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Distribution, Characterisation, and Reclamation of Waterlogged Soils: A Review

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Review Article

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Abstract

Waterlogged soils represent one of the most challenging constraints to global food security and sustainable land management, affecting an estimated 640 million hectares worldwide. This review synthesises current knowledge on the global distribution, paedogenic characterisation, and reclamation strategies of waterlogged

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soils. It examines geomorphological and climatic drivers of waterlogging across major agroecological zones, analyses soil morphological, physical, chemical, and biological characteristics under prolonged saturation, and critically evaluates established and emerging reclamation technologies. Evidence from over 150 peer-reviewed studies published between 1990 and 2024 was integrated. The findings indicate that waterlogging-induced anaerobic conditions trigger cascading redox reactions, including iron and manganese reduction, denitrification, and methanogenesis, which substantially alter nutrient cycling, soil structure, and microbial communities. Reclamation success depends on accurate diagnosis of the cause of waterlogging, integration of drainage engineering with biological and chemical amendments, and long-term monitoring. Future directions include precision drainage design, climate-adaptive management, and the use of remote sensing for large-scale waterlogging mapping. This review provides a reference for soil scientists, agronomists, and land-use planners managing waterlogged landscapes.

Keywords: Gleysols; subsurface drainage; land reclamation; hydric soils; anoxia; wetland management.

1. Introduction

Waterlogged soils are characterised by extended or permanent saturation of soil pores with water, resulting in oxygen deprivation and substantially altered biogeochemical processes. These soils constitute an important interface between terrestrial and aquatic ecosystems and occupy a sizeable portion of the Earth's terrestrial surface (Vepraskas & Craft, 2016). Between 570 and 700 million hectares of waterlogged and hydromorphic soils are estimated to exist worldwide, accounting for 4–5% of the ice-free land surface (FAO, 2022). Waterlogged soils are typically low in oxygen (O_2), whereas plant roots require oxygen for respiration, nutrient acquisition, and the prevention of ion toxicities (Zhang et al., 2025).

The importance of wet soils for agriculture and the environment is considerable. Waterlogging is a major biophysical limitation that causes yield penalties of 20–80% in cereal crops in developing countries in South and Southeast Asia, Sub-Saharan Africa, and Latin America (Setter & Waters, 2003). Waterlogging refers to soil flooding and is one of the abiotic stresses associated with flooding. It occurs when water, derived from rainfall or flooding, accumulates above the soil layer and exceeds the rate of surface drainage and evapotranspiration (Modgil & Talekar, 2024). A major reason for increased flooding or waterlogging is the increasing frequency of extreme precipitation events and consecutive wet days (Kaur et al., 2020). This reduces metabolic capacity, significantly decreases root growth, weakens absorptive capacity, and affects nutrient uptake by plants (Luo et al., 2024). In addition to acting as carbon sinks and reservoirs of biodiversity, these soils also regulate hydrological cycles. However, when waterlogging is caused by human activity, such as poor land grading or inadequate irrigation management, it constitutes a form of land degradation that requires timely restoration (Oldeman et al., 1990; Ghassemi et al., 1995).

Since the foundational work of Ponnamperuma (1972), who systematically described the electrochemical alterations accompanying soil submergence, scientific understanding of wet soils has advanced substantially. Soil morphological diagnosis (Vepraskas, 1992), hydrological modelling (Skaggs et al., 1994), remote sensing-based mapping (Bartsch et al., 2012), and integrated reclamation technology (Nijland et al., 2005; Ritzema, 2016) have advanced in the subsequent decades. Despite these advances, there remains a need for a comprehensive global synthesis that examines distribution patterns, diagnostic characterisation, and reclamation effectiveness.

This review aims to: (1) describe the global distribution of waterlogged soils and their climatic-geomorphological drivers; (2) characterise the physical, chemical, and biological properties of waterlogged soils; (3) examine diagnostic criteria and classification systems; and (4) critically evaluate reclamation strategies and their agronomic and environmental outcomes. A total of over 150 peer-reviewed publications, FAO reports, and international soil survey data published between 1990 and 2024 were reviewed. Special attention is given to integrating knowledge across soil taxonomy frameworks (WRB and USDA Soil Taxonomy) and major global agroecological zones.

1.1 Scope and Objectives

This review covers both naturally occurring hydromorphic soils and artificially waterlogged agricultural areas in mineral and organic soils across temperate, tropical, and arid/semi-arid zones. Despite their similarities, coastal wetlands and tidal marshes are discussed only in relation to acid sulphate soils and tidal drainage. Submerged aquatic soils beneath permanent water bodies are not the main focus of the review.

2. Global Distribution of Waterlogged Soils

2.1 Extent and Geographic Patterns

The distribution of wet soils is fundamentally governed by the balance between water inputs (precipitation, irrigation, and groundwater recharge) and outputs (evapotranspiration, surface runoff, and deep drainage). According to FAO's 2022 projection, 640 million hectares of soils worldwide experience periodic or persistent waterlogging, with the tropics and subtropics accounting for about 350 million hectares. The spatial pattern of occurrence shows strong continental and latitudinal gradients, with the largest areas found in humid tropical lowlands, boreal peatlands, and irrigated river basins (Kottek et al., 2006).

