

Implications of Computer-Aided Instruction (CAI) in Reconfiguring the Contaminated Site Management Pedagogy

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Abstract: *This paper analyses the pedagogical and practical valences of Computer-Assisted Instruction (CAI) within the context of integrated management of contaminated sites and waste, a field characterized by high technical and decisional complexity. We propose a conceptual reference framework (CRF) based on a triad of digital competencies - cognitive, operative, and strategic - designed to transform the educational process from a passive information flow into an interactive and adaptive experience. The study explores how the integration of specialized software platforms facilitates the simulation of invisible physico-chemical processes, allowing learners to test management hypotheses in a controlled, risk-free "sandbox" environment. Through progressive work scenarios, ranging from basic auditing to global waste governance, this research demonstrates that CAI develops systemic thinking and decisional resilience. Ultimately, the paper argues that the future of environmental expertise depends on a paradigm shift toward technology-mediated, constructivist learning models.*

Keywords: *Contaminated sites, instructional design, digital competencies, environmental protection*

1. Introduction

The management of contaminated sites represents one of the most complex challenges in contemporary environmental engineering, involving a heterogeneous mix of technical, legislative, and socio-economic variables [1-3]. The transition from traditional approaches to integrated management requires not only advanced technological solutions but also a highly skilled workforce capable of operating within a decision-making landscape marked by uncertainty [4, 5]. In this context, the training of future specialists can no longer be limited to conventional didactic methods; the complexity of pollutant transport phenomena in soil and groundwater demands training models that allow for the visualization and manipulation of virtual scenarios.

This is where the pedagogical valences of Computer-Assisted Instruction (CAI) intervene - an applied discipline that transforms the learning process from a passive flow of information into an interactive and adaptive experience for diverse situations (Fig. 1). The pedagogical essence of CAI in this field resides in its ability to simulate physico-chemical processes invisible to the naked eye.

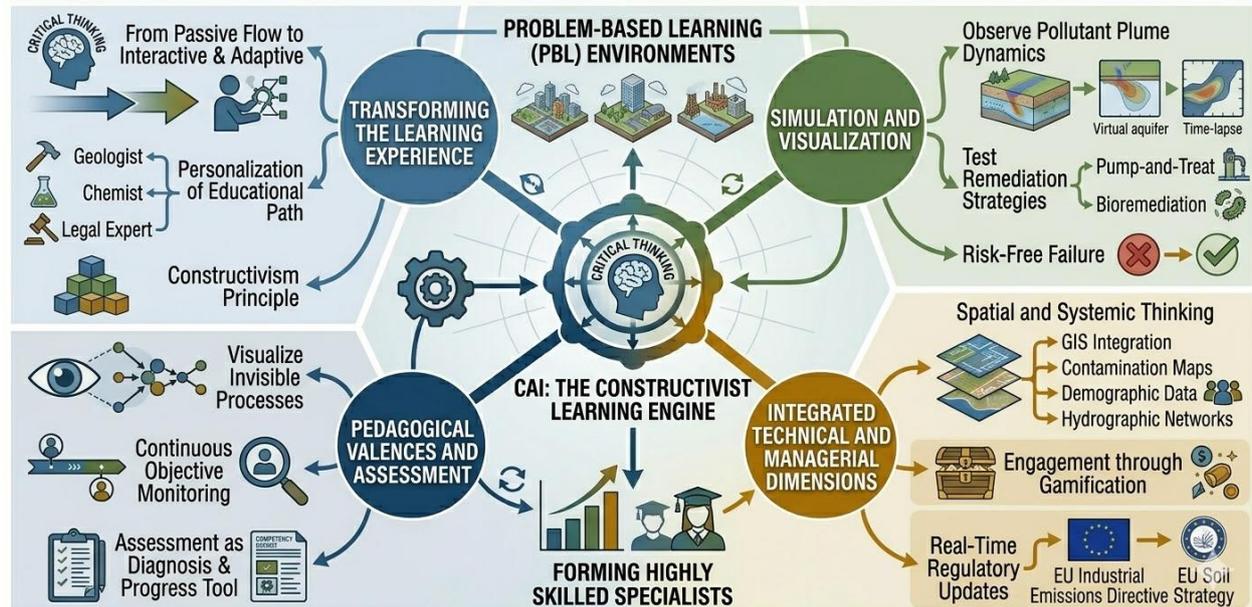


Fig. 1. Integrated workflow of CAI in CSMP - from passive flow to interactive and adaptive learning path (source: generated with Gemini 3 flash)

