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EVOLVING TOOLS IN CONSTRUCTED WETLAND RESEARCH: FROM RADIOISOTOPE TRACERS TO PREDICTIVE HYDROLOGICAL MODELS

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ABSTRACT

Constructed wetlands (CWs) have become a key nature-based technology for sustainable wastewater treatment and ecological restoration, yet their performance remains highly dependent on complex interactions among hydrodynamics, biogeochemistry, vegetation, and operational conditions. This paper traces the evolution of research and troubleshooting tools used in CW studies, starting from early radiotracer applications and progressing towards contemporary data rich, model driven frameworks. The paper then presents the recent advances including remote sensing and UAV based monitoring, sensor networks, computational fluid dynamics (CFD), process based hydrological and reactive transport models, integrated systems, and the renewed but regulated use of radioisotope and dye tracers. In parallel, the role of dedicated simulation software in CW design and optimization is analyzed through six main platforms: BIO_PORE, HYDRUS Wetland Module, Wetland Water Quality Model (WWQM), WEST, AQUASIM, and SWAT. A comparative assessment highlights how each tool targets specific spatial scales and processes, from pore scale clogging dynamics to watershed level pollutant loading. The results demonstrate that no single technique or software package can capture the full multi scale complexity of CWs; instead, maximum benefit is achieved by combining complementary tools into integrated monitoring–modelling frameworks. The paper concludes by emphasising the need for multi model, multi-source strategies and outlines future directions involving AI, digital twins, and tighter coupling between field diagnostics and predictive simulation to support more resilient, efficient, and sustainable CW systems.

Keywords: CWs, CFD, BIO_PORE, HYDRUS, WWQM, WEST, AQUASIM, SWAT

1 INTRODUCTION

CWs have become an essential nature-based solution for sustainable water management, wastewater treatment, and ecological restoration [1]. Their design relies on harnessing the physical, chemical, and biological processes that naturally occur in wetland ecosystems, including sedimentation, filtration, adsorption, plant uptake, and microbial transformation. Because these mechanisms operate simultaneously and are strongly influenced by hydrodynamics, accurate evaluation of CW performance requires tools capable of characterizing water flow patterns, solute transport,

and biogeochemical reactions across multiple spatial and temporal scales [2, 3]. Early CW research was constrained by limited tools for examining subsurface processes. Most studies relied on bulk inflow–outflow measurements and empirical removal coefficients, which provided only partial insight into internal functioning [4].

The earliest quantitative investigations of CW hydrodynamics used radioisotope tracers such as tritium (^3H) to determine residence time distributions (RTDs) [5,6], dispersion, and short circuiting in treatment wetlands [7]. These tracers allowed highly sensitive detection of tracer breakthroughs and supported the development of one-dimensional transport models for wastewater flow in subsurface flow beds and ponds. Safety concerns, regulatory constraints, and the need for simpler field protocols led to a gradual shift from radioisotopes to non-radioactive conservative tracers, mainly bromide salts and fluorescent dyes [8]. Subsequent work has reinforced that ideal tracers should be conservative, easily detectable at low concentrations, nontoxic, and hydraulically representative of water flow [9]. Tracer based RTDs have also been used to develop conceptual hydraulic models of wetlands. For instance, [10] proposed a non-site specific RTD model capable of reproducing experimental responses from multiple wetlands and lagoons, supporting the use of compartment and tanks in series representations for design and diagnosis. These early hydrodynamic tools established the conceptual basis for later numerical models by explicitly linking geometry, flow paths, and treatment performance.

As tracer testing became standard practice, methodological guidance emerged to improve experimental design and data interpretation. A practical guide on hydraulic tracer studies in treatment wetlands consolidated theory, dosing strategies, sampling protocols, and common pitfalls, emphasizing the importance of proper mixing at the inlet, sufficient monitoring duration, and careful evaluation of tailing behaviour in breakthrough curves [11]. More recently, [12] highlighted how RTD analysis, when coupled with compartment models or CFD, can quantify metrics such as hydraulic efficiency and short-circuiting indices, and serve as a key calibration dataset for process-based simulations [13]. At the same time, case studies continue to refine tracer use under different loading and operating regimes, including vertical flow systems with intermittent feeding, where non steady inflows complicate RTD interpretation [14]. The evolution from radiotracers to bromide and dyes reflects both stricter safety requirements and the need for routine, repeatable diagnostics that can be integrated into long term monitoring and modelling workflows.

