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Before the Peat Burns: Reframing Indonesia's Peatland-Fire Governance from Reactive Suppression to Hydrological Prevention and Anticipatory Risk Management

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ABSTRACT

Indonesia's recurrent peatland fires are often approached through emergency-oriented interventions implemented after fire danger has already escalated, including firefighting, water bombing, weather modification, temporary task forces, and post-fire law enforcement. This qualitative literature review reassesses that response architecture through recent evidence on tropical peat hydrology, fire behaviour, restoration, early warning, governance, health, economics, and community participation. The synthesis indicates that peat-fire risk is produced well before ignition through interacting processes involving drainage, groundwater-table recession, peat desiccation, vegetation change, drought, anthropogenic ignition, and institutional fragmentation. Consequently, effective risk reduction requires shifting the principal intervention point upstream. Hydrological restoration, canal-network management, groundwater monitoring, climate and soil-moisture information, locally calibrated decision thresholds, permanent preparedness capacity, and community-compatible livelihood systems should operate continuously rather than only during severe dry seasons. Nevertheless, the evidence does not support replacing conventional suppression altogether: firefighting, water bombing, enforcement, and emergency operations remain indispensable for residual risk.

The article proposes a **Hydrological Safety Envelope–Anticipatory Governance Framework** integrating prevention, monitoring, trigger-based action, preparedness financing, suppression, recovery, and adaptive learning at the peat-hydrological-unit scale. The framework reframes peatland-fire policy from managing flames after ignition toward managing the ecological and institutional conditions that determine whether major fires occur.

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Introduction

Peatland fire as a pre-fire systems problem

Tropical peatlands are unusual terrestrial ecosystems because their ecological stability depends fundamentally on persistent waterlogging. Organic matter accumulates because oxygen-limited conditions slow decomposition, allowing peat layers and substantial carbon stores to develop over centuries to millennia. Once drainage networks lower groundwater levels, however, the ecological function of the system changes: previously waterlogged peat becomes aerated, oxidation accelerates, subsidence occurs, vegetation composition changes, and the combustible peat profile becomes progressively more vulnerable to drought and fire. Thus, peatland fire should not be interpreted solely as an ignition event; it is the terminal manifestation of a longer hydrological and land-use disturbance pathway. Recent radiocarbon-based evidence from Central Kalimantan further demonstrates that drainage and

subsequent burning can mobilise carbon that had remained stored for centuries or millennia [1-4].

This distinction matters because the physical behaviour of peat fires differs substantially from many above-ground vegetation fires. Once dry peat ignites, combustion can propagate beneath the surface as persistent smouldering, making visual detection, containment, and extinguishment difficult. Field measurements in Indonesia have documented both horizontal and vertical peat combustion, while experimental work confirms that suppression can require large quantities of water because water must penetrate the combustible peat matrix rather than merely extinguish surface flames. Models likewise show that water-table position, preceding dry conditions, and human ignition interact strongly in determining fire spread [5-7].

The societal consequences extend beyond the burned landscape. Peat combustion produces large quantities of particulate matter, greenhouse gases, and other atmospheric pollutants, creating transboundary haze, population exposure to air pollution, health burdens, ecological degradation, and economic disruption. Health research consistently associates severe haze episodes with meaningful public-health risks, although estimates differ

depending on exposure assumptions, epidemiological response functions, and geographic coverage. Economic analysis likewise indicates that reducing fire occurrence can yield benefits through avoided health impacts, reduced carbon emissions, and prevented land-cover losses [8-12]

These characteristics expose an important timing problem. If management attention intensifies only once smoke, hotspots, and active flames become visible, policy is intervening after several key risk-generating processes have already occurred. Water bombing, ground suppression, emergency mobilisation, and weather modification can all be necessary in a crisis ; the problem is not that these measures are intrinsically inappropriate. The problem arises when emergency instruments become the dominant architecture while upstream hydrological deterioration receives insufficient continuous management. Fire-management studies in Indonesia have repeatedly demonstrated the complexity of interventions and the importance of targeting both biophysical and social drivers rather than treating fires as isolated emergency events [13,14].