Through simulation software, students and practitioners can observe the dynamics of a pollutant plume under the influence of various remediation strategies - such as pump-and-treat or bioremediation - without the costs or risks associated with a real site. Instructional design applied to environmental management must be based on the principle of constructivism. CAI facilitates this by creating problem-based learning (PBL) environments, where the user is placed in front of a virtual contaminated site and must select, based on the provided data, the most effective investigation and remediation techniques. Key benefits for specialist training as follows:

- **Personalization of the educational path** - intelligent instruction systems can adapt the difficulty level and content according to the user's profile - whether geologist, chemist, or legal expert - ensuring an optimal learning curve for every specialization in the integrated management team.
- **Learning by failure in a controlled environment** - in real-world site management, a wrong decision can lead to ecological disasters or massive financial losses. In a CAI virtual environment, the learner can test the limits of a technical solution, understanding the consequences of failure without compromising environmental integrity.
- **Spatial and systemic thinking** - integrating Geographic Information Systems (GIS) into CAI platforms adds a critical spatial dimension to environmental education. The ability to overlay contamination maps, demographic data, and hydrographic networks develops the systemic thinking essential for a holistic approach to contaminated sites.
- **Engagement through gamification** - using gamification elements can increase motivation, transforming dry tasks - such as legislative compliance analysis or environmental auditing - into engaging learning experiences.
- **Real-time regulatory updates** - digital platforms allow for the instantaneous integration of new EU standards (such as the *Industrial Emissions Directive* or the *EU Soil Strategy*), ensuring training remains synchronized with administrative and technical realities.

A major pedagogical advantage is objective and continuous assessment. CAI platforms can monitor every step of the user during a site management simulation, providing immediate feedback and detailed analysis of acquired competencies.

This monitoring transforms assessment from a mere grade into a tool for diagnosis and educational progress. Introducing CAI into the integrated management of contaminated sites (IMCS) represents a pedagogical paradigm shift. It responds to the need for forming experts capable of managing environmental complexity through solid digital competencies, critical thinking, and strategic simulation capabilities.

2. Current State of Knowledge and Literature Review: The Convergence of E-Learning and Environmental Remediation

The evolution of specialized literature in the field of contaminated sites has undergone a visible transition, moving from purely technical studies on adsorption processes or chemical oxidation to complex analyses of decision support systems, even for risk-based management [6, 7]. Recent research highlights that the primary barrier to implementing integrated management is not a lack of technology, but rather a deficit in transdisciplinary competencies. Foundational works indicate that numerical modeling of pollutant transport represents the gold standard in risk assessment; however, the pedagogy behind these models often remains opaque to non-specialists.

Research in the field of CAI has demonstrated that the use of interactive computer simulations (ICS) significantly reduces the retention time of abstract concepts, such as hydrodynamic dispersion or in-situ biodegradation. Comparative studies between control groups (traditional instruction) and experimental groups (CAI-based) in environmental engineering reveal up to a 40% increase in the ability to solve unforeseen field problems, from regulation and mapping exposure to priority treatment, and remediation strategies [8-10]. This environmental digital literacy is now recognized as an essential meta-competency in the curricula of prestigious universities.

