverage, rather than the full PRISMA reporting flow associated with formal systematic reviews (e.g., database hit counts, duplicate removal tallies, and multi-stage exclusion diagrams). PRISMA principles are therefore applied here to structure the synthesis, namely scope definition, thematic grouping, and transparent organization of evidence, rather than to report a complete systematic search audit trail. This distinction is made explicit so that the review is correctly read as a structured thematic synthesis informed by systematic review principles, rather than as a full systematic literature review in the PRISMA sense.

To make this review logic explicit, Figure 1 summarizes the workflow followed in this study, from source identification and relevance screening to thematic classification and comparative synthesis.

Table 1. Review scope and literature synthesis framework.

Dimension	Focus in this review	Typical study types included	Relevance to illegal abstraction detection
EO monitoring	Irrigation mapping, vegetation dynamics, SM, ET, phenology	EO application papers, hydrology and agricultural RS studies	Provides observable environmental signals potentially linked to suspicious water use
AI/ML analytics	Classification, regression, time series analysis, anomaly detection	ML and deep learning studies in EO, environmental monitoring, and hydrology	Supports detection of subtle, non linear, or temporally evolving patterns
Governance relevance	Permits, metering, abstraction accounting, parcel context, compliance	Policy reports, irrigation accounting reviews, operational studies	Needed to translate environmental anomalies into compliance oriented evidence
Methodological quality	Validation, uncertainty, interpretability, scalability	Review papers, comparative studies, benchmark style analyses	Critical for operational adoption by water authorities

2.1 Earth Observation for Water Monitoring

EO has become a central tool for water related environmental monitoring, particularly in agriculture and hydrology. Open access satellite missions such as Sentinel-1, Sentinel-2, Landsat, and MODIS have greatly expanded the capacity to monitor land surface conditions at multiple spatial and temporal scales. Optical EO data are widely used to derive vegetation indices and assess crop vigor, land cover, and seasonal development, while radar-based satellite imagery, especially Synthetic Aperture Radar (SAR), is particularly valuable because it is less affected by cloud cover and supports SM retrieval and irrigation event detection.[9,10]

Recent reviews show that EO based irrigation monitoring is increasingly moving toward integrated estimation of irrigation water use rather than simple binary irrigation mapping. Muturi, Ndehedehe, and Kennard[11] review RS techniques for assessing irrigation water use and emphasize both the growing maturity of satellite based irrigation monitoring and the persistent difficulties associated with scale, validation, and hydrological interpretation. In parallel, Benli, Cassiano, and Giannoccaro[12] show that RS is becoming highly relevant to irrigation accounting systems, particularly where water managers require basin scale evidence on withdrawals, consumptive use, and irrigation performance. Together, these studies show that EO can support not only environmental observation, but also accounting logic that is more directly connected to governance needs.

Within this broader context, Sentinel-1 based SM monitoring remains one of the most practically important developments. Zappa et al.[9] showed that spatiotemporal SM patterns can be used to identify irrigation events and estimate irrigation amounts at 500 m resolution, providing useful information in data scarce agricultural settings. Complementary work by Chakhar et al.[10] demonstrated that the fusion of Sentinel-1 radar observations with Sentinel-2 optical time series improves the discrimination of irrigated and rainfed orchards. These studies confirm that irrigation related water use can be detected indirectly through EO, but they also underline limitations related to field size, revisit frequency, ground truth availability, crop type, and local irrigation practice.

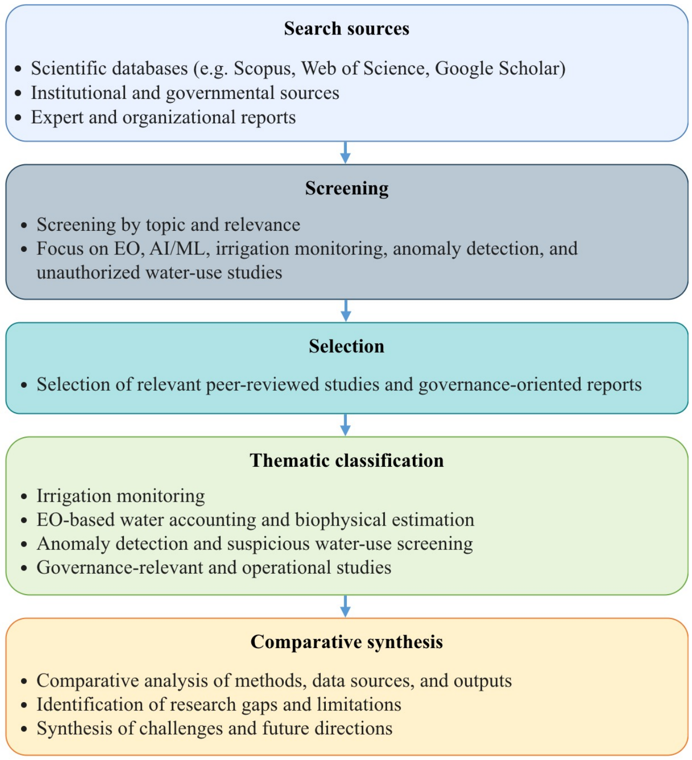

Figure 1. Structured literature review workflow adopted in this study, from source identification and screening to thematic classification and comparative synthesis.

Another important EO contribution concerns land surface phenology and seasonal vegetation behaviour. Gašparović et al.[13] show that phenological monitoring from satellite time series provides valuable information on vegetation cycles, crop seasonality, and environmental response over time. In the context of illegal abstraction, this is relevant because unauthorized irrigation may alter expected seasonal trajectories of crop development, especially under drought or water stress conditions. Similarly, recent work on high resolution EO products for SM and ET emphasizes that the coupling between these variables is central to understanding agricultural water dynamics and that improved products are increasingly bridging the gap between RS science and real world water management.[14]

At a more operational level, the Water Over-abstraction and illegal water abstraction Detection and Assessment (WODA) initiative and its follow-up phase (WODA2) show that EO can support not only environmental observation but also compliance oriented abstraction monitoring when combined with adequate auxiliary data.[2,3] These reports stress that EO products become genuinely useful for water governance only when linked to parcel boundaries, crop maps, meteorological observations, abstraction permits, and metering information. In this sense, EO provides the observational layer, but not the full decision layer required for detecting illegal water use.