Recent evidence makes the upstream argument increasingly compelling. Across Indonesian peatlands, drainage density and land cover interact strongly with fire occurrence : drained peatlands in the Salmayenti et al. Study experienced annual mean hotspot densities up to thirteen times those found in peatlands without

canals. Restoration evaluations published in 2026 additionally indicate that canal blocking and pumped groundwater can reduce fire occurrence, although impacts vary considerably by ecosystem condition, climate, intervention type, spatial configuration, and year These findings support prevention while simultaneously warning against simplistic prescriptions The central argument of this article is therefore that [15,16,17].

Indonesia's Peatland-Fire Challenge is Simultaneously a Hydrological, Ecological, Social, and Institutional Timing Problem.

The practical implication is not “stop firefighting and build canal blocks.” Rather, fire suppression should become the final protective layer of a broader risk architecture whose upstream components continuously manage hydrology, detect deterioration, activate predefined preparedness measures, and reduce the probability that peat reaches a highly combustible state.

Figure 1 Illustrates This Shift from a Predominantly Reactive Sequence Toward An Anticipatory Governance Cycle.

Structural drivers and hydrological deterioration occur before ignition; consequently, monitoring and preventive action need to operate before the emergency-response phase. Firefighting remains within the framework but is repositioned as management of residual risk rather than the first substantive intervention.

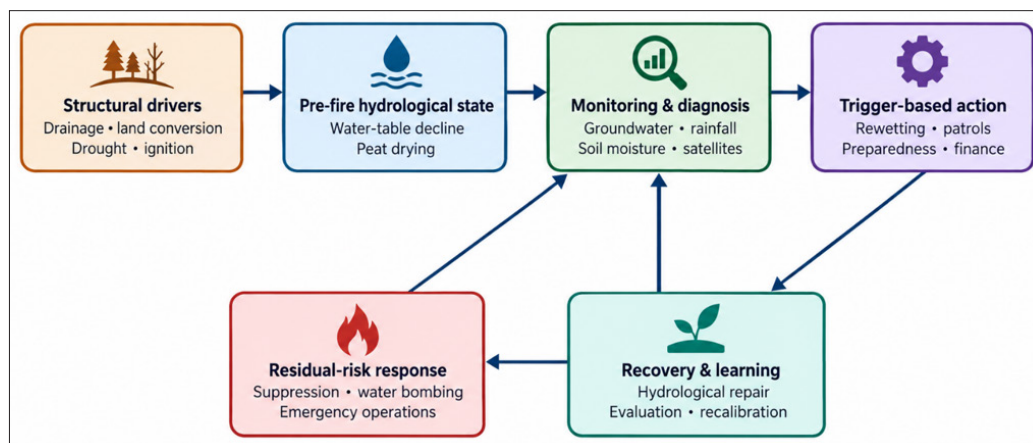


Figure 1: From Reactive Firefighting to Anticipatory Peatland-Fire Governance. Source : Author ’s synthesis based on the reviewed literature. The conceptual significance of Figure 1 is the movement of the primary decision point. A reactive system asks how quickly institutions can respond once fire is visible. An anticipatory system instead asks whether environmental deterioration can be identified soon enough to alter the risk trajectory. This requires permanent observation and institutional capacity rather than a system activated only by seasonal crisis.

Research Gap and Contribution

The literature on Indonesian peatlands is substantial but often segmented. Hydrological studies analyse groundwater recession and rewetting; fire researchers examine ignition and combustion; remote-sensing researchers monitor hotspots; governance studies investigate policy coherence; restoration studies evaluate canal blocking and revegetation; livelihood research focuses on community acceptance; and health or economic studies estimate downstream damages. What remains less developed is an integrated architecture showing how these bodies of evidence can be linked through a sequence of **risk production** → **environmental monitoring** → **decision threshold** → **preventive action** → **preparedness** → **residual suppression** → **recovery and institutional learning**.