A significant segment of recent literature explores the use of Virtual Reality (VR) and Augmented Reality (AR) as extensions of CAI. These technologies allow the learner to be immersed in a living contaminated site, where monitoring data from sensors is projected in real-time over the visual environment. While promising, these approaches raise questions regarding instructional design: *How can we prevent cognitive overload when a site manager is simultaneously exposed to geochemical data, budgetary constraints, and legislative pressures within a virtual environment?*

The methodology proposed for this article is based on a mixed model, integrating the quantitative analysis of technical efficiency with the qualitative evaluation of the learning process. The starting point is the site management systemic architecture (SMSA), which is transposed into a digital training environment. The research is structured across 3 methodological pillars, as follows:

- **Data modeling** - in the first phase, real datasets from decommissioned industrial sites are utilized. These data (e.g., *heavy metal concentrations, hydrogeological parameters, and industrial activity history*) are processed to create the geometry of the problem; the methodology involves using spatial interpolation algorithms to generate contamination maps that serve as interactive teaching material within the CAI platform.
- **Instructional scenario design** - the second phase applies the ADDIE model (Analysis, Design, Development, Implementation, Evaluation) adapted for environmental engineering; in this context, decision trees are constructed where each user choice (e.g., *choosing a permeable reactive barrier instead of excavation*) triggers a simulation of the cost-benefit evolution and long-term residual impact. This method allows for the testing of management hypotheses within a sandbox structure.
- **Evaluation and validation** - the third pillar uses dual Key Performance Indicators (KPIs). On one hand, the accuracy of the technical solution proposed by the learner is measured (e.g., *reaching threshold values for pollutants within a given timeframe*). On the other hand, the user experience is evaluated through Likert-scale questionnaires and think-aloud protocols to determine the extent to which the CAI interface facilitated the understanding of complex environmental phenomena.

An innovative aspect of this methodology is the introduction of instructional life cycle analysis (ILCA). This evaluates not only the immediate success of a training session but also the sustainability of the competencies acquired over time. The goal is to observe whether specialists trained through CAI manifest greater decisional resilience in the face of real-world accidental pollution scenarios compared to those trained through classical methods.

The methodological framework is validated through a series of expert-review iterations, where senior environmental protection specialists and instructional design experts audit the coherence between learning objectives and the technical complexity of the simulations. This rigorous approach ensures that the CAI platform is not only a visualization tool but a robust educational ecosystem capable of generating authentic expertise in integrated environmental management.

3. Development of a Conceptual Reference Framework and Generation of Sustainable Work Scenario Proposals

3.1 From perception to phenomenological understanding (cognitive or input level)

The cognitive level constitutes the foundation upon which the entire expertise is built. In the management of contaminated sites, the primary barrier is the invisibility of the phenomenon; pollutants migrate through opaque media (*soil, rock, aquifers*). The role of CAI at this level is to provide ontological transparency. By utilizing advanced data visualization, the platform transforms spreadsheets containing thousands of concentrations into intuitive 3D models. This stage is not only about viewing, but about pattern recognition.

Pedagogically, this level is grounded in cognitive load theory; the specialist learns to decode the signature of a pollution event. For instance, understanding how a dense non-aqueous phase liquid accumulates at the base of an aquifer on an impermeable layer requires a spatial representation that no theoretical lecture can match. In this particular case, CAI facilitates assisted observational learning, where the user can virtually section the site along any plane to understand the relationship between lithology and pollutant distribution.

3.2 Mastering models and simulation of interventions (operative or process level)

The transition to the operative level marks the transformation of the learner from a passive observer into an active agent. At this stage, the integration of MODFLOW and PHREEQC becomes essential. The conceptual framework proposes that CAI functions as a virtual testing laboratory. The specialist does not merely run a model but learns to calibrate it.

This stage is critical for demystifying the software; the user understands that a model's output depends strictly on the quality of the input assumptions (the garbage-in, garbage-out principle). The primary pedagogical valence of this level is iterative experimental learning. Within a CAI environment, the specialist can simulate, for example, in-situ chemical oxidation; the user manipulates process variables: *oxidant dosage, the number of injection points, and the radius of influence*. If the model shows a concentration rebound, the learner must analyze desorption processes from the soil matrix. This direct interaction with transport and reaction mechanisms transforms theoretical biochemical knowledge into applicable technical competencies.