Table 1 summarises the estimated global distribution of waterlogged soils by major region, based on the FAO Global Soil Map, the GLWD (Global Lakes and Wetlands Database), and regional land surveys (Lehner & Döll, 2004; FAO, 2014).

Table 1. Global distribution of waterlogged soils by major geographic region. Data compiled from FAO (2022), Lehner & Döll (2004), and IGBP-DIS (1999)

Region	Area (M ha)	% Global Total	Dominant Type	Primary Cause
Asia (South & SE)	~220	~35%	Paddy/Gleysol	Monsoon + Topography
Sub-Saharan Africa	~110	~17%	Vertisol/Gleysol	Seasonal flooding
South America	~90	~14%	Histosol/Gleysol	High rainfall + clay
Europe	~60	~9%	Gleysol/Planosol	Low gradient + glacial till
North America	~80	~13%	Histosol/Hydric	Glacial landforms
Australia & Pacific	~35	~5%	Vertisol/Solonchak	Seasonal inundation
Middle East & Others	~45	~7%	Planosol/Solonetz	Irrigation waterlogging

2.2 Factors Controlling Waterlogging

Several interacting factors govern the distribution and intensity of soil waterlogging. These may be broadly classified as climatic, geomorphological, paedogenic, and anthropogenic drivers (Rengasamy, 2002).

2.2.1 Climatic Drivers

The primary climatic factor is the precipitation regime. Seasonal saturation can occur for three to six months each year in monsoonal climates, especially in the Indo-Gangetic Plains, Mekong Delta, and West African lowlands (Sahrawat, 2004). Waterlogging occurs in temperate oceanic regions, such as north-western Europe, when low-intensity rainfall persists and winter evapotranspiration is reduced. Snowmelt and the limited permeability of frozen or permafrost-affected subsoils are the main causes of waterlogging in boreal regions (Vitt et al., 2000).

2.2.2 Geomorphological Drivers

Waterlogging is strongly influenced by topographic position. Water accumulates in low-lying regions, floodplains, river terraces, and internal drainage basins because of lateral flow, flooding, and restricted gravitational drainage. Pans in semi-arid savanna soils and gilgai microrelief depressions in Vertisol-dominated landscapes produce localised waterlogging that sustains specialised vegetation communities (Tiner, 2016). Waterlogging and secondary salinisation occur where saline groundwater rises under excessive irrigation because of continental-scale drainage endorheism, as observed in the Murray-Darling lowlands and the Chad Basin (Ghassemi et al., 1995).

2.2.3 Paedogenic Drivers

Soil texture and structure largely determine hydraulic conductivity and, therefore, susceptibility to waterlogging. Heavy-textured soils (clays and clay loams with >40% clay content) and soils with well-developed argillic or fragipan horizons effectively impede vertical water movement, promoting perched water tables (IUSS Working Group WRB, 2006). Smectitic and vertic clays, dominant in tropical black soils, exhibit high shrink-swell potential and form slickensides, but their seasonal cracking permits episodic drainage. Histosols, dominated by organic matter, have enormous water-holding capacity but low unsaturated hydraulic conductivity when saturated (Boelter, 1969).

2.2.4 Anthropogenic Drivers

The main anthropogenic causes of waterlogging include over-irrigation, inadequate drainage systems, evapotranspiration loss from deforestation, and improper land levelling. Pakistan's Indus Basin provides a historical case study, where unlined canal irrigation without drainage caused salinity and waterlogging on about 12 million hectares by the 1960s (Qureshi et al., 2010). Similar issues have been reported in the Po Plain (Italy), the Nile Delta (Egypt), and the Aral Sea basin (Central Asia). These examples show that agricultural waterlogging is both a biophysical and a socio-technical issue.

2.3 Remote Sensing and GIS Mapping

Advances in satellite-based Earth observation have transformed the mapping of waterlogged soils at regional and global scales. The Global Surface Water Explorer (Pekel et al., 2016), MODIS-derived inundation products (Prigent et al., 2007), and Sentinel-1 SAR imagery now provide near-real-time detection of surface waterlogging. Passive microwave radiometers can detect sub-canopy inundation in tropical forests. Integrating remote sensing with digital elevation models (DEMs) and soil property databases enables predictive mapping of waterlogging susceptibility at 30–90 m resolution (Bartsch et al., 2012). Machine learning approaches, including random forests and support vector machines, have recently improved classification accuracy to >85% for hydromorphic soil identification in multi-temporal Landsat composites.

3. Characterisation of Waterlogged Soils

Characterisation of waterlogged soils spans morphological, physical, chemical, and biological dimensions. The transformations induced by waterlogging represent a cascade of interlinked processes that collectively define the diagnostic properties recognised in modern soil classification systems (Fiedler & Sommer, 2004).

3.1 Morphological Characteristics

The visual and tactile properties of waterlogged soils provide valuable diagnostic information through field examination. The most distinctive morphological features include gleying, mottles (redoximorphic features), and organic matter accumulation (Vepraskas, 1992).