While tracer studies provide detailed information on internal hydraulics [15], they offer limited insight into spatial patterns at the surface [16], such as vegetation heterogeneity or spatially variable water levels. Advances in remote sensing and unmanned aerial vehicles (UAVs) have filled this gap by enabling high resolution mapping of vegetation, moisture, and temperature patterns in natural and CW. A study by Van Alphen et al [17] showed that UAV multispectral and LiDAR data, coupled with a random forest classifier, can support robust wetland habitat classification using relatively simple processing workflows. Similar studies applying centimetres scale imagery have successfully mapped plant communities and structure in wetland systems, highlighting UAV photogrammetry as a fundamental tool for detailed ecosystem monitoring [18]. Broader reviews of remote sensing in wetlands emphasize the complementary roles of optical, thermal, and synthetic aperture radar (SAR) data. A recent comprehensive review noted that SAR's all weather, day night capability and sensitivity to surface roughness and vegetation structure make it particularly valuable for monitoring water level dynamics and phenology in wetlands [19]. GIS based approaches integrating satellite and UAV data have also been proposed for environmental monitoring and simulation of wetland conditions on cloud platforms, incorporating AI methods for data analysis and prediction [20]. In CWs specifically, UAV based thermal and colour infrared imaging has been used to track surface water distribution, detect thermal anomalies associated with preferential flow, and assess vegetation stress, especially when combined with stable isotope tracers or ground measurements [21]. These tools provide spatially continuous boundary conditions and state variables that can be assimilated into hydrological or reactive transport models [22].

The application of CFD marked a major step forward in resolving detailed flow fields inside CWs. For example, [23] used a commercial CFD code to simulate subsurface flow wetlands, representing the porous medium as a homogeneous porous zone and demonstrating how inlet distribution and media properties affect velocity distributions and short circuiting. Since then, CFD models have become increasingly sophisticated. Recent studies used three dimensional CFD to investigate hydrodynamics in ponds with floating treatment wetlands, exploring how raft geometry, placement, and inlet/outlet configuration affect circulation patterns and mixing, with implications for pollutant removal [24]. Other work has applied CFD to optimize baffle arrangements and distribution structures in horizontal subsurface flow wetlands, achieving improvements in hydraulic performance and reduction of stagnant zones [25]. A 2024–2025 line of research has broadened CFD's role from case specific studies toward generalizable design tools. For example, the authors in [26] noted that CFD can address porous media flow, steady and unsteady states, and multi-dimensional flow regimes, helping to design cost effective CWs with improved hydraulic conditions. [27] proposed an integrated CFD framework for advanced flow modelling in treatment wetlands, highlighting the potential for coupling CFD outputs with empirical or process-based reaction models. CFD has therefore evolved from a specialized research tool to a central component of model-based design, although challenges remain in representing media heterogeneity, plant–flow interactions, and clogging processes realistically.

Parallel to CFD developments, process based numerical models have been developed to simulate coupled water flow, solute transport, and biogeochemical reactions in CWs. The most widely used platform is the HYDRUS Wetland Module, which extends HYDRUS 2D/3D to include wetland specific biokinetic models such as CW2D and CWM1 [28]. [29] provided a comprehensive review of numerical models for subsurface flow CWs, categorizing them into hydraulic, reactive transport, biochemical, plant, and clogging sub models, and discussing how these subcomponents are combined in comprehensive frameworks such as HYDRUS–CW2D/CWM1, BIO_PORE, and other coupled systems. They emphasized that process-based models can reveal internal “black box” mechanisms underlying observed inflow outflow behaviour, but their application is limited by data intensive calibration and parameter uncertainty.

Applications of HYDRUS–CW2D and related models have expanded steadily. Case studies using HYDRUS–CW2D for design support and performance estimation in horizontal flow wetlands polishing sequencing batch reactor (SBR) effluent have shown good agreement between measured and simulated removal of organic matter and nutrients [30]. A recent review of HYDRUS–based CW2D applications summarized uses across domestic, agricultural, and industrial wastewaters, and highlighted strengths such as flexible geometry representation and explicit biofilm simulation [31]. Beyond HYDRUS, other hydrological and water quality models have been proposed to address specific processes, catchment scale integration, or long-term evolution [32]. Many of these frameworks rely on hydraulic parameters derived from tracer tests and are increasingly being informed by remote sensor network data.