3.3 Synthesis and multi-criteria decision-making (strategic or output level)

The strategic level represents the apex of the triad, where environmental engineering intersects with project management; at this stage, CAI platforms no longer evaluate if the pollutant was removed, but how it was removed. The specialist is presented with multi-criteria decision analysis scenarios. In integrated management, success is not defined solely by reaching cleanup thresholds, but by optimizing a triple constraint triangle: public health protection, cost minimization, and the reduction of the ecological footprint of the intervention itself. From an instructional design perspective, this level employs the divergent scenarios method. The learner proposes a strategy, and the CAI system simulates the outcomes over a 20-year horizon. This temporal feedback is vital. The manager learns to think long-term, understanding, for example, that a low-cost solution today (such as monitored natural attenuation) could lead to immense legal costs in the future if the contaminant plume migrates under residential properties.

The proposed conceptual reference framework (CRF) architecture ensures an organic connection between the mentioned 3 levels through continuous feedback loops. What the learner discovers at the strategic level (e.g., *that a specific technology is cost-prohibitive*) forces a return to the operative level to optimize the technical design in MODFLOW, which, in turn, necessitates a re-evaluation of the initial cognitive data. This circularity mimics the adaptive management process utilized in large-scale environmental projects.

This CRF transforms CAI into a support system for the development of hybrid intelligence. The future manager of contaminated sites will not be a mere executor but an architect of solutions, capable of navigating fluidly between the rigor of differential transport equations and the pragmatism of economic decisions. CAI becomes the backbone of a new professional culture in environmental protection: one that is more transparent, precise, and, ultimately, more responsible toward our natural heritage.

3.4 Sustainable Work Scenarios for Computer-Assisted Instruction (CAI)

The following scenarios integrate the previously discussed software ecosystem into a coherent educational pathway, ranging from local technical issues to global environmental governance.

- 1) **Seepage assessment at a former fuel distribution station** (technical level)
 - Focus - identifying the contamination source and subsurface migration pathways;
 - CAI pedagogical task - utilizing 3D visualization software to overlay chemical analysis results onto a digital soil model; the future specialists learn to delineate the critical intervention zone through spatial interpolation, defining the soil volume for remediation.
- 2) **Integrated leachate management in a non-compliant landfill** (compliance level)
 - Focus - groundwater protection and liquid emission monitoring;
 - CAI pedagogical task - simulating the operation of a reverse osmosis treatment plant based on precipitation fluctuations; the user learns to balance storage volumes with treatment capacity, preventing accidental discharges into natural water bodies.
- 3) **Brownfield redevelopment into a residential area** (strategic level)
 - Focus - human health risk assessment and future resident safety;
 - CAI pedagogical task - running a risk calculation model to determine target cleanup concentrations; the concept of use-based safety is introduced, optimizing remediation costs according to the future land use.
- 4) **Aquifer remediation via permeable reactive barriers** (advanced level)
 - Focus - reactive transport processes and in-situ chemical kinetics;
 - CAI pedagogical task - integrating a PHREEQC module to predict the lifespan of the reactive material; the learner understands how chemical reactions can alter barrier permeability over time, requiring predictive maintenance.
- 5) **Transboundary water pollution management** (regional level)
 - Focus - water quality monitoring and early warning protocols;
 - CAI pedagogical task - operating a virtual crisis platform where IoT sensor data are used to model the propagation of a pollution wave between neighboring states; the task targets technical coordination and timely official notification.
- 6) **Ecodesign and life cycle assessment (LCA) for production streams** (systemic level)
 - Focus - reducing environmental impact from cradle to grave;
 - CAI pedagogical task - using LCA software to compare the carbon footprint and toxicity of two alternative materials; the learner understands the direct link between design decisions and the complexity of end-of-life waste.
- 7) **Circular economic systems in an industrial park** (integrated level)
 - Focus - industrial symbiosis and the recovery of waste as secondary raw materials;
 - CAI pedagogical task - managing a resource exchange network within a flow simulator; the user must maintain park profitability while minimizing final waste disposal by transforming outputs into inputs for neighboring facilities.
- 8) **Climate change impact on isolated historical sites** (global level)
 - Focus - resilience of remediation measures against extreme weather events;
 - CAI pedagogical task - simulating a major flood or sea-level rise scenario over a contaminated site; the task is to redesign protection systems to prevent pollutant remobilization under projected future climate conditions.
- 9) **Global governance of plastic waste and microplastics** (ethical and policy level)
 - Focus - international pollutant flows and extended producer responsibility;
 - CAI pedagogical task - a multiplayer simulation exercise where learners represent global actors that negotiate an environmental treaty.