2.2 Artificial Intelligence in Remote Sensing

Alongside the growth of EO datasets, AI and ML methods have become increasingly central to RS analysis. Their value lies in the ability to extract non linear relationships, identify subtle spatial patterns, and model temporal dependencies in large and heterogeneous geospatial datasets. In the literature, ML has been widely applied to land use classification, crop mapping, SM retrieval, irrigation detection, and environmental change analysis.[1]

In agricultural EO, supervised learning methods such as Support Vector Machine (SVM) and Random Forest remain among the most common modelling strategies. They are particularly useful when spectral, temporal, and radar derived features must be interpreted jointly, as shown in studies of irrigated versus rainfed classification and crop type discrimination. At the same time, recent reviews indicate that the field is moving toward more advanced ML and deep learning methods, especially for time series interpretation, EO fusion, and hydrological variable estimation.[5,15]

The growing importance of AI is especially clear in SM and ET modelling. Huang et al.[14] note that high resolution EO products for SM and ET increasingly rely on AI enabled downscaling, fusion, and modelling strategies to improve relevance at management scales. Similarly, Wang et al.[16] show that recurrent and hybrid deep learning models can capture temporal dependencies in SM prediction more effectively than static approaches. These developments are particularly relevant because illegal abstraction is not a static condition, but a dynamic behaviour that may only become visible through temporally coherent deviations from expected environmental patterns.

AI is also highly relevant to anomaly detection. Venegas Quiñones et al.[7] illustrate how RS indicators and analytical screening can be used to identify potentially illegal water use under drought conditions. More general EO anomaly detection frameworks, such as Wei et al.,[17] show that departures from expected environmental states can be identified using knowledge based and feature driven logic. Although these studies do not yet provide fully operational illegal abstraction detection systems, they demonstrate that AI can move EO analysis from descriptive observation toward suspicion based inference.

However, the literature also identifies important constraints. Reviews of integrated RS, geographic information systems (GIS), and ML for water management emphasize persistent issues of data heterogeneity, limited training data, weak interpretability, and uncertain transferability across regions and governance contexts.[1] This is particularly important in compliance oriented settings, where model outputs must be understandable and defensible rather than merely accurate. Thus, although AI has clearly strengthened EO analytics, its role in illegal abstraction detection remains promising but not yet fully operationalized.

2.3 Current Approaches to Water Use Detection

Current approaches to water use detection can be grouped into three broad categories: irrigation mapping, biophysical estimation, and anomaly based screening. Each category contributes important analytical capabilities, but each also has limitations when the objective shifts from describing agricultural water use to identifying potentially illegal abstraction.

The first category, irrigation mapping, aims to determine whether irrigation occurred and, in some cases, when. This is the most mature part of the literature and includes optical, radar, and fusion based approaches. EO based irrigation mapping can detect irrigation events, characterize seasonal irrigation patterns, and distinguish irrigated from rainfed land with promising performance. However, such approaches generally stop at identifying water use behaviour and do not, by themselves, determine whether the observed behaviour was legal.

The second category, biophysical estimation, attempts to quantify environmental variables such as SM, ET, irrigation amount, or irrigation withdrawals. This line of work is especially important because irrigation is often inferred through hydrological response rather than directly observed. Foster, Mieno, and Brozović[18] showed that satellite based monitoring of irrigation water use has major policy potential, but also that measurement errors can have important implications for water management decisions. More recent work by Zipper et al.[19] extends this discussion by evaluating the use of remotely sensed ET data to estimate irrigation water use across field, water right, and regional scales, explicitly highlighting uncertainty sources and scale sensitive performance. This is highly relevant for illegal abstraction studies because it shows both the promise and the fragility of ET based inference when managers seek governance grade evidence.

The third category, anomaly based screening, is the most directly relevant to illegal abstraction detection. Here the aim is not simply to map irrigation or estimate water use, but to identify unusual environmental patterns that may indicate suspicious or unauthorized behaviour. Venegas Quiñones et al.[7] provide an important example by using multispectral vegetation indicators to identify potentially illegal water use in a drought affected basin. Sassani, Bigdeli, and Saghravani[20] extend this logic to unauthorized groundwater extraction through illegal wells using GIS spatial analysis and EO derived probability mapping. These studies are especially important because they shift the analytical focus from descriptive monitoring toward risk informed screening.

Despite these developments, the literature still lacks mature frameworks that connect EO observations, AI analytics, hydrological interpretation, and regulatory context in a unified way. Most methods detect irrigation, estimate water related variables, or flag anomalies, but few explicitly connect these outputs with permits, abstraction points, cadastral boundaries, or governance thresholds. This is why recent irrigation accounting reviews are particularly useful: they show that operational relevance depends on integration, uncertainty handling, and institutional context rather than on sensor performance alone. Viewed collectively, the reviewed studies reveal a progression from observational inputs to analytical tasks and, ultimately, to governance relevant outputs. This progression is summarized in Figure 2, which synthesizes the main data, modelling, and decision support layers emerging from the literature. To complement this conceptual synthesis, Table 2 compares representative studies in terms of scope, EO data, analytical task, modelling strategy, main contribution, and relevance to illegal abstraction detection.