3.1.1 Gleying

The term "gleying" describes the blue-grey or greenish hue of soil that results from the anaerobic conversion of ferric iron (Fe^{3+}) to ferrous iron (Fe^{2+}). Ferrous iron is mobilised in the soil solution and has characteristic Munsell colour values of 5Y, 5BG, or 5GY with low chroma (<2). Under extended saturation, it may precipitate as vivianite ($Fe_3(PO_4)_2 \cdot 8H_2O$) or siderite ($FeCO_3$). Gleying is a required diagnostic characteristic for Gleysols in the WRB and Aquic suborders in USDA Soil Taxonomy (IUSS Working Group WRB, 2022). The depth at which gleying begins is used to infer the average water table position over decadal periods.

3.1.2 Redoximorphic Features (Mottles)

Mottles represent zones of localised oxidation (orange to reddish-brown) and reduction (grey) within the soil matrix, and may indicate fluctuating water tables or preferential oxygen flow along root channels and macropores. Formally known as redoximorphic concentrations and depletions, these characteristics develop over years to decades and persist even after drainage has improved (Vepraskas & Faulkner, 2000). Their colour, quantity, and vertical distribution are used to reconstruct past water table dynamics and guide drainage design.

3.2 Physical Characteristics

Prolonged waterlogging alters soil physical properties through aggregate disruption, pore clogging, and altered bulk density. The major physical changes are summarised alongside chemical changes in Table 2.

Table 2. Comparative physicochemical properties of well-drained versus waterlogged soils and their agronomic/ecological consequences. Values represent typical ranges; actual values vary by soil type and duration of saturation (Ponnamperuma, 1972; Reddy & DeLaune, 2008)

Property	Well-Drained Soil	Waterlogged Soil	Ecological/Agronomic Impact
Soil Eh (mV)	+200 to +700	-200 to +200	Controls redox reactions; Fe/Mn reduction
Soil pH	5.5–7.5	6.5–7.5 (neutralisation)	Nutrient availability shifts
O2 diffusion rate	>40 µg cm^{-2} min^{-1}	<10 µg cm^{-2} min^{-1}	Root anoxia, aerobic microbial death
CO2 concentration	0.03–0.3%	5–20%	Root respiration inhibition
Methane (CH4)	Absent/trace	High (0.1–5 µmol/L)	Greenhouse gas emission
Available N (NO3^{-})	Moderate–high	Low (denitrification)	Nitrogen loss, crop yield reduction
Available Fe2+	Negligible	Very high (toxic)	Iron toxicity in crops
Available Mn2+	Low	High	Manganese toxicity
Bulk Density (g/cm^3)	1.2–1.6	0.8–1.3	Compaction and structure loss
Hydraulic conductivity	Moderate–high	Very low	Poor drainage perpetuates flooding

Waterlogging causes a 15–40% reduction in macroporosity due to swelling of clay particles, microbial gas production (CO2, CH4), and dispersal of colloids upon wetting (Horn & Smucker, 2005). Hydraulic conductivity may decrease by one to three orders of magnitude compared with drained states. Surface soil compaction, which is paradoxically common in waterlogged arable soils because of machinery traffic on wet ground, further reduces infiltration rates and creates self-reinforcing waterlogging cycles.

3.3 Chemical Characteristics and Redox Biogeochemistry

The most profound transformations in waterlogged soils are chemical. When soil pores are water-saturated, diffusion of oxygen (O_2) into soil decreases to approximately 10^{-4} times its rate in air (Greenwood, 1961). Microbial respiration rapidly depletes residual O_2 within hours to days, establishing anaerobic conditions. Soil redox potential (Eh) then falls progressively as successive terminal electron acceptors are reduced in a thermodynamically predictable sequence (Ponnamperuma, 1972; Reddy & DeLaune, 2008):

> O_2 reduction (+600 to +400 mV) → NO_3^- denitrification (+400 to +200 mV) → MnO_2 reduction (+400 to +200 mV) → $Fe(OH)_3$ reduction (+200 to -100 mV) → SO_4^{2-} reduction (-100 to -200 mV) → CH_4 production (-200 to -300 mV)

Each of these reductive steps has significant consequences for nutrient availability, toxicity, and greenhouse gas emissions. Denitrification leads to substantial losses of soil nitrogen (N_2O and N_2 gas), reducing fertiliser use efficiency. Iron and manganese reduction release soluble Fe^{2+} and Mn^{2+} into the rhizosphere at concentrations that may be toxic to crops; submergence injury in rice, for example, is often exacerbated by high Fe^{2+} (Sahrawat, 2004). Sulphate reduction generates hydrogen sulphide (H_2S), which is directly phytotoxic and contributes to bronzing disease in lowland rice (IRRI, 2015). Methanogenesis under prolonged saturation makes rice paddies and peatlands significant sources of atmospheric methane, contributing approximately 10–15% of global CH_4 emissions (Kirschke et al., 2013).

3.4 Biological Characteristics

Soil microbial populations are significantly altered by waterlogging, which inhibits aerobic decomposers and promotes anaerobic fermenters, iron/sulphate reducers, and methanogens. Soil enzyme activity is markedly decreased, especially oxidase enzymes (laccase and peroxidase), which slows the decomposition of organic matter and leads to the accumulation of partially decomposed organic molecules, including peat formation in continuously wet systems (Freeman et al., 2001). The soil food web also changes: anaerobic protozoans and nematode populations shift into functional guilds adapted to low-oxygen conditions, whereas earthworm activity decreases sharply within 24 to 48 hours of saturation.