3.5 Domain-specific software - the digital engineer's toolkit

To ensure Integrated Contaminated Site Management (ICSM) according to modern standards, the use of specialized software is no longer optional but a critical necessity (Fig. 2). These tools allow for the transformation of massive volumes of geochemical, hydrogeological, and topographic data into coherent decision-making models. From a CAI perspective, these platforms serve as digital laboratories where specialists can simulate interventions without real-world risks. The integration of these solutions into the training and operational process enables a holistic approach to the site. Instead of analyzing soil, water, and air in isolation, integrated software allows for the visualization of complex interactions between these media. This capacity for synthesis is essential for the Operative pillar of the competency triad, providing the user with the necessary leverage to manipulate environmental variables within a controlled framework.

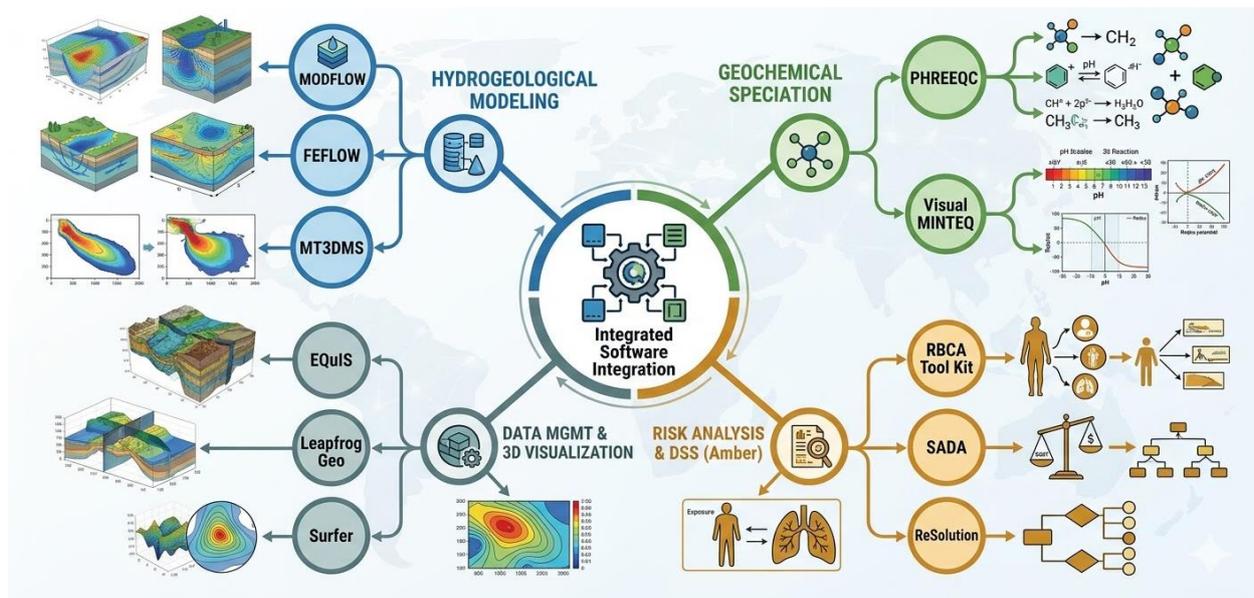


Fig. 2. Integrated workflow of CAI in CSMP - the digital toolset proposed (source: generated with Gemini 3 flash)