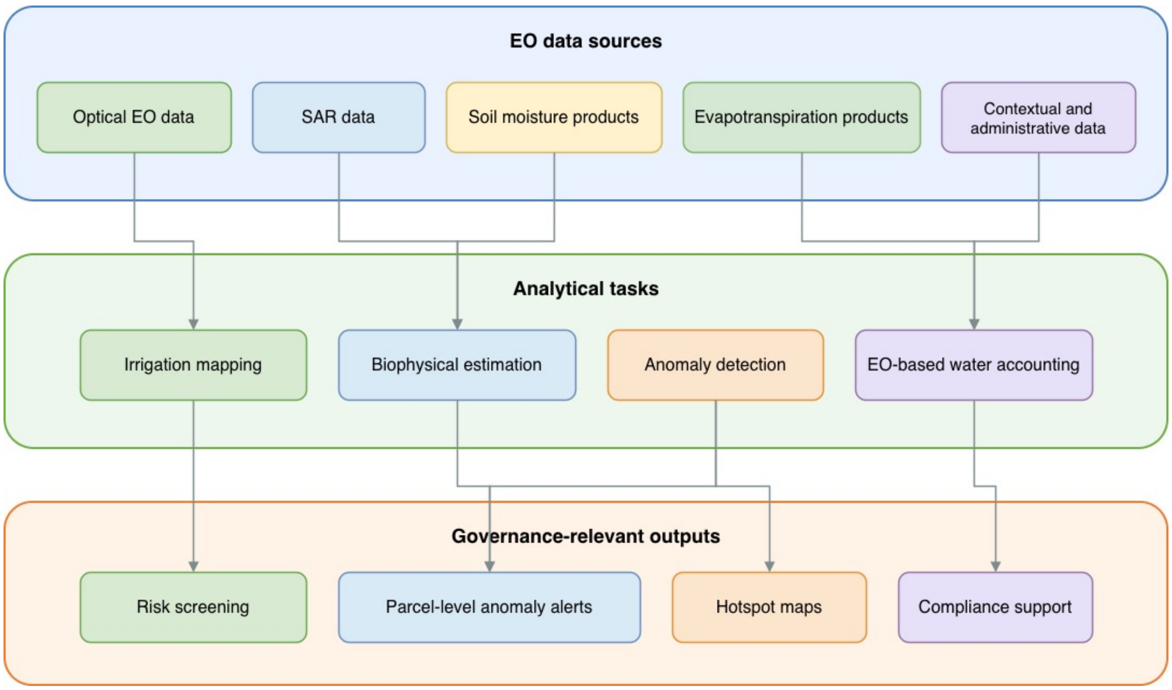

Figure 2. Methodological landscape of the reviewed literature, linking Earth Observation data sources, analytical tasks, and governance relevant outputs in studies related to illegal water abstraction detection.

The literature reviewed in this section supports a clear conclusion: the building blocks for future illegal abstraction detection systems already exist, but they are distributed across multiple domains and are rarely combined into operational, interpretable, and compliance oriented frameworks. As also reflected in Table 2, the studies most directly relevant to illegal abstraction detection remain limited in number, while a larger body of work contributes indirect but essential capabilities through irrigation mapping, biophysical estimation, and uncertainty aware water use assessment. The reviewed evidence therefore shows that the technical foundations of the field are already substantial, but still fragmented. This motivates a closer examination of the principal challenges and limitations that currently prevent these capabilities from evolving into robust and governance ready monitoring systems.

3. RESEARCH CHALLENGES AND LIMITATIONS

Despite substantial progress in EO, geospatial analytics, and AI, the detection of illegal water abstractions remains a difficult and still insufficiently addressed research problem. As shown in Section 2, the field has developed strong capabilities in irrigation mapping, SM estimation, ET based water use assessment, vegetation and phenology monitoring, and anomaly screening. However, these capabilities have largely evolved in parallel and

Table 2. Comparative summary of representative studies relevant to illegal abstraction detection.

Study	Scope and EO data	Analytical task and method	Main contribution	Main limitation	Relevance
Zappa et al.[9]	Agricultural test sites; Sentinel-1 SM	Irrigation event detection and amount estimation; spatiotemporal SM analysis	Shows operational value of SAR derived SM for irrigation monitoring	Mixed pixels, revisit constraints, and field size effects	Indirect evidence of irrigation intensity
Chakhar et al.[10]	Fruit orchards; Sentinel-1 and Sentinel-2	Irrigated vs. rainfed discrimination; SVM	Demonstrates the value of optical and radar fusion	Ground truth and local variability constraints	Useful for screening irrigated behaviour
Venegas Quiñones et al.[7]	Laguna de Aculeo, Chile; multispectral EO indices	Suspicious water use screening; analytical screening / clustering logic	Links EO anomalies to potentially illegal use under drought	Does not prove illegality directly	High direct relevance
Sassani et al.[20]	Bastam, Iran; Landsat 8, Sentinel-2, and GIS	Illegal well probability mapping; GIS spatial analysis and image fusion	Extends screening to infrastructure linked unauthorized extraction	Focuses on well risk inference rather than full abstraction accounting	High direct relevance
Foster et al.[18]	Policy oriented study; satellite irrigation monitoring	Irrigation water use measurement and policy analysis; EO based assessment	Highlights policy value and consequences of measurement error	Uncertainty affects management decisions	Strong governance relevance
Zipper et al.[19]	Field to regional scales; ET based RS products and ancillary data	Irrigation water use estimation; ET based accounting with uncertainty analysis	Explicitly addresses scale dependent uncertainty	Linking water use to rights and uses remains difficult	Strong relevance to compliance interpretation
Huang et al.[14]	Review study; SM and ET RS products	High resolution SM–ET monitoring; review of products and modelling	Connects high resolution EO science to water management usability	Bridging science to deployment remains incomplete	Supports future integrated frameworks
Benli et al.[12]	Review study; RS irrigation accounting products	Irrigation accounting systems; review	Connects EO to water accounting and basin implementation	Implementation challenges remain substantial	Strong governance and accounting relevance

only rarely within frameworks designed explicitly for compliance oriented detection of unauthorized abstraction. The central limitation is therefore not the absence of useful technical components, but the lack of integrated, validated, and governance ready systems.