Recent reviews stress that no single tool can fully capture the multi scale complexity of CWs. [12] synthesised experimental methods and numerical models for treatment wetlands and advocated for integrated frameworks where tracer derived RTDs are used to calibrate hydraulic or CFD sub models, sensor networks provide dynamic boundary conditions, and process-based models are employed for scenario analysis and design optimisation. At the same time, emerging work is exploring the integration of AI, machine learning, and digital twins with established hydrological models, using remote sensing and high frequency monitoring data to continuously update and improve predictions [33]. In this context, the historical progression from radioisotope tracers to predictive hydrological and reactive transport models represents not just a change in tools, but a shift toward multi source, data rich, and model driven approaches to CW design and operation.

Despite these advancements, each tool presents trade-offs between accuracy, complexity, cost, and the type of information produced. As the design and application of CWs expand particularly in the context of climate change, urbanization, and decentralized treatment systems researchers increasingly require integrated approaches that combine multiple tools. Understanding the evolution of these tools is therefore essential for identifying best practices, recognizing methodological gaps, and guiding the development of next generation monitoring and modelling strategies.

This paper reviews the progression of research tools used in CW studies, beginning with early radioisotope techniques and moving toward contemporary modelling frameworks. By examining their strengths, limitations, and applications, we aim to provide a comprehensive overview that supports improved scientific understanding and more effective engineering design of CW systems.

2 TRADITIONAL CWS TROUBLESHOOTING METHODS

Effective troubleshooting of CWs requires a systematic approach combining hydraulic assessments, water quality monitoring, structural inspection, and modelling-based diagnostics. Because CWs operate as complex eco hydrological systems, performance issues often arise from interactions among hydraulics, substrates, vegetation, microbial communities, and external loading conditions. The traditional CWs troubleshooting methods are:

2.1 Hydraulic Troubleshooting

Tracer tests are indispensable for diagnosing hydraulic anomalies such as short circuiting, dead zones, bypassing around clogged areas, and low hydraulic residence time (HRT) [34]. Monitoring water levels and inflow/outflow helps detect improper hydraulic loading, blocked pipes, leakage or seepage losses [35]. Visual observation of flow patterns can provide early warning of maldistribution [36].

2.2 Clogging Diagnosis and Management

Clogging is one of the most common failures in CWs. Low infiltration rates or reduced hydraulic conductivity indicate early clogging [37]. Core sampling of substrates can identify fine particle accumulation, organic buildup, and biofilm thickness [38]. Hydraulic conductivity surveys and slug or infiltrometer tests help map subsurface flow impediments and porosity loss [39].

2.3 Water Quality Troubleshooting

Routine water chemistry monitoring of COD/BOD, ammonia, nitrate, phosphate, DO, ORP, pH, EC, and TSS at inlet, mid bed, and outlet zones allows diagnosis of poor bioreaction, overloading, or toxic influents [40]. Sensor networks enable continuous monitoring to detect sudden shocks and track diurnal or seasonal performance changes.

2.4 Vegetation Troubleshooting

Visual plant inspection may reveal yellowing or dead patches—signs of hydraulic stagnation or toxicity. Biomass sampling is especially useful in subsurface systems where aeration or substrate compaction may hinder root growth. Remote sensing of vegetation health and density also supports early detection of plant stress zones.

2.5 Microbial and Biochemical Diagnostics

Biofilm overgrowth can reduce porosity and accelerate clogging—examination of biofilm thickness and microbial community shifts can identify bottlenecks. Oxygen transfer assessments help determine whether oxygen limitation is constraining treatment performance.

2.6 Structural and Mechanical Troubleshooting

Inspection of inlet/outlet structures for blockage, damage, or improper water level settings is essential. Leak detection via water balances, level monitoring is imperative when retention times fall unexpectedly.

2.7 Modelling Based Troubleshooting

CFD simulations can identify velocity distribution anomalies, dead zones, and structural inefficiencies for hydraulic optimization. Process based hydrological and biogeochemical models can test whether treatment failure is due to biological limits or hydraulic issues and evaluate scenarios.

3 RECENT CWS TROUBLESHOOTING METHODS

Recent advances in monitoring and modelling have transformed how CWs are diagnosed, controlled, and optimized. Beyond traditional tracer tests and routine sampling, a new generation of troubleshooting tools now provides high-resolution spatial, temporal, and process-level insight into wetland hydrodynamics and treatment performance. This section reviews the main recent methods used to identify and resolve operational problems in CWs, including remote sensing and UAV-based surveys, real-time sensor networks, CFD, mechanistic hydrological and reactive-transport models, integrated “smart wetland” frameworks, and both radioisotope and dye tracer techniques. Together, these approaches enable practitioners to detect anomalies earlier, understand internal processes more deeply, and design more resilient and efficient CW systems.