Root responses to waterlogging include the formation of aerenchyma (gas-filled cortical tissue), adventitious roots, and hypertrophied lenticels, enabling oxygen transport from shoots to root tips in tolerant species (Armstrong et al., 1994). Intolerant crops exhibit ethylene-mediated stomatal closure, leaf epinasty, root death, and, ultimately, whole-plant senescence when anaerobiosis persists beyond species-specific thresholds.

3.5 Classification and Diagnostic Criteria

Major soil classification systems address waterlogged soils through specific diagnostic horizons and properties. Table 3 presents the principal diagnostic features used to identify waterlogged soils under the World Reference Base (WRB) and USDA Soil Taxonomy frameworks.

Table 3. Diagnostic morphological features of waterlogged soils and their equivalents in the WRB (IUSS Working Group, 2022) and USDA Soil Taxonomy (Soil Survey Staff, 2022)

Diagnostic Feature	Observation	Soil Depth (cm)	Classification	WRB/USDA Equivalent
Gleying (blue-grey)	Ferrous iron reduction	0–100 cm	Gleysols	Aquents/Aquepts
Mottles (orange)	Fe/Mn oxidation zones	20–80 cm	Stagnosols	Fragiaquults
Plinthite	Hard iron concretions	40–100 cm	Plinthosols	Plinthaquults
Peat/Muck layer	Organic accumulation	0–40 cm	Histosols	Histosols (USDA)
Albic horizon	Bleached sandy layer	5–30 cm	Planosols	Argiaquolls
Sulfidic material	Sulfide smell (H2S)	20–80 cm	Thionic Gleysols	Sulfaquents

Under WRB 2022, Gleysols are the primary reference soil group for waterlogged soils, with qualifiers such as Thionic (sulfidic), Folic (peat-rich), and Stagnic (perched water table) modifying the base group. Histosols, defined by the presence of a histic horizon (>12–18% organic C, depending on clay content) deeper than 40 cm in the upper 80 cm, constitute a separate major group. In USDA Soil Taxonomy, waterlogged soils are distributed across multiple orders, including Histosols, Inceptisols (Aquepts), Entisols (Aquents), Mollisols (Aquolls), Alfisols (Aqualfs), and Ultisols (Aquults), with the 'Aquic' modifier denoting periodic saturation and reducing conditions (Soil Survey Staff, 2022).

4. Processes and Interactions in Waterlogged Soils

Understanding waterlogged soils requires appreciation of how physical, chemical, and biological processes interact across temporal scales from minutes (gas exchange) to millennia (peat formation). The schematic in Fig. 1 illustrates the key process chains initiated by waterlogging.

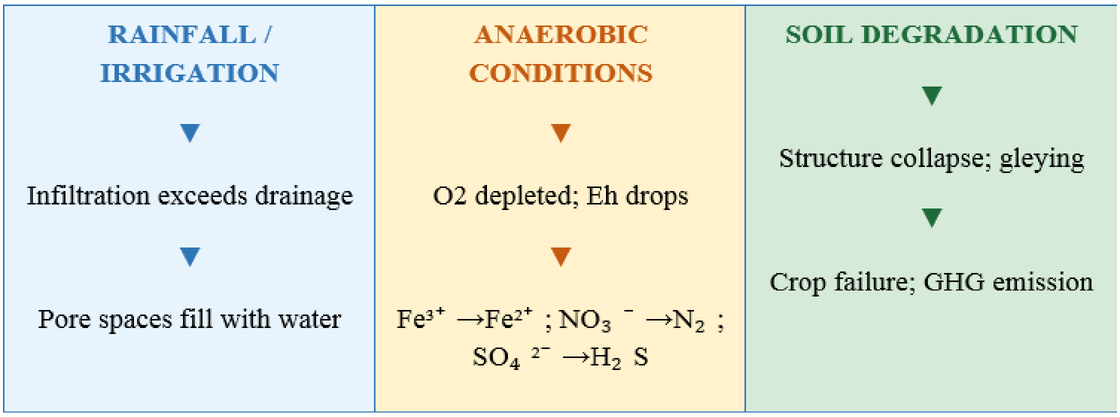

Fig. 1. Schematic overview of the cascade of processes initiated by soil waterlogging, from initial saturation through anaerobic transformations to soil degradation outcomes

4.1 Water Table Dynamics and Seasonal Patterns

Few wet soils remain consistently saturated throughout the year. The water table typically fluctuates seasonally, passing through periods of unsaturation (dry season, drainage) and saturation (recharge, monsoon). Long-term pedogenic trajectories are determined by cyclical oxidation-reduction pulses driven by these oscillations. Ponnamperuma (1972) described four phases of soil chemistry after submergence: (1) rapid Eh decline and pH equilibration; (2) peak reductive dissolution of Fe and Mn; (3) steady-state anaerobic conditions; and (4) re-oxidation and the formation of iron oxide nodules and concretions upon drainage. The length and frequency of these phases determine the type and appearance of redoximorphic characteristics.