The need for integration is reinforced by governance research. National objectives can be difficult to implement when technical rules do not fit local land-use practices, institutional responsibilities overlap, or implementation incentives differ among government agencies, private actors, and communities Peat-restoration stakeholders have also expressed differing interpretations of what restoration should accomplish, demonstrating that successful restoration involves negotiated social and ecological outcomes rather than a purely engineering objective. Policy-coherence research on the Kampar Peninsula likewise identifies problems created by overlapping regulatory and spatial arrangements This article contributes an integrative qualitative synthesis focused on six questions: how peat-fire risk is produced; how hydrological interventions affect susceptibility; how monitoring can detect pre-fire deterioration;

how information can become predetermined action; which governance and financing arrangements are needed for continuity; and how local livelihoods and social legitimacy affect restoration durability. On this basis, the article develops a new synthesis termed the **Hydrological Safety Envelope–Anticipatory Governance Framework [18-21]**.

Literature Review

Peatland Hydrology as the Foundation of Fire Susceptibility

Peat swamp ecosystems depend upon interactions among rainfall, peat structure, topography, vegetation, surface storage, drainage pathways, and groundwater dynamics. Drainage canals alter those interactions by providing artificial pathways for water loss. The consequences are spatially heterogeneous : groundwater behaviour varies with distance from drainage, rainfall intensity, land use, peat characteristics, and canal configuration. Research on Padang Island, Sumatra, documented large spatial and temporal differences in water-table depth associated with drainage intensity, highlighting why point measurements alone cannot represent an entire peat landscape [22].

The significance of groundwater lies in its influence on moisture availability in the combustible peat profile. When the water table falls, the unsaturated zone deepens, capillary supply weakens, and peat closer to the surface can become progressively drier. Drought-fire modelling in Indonesian peatlands demonstrates that fire danger reflects not only rainfall deficits but also soil-water retention and groundwater conditions. found that fires in their study context were associated with groundwater-table depths exceeding approximately 60 cm. However, such values should not automatically be converted into a universal national threshold because peat hydraulic properties, land cover, drainage geometry, and climatic conditions vary. The frequently cited 40-cm management level therefore requires careful interpretation. It can function as a precautionary policy reference, but research should distinguish a regulatory benchmark from a universal physical ignition threshold. Evidence shows that water-table behaviour is highly site specific, and fire likelihood emerges from interacting variables rather than one groundwater value alone Hydrology-enhanced forecasting reinforces this conclusion : adding modelled soil moisture and groundwater dynamics improves fire prediction relative to reliance on atmospheric weather indices alone [23,24].

Figure 2 Summarises the Principal Causal Pathway identified Across the Hydrological and Fire literature. It Visualises how Drainage can shift peatlands from Hydrological Disturbance to fuel desiccation, ignition, smouldering combustion, and wider environmental and socioeconomic losses.