3.1 Remote Sensing and UAV Based Monitoring

Remote sensing technologies have greatly expanded the ability to monitor CWs at large spatial scales and high temporal frequency. UAV based multispectral, thermal, and LiDAR sensors allow for detailed mapping of vegetation health, surface water distribution, and thermal anomalies, which can reveal preferential flow or clogging zones. For example, remote sensing vegetation indices such as NDVI and MSAVI have been shown to correlate with hydrological parameters in large scale treatment wetlands receiving industrial effluents [41]. Similarly, reviews highlight the advantages of combining optical, thermal, and SAR data for wetland monitoring and classification [42]. Although remote sensing cannot resolve subsurface hydrodynamics, it offers essential spatial information that complements tracer studies and hydrological modelling frameworks.

3.2 Sensor Networks and Real Time Monitoring

Modern CWs increasingly employ distributed sensor networks capable of continuously measuring DO, pH, temperature, ORP, EC, and flow. These systems enable real time process control, detection of treatment anomalies, and improved calibration of hydrodynamic or reactive transport models. Maurice et al. developed a full monitoring environment for a large surface flow wetland, demonstrating the potential for continuous, remotely accessible hydrological and water quality data streams [43]. Integration of sensor networks with remote sensing and data driven analytics is rapidly advancing toward the creation of fully autonomous “smart wetlands.”

3.3 Computational Fluid Dynamics (CFD)

CFD is now widely used for resolving 3D hydrodynamic patterns in CWs, including velocity fields, turbulence structures, and solute transport. By simulating flow through porous media, CFD can identify short circuiting zones, dead zones, and inefficient distribution patterns that reduce treatment performance. Fan et al. demonstrated early applications of CFD

to subsurface flow wetlands, showing significant improvements in understanding hydraulic behaviour. Recent developments include CFD based optimisation of baffles, inlet structures, and floating treatment wetlands. CFD remains limited by computational intensity and the difficulty of representing heterogeneity and biofilm growth, but its role in design optimisation is rapidly expanding.

3.4 Process Based Hydrological and Reactive Transport Models

Mechanistic models such as HYDRUS/CW2D simulate multi component reactive transport under variably saturated conditions. These tools capture biological transformations of organics, nitrogen, phosphorus, and emerging contaminants with explicit representation of microbial processes and environmental conditions. [44] established CW2D as a foundational module for subsurface CW modelling. A major recent trend is the integration of tracer derived hydraulic data, real time sensor readings, and remote sensing datasets to enhance model calibration and predictive reliability. Numerical model reviews emphasise the need for further refinement in representing clogging, biofilm heterogeneity, and plant-microbe interactions [45, 46].

3.5 Integration and Smart Wetland Frameworks

Recent advances focus on the integration of multiple data sources including sensors, tracers, UAV imagery, and CFD to construct digital twin systems capable of real time forecasting and optimisation. GIS based decision support tools increasingly incorporate hydrological models to aid in siting, designing, and evaluating CW ecosystem services [47]. Emerging applications of machine learning further support anomaly detection, performance prediction, and operational optimization in both natural and CWs.

3.6 Radioisotope Tracers

Modern radiotracer studies are conducted under strict regulatory controls and are typically used only when other tracers are insufficient [T33]. For example, in deep subsurface wetlands, large industrial CWs, or systems requiring ultra precise residence time distributions. Radiotracers such as tritium (^3H) or bromine 82 allow accurate identification of hydraulic anomalies, preferential flow paths, and flow component separation even at extremely low concentrations. The International Atomic Energy Agency (IAEA) has recently renewed interest in radiometric methods, promoting combined radiotracer CFD approaches to improve hydraulic modelling accuracy [49]. Though safety considerations limit widespread use, radiotracers remain an advanced and powerful tool for specialised hydrodynamic investigations. The advantages of using radiotracer in CW are; High sensitivity and detectability, Ability to quantify mixing, flow paths, and retention efficiency, and Useful for validating conceptual models. Otherwise, it is limited by Regulatory restrictions and safety concerns, high operational costs, and potential environmental risks. Despite their limitations, radioisotope tracers established foundational knowledge on the hydrodynamics of CWs.

3.7 Dye Tracers and Modern Conservative Tracer Techniques

Fluorescent dyes (Rhodamine WT, fluorescein) and conservative ions (bromide, lithium chloride) are among the most widely used tools for modern hydraulic characterization in CWs. Improvements in fluorometry, automated sampling, and sensor integration have made dye tracer studies easier, more cost effective, and more precise. These tracers are central to evaluating Hydraulic Residence Time (HRT), dead zone volumes, short circuiting, and flow through efficiency. Contemporary studies emphasise impulse and step tracers for real time hydraulic assessment, linking breakthrough curves to CFD and reactive transport models for a full description of system performance [50 51]. Advanced dye tracing setups now use automated fluorometric detection combined with GIS mapping, enabling spatially explicit hydraulic analysis. Because they are nontoxic, easily detectable, and regulatory friendly, dye tracers represent one of the most important modern tools for both research and routine operational monitoring.