The integration of professional software tools within a CAI framework allows for the digital replication of complex environmental phenomena. These instruments are categorized into 4 functional groups:

- 1) **Hydrogeological and pollutant transport modeling** - serve as computational engines that predict the trajectory and velocity of contaminants within groundwater systems.
 - *MODFLOW (via groundwater modeling system)* - the global standard for groundwater flow simulation. In a CAI context, the user learns to define boundary conditions and observe how well pumping alters the direction of a contaminant plume.
 - *FEFLOW* - an advanced finite-element modeling tool, ideal for sites with complex or fractured geology. It enables the simulation of heat transport and chemical reactions coupled with fluid dynamics.
 - *MT3DMS* - often used as an extension for MODFLOW, this software is specifically dedicated to chemical species transport, allowing for the calculation of advection, dispersion, and adsorption/decay reactions.
- 2) **Geochemical and speciation modeling** - essential digital tools for understanding the chemical state and mobility of a pollutant based on environmental parameters such as pH and redox potential.
 - *PHREEQC* - a versatile geochemical calculation tool. Learners can simulate how the injection of an oxidizing agent interacts not only with the target pollutant but also with native soil minerals.
 - *Visual MINTEQ* - used to determine chemical equilibrium in aqueous solutions; it is vital for designing leachate treatment plants or managing acid mine drainage.

- 3) **Risk analysis and decision support systems** - these programs bridge the gap to the strategic pillar, evaluating impacts on human health and remediation costs.
 - *RBCA (risk-based corrective action) tool kit* - assists site managers in determining if contamination requires immediate intervention or if the human health risk is acceptable based on exposure scenarios (inhalation, ingestion).
 - *SADA (spatial analysis and decision assistance)* - freeware that integrates GIS, geostatistics, and risk analysis modules, ideal for training students in visualizing data uncertainty.
 - *ReSolution* - dedicated to optimizing remediation strategies, allowing for cost comparisons between different technologies throughout the project's life cycle.
- 4) **Data management and 3D visualization** - integrated management requires a digital memory of the site, where thousands of data points are logically organized.
 - *EQulS (EarthSoft)* - the world's most widely used environmental data management system, ensuring data integrity from tablet-based field collection to regulatory reporting.
 - *Leapfrog Geo/Hydro* - enables the creation of highly dynamic 3D geological models. Pedagogically, it is revolutionary as it allows for instantaneous cross-sectional slicing, facilitating the understanding of subsurface structures.
 - *Surfer (Golden Software)* - a geostatistical tool used for generating isoconcentration maps. It is often the first software a learner interacts with to visualize the extent of a pollution plume.

The value of these software solutions in the IMCS increases exponentially when they are used in combination. For instance, a learner can extract raw data from an EQulS database, construct the geological model in Leapfrog, run the hydraulic simulation in MODFLOW, and finally evaluate the community risk using RBCA (Risk-Based Corrective Action). This interoperability represents the "holy grail" of integrated contaminated site management. From an educational perspective, the task of CAI is not to teach every single button of each program, but to train the specialist on how to transfer information between these platforms to ultimately achieve a faithful representation of field reality. The use of software enables "what-if" analysis; the environmental manager can simulate extreme climate scenarios and observe in real-time how site risks are redistributed.

This predictive capability transforms contaminated site management from a reactive activity into a proactive and resilient one. Dedicated software tools represent the backbone upon which modern integrated management rests. Without them, decisions would remain based on intuition or dangerous simplifications. Their integration into the CAI pathway ensures that the next generation of experts will possess not only theoretical knowledge but also the practical ability to navigate the digital complexity of environmental protection.

4. Strategic Perspectives and Best Practices for CAI-CSM Competency Assessment

The transition to a circular economy in Romania requires a structural reform in environmental engineering education, moving from memorizing technological flows to continuous systemic optimization. Assessment mediated by CAI offers a dynamic perspective permanently updated to reflect EU legislation and local socio-economic realities.