In this context, Figure 3 provides a compact synthesis of the research landscape reviewed in Section 2. It links the main observational inputs, current analytical practices, and governance motivations with the principal bottlenecks that still constrain illegal water abstraction detection. More specifically, it connects the observational layer, which includes EO, contextual data, and AI based inputs, with the methodological layer of current monitoring approaches and the strategic layer of future research directions. This framing clarifies that illegal abstraction detection is not a single classification task, but a broader challenge involving data integration, temporal reasoning, uncertainty management, interpretability, and institutional context.

The following subsections discuss the principal challenges that emerge consistently across the literature.

3.1 Data Integration Complexity

A major challenge in this field is the integration of heterogeneous data sources. Current approaches often combine optical imagery, radar observations, vegetation indices, SM products, ET data, meteorological records, and GIS based contextual layers. Although such integration can improve monitoring capability, it also introduces substantial complexity because these datasets differ in spatial resolution, temporal frequency, uncertainty structure, and preprocessing requirements.[5,15]

This challenge is becoming more important as the field moves from simple irrigation detection toward irrigation accounting and water use estimation, where data fusion is essential rather than optional.[11,12] The growing availability of higher resolution SM and ET products further expands the opportunities, but also raises new questions regarding consistency, harmonization, and interpretation across scales.[14]

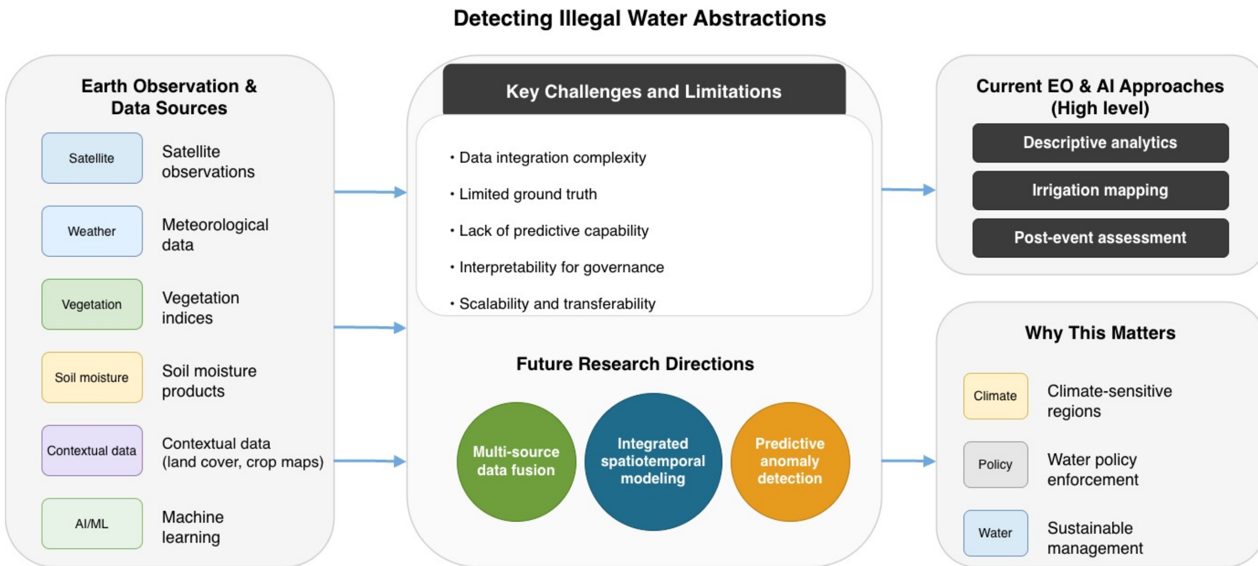

Figure 3. Conceptual overview of the research landscape for detecting illegal water abstractions using Earth Observation and artificial intelligence, highlighting the relationships among data sources, current analytical bottlenecks, future research directions, and governance relevance.

In practice, optical EO data provide rich spectral information for vegetation monitoring but remain vulnerable to cloud cover and atmospheric effects. Radar products, especially SAR, are less affected by weather conditions and support SM estimation, yet they remain sensitive to vegetation structure, surface roughness, and topographic variability.[9] Phenological indicators derived from EO time series add another useful dimension, but require interpretation relative to crop calendars and seasonal climate conditions.[13] As a result, although fusion based approaches are increasingly common, there is still no broadly established framework for combining these sources specifically for illegal abstraction detection.

The difficulty increases further in governance settings, where EO signals must be linked with parcel boundaries, crop types, meteorological observations, abstraction permits, metering records, and hydrological context. The WODA and WODA2 reports repeatedly emphasize that EO methods become operationally useful only when such supporting data are available, georeferenced, and interoperable.[2,3] Illegal abstraction detection is therefore not only a sensing problem, but also an information integration problem.

3.2 Limited Ground Truth Data

A second major limitation is the scarcity of reliable ground truth data. Many EO based studies in irrigation monitoring and SM analysis acknowledge that validation remains constrained by the availability of field measurements, parcel level irrigation logs, metering records, or expert verified observations.[9,18] This issue is especially severe in illegal water abstraction detection because confirmed labels are rarely available in open or research ready datasets.

This lack of benchmark data has several consequences. First, it limits fair comparison across regions and case studies. Second, it encourages reliance on indirect proxies such as irrigated area, vegetation condition, ET anomalies, or estimated water demand, which are informative but do not directly represent illegal abstraction. Third, it reduces confidence in model transferability across climatic zones, cropping systems, and governance settings.

Recent work on remotely sensed irrigation water use and ET based accounting reinforces this concern by showing that uncertainty and validation quality remain decisive at field, water right, and regional scales.[19] In a compliance oriented context, this is critical because a system must produce outputs that are not only suspicious, but also sufficiently reliable for follow up action.

For this reason, the literature increasingly points to stronger validation strategies, including controlled pilot studies, indirect validation against administrative records, expert assisted annotation, and hybrid evidence frameworks that combine EO based inference with domain knowledge. Without more robust validation, illegal abstraction detection will remain largely at the level of plausible environmental screening.