4 CWS MODELLING AND SIMULATION SOFTWARE

Simulation software plays an increasingly vital role in the design, operation, and optimization of CWs [52]. As CWs rely on complex interactions among hydrology, substrate properties, plant dynamics, microbial processes, and pollutant transformation pathways, traditional empirical design approaches often fail to capture the true behavior of these systems [53, 54]. Advanced modelling tools such as BIO_PORE, HYDRUS Wetland Module, WWQM, WEST, AQUASIM, and SWAT allow researchers and engineers to simulate processes such as hydraulic flow patterns, solute transport, nutrient cycling, clogging development, plant-microbe interactions, and watershed scale pollutant loading. These models integrate hydrodynamic, biogeochemical, and ecological components, providing a mechanistic understanding that supports more accurate predictions of wetland performance under various environmental and operational conditions.

The importance of these simulation tools has grown significantly as CWs are increasingly applied to complex wastewater streams, climate sensitive systems, and large watershed-based treatment schemes. Modelling enables early

identification of bottlenecks, optimization of hydraulic configurations, evaluation of design alternatives, and anticipation of long-term issues such as clogging and nutrient saturation. Tools such as HYDRUS and BIO_PORE provide detailed insight into subsurface flow processes, while WWQM, AQUASIM, and WEST support water quality forecasting and full plant integration. Meanwhile, SWAT helps assess the influence of wetlands at the catchment scale, guiding site selection and watershed management decisions. Overall, simulation software enhances the reliability, sustainability, and cost effectiveness of CWs by transforming them from empirical “black box” systems into scientifically informed, optimized nature-based treatment technologies.

4.1 BIO_PORE

BIO_PORE is a mechanistic model specially developed to simulate the combined effects of flow hydrodynamics, solute transport, microbial biofilm growth, and substrate porosity reduction in porous media systems such as subsurface flow CWs. The model was calibrated for CWs and includes a “clogging sub model” that describes particulate deposition, biofilm accumulation, and hydraulic conductivity reduction over time [55]. The Key features of BIO_PORE are detailed representation of biofilm growth kinetics and its effect on pore space and hydraulic performance. Also, it integrates hydrodynamics and reactive transport with substrate property changes. The Limitations of this software are the relatively complex in parameterization and requires detailed data on hydraulic conductivity changes, biofilm growth rates, and substrate properties. Also, it is less commonly used for free-surface CWs or large-scale wetlands with complex hydraulics.

4.2 HYDRUS Wetland Module

This refers to the CW modules (CW2D, CWM1) incorporated in the HYDRUS 2D/3D software for variably saturated flow and reactive transport [56]. CW2D capable of simulating the transformation of organics, nitrogen, phosphorus under variably saturated conditions in subsurface flow CWs [57]. The features of this software are; it capable of simulates variably saturated flow combined with multicomponent reactive transport under subsurface conditions. Also, it supports modelling of plant uptake, biofilm, multiple reactive species, and different flow regimes. The limitations of this software are; it requires extensive parameterization which can limit usability for practitioners without strong data. And also, it does not inherently include a detailed dosing for clogging.

4.3 Wetland Water Quality Model (WWQM)

The WWQM was developed for large free surface flow treatment wetlands with the primary objective of modelling phosphorus removal, sediment interactions, and macrophyte/periphyton compartments. [58] describes its architecture: hydrodynamics is calculated first, then chemical interactions between water column and compartments are simulated. The features of this software are; it is 2D dynamic hydrodynamics, coupled with large state variable sets and it suitable for phosphorus removal in large wetland systems. While the limitations are very high complexity and computational demand, large data requirement; not widely used in design practice. Also, it is less suitable for smaller subsurface flow systems or when detailed hydraulics are needed.

4.4 WEST

WEST is a dynamic simulation platform originally developed for Wastewater Treatment Plants (WWTPs) but also configurable for CW units within a treatment train. According to DHI documentation, WEST allows comparison of design alternatives, performance evaluation, optimization of energy/carbon footprint, and integration of catchment, collection, and treatment systems [59]. The features of this software are it is customizable unit-process libraries, integration of control strategies, operability with catchment/trains. Also, it is suitable when CWs are part of a broader treatment system (WWTP + wetland polishing). The limitations are; while flexible, the CW specific modules may not be as detailed hydraulically or biologically as models dedicated solely to CWs. Also, it focused more on system integration than detailed substrate or flow hydraulics.