- 1) **Transition to performance analytics** via:
 - *From testing to tracking* - shift from traditional multiple-choice testing to a system based on performance analytics.
 - *Granular monitoring* - record the student's entire decision-making trajectory to identify the exact moment a technical rationale becomes suboptimal or non-compliant.
 - *Integrated matrix* - utilizes the ICAM to divide performance into technical accuracy, regulatory compliance, and sustainability.
 - *Visual feedback* - provides interactive rubrics that offer students immediate feedback via radar charts upon task completion.
- 2) **Key digital metrics for engineering excellence** via:
 - *Modeling fidelity index* - measures the proximity of student simulations to real-world data from certified environmental reports.

- *Algorithmic efficiency* - evaluate the ability to select the most cost-effective technological flows to achieve mandatory recycling targets.
 - *Anomaly response time* - test the speed and accuracy of interventions during simulated environmental incidents, such as methane emission limit exceedances.
 - *Problem-based scenarios* - use what-if challenges and data noise to force students to re-evaluate and re-adapt management strategies.
- 3) **Professional deliverables and industry readiness** via:
- *Task-centered instruction* - ensure each CAI module culminates in a professional-grade technical document or digital model.
 - *Software interoperability* - assesses the student's ability to correlate input parameters across suites like SimaPro, ArcGIS, and STAN.
 - *Digital portfolios* - foster the creation of a digital project portfolio that certifies the graduate's ability to operate complex IWM tools.
 - *Employability advantage* - use LCA models and GIS risk maps as powerful tools for students to gain a competitive edge in the job market.
- 4) **Ethical and strategic evaluation** via:
- *Temporal Perspectives* - use interactive digital case studies to illustrate the long-term consequences of illegal dumping, which traditional textbooks cannot convey.
 - *Corporate Social Responsibility* - utilize virtual environments to foster CSR skills by presenting ethical dilemmas between low-cost and sustainable solutions.
 - *Strategic capstone* - replace simple written exams with the defense of a comprehensive waste management master plan, fully optimized through CAI.
 - *Smart city integration* - evaluate the configuration of IoT/AI networks for real-time waste monitoring and predictive management.

Table 1: Comparative synthesis related to traditional vs. CAI-enhanced instruction in CSM

Instructional factor	Traditional scenario (classic)	CAI-enhanced scenario (Industry 4.0)
1. Knowledge acquisition	Passive, lecture-based; focused on memorizing static remediation standards and protocols	Active, constructivist; based on navigating complex, high-volume data ecosystems
2. Problem-solving logic	Linear and theoretical; limited to simplified textbook examples with predictable outcomes	Non-linear and systemic; utilizing what-if analyses to anticipate climate change impacts
3. Modeling & simulation	Abstract conceptualization; inability to visualize subsurface contaminant migration in real-time	Digital Twins and 3D modeling; real-time visualization of plume dynamics and remediation efficacy
4. Technical tooling	Manual calculations; reliance on static maps and historical reports	Software-mediated (GIS, MODFLOW, SimaPro); integration of IoT data for site monitoring
5. Risk management	Purely theoretical discussion of safety and environmental hazards	Immersive simulations; testing intervention strategies in risk-free, high-fidelity virtual environments
6. Feedback mechanism	Delayed (after grading); often disconnected from the active decision-making phase	Real-time, iterative feedback; immediate correction of design flaws through algorithmic validation
7. Competency assessment	Static, based on the final report's technical correctness at a specific point in time	Dynamic, assessment of the entire decision-making trajectory and adaptive resilience
8. Learning outcome	Theoretical expert with fragmented knowledge of site management components	Decisional strategist capable of transforming massive data into coherent, actionable models

5. Conclusions

The introduction of CAI into the IMCS marks a fundamental pedagogical paradigm shift, transitioning from a passive information flow to an interactive and adaptive experience. This approach addresses the high technical and decisional complexity of contemporary environmental engineering, providing future specialists with the capacity to operate within a landscape marked by uncertainty. By utilizing specialized software platforms, invisible physico-chemical processes become transparent through intuitive 3D simulations and models.