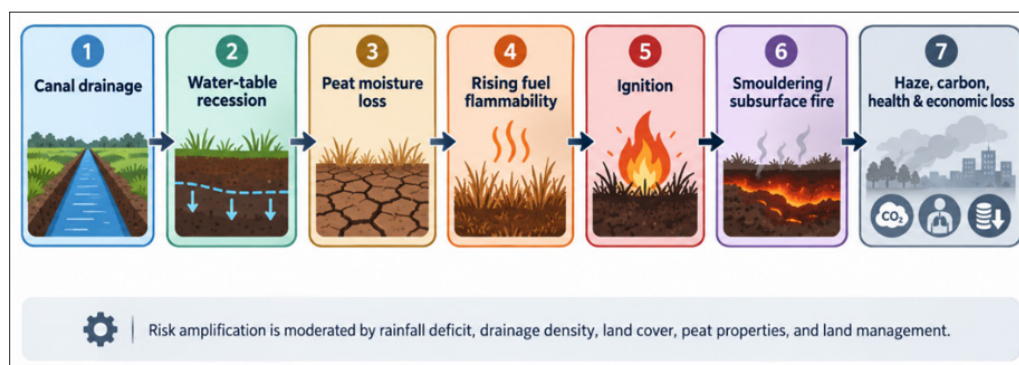


Figure 2: Causal Pathway from Drainage to Peat-Fire Impacts. Source : Author's synthesis based on the reviewed literature. The pathway should not be interpreted as mechanically deterministic. Drainage does not automatically cause fire, and ignition remains essential. Rather, drainage changes the probability structure: it creates conditions under which periods of low rainfall and anthropogenic ignition are more likely to result in severe combustion. Fire governance therefore needs to manage both **susceptibility** and **ignition**, rather than concentrating exclusively on either one.

From Drainage to Smouldering Combustion

Peat fire emerges from the coupling of dry fuel and ignition. The Peat Fire agent-based model demonstrates the importance of groundwater depth, peat dryness, preceding dry days, and human ignition in determining fire dynamics. Satellite-based and field approaches similarly show that fire occurrence varies with climatic and landscape conditions. These findings support conceptualising fire risk as a dynamic state rather than a binary condition. Once ignition penetrates dry peat, fire can continue as smouldering below the surface measured horizontal and vertical peat-fire spread in Kalimantan and demonstrated how estimated carbon emissions vary substantially depending upon burn depth and environmental conditions through controlled field experiments in Sumatra, likewise demonstrated the persistence of peat combustion and challenges of extinguishment. Such behaviour helps explain why late intervention can become technically difficult and resource intensive [25].

Fire also alters future ecosystem trajectories. showed that fire changes peat and biomass carbon pools, while found significant effects on tree-species composition and diversity. Documented substantial ecological impacts but also prospects for recovery under suitable conditions. Post-fire carbon effects can persist long beyond the original event ; work from Brunei indicates continued alteration of carbon dynamics after repeated fire. These consequences strengthen the economic logic of prevention. Suppression costs represent only one component of the total fire burden. Avoided emissions, reduced health exposure, preserved ecosystem services, lower subsidence, and reduced recovery expenditure should also be considered when evaluating investments in prevention [26-.30].

Hydrological Restoration and Rewetting

Rewetting is intended to restore parts of the hydrological function lost through drainage. Canal blocking reduces artificial drainage and can raise surrounding groundwater levels, while deep wells may supply water for targeted interventions. Rewetting can also support broader objectives such as slowing peat oxidation and subsidence, facilitating forest regeneration, and reducing fire susceptibility. Empirical evidence increasingly supports these mechanisms, although effect sizes vary. Lestari, Murdiyarso and found that rewetting can reduce net greenhouse-gas emissions in degraded Riau peatlands, while reported lower fire hazard associated with rewetting. In a large-scale 7.5-year restoration trial in Sumatra, found that 257 peat dams raised water tables from approximately -0.6 m toward -0.3 m, halved subsidence rates in rewetted areas, and supported spontaneous regeneration of native peat-swamp forest species. Complementary L-band InSAR evidence from the Kahayan-Sebangau Peat Hydrological Unit also shows markedly lower post-restoration subsidence, reinforcing the value of landscape-scale monitoring alongside ground measurements. Importantly, restoration should remain adaptive because hydrological responses, infrastructure durability, and climatic stresses vary across sites and through time. The strongest recent evidence comes from attempts to estimate causal rather than merely correlational effects. Compared restored and matched control areas and found significant reductions in fire-hotspot density during 2019, although the effect was not detectable in the much lower-fire year 2023. Evaluated thousands of canal blocks in Kalimantan using a counterfactual approach and found heterogeneous results, with overlapping rewetted areas performing especially well. Their modelling suggests that scaling the most effective configurations could prevent a measurable share of burned area.