4.5 AQUASIM

AQUASIM is a general modelling environment for aquatic systems that supports advection–dispersion–reaction simulation of biogeochemical processes. A study on free water surface CWs used AQUASIM to couple hydrodynamics and biokinetics for eutrophic water treatment [60]. The features of this software are; it is good for mechanistic modelling of water quality processes in wetland systems. And Scripting / customisable reactions, flexible domain geometries. where the limitations: it is not specialized for CW hydraulics especially subsurface flow, may require custom setup. And it requires strong modelling expertise and data for reaction kinetics.

4.6 SWAT

SWAT is a watershed scale hydrological and water quality model used to simulate land use, crop, soil and hydrology interactions. Though not built specifically for CWs, SWAT has been used to assess the role of CWs or wetland BMPs within a larger watershed context. SWAT simulated discharge and water quality for watersheds with engineered

wetlands [61]. The features of this software are it can simulate runoff, sediment, nutrient loading, land use effects at watershed scale. Also, it is useful for evaluating placement and watershed impact of CWs rather than internal CW processes. the limitations are the lacks detailed CW hydraulic/biological modelling capacity; internal CW processes must often be parameterised simply. And calibration can be challenging due to spatial heterogeneity and data requirements.

5 RESULTS AND DISCUSSIONS

In this section we will compare and discuss the analytical tools and software that are used in CWs analysis and troubleshooting and propose an integration between these techniques and software for optimum use of them to maximizes the CWs performance.

5.1 Comparative Analysis of CWs Tools

Understanding the strengths, limitations, and appropriate applications of modern research tools is essential for advancing CW design, monitoring, and optimization. The seven techniques presented in Section 3 represent a diverse set of approaches that operate across different spatial scales and analytical depths. Table (1) shows the main purpose and typical applications of CWs troubleshooting methods. Each tool captures a distinct dimension of wetland function, ranging from broad ecosystem level observations to highly detailed simulations of internal hydraulics and biochemical processes. Comparative analysis shown in tables (2, 3) provides a foundation for understanding how these techniques complement one another, where their capabilities overlap, and how they can be strategically combined to enhance the reliability and effectiveness of CWs assessment and management.

Table 1: Main purpose and typical applications of CWs troubleshooting methods

Technique	Main Purpose	Typical Application
Remote Sensing & UAVs	Spatial mapping	Vegetation health, surface water patterns
Sensor Networks	Continuous monitoring	Water quality, flow, early warning
CFD	Detailed hydrodynamics	Flow optimization, dead zone detection
Process Based Models	Process simulation	Nutrient removal, clogging, system design
Integrated/Smart Systems	System wide optimization	Full wetland management
Radioisotope Tracers	Precise hydraulic tracing	Complex systems require high sensitivity
Dye/Conservative Tracers	Hydraulic residence time analysis	Routine CW hydraulic assessment

Table 2: Comparison between CWs troubleshooting methods

Technique	Spatial Resolution	Temporal Resolution	Accuracy	Operational Difficulty	Cost
Remote Sensing	High	Moderate	High	Moderate	Medium–High
Sensor Networks	Point based	High	Very high	Moderate–High	Medium
CFD	Very high	Moderate	Extremely high	High	High
Process Based	Medium	Medium	High	Medium–High	High
Integrated Systems	Multiscale	High	Extremely high	Very High	Very High
Radioisotopes	High	High	Extremely high	High	High
Dye Tracers	Medium High	Medium High	High	Low–Medium	Low

Table 3: Comparative analysis of CWs Troubleshooting Methods

Technique	Hydraulics	Water Quality	Spatial Mapping	Subsurface Insight	Prediction	Safety
Remote Sensing	Moderate	Very Good	Excellent	Poor	Moderate	Safe
Sensor Networks	Very Good	Excellent	Poor	Moderate	Very Good	Safe
CFD	Excellent	Moderate	Moderate	Excellent	Very Good	Safe
Process Based Models	Very Good	Very Good	Moderate	Very Good	Excellent	Safe
Integrated Systems	Excellent	Excellent	Excellent	Excellent	Excellent	Safe
Radioisotope Tracers	Excellent	Moderate	Moderate	Excellent	Moderate	Regulated
Dye Tracers	Very Good	Moderate	Moderate	Very Good	Moderate	Safe