4.2 Greenhouse Gas Emissions

Waterlogged soils are major global sources of CO_2, CH_4, and N_2O. The low decomposition rates under anaerobia, compared with aerobic decomposition, limit CO_2 emissions, but CH_4 emissions can be very significant, especially from northern peatlands (Blodau, 2002) and rice paddies (Neue, 1993). N2O emissions, which are mainly linked to nitrification-denitrification interfaces at the oxic-anoxic boundary, vary substantially depending on nitrogen inputs and drainage status (Saggar et al., 2013). Global estimates indicate that natural and managed waterlogged soils collectively contribute about 20–25% of total atmospheric CH_4. The climate-carbon feedbacks of tropical peat drainage are particularly concerning: draining 1 ha of peat forest releases an estimated 50–100 Mg C over the following ten years due to rapid oxidation (Page et al., 2011).

4.3 Nutrient Cycling

The nitrogen cycle is particularly disrupted by waterlogging. Nitrification ($NH_4^+ \rightarrow NO_3^-$) is an aerobic process that ceases under anaerobia, allowing ammonium to accumulate. Simultaneously, denitrification converts NO_3^- to N_2 and N_2O gases, creating a net nitrogen sink. This has important agronomic implications: urea-based fertilisers applied to waterlogged soils can experience >50% N loss through volatilisation and denitrification (Sahrawat, 2008). Phosphorus availability initially increases under anaerobic conditions due to reductive dissolution of Fe-P complexes (Reddy & DeLaune, 2008), potentially causing eutrophication of adjacent water bodies through P release from saturated sediments.

5. Reclamation of Waterlogged Soils

Reclamation aims to restore waterlogged soils to productive or ecologically functional states by removing excess water, improving soil aeration, and rehabilitating soil biological and chemical properties. A range of approaches exists, from engineering-intensive drainage to low-input biological methods. Effective reclamation requires accurate diagnosis of the cause and type of waterlogging, followed by the selection of context-appropriate strategies (Ritzema, 2016).

5.1 Diagnostic Framework for Reclamation Planning

Before implementing any reclamation measure, it is essential to determine whether waterlogging is caused by: (a) excess surface water accumulation (ponding); (b) a shallow, perched water table above an impermeable layer; (c) a shallow regional water table; or (d) lateral seepage from adjacent water bodies or irrigation canals (Nijland et al., 2005). Each cause requires a different drainage strategy. The diagnostic and decision flowchart (Fig. 2) provides a systematic framework for moving from field identification through laboratory analysis to reclamation implementation and monitoring.

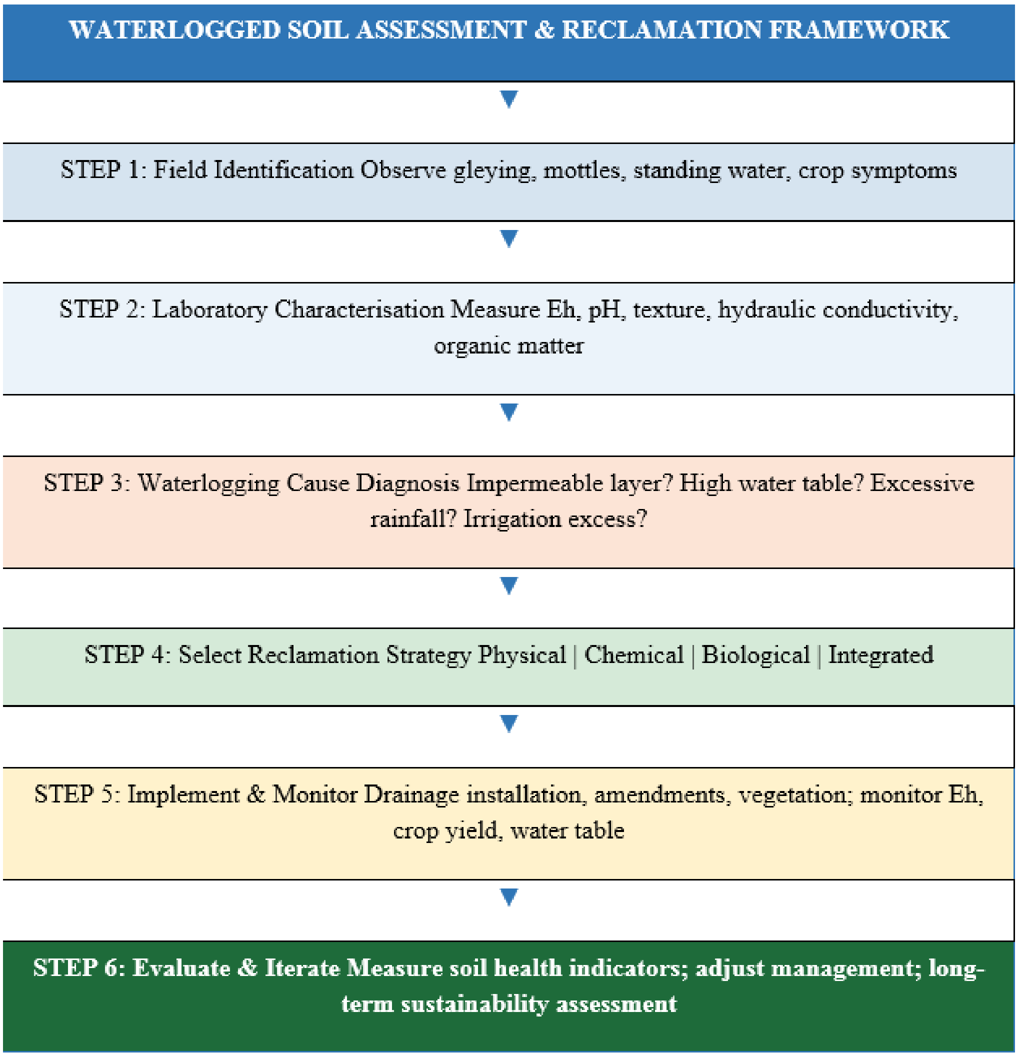

Fig. 2. Systematic decision flowchart for waterlogged soil assessment and reclamation planning, from initial field identification through monitoring and adaptive management

5.2 Physical and Engineering Methods

Engineering drainage remains the most widely applied reclamation approach for waterlogged agricultural soils. Table 4 compares major reclamation methods in terms of technique, effectiveness, cost, and suitability.