3.3 Lack of Predictive Capability

A further challenge is that most existing approaches remain descriptive rather than predictive. Much of the current literature focuses on mapping irrigated land, estimating SM or ET, detecting irrigation events, or identifying anomalies after they have already occurred.[7,10] While these outputs are useful for environmental monitoring, they do not yet provide the proactive intelligence required for operational detection of suspicious abstraction behaviour.

This is a fundamental limitation because illegal water abstraction is not simply an environmental state, but a dynamic behaviour that unfolds across space and time. A field may appear unusually green during drought, or an SM signal may deviate from expectations, but such observations do not necessarily indicate illegality unless they are interpreted relative to expected crop response, meteorological forcing, irrigation history, and administrative context. Current methods can identify irregular patterns, but rarely support early detection or behaviour based screening.

The anomaly detection and environmental time series literature suggests that more predictive and temporally aware systems are feasible. Wei et al.[17] proposed a framework that compares EO observations against expected environmental states using prior knowledge, while Wang et al.[16] showed that temporally aware deep learning methods can capture SM dynamics more effectively than static approaches. However, the adaptation of such predictive logic to illegal abstraction detection remains limited. One of the clearest gaps is therefore the absence of systems capable of moving from post hoc anomaly recognition toward forward looking risk indication.

3.4 Interpretability for Governance

Interpretability is another critical limitation. In regulatory and compliance oriented contexts, it is not sufficient for a model to flag an anomaly or assign a high risk score; authorities must also understand why a parcel, well, or area is being classified as suspicious. This is especially important where model outputs may influence inspections, administrative decisions, or legal procedures.

Although ML and deep learning methods have shown strong performance in environmental monitoring, many remain difficult to interpret because they rely on high dimensional features, complex temporal dependencies, or non linear relationships that are not directly transparent to end users.[1,21] In practice, this creates a gap between technical performance and institutional usability. A system that performs well statistically may still fail in governance settings if its outputs cannot be explained in a defensible way.

This issue is particularly important for illegal abstraction detection because environmental anomalies are inherently ambiguous. A strong vegetation signal, unusual ET estimate, or persistent SM anomaly may indicate unauthorized water use, but it may also reflect crop specific management, legal irrigation rights, or local climatic variation. Interpretability is therefore essential for distinguishing suspicion from inference and inference from action.

The literature increasingly points to the need for explainable AI and interpretable geospatial analytics in environmental decision support. For illegal abstraction detection, this means that future systems should not simply output anomaly scores, but should also provide evidence layers such as parcel level comparisons against expected vegetation trajectories, moisture anomalies relative to local norms, or ranked risk indicators linked to geospatial and administrative context. Without such interpretability, adoption in water governance practice is likely to remain limited.

3.5 Scalability and Operational Deployment

The final major challenge concerns scalability and operational deployment. Many published studies report promising results in specific regions or under particular environmental conditions, but their broader applicability remains uncertain. Agricultural systems differ substantially in crop type, irrigation method, field size, climate, hydrogeology, and governance structure. Consequently, methods that perform well in one region may not generalize effectively to another without recalibration or substantial adaptation.[5,15]

Scalability is therefore not only a computational issue, but also a methodological and institutional one. EO and AI systems intended for illegal abstraction detection must be robust across different environmental conditions and deployable within real administrative settings. This requires reliable preprocessing pipelines, transferable feature representations, and compatibility with external datasets such as permit databases, cadastral systems, and inspection records. The WODA literature makes clear that the operational value of EO depends heavily on whether auxiliary data are digitally available, georeferenced, and institutionally interoperable.[2,3] The paradigm of Cyprus Earth Observation Data Cube showcased how EO data can be translated into semantic-based datasets and correlated with ground-truth data into a generalized and operational framework towards the monitoring of water resources security.[22]

Recent irrigation accounting studies reinforce this point by showing that operational relevance depends not only on model accuracy, but also on the consistency of outputs across scales and administrative units.[12,19] Another important limitation is that outputs useful for scientific benchmarking are not always the same as outputs useful for water authorities. Academic studies often emphasize detection accuracy or estimation precision, whereas operational systems may require interpretable parcel level alerts, ranked inspection zones, or region wide hotspot maps that support prioritization and enforcement.

Taken together, these observations show that the central challenge is not the absence of useful EO or AI methods, but the absence of integrated and operationally mature frameworks designed specifically for illegal water abstraction detection. From a review perspective, these recurring limitations can be consolidated into a smaller set of cross cutting research gaps. Table 3 provides this synthesis by summarizing the principal gaps emerging from the literature, their implications for illegal abstraction detection, and the corresponding priorities for future work.

Overall, the literature suggests that illegal water abstraction detection remains constrained by a combination of data, method, validation, and governance limitations. These gaps justify the future research directions presented in the next section and clarify why Figure 3 should be read not only as a conceptual overview, but also as a synthesis of the field's current bottlenecks.

4. FUTURE RESEARCH DIRECTIONS

The research gaps summarized in Table 3 indicate that progress in illegal water abstraction detection will depend on integrated, interpretable, and governance ready monitoring systems rather than isolated improvements in individual models. As illustrated in Figure 3, three directions are especially important: EO data fusion, integrated spatiotemporal modelling, and predictive anomaly detection. Together, they respond directly to the principal limitations identified in Section 3.

4.1 EO Data Fusion

A first priority is the development of robust and operationally flexible EO data fusion frameworks. The reviewed literature already shows that combining optical and radar EO improves irrigation monitoring and water use inference, while recent reviews also emphasize the growing relevance of RS for irrigation accounting and water governance support.[10–12] This suggests that future illegal abstraction research should move beyond single variable monitoring toward fusion based frameworks that integrate vegetation condition, SM, ET, phenology, and hydrometeorological context.

This integration is essential because no individual signal is sufficient on its own. Optical data may reflect vegetation vigor and crop stress, radar data may capture moisture dynamics, ET products may indicate consumptive water use, and phenological indicators may reveal unusual seasonal persistence or altered growth trajectories.

Table 3. Main research gaps identified in the reviewed literature.