The comparative analysis illustrates that each of the seven techniques contributes uniquely to CW research, and no single tool can provide a complete understanding of system behavior on its own. Instead, these methods are highly complementary, addressing different spatial scales, temporal resolutions, and functional aspects of CW hydrology and treatment performance. Remote sensing and UAV based monitoring excel in providing broad spatial coverage and identifying surface level heterogeneities such as vegetation stress and water distribution patterns. However, they lack the ability to capture subsurface flow behaviour, which remains central to hydraulic performance. This gap is effectively addressed by both dye tracers and radioisotope tracers. Dye tracers offer a safe, cost effective, and operationally straightforward means of assessing hydraulic residence time and identifying preferential flow paths, making them well suited for routine field applications. In contrast, radioisotope tracers, despite their regulatory constraints, remain unmatched in precision and are best reserved for large, complex, or highly sensitive hydrological investigations where very high sensitivity is required.

Sensor networks represent a major technological step forward by enabling high frequency, real time monitoring of water quality and hydrological parameters [62]. This continuous data stream can detect short term fluctuations and operational anomalies that discrete sampling would miss. However, sensor systems cannot independently explain internal flow mechanisms, which is where CFD and process-based models play a crucial role. CFD allows detailed visualization of internal flow fields and structural inefficiencies, while process-based models simulate biochemical transformations and long-term system behaviour. These approaches complement empirical tools like tracer studies by offering predictive power and mechanistic insights [63]. Integrated and smart wetland frameworks represent the natural progression toward data fusion, in which multiple tools remote sensing, sensors, tracers, CFD, and mechanistic models are combined to create a holistic picture of wetland function. These systems hold the greatest potential for real time decision making, operational optimization, and long-term planning, although they are limited by complexity, cost, and the need for multidisciplinary expertise.

In summary, the comparison highlights that effective CW research and management depend on selecting the appropriate combination of tools based on objectives, system scale, available resources, and regulatory context. Traditional tools such as dye tracers remain highly relevant, modern tools such as UAVs and process-based models expand analytical capabilities, and integrated frameworks represent the future direction of high-performance wetland monitoring and optimization.

5.2 Comparative Analysis of CWs Simulation Software

CW simulation tools vary widely in their modelling approaches, objectives, spatial scales, and process complexity. As CWs are highly heterogeneous systems that integrate hydrological, biochemical, ecological, and geomorphological processes, no single model can fully capture all aspects of their behaviour. Therefore, comparing the major software packages; BIO_PORE, HYDRUS Wetland Module, WWQM, WEST, AQUASIM, and SWAT is critical for understanding their suitability for different applications. Table (4) show the comparison between CWs these software packages. Each tool has been developed with specific priorities, such as clogging prediction, reactive transport modelling, ecosystem scale nutrient dynamics, wastewater treatment integration, or watershed level hydrological assessments. This comparison highlights the strengths, limitations, and ideal use cases of these six modelling platforms, providing a foundation for selecting the most appropriate tool for research, design, optimization, or management of CWs systems.

Table 4: Comparison between CWs Simulation Software

Feature	BIO_PORE	HYDRUS	WWQM	WEST	AQUASIM	SWAT
Main Purpose	Subsurface flow CWs modeling	Water flow & solute transport in wetlands	Nutrient removal & water quality	WWT process optimization	Aquatic systems & wetland dynamics	Watershed scale hydrology & water quality
Flow Type	Subsurface flow	Surface & subsurface flow	Surface & subsurface flow	Surface & subsurface flow	Surface & subsurface flow	Surface flow
Water Flow Modeling	Richards equation	Richards equation	Empirical equations	Process based hydraulic	Process based hydrodynamic	Hydrological model
Pollutant Transport	Nitrogen, carbon, phosphorus, oxygen	Nitrogen, phosphorus, organics, heavy metals	Nitrogen, phosphorus	Nitrogen, COD, phosphorus, BOD,	Nitrogen, phosphorus, organics	Sediment, nitrogen, phosphorus
Biochemical Processes	Microbial reactions, oxygen transport	Biodegradation, denitrification, plant uptake	Nutrient cycling, sedimentation	Biological & chemical treatment reactions	Microbial & chemical transformations	Nutrient cycles, sediment transport
Hydraulic Complexity	Simple to moderate	Complex	Moderate	Complex	Moderate	Complex
Spatial Scale	Small	Small to medium	Medium	Small to medium	Small to medium	Large
Graphical Interface	Moderate	Advanced	Simple	Advanced	Moderate	Moderate
Ease of Use	Moderate	Moderate to high	Moderate	High	Moderate	Moderate to high
Integration with Other Models	No	MODFLOW, PHREEQC	No	MATLAB, OpenMI	MATLAB, Simulink	ArcGIS, MODFLOW
Best For	Researchers focusing on microbial & subsurface CW processes	Engineers & researchers analyzing water flow & pollutant transport	Water quality professionals assessing nutrient removal efficiency	Engineers optimizing CWs in wastewater treatment plants	Researchers modeling CWs in aquatic ecosystems	Hydrologists & environmental planners modeling large scale CW impacts