5.2.1 Surface Drainage

Surface drainage involves reshaping land to direct excess water into surface channels. Land smoothing and grading to achieve slopes of 0.1–0.3% are standard practices in lowland rice cultivation areas and subsistence farming systems in sub-Saharan Africa (Zhu et al., 2002). Open drains at 0.5–1.5 m depth can handle peak discharge events but require regular maintenance to remain effective. In paddy systems, controlled surface drainage is combined with bund management to regulate ponding depth for weed suppression while avoiding prolonged anoxia that is detrimental to non-rice crops.

Table 4. Comparison of major reclamation methods for waterlogged soils. Cost ranges are indicative; actual costs depend on site conditions, labour rates, and equipment availability (Ritzema, 2016; El-Sadek, 2007)

Method	Technique Details	Effectiveness	Cost (USD/ha)	Suitability
Open Ditch Drainage	Surface channels cut at 0.5–1.5 m depth	High (surface water)	$200–500	Flat terrain
Sub-surface Pipe Drain	Perforated PVC/clay tiles at 0.8–1.5 m	Very high	$800–2000	Agricultural land
Mole Drainage	Pulled cylindrical channel at 0.4–0.6 m	Moderate	$150–300	Clayey soils
Deep Ploughing/Subsoiling	Breaks impermeable hardpan layers	Moderate–high	$120–400	Hardpan soils
Raised Bed Cultivation	Elevated planting surface 20–50 cm	Moderate	$80–200	Smallholder farms
Biological Drainage	Deep-rooted trees (Eucalyptus, Poplar)	Low–Moderate	$50–150	Marginal lands
Gypsum Application	CaSO4 at 2–10 t/ha, improves structure	Moderate (salinity)	$200–600	Saline-sodic soils
Phytoremediation	Wetland plants (Phragmites, Typha)	Low–Moderate	$100–300	Contaminated soils
Electro-osmosis	Electrical gradient moves water	Experimental	$2000–5000	Peat/urban soils

5.2.2 Subsurface Drainage

Subsurface pipe drainage, using perforated PVC or clay tile pipes installed at 0.6–1.5 m depth and 10–80 m spacing, is the most effective method for controlling water table depth in agricultural soils. Design follows Hooghoudt's equation or the Ernst formula for steady-state drainage (Skaggs et al., 1994). In the Netherlands, the United States Corn Belt, and Punjab (India/Pakistan), large-scale subsurface drainage programmes have converted millions of hectares of hydromorphic soils to highly productive arable land. However, subsurface drainage is capital-intensive (USD 800–2000/ha) and may accelerate nitrate leaching to groundwater if it is not managed with controlled drainage structures (Skaggs et al., 1994).

5.2.3 Mole Drainage

Mole drainage involves pulling a cylindrical steel plug through soil at 0.4–0.6 m depth to create unlined channels that persist for 3–8 years in stable clay soils. It is much cheaper than pipe drainage and is widely used in temperate grassland and arable systems in the UK, Ireland, Australia, and New Zealand. Effectiveness is highest in soils with >40% clay content and stable ped structure; the method is unsuitable for sandy, organic, or very wet soils.

5.3 Chemical Amendments

Chemical approaches to reclamation target soil structural improvement, pH adjustment, or remediation of specific toxic compounds. Gypsum ($CaSO_4 \cdot 2H_2O$) applied at 2–10 t/ha is the primary amendment for sodic-waterlogged soils, where Na^+ dispersion of clay particles suppresses hydraulic conductivity. Calcium ions from gypsum displace sodium on cation exchange sites, flocculating clays and restoring macroporosity (Qadir et al., 2006). Lime application ($CaCO_3$ or CaO) corrects soil acidity in acid sulphate soils, where pyrite oxidation upon drainage releases sulphuric acid, lowers pH to <3.5, and mobilises toxic Al^{3+} and Fe^{2+} (Dent & Pons, 1995).

Organic matter amendments, including compost and biochar, have also shown promise in improving soil water regulation and microbial rehabilitation.

5.4 Biological and Agroecological Methods

Biological reclamation exploits plant and microbial processes to improve soil conditions. Deep-rooted trees such as *Eucalyptus camaldulensis* and *Populus spp.* can lower shallow water tables through high transpiration rates (biological drainage), achieving water table reductions of 0.5–1.5 m in suitable conditions (Heuperman, 1999). This approach is particularly relevant in peri-urban areas and for saline-waterlogged lands in South Asia. In Pakistan's Indus Basin, agroforestry with *Eucalyptus* achieved water table control comparable to tube-well drainage at 10–20% of the cost.