Research gap	How it appears in the literature	Why it matters for illegal abstraction detection	Priority for future work
Fragmented data integration	EO, GIS, meteorological, and administrative data are often analysed separately	Prevents holistic interpretation of suspicious water use behaviour	Develop modular data fusion frameworks
Weak ground truth and validation	Limited access to verified illegal use cases, permits, and meter linked observations	Reduces trust, benchmarking quality, and transferability	Build pilot datasets, indirect validation protocols, and expert assisted annotation
Predominantly descriptive monitoring	Most studies map irrigation or estimate water use retrospectively	Limits early warning and proactive intervention	Shift toward predictive and temporally aware anomaly screening
Limited interpretability	High performing models often act as black boxes	Restricts adoption in governance and compliance contexts	Prioritize explainable AI and evidence linked outputs
Low operational transferability	Methods often remain case specific	Weakens applicability across crops, climates, and institutions	Test cross region robustness and governance ready deployment
Weak linkage to legal or administrative context	Few studies connect EO outputs to permits, water rights, or cadastral information	Makes anomaly detection insufficient for compliance interpretation	Integrate regulatory context into monitoring workflows

At the same time, parcel boundaries, crop types, permits, metering records, and topographic context are needed to interpret these observations within a governance framework.[2,3] Future research should therefore treat EO products and contextual datasets as complementary layers of a unified monitoring system rather than as separate inputs.

Another important direction concerns adaptive and modular design. Data availability differs substantially across regions and institutions. Some settings may include detailed permit and cadastral databases, whereas others may rely mainly on EO observations and limited contextual information. Future frameworks should therefore operate under different levels of data completeness and accommodate missing or uncertain inputs without undermining the whole analytical workflow. Such flexibility would significantly improve the practical usability of illegal abstraction screening systems.

4.2 Integrated Spatiotemporal Modelling

A second major direction concerns integrated spatiotemporal models capable of capturing both the spatial heterogeneity and temporal evolution of agricultural water use behaviour. This need follows directly from Section 3: illegal abstraction is not a static land cover condition, but a dynamic behaviour that emerges through interactions among crop development, irrigation practice, meteorological forcing, and hydrological response.

The literature already provides a scientific basis for this transition. Land surface phenology studies show that vegetation trajectories derived from EO time series provide meaningful information about seasonal agricultural behaviour,[13] while recent work on SM and ET shows that higher resolution monitoring increasingly supports decision relevant interpretation of land–water interactions.[14] Similarly, deep learning studies in hydrology demonstrate that temporally aware models can capture environmental dynamics more effectively than static or purely cross sectional approaches.[16,21]

Future work should therefore move toward frameworks that compare observed EO signals against expected spatiotemporal behaviour under local crop, climate, and hydrological conditions. In practice, this means shifting the analytical focus from asking only whether irrigation occurred to asking whether the timing, persistence, and magnitude of observed signals are consistent with expected agricultural and hydrological dynamics. This would strengthen the capacity of monitoring systems to distinguish normal irrigation related variability from potentially suspicious abstraction patterns.

At the same time, future spatiotemporal modelling should retain operational interpretability. In governance settings, greater model sophistication is useful only if the resulting outputs remain understandable to end users. Future research should therefore balance temporal modelling power with transparent environmental reasoning, ensuring that detected deviations can be traced back to meaningful spatiotemporal evidence rather than opaque model behaviour.

4.3 Predictive Anomaly Detection

A third and particularly promising direction is predictive anomaly detection. As shown in Table 3, one of the clearest gaps in the current literature is the predominance of descriptive monitoring. Most existing methods detect anomalies retrospectively, after unusual vegetation behaviour, moisture response, or irrigation patterns have already emerged. From the perspective of water governance, much greater value would come from systems capable of detecting suspicious trends early or anticipating abnormal water use behaviour before it develops into stronger hydrological pressure.

The anomaly detection literature already provides a useful basis for this shift. Wei et al.[17] demonstrate the value of comparing observations against expected environmental states, while Venegas Quiñones et al.[7] show that EO derived indicators can support screening of suspicious water use under drought conditions. Future research should extend these ideas toward predictive systems that learn normal seasonal and parcel level behaviour and then identify deviations that are unlikely to be explained by ordinary variation alone.

Importantly, future anomaly detection should be framed as risk informed screening rather than automatic legal classification. Illegal abstraction is a legally and institutionally sensitive issue, and EO based systems are more realistically positioned as tools that support evidence prioritization rather than direct adjudication. Accordingly, future predictive anomaly detection systems should aim to produce ranked alerts, parcel level indicators, confidence aware risk maps, or hotspot lists for expert or administrative follow up. This framing is more operationally credible and more consistent with the nature of the available evidence.

A further priority is the incorporation of context aware reasoning into anomaly detection. An anomaly in vegetation condition or ET should not be interpreted in isolation, but relative to local rainfall, crop phenology, field characteristics, irrigation calendars, and regulatory context. Future research should therefore prioritize anomaly models that are explicitly conditioned on expected system dynamics rather than relying only on threshold exceedance. This would improve both interpretability and governance relevance.

Taken together, these three directions suggest that the future of illegal water abstraction monitoring lies in the convergence of EO fusion, spatiotemporal environmental modelling, and predictive anomaly screening. In direct correspondence with the gaps summarized in Table 3, such progress would help move the field from fragmented descriptive monitoring toward more integrated, explainable, and operationally relevant frameworks. The future agenda is therefore not only technological, but also methodological and institutional, requiring closer alignment among RS, AI, hydrology, and water governance practice.

5. DISCUSSION

The evidence synthesized in this review suggests that illegal water abstraction detection is a boundary problem between environmental observation and regulatory decision making. While RS and AI have advanced irrigation mapping, SM retrieval, ET estimation, phenological monitoring, and anomaly detection, these capabilities do not automatically translate into compliance ready systems. As reflected in Figure 3 and Table 3, the main barrier is not the lack of sensing or modelling tools, but fragmentation across observational, analytical, and institutional layers. EO products can indicate unusual vegetation response, elevated ET, abnormal SM persistence, or suspicious irrigation timing, but without parcel, crop, permit, and hydrological context these signals remain suggestive rather than operational.