The comparative analysis of the six simulation software tools demonstrates that each model serves a distinct role within the broader field of CW management. The results clearly indicate that highly mechanistic tools such as HYDRUS and BIO_PORE offer the greatest depth for understanding internal wetland processes, particularly subsurface hydrodynamics, biochemical transformations, and clogging evolution. In contrast, ecosystem scale models such as WWQM and AQUASIM are better suited for free water surface systems where nutrient cycling, algal dynamics, and sediment interactions dominate overall performance. Meanwhile, WEST provides essential capabilities for integrating CWs into full wastewater treatment plants, highlighting the importance of wetland units in plant wide optimization and operational control. At the largest scale, SWAT extends the utility of CW modelling beyond individual systems to watershed level planning, demonstrating how wetlands function as landscape based best management practices for pollutant reduction.

The comparison underscores that none of these tools alone is universally applicable, and the choice of software must be aligned with the specific objectives, spatial scale, and data availability of the project. The strengths and limitations revealed by this evaluation suggest that the most effective approach often involves combining multiple models, for example, using SWAT to estimate watershed inflows, HYDRUS to simulate internal wetland performance, and WEST to assess interactions with other treatment units. The comparative results therefore emphasise the need for a multi model,

multi scale strategy in modern CW design and research, enabling more accurate predictions, better optimization, and more sustainable management of CW systems.

6 CONCLUSION

This paper has reviewed and synthesised the evolution of tools used in CW troubleshooting, and design, from early radioisotope tracers to advanced predictive hydrological and reactive transport models. Traditional diagnostic approaches, including hydraulic tracer tests, clogging assessments, water quality monitoring, vegetation surveys, and structural inspection, remain indispensable for identifying operational problems such as short circuiting, dead zones, clogging, and treatment failure. These methods provide the empirical grounding on which more advanced numerical tools are calibrated and validated, ensuring that modelling efforts remain anchored in real system behaviour. Recent developments have significantly expanded the spatial and temporal resolution at which CWs can be assessed. Remote sensing and UAV based monitoring enable detailed mapping of vegetation health, surface water distribution, and thermal anomalies, while sensor networks provide high frequency, real time records of key hydrological and water quality parameters. Together, these technologies transform CWs from intermittently monitored systems into continuously observed environmental reactors, capable of supporting early warning, performance tracking, and adaptive management. However, they cannot on their own fully explain subsurface hydrodynamics or biogeochemical pathways, underscoring the need for complementary tracer tests, CFD analyses, and process-based models.

The comparative analysis of troubleshooting techniques shows that each method captures a distinct dimension of CW functioning. Radioisotope and dye tracers continue to provide high precision insight into flow paths and residence time distributions; CFD offers a detailed three-dimensional view of hydraulic behaviour and structural inefficiencies; and mechanistic models such as HYDRUS/CW2D link hydraulic conditions with multi component reactive transport. Integrated and smart wetland frameworks represent the logical culmination of these developments, combining remote sensing, sensor networks, tracer data, CFD, and numerical models into coherent decision support systems. Although such integration is demanding in terms of data, expertise, and computational resources, it offers unparalleled potential for real time optimisation and long term strategic planning.

A parallel comparison of six major CW simulation platforms—BIO_PORE, HYDRUS Wetland Module, WWQM, WEST, AQUASIM, and SWAT—confirms that each has been designed with specific priorities and scales in mind. BIO_PORE and HYDRUS are best suited to detailed subsurface investigations of hydrodynamics, clogging, and biogeochemical transformations; WWQM and AQUASIM focus on free water surface systems and ecosystem scale nutrient dynamics; WEST emphasises plant wide integration of CWs into wastewater treatment systems; and SWAT extends the analysis to watershed level hydrology and non-point source pollution control. None of these tools is universally applicable, but together they form a toolkit capable of addressing CW performance from the pore scale to the catchment scale.

STATEMENTS ON COMPLIANCE WITH ETHICAL STANDARDS

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