Phytoremediation using wetland macrophytes (*Phragmites australis*, *Typha latifolia*, *Scirpus spp.*) is employed on waterlogged soils contaminated with heavy metals or persistent organic pollutants. These plants accumulate contaminants in root and shoot biomass and, through root-mediated oxidation, create oxidised rhizosphere zones that immobilise Fe, Zn, and Pb (Vymazal, 2014). Constructed wetland systems based on this principle are now widely used for the treatment of agricultural runoff.

Green manuring with flood-tolerant legumes (*Sesbania* and *Astragalus*) improves nitrogen supply and organic matter content in waterlogged paddy soils between rice cycles (Ponnamperuma, 1984). The *Azolla-Anabaena* symbiosis, a pteridophyte-cyanobacteria N_2 fixation system, provides additional biological nitrogen in flooded rice systems, reducing fertiliser requirements by 25–40 kg N/ha.

5.5 Integrated and System Approaches

Modern reclamation increasingly adopts integrated approaches that combine drainage engineering with agronomic management, biological methods, and precision technology. Controlled drainage, using adjustable outlet structures to maintain water tables at specified depths, allows seasonal optimisation of drainage versus water conservation. This approach reduces nitrate leaching by 30–50% compared with free drainage while maintaining comparable crop yields. Precision agriculture tools, including soil moisture sensor networks, GPS-guided land levelling, and drone-based monitoring, are enabling more efficient and targeted reclamation interventions (Mulla, 2013).

6. Regional Case Studies

6.1 South Asia: Waterlogging in the Indo-Gangetic Plains

The Indo-Gangetic Plains spanning India, Pakistan, Bangladesh, and Nepal represent one of the world's most extensively waterlogged agricultural regions. An estimated 8.5 million hectares in Pakistan alone suffer from waterlogging and secondary salinity, primarily in the Indus Irrigation System (Qureshi et al., 2010). The SCARP (Salinity Control and Reclamation Project) programme, implemented between 1959 and 2002, installed over 13,000 public tube-wells and 50,000 km of surface drains, reclaiming approximately 3.8 million hectares. However, unsustainable groundwater pumping, inadequate maintenance, and political economy challenges have limited long-term success. Lessons include the need for farmer participation, integration of biological and engineering approaches, and cost-recovery mechanisms.

6.2 West Africa: Inland Valley Swamps

Inland valley swamps in West and Central Africa cover 23–31 million hectares and are major untapped resources for rice and vegetable production (Windmeijer & Andriesse, 1993). These are shallow, seasonally waterlogged depressions with gleyed soils and are often underlain by ironpan (plinthite). Traditional communities have developed indigenous water management systems, including bunds, diversions, and hand-dug drains, that partially control waterlogging. Large-scale investments in valley bottom development, including bunded paddy systems, small reservoirs, and drainage channels, have increased rice production but have also raised environmental concerns regarding biodiversity loss and downstream hydrology (Kiepe, 1995).

6.3 Europe: Netherlands Polders

The Netherlands represents a global benchmark in waterlogged soil reclamation, having converted large areas of peat and marine clay soils to productive agricultural land over centuries. The Dutch 'polder' system, comprising areas enclosed by dikes and continuously pumped to maintain artificially low water tables, sustains highly intensive dairy farming and horticulture. However, polder drainage has caused 2–5 m of surface subsidence in peat areas due to oxidation and compaction, creating permanent flood risk (Hooijer et al., 2012). Dutch policy now promotes 'peat meadow restoration' and 'paludiculture' (wet agriculture) as adaptive strategies that combine partial waterlogging with biomass production from wetland crops.

6.4 Tropical Peatlands: Southeast Asia

The peatlands of Sumatra, Kalimantan (Borneo), and Papua New Guinea store an estimated 69 Pg of carbon in tropical peat deposits of 1–20 m depth (Page et al., 2011). Drainage for oil palm and *Acacia* plantations beginning in the 1980s has converted millions of hectares of permanently waterlogged Histosols, releasing large quantities of CO_2 through peat decomposition and triggering severe peat fires in El Niño drought years. The 2015 Indonesian fire season emitted an estimated 1.75 Pg CO_2 equivalent, comparable to annual emissions of Japan (Huijnen et al., 2016). International REDD+ mechanisms and the Indonesia Peatland Restoration Agency (BRG) have been established to reverse drainage and restore peatland hydrology, demonstrating the global climate relevance of waterlogged soil management.

7. Future Directions and Challenges

7.1 Climate Change Impacts

The global distribution, severity, and seasonality of waterlogging will change due to climate change. Extended dry seasons and more intense rainfall episodes will intensify the hydrological cycle, increasing flash waterlogging in certain areas while decreasing chronic waterlogging in others (IPCC, 2021). Coastal lowland soils are at risk from sea level rise due to increased tidal inundation and saltwater intrusion, which can turn productive paddy soils into salt marshes or acid sulphate soils. According to Schuur et al. (2015), thawing permafrost in Arctic and subarctic regions is expected to create new, extensive wet areas with significant CH_4 emissions and rapid peat breakdown, which are positive climate feedbacks. Adaptation measures must anticipate these shifts in crop choices, land-use planning, and drainage design standards.