From an environmental perspective, the implications are substantial. Illegal or unreported abstractions can intensify groundwater depletion, disturb ecological flows, increase salinization risk in vulnerable aquifers, and undermine the resilience of already stressed hydrological systems. These pressures are especially severe in semi arid and Mediterranean landscapes, where agricultural water demand is high and climatic variability reduces the margin for unsustainable withdrawals.[1] The environmental stakes therefore justify moving beyond descriptive water monitoring toward frameworks that support earlier recognition of suspicious use patterns. In this respect, EO is valuable not only because it provides observations, but also because it offers the spatial continuity and revisit frequency needed to monitor water related behaviour at scales that are difficult to cover through field inspection alone.

The review also highlights the importance of scale as both a scientific and governance issue. Many studies demonstrate strong performance at field, parcel, or local basin scale, yet their direct extension to broader administrative contexts remains uncertain. This is especially evident in irrigation accounting and ET based estimation, where uncertainty behaves differently across field, water right, and regional scales.[18,19] A method that is scientifically informative at one scale may not automatically be suitable for enforcement or compliance assessment at another. Scale should therefore be understood not simply as a technical parameter, but as a factor that shapes the legal interpretability, operational usability, and institutional credibility of the resulting evidence.

A second major discussion point concerns the role of AI in governance oriented monitoring. The current literature often presents AI primarily as an instrument for improving predictive accuracy or classification performance. While these advances are clearly valuable, the findings of this review suggest that the most meaningful future role of AI lies in strengthening the interpretive and prioritization capacity of monitoring systems. In other words, AI is likely to be most useful when it supports structured suspicion screening, context aware anomaly interpretation, and evidence ranking, rather than when it attempts to function as an autonomous adjudicator of illegality. In regulatory settings, black box predictions are unlikely to be sufficient unless they are accompanied by clear explanatory logic and links to observable environmental evidence.[1,21]

This leads to a third key issue: illegal abstraction detection should be framed as risk informed environmental intelligence rather than as a purely deterministic classification problem. The literature consistently shows that most existing methods identify anomalies, irregularities, or suspicious patterns rather than direct proof of unlawful behaviour.[7,20] This is not a weakness of the field; it reflects the nature of the problem itself. Environmental data can rarely establish illegality in isolation. What they can do is provide timely, spatially explicit, and evidence rich indications of where further expert or administrative scrutiny is justified. Framed in this way, EO and AI based systems become tools for prioritization, inspection support, and transparency enhancement rather than substitutes for governance processes.

The review further suggests that methodological maturity in this field will increasingly depend on interoperability rather than on EO performance alone. This is one of the clearest lessons emerging from the WODA reports and from recent irrigation accounting literature. The usefulness of a monitoring system depends on whether EO derived signals can be linked to cadastral units, abstraction permits, metering information, crop calendars, and hydrological context.[2,3,12] As a result, the problem should be seen not only as one of algorithm development, but also as one of system architecture and institutional data integration. Studies that remain entirely within an RS benchmark framework may contribute valuable technical insights, but they will have limited influence on real world compliance systems unless they engage more directly with governance relevant data structures.

A further implication of the review concerns the role of structured literature synthesis itself. By organizing the evidence thematically and comparatively, this paper shows that adjacent fields such as irrigation monitoring, irrigation accounting, phenology analysis, and anomaly detection are already producing many of the conceptual and technical elements required for illegal abstraction research. However, these contributions remain dispersed across different communities and publication venues. One contribution of the present review is therefore to make these connections explicit and to clarify that future progress will likely come from cross domain integration rather than from isolated advances within a single subfield.

6. CONCLUSIONS

This paper presented a structured literature review on the use of EO and AI for detecting illegal water abstractions. The review showed that substantial progress has already been achieved in adjacent domains, including irrigation monitoring, SM estimation, ET based water use assessment, land surface phenology analysis, geospatial screening, and environmental anomaly detection. Together, these domains provide a strong methodological basis for future systems aimed at identifying suspicious or unauthorized water use.

At the same time, the review showed that illegal water abstraction remains comparatively underdeveloped as a research target in its own right. Most existing studies still focus on descriptive objectives, such as irrigation mapping, environmental monitoring, or estimation of water related variables, rather than on compliance oriented detection of potentially unlawful behaviour. A clear gap therefore remains between the technical capabilities currently available in EO and AI and the operational requirements of water governance authorities.

The analysis further showed that this gap is driven by several interconnected limitations, including heterogeneous data integration, limited ground truth, the predominance of retrospective rather than predictive approaches, restricted interpretability, and uncertain scalability across environmental and governance contexts. As summarized in Table 3, these are not isolated technical issues, but part of a broader fragmentation between observational, analytical, and institutional layers of the problem.

A central conclusion of this review is that future progress will depend less on entirely new sensing technologies and more on integrating existing capabilities into coherent, interpretable, and governance ready monitoring systems. In particular, EO fusion, integrated spatiotemporal modelling, and predictive anomaly detection emerge as the most promising directions for advancing the field. However, these developments will only become practically meaningful if they are designed in close connection with administrative, legal, and hydrological context.

Overall, illegal water abstraction detection should be understood as a multidisciplinary challenge at the intersection of RS, AI, geospatial analytics, hydrology, and environmental governance. By synthesizing recent literature, identifying the main methodological limitations of current research, and outlining a more integrated agenda, this paper provides a clearer basis for future work. In water stressed agricultural regions, such progress could support improved environmental observation, stronger compliance monitoring, more transparent water management, and greater long term resilience of vulnerable hydrological systems.

APPENDIX: SUMMARY OF ALL REVIEWED STUDIES

Table 4 lists all 22 sources identified and used in this review, as referenced throughout Sections 2–5, together with a one-sentence summary of each study, the topics or variables it covers, and an assessment of its methodological quality and relevance to illegal water abstraction detection made by the authors. Studies are listed in the order in which they first appear in the manuscript.