The proposed CRF is built upon a triad of digital competencies - cognitive, operative, and strategic - designed to guide the learner from recognizing pollution patterns to calibrating numerical models and making strategic decisions. Utilizing computational engines such as MODFLOW or PHREEQC allows for the testing of remediation hypotheses in a controlled sandbox environment, eliminating the ecological and financial risks associated with real-world errors. The interoperable integration of modeling, risk analysis, and visualization tools represents the holy grail of integrated management, transforming massive volumes of data into coherent decision-making models. This methodology develops systemic thinking and decisional resilience, preparing experts to anticipate climate change impacts through what-if analyses. The future of environmental expertise depends on the adoption of these technology-mediated, constructivist learning models that merge scientific rigor with decisional pragmatism for a responsible protection of our natural heritage.

References

- [1] Swartjes, Frank A. "Introduction to Contaminated Site Management", pp 3–89. In: Swartjes, F. (ed.). *Dealing with Contaminated Sites*. Dordrecht, Springer, 2011. 10.1007/978-90-481-9757-6_1.
- [2] Dupuis, Johann, and Peter Knoepfel. *The Politics of Contaminated Sites Management*. Cham, Springer, 2015. 10.1007/978-3-319-11307-4.
- [3] Vidojević, Dragana, Nemanja Jevtić, Aleksandra Tomic, and Bozidar Djokic. "Improved management of contaminated sites in Serbia." Paper presented at International Conference on Contaminated Sites 2020 (ICCS 2020), Trnava, Slovak Republic, June 10–12, 2020 (initial date, postponed).
- [4] Yu, Jingjing, Tian Liang, Huilong Luo, Panpan Wang, Bin Yang, Lina Wang, and Fasheng Li. "Case Analysis and Environmental Management Significance of Contaminated Site Reuse in China from 2011 to 2021." *Research of Environmental Sciences* 35, no. 5 (2022): 1110-1119. 10.13198/j.issn.1001-6929.2022.02.03.
- [5] Samlani, Nouha, Cristina Deperon Maluf, Reginaldo Bertolo, and Tannaz Pak. *A New Data-Driven Framework for Operationalising Complexity in Contaminated-Site Management*. Preprint article, 2026. 10.2139/ssrn.6349411.
- [6] Marcomini, Antonio, Glenn Walter Suter II, and Andrea Critto. *Decision Support Systems for Risk-Based Management of Contaminated Sites*. 1st edition. New York, Springer, 2009. 10.1007/978-0-387-09722-0.
- [7] Agostini, Paola, Lisa Pizzol, Andrea Critto, Marco D'Alessandro, Alex Zabeo, and Antonio Marcomini. "Regional risk assessment for contaminated sites Part 3: Spatial decision support system." *Environment International* 48 (2012): 121-32. 10.1016/j.envint.2012.07.005.
- [8] Litauriya, Disha. "From Regulation to Remediation: Strengthening Rule of Law in the Governance of Pollution Affected and Contaminated Sites in India." *International Journal of Research and Analytical Reviews* 6, no. 12 (2025): 5315-5322. 10.55248/gengpi.06.1225.4222.
- [9] Vacca, Daniela, Enrico Olla, Giovanna Pala, Stefano Tersigni, and Luigi Minerba. "An experimental approach to mapping exposure in contaminated sites." *Rivista Italiana di Economia Demografia e Statistica* 80, no. 3 (2026): 273-284. 10.71014/sieds.v80i3.459.
- [10] Trobec, Tajan, Barbara Lampič, Blaž Repe, Katja Vintar Mally, Nejc Bobovnik, and Lea Rebernik. "A Data-driven Approach to Assess the Need for Priority Treatment of Potentially Contaminated Sites (PCSs) in Slovenia." *European Journal of Geography* 17, no. 1 (2026): 72-92. 10.48088/ejg.t.tro.17.1.072.092.