7.2 Remote Sensing and Digital Soil Mapping

The integration of satellite remote sensing, airborne geophysics (EM38 and electromagnetic induction), and digital soil mapping offers transformative potential for waterlogged soil monitoring. Time-series analysis of Sentinel-1 SAR imagery can detect seasonal flooding patterns at 10 m resolution globally, enabling near-real-time waterlogging alerts for farmers and land managers (Twele et al., 2016). The Global Soil Map project aims to provide 90 m resolution predictions of key soil hydraulic properties globally, enabling mechanistic modelling of waterlogging risk under future climate scenarios (Arrouays et al., 2014). Machine learning algorithms trained on global soil profile databases are increasingly capable of predicting waterlogging indicators, such as Eh and redox features, from remotely sensed spectral data.

7.3 Precision Drainage and Smart Water Management

"Smart drainage", the adaptive management of water tables in response to agricultural requirements, weather forecasts, and environmental goals, is made possible by the convergence of IoT (Internet of Things) sensors, real-time weather forecasting, and automated control systems (Skaggs et al., 1994). By optimising drainage timing, sensor networks that measure soil water potential, electrical conductivity, and soil gas concentrations can maximise yields while minimising energy use and environmental effects. Large-scale deployments of these technologies are already underway in the US Midwest, the Netherlands, and parts of China. As sensor costs decline, these technologies may be adapted to developing-country contexts.

7.4 Paludiculture and Wetland Ecosystem Services

There is increasing awareness that some soils are most useful when their wet state is preserved or restored for ecosystem functions, rather than reclaiming all wet soils for traditional agriculture. Paludiculture, the cultivation of wetland-adapted crops on wet organic soils, provides a route to sustainable land use that integrates carbon storage, biodiversity, and biomass production. In Europe, crops such as *Phragmites* (for biogas), *Typha* (for construction boards and insulation), and *Sphagnum* moss (for horticultural growing media) are being produced commercially. This strategy represents a significant paradigm shift from drainage and intensification to wetland stewardship.

7.5 Socioeconomic and Policy Dimensions

Technological solutions to waterlogging can achieve their full potential only when they are integrated into supportive institutional and socioeconomic frameworks. Investment in drainage infrastructure is discouraged by land tenure insecurity; smallholder farmers in flooded areas frequently lack access to the markets, credit, and extension services needed to benefit from reclamation investments (FAO, 2017). Water user associations for collective drainage management, payments for ecosystem services that recognise the water and carbon functions of wet soils, and the inclusion of waterlogging risk in national adaptation plans under the UNFCCC are necessary policy tools to support sustainable management. Transboundary waterlogging, which is common in shared river basins, necessitates international coordination systems that remain in their infancy in most regions.

8. Conclusion

Waterlogged soils are globally significant, covering ~640 million hectares across tropical, temperate, and boreal zones, with distribution controlled by the interplay of climate, geomorphology, pedology, and human land management. Waterlogging induces cascading chemical transformations following the thermodynamic sequence of electron acceptor reduction, from O_2 to CH_4, with major consequences for nutrient cycling, toxicity, and greenhouse gas emissions. Diagnostic characterisation using redoximorphic features, soil Eh measurements, and classification systems (WRB and USDA Soil Taxonomy) provides a robust framework for identifying and mapping waterlogged soils. Reclamation success requires accurate diagnosis of the cause of waterlogging, followed by the selection of appropriate measures from a spectrum ranging from subsurface pipe drainage to biological methods, with integrated approaches showing the highest long-term sustainability. Regional case studies from South Asia, West Africa, Europe, and Southeast Asia demonstrate both the transformative potential of drainage-based reclamation and its ecological risks, particularly in peatland contexts. Future advances in remote sensing, smart drainage technology, and paludiculture offer new paradigms for managing waterlogged soils in the context of climate change and sustainable development goals.

9. Limitations

This review depends on published studies, reports, and case-based evidence, and therefore inherits differences in scale, methods, terminology, and regional data availability. Quantitative comparisons across reclamation strategies are limited by variation in soil type, climate, drainage design, monitoring period, and management intensity. Some emerging technologies are discussed mainly from available evidence rather than long-term field validation.

10. Recommendation

Waterlogged soil management is located at the nexus of ecosystem protection, climate change mitigation, and food security. Interdisciplinary cooperation among soil scientists, hydrologists, ecologists, economists, and policymakers is needed to address the conflicts between agricultural productivity, carbon storage, and biodiversity in wet landscapes. In addition to identifying priority areas for future research and funding, this review provides a basis for such collaboration.

Declaration of AI Use

This manuscript was prepared through the combined contributions of all author(s), including contributions to the study design, data, content development, results, interpretation, and related scholarly work. The author(s) acknowledge the use of Grammarly and ChatGPT to assist with grammar checking, language refinement, reference formatting. These AI-assisted tools were not used as authors and did not replace the intellectual contributions or scholarly judgment of the author(s). All AI-assisted outputs, including content, references, and interpretations, were carefully reviewed, revised, verified, and approved by the author(s). The author(s) accept full responsibility for the accuracy, integrity, and final content of the manuscript.

Competing Interests

Authors have declared that they have no known competing financial interests OR non-financial interests OR personal relationships that could have appeared to influence the work reported in this paper.

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