Table 4: Summary of all studies reviewed in this paper, including a one-sentence summary, topics/variables covered, and assessment of quality and relevance to illegal water abstraction detection.

Study	One-sentence summary	Topics / variables covered	Quality and relevance assessment
Rabie et al.[1]	Reviews how RS, GIS, and ML are jointly applied to water resources management in arid agricultural regions.	RS, GIS, ML integration; water resources management	High (peer-reviewed review); indirect relevance: synthesizes enabling technologies rather than illegal abstraction directly
EC[2]	EU policy report examining how EO can support detection of non-authorised water abstractions.	Governance, regulatory frameworks, EO policy applications	Governance reference document; direct relevance: foundational compliance framing (WODA)

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Table 4 – continued from previous page

Study	One-sentence summary	Topics / variables covered	Quality and relevance assessment
IMPEL[3]	Guidance document (WODA2) on detecting and assessing illegal water abstraction at the institutional level.	Compliance monitoring, institutional data integration	Governance reference document; direct relevance: defines operational requirements for compliance oriented EO use
Neophytides et al.[4]	Applies ML and RS to assess water stress in Mediterranean citrus orchards.	Crop water stress, ML classification, Mediterranean agriculture	High (peer-reviewed conference paper); indirect relevance: regional case study supporting EO/ML applicability
Mkhwenkwana et al.[5]	Critically reviews the use of Sentinel satellite datasets for soil moisture assessment in crop production.	Sentinel missions, SM retrieval, crop production	High (peer-reviewed review); indirect relevance: technical foundation for SM based screening
Neophytides et al.[6]	Presents a Cyprus case study on improved water resources management for smart farming.	Water resources management, smart farming, regional case study	High (peer-reviewed journal); indirect relevance: governance-oriented regional implementation example
Venegas Quiñones et al.[7]	Proposes a neural network and RS based method to identify potential illegal water use locations in Chile.	Anomaly screening, neural networks, drought conditions	Moderate (preprint/non-traditionally peer-reviewed venue); high direct relevance: one of few studies explicitly targeting illegal abstraction
Page et al.[8]	Defines the PRISMA 2020 reporting guideline for systematic reviews.	Systematic review methodology	Methodological standard (highly cited guideline); used here for synthesis structure rather than topical content
Zappa et al.[9]	Uses Sentinel-1 soil moisture to detect and quantify irrigation water amounts at 500 m resolution.	SAR-based SM, irrigation event detection	High (peer-reviewed journal); indirect relevance: core technical basis for irrigation inference
Chakhar et al.[10]	Fuses Sentinel-1 and Sentinel-2 time series to discriminate irrigated from rainfed orchards.	SAR/optical fusion, irrigated vs. rainfed classification	High (peer-reviewed journal); indirect relevance: methodological basis for fusion based screening
Gašparović et al.[13]	Reviews satellite-based monitoring and prediction of land surface phenology.	Phenology, seasonal vegetation dynamics	High (peer-reviewed review); indirect relevance: supports seasonal anomaly interpretation

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Table 4 – continued from previous page

Study	One-sentence summary	Topics / variables covered	Quality and relevance assessment
Huang et al.[14]	Reviews high-resolution soil moisture and evapotranspiration products bridging RS science and water management practice.	SM, ET, product resolution, science-practice translation	High (peer-reviewed journal); indirect relevance: connects biophysical estimation to operational usability
Muturi et al.[11]	Reviews RS techniques for assessing irrigation water use, noting persistent validation and scale challenges.	Irrigation water use assessment, RS methodology	High (peer-reviewed review); indirect relevance: situates irrigation accounting within governance needs
Benli et al.[12]	Reviews RS applications for improving irrigation accounting systems at the basin scale.	Irrigation accounting, basin scale withdrawals	High (peer-reviewed review); strong governance and accounting relevance
Wei et al.[17]	Proposes a real-time RS anomaly detection framework based on a prior knowledge base.	Anomaly detection, knowledge-based screening	High (peer-reviewed journal); indirect relevance: predictive/anomaly methodology transferable to abstraction screening
Wang et al.[16]	Presents a comprehensive deep learning study for temporally aware soil moisture prediction.	Deep learning, temporal SM modelling	High (peer-reviewed journal); indirect relevance: supports predictive, temporally aware monitoring directions
Foster et al.[18]	Assesses measurement errors in satellite-based irrigation monitoring and their policy implications.	Measurement uncertainty, irrigation policy	High (peer-reviewed journal); strong governance relevance: highlights evidentiary fragility
Zipper et al.[19]	Evaluates ET-based RS estimation of irrigation water use and its uncertainty across field, water right, and regional scales.	ET-based accounting, multi-scale uncertainty	High (peer-reviewed journal); strong relevance to compliance interpretation
Sassani et al.[20]	Uses GIS analysis and Landsat 8/Sentinel-2 fusion to detect illegal wells in Bastam, Iran.	Illegal well detection, GIS probability mapping	High (peer-reviewed journal); high direct relevance: one of few studies explicitly targeting unauthorized extraction
Teixeira et al.[15]	Systematically reviews soil moisture estimation using RS data for agricultural applications.	SM estimation, agricultural RS	High (peer-reviewed systematic review); indirect relevance: technical foundation for SM based inference
Shawon et al.[21]	Extensively reviews soil moisture measurement techniques and AI-based prediction methods.	SM measurement, AI prediction, interpretability	High (peer-reviewed systematic review); indirect relevance: supports interpretability and predictive capability discussion

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Table 4 – continued from previous page

Study	One-sentence summary	Topics / variables covered	Quality and relevance assessment
Neophytides et al.[22]	Presents the Cyprus Earth Observation Data Cube as an operational framework for water resource monitoring under climate stress.	EO data cubes, semantic data integration, operational deployment	High (peer-reviewed journal); strong relevance to scalability and operational deployment

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