These findings are critical because they shift the restoration debate from the question “Does canal blocking work?” toward more useful questions: **Where does it work? Under what hydrological conditions? At what density? How should interventions be spatially configured? Who maintains them? What happens during different climatic years?** Restoration is therefore an adaptive landscape-management process, not a one-time construction programme. Similarly emphasise restoration prioritisation at the peat-hydrological-system level, integrating topographic, hydrological, and remote-sensing information. This is consistent with the physical reality that water does not follow concession or administrative boundaries [31-34].

Monitoring and Prediction

Effective prevention requires detecting the deterioration of peat conditions before fire becomes established. A monitoring architecture can integrate groundwater wells, rainfall measurements, weather observations, soil moisture, vegetation indicators, hotspot data, remote sensing, UAV measurements, and hydrological models. Demonstrate the value of improved evaluation indicators for Indonesian peat fires, while hydrological observations from illustrate the spatial variability that ground networks need to capture. Further show that simulated water-table and soil-moisture information can materially improve active-fire prediction. Recent remote-sensing studies strengthen this monitoring architecture : time-series L-band InSAR can detect restoration-related changes in peat-surface displacement, while radar-derived peat motion can support scalable monitoring, reporting, and verification of carbon losses and hydrological condition Groundwater monitoring should therefore be considered not simply a restoration-performance metric but part of integrated operational risk intelligence. A key governance issue follows:

Monitoring Without Predetermined Response Rules May Produce Information Without Action

Institutions can observe water tables falling yet still wait until hotspots appear. The effectiveness of monitoring therefore depends on converting indicators into operational trigger levels tied to concrete actions, budgets, personnel, and responsibilities.

Figure 3 introduces the proposed Hydrological Safety Envelope as a conceptual alternative to relying on a single universal groundwater threshold. The figure emphasises a graded risk transition in which locally calibrated combinations of hydrological stressors determine when management should move from routine monitoring toward preventive and emergency action.

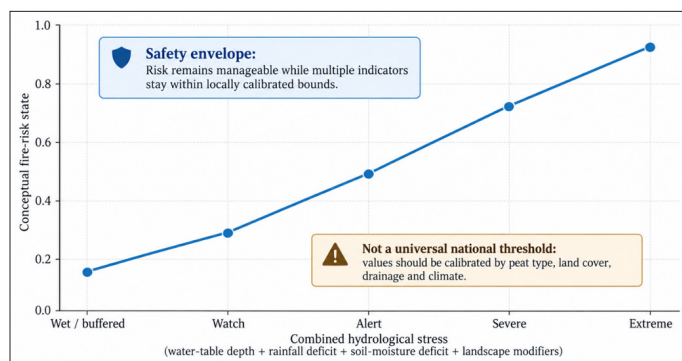


Figure 3 : Conceptual Hydrological Safety Envelope. Source: Author's synthesis based on the reviewed literature. The safety envelope is defined as the combination of hydrological and climatic conditions within which peat-fire susceptibility remains comparatively manageable. Water-table depth is its principal indicator, but not the sole indicator. Rainfall deficit, soil moisture, drainage density, land cover, peat properties, and ignition pressure modify the effective risk state. This concept is an analytical synthesis proposed by this article, not an existing statutory classification.

Governance, Institutional Fit, and Social Legitimacy

Biophysical interventions operate within institutional and livelihood systems. Demonstrate that peatland regulations may experience weak technical, political, or cultural fit with local land-user practices, while identify institutional constraints affecting adaptive restoration governance in Central Kalimantan emphasise policy coherence across sectors and jurisdictions, and recent multilevel-governance research in Riau documents persistent coordination, actor-network, and power-asymmetry challenges in programme implementation More broadly, adaptive-governance research indicates that peatland restoration benefits from polycentric coordination, flexible institutions, and the deliberate integration of scientific and local Together, these studies show that a technically appropriate hydrological target can still fail if governance arrangements do not fit landscape realities. Restoration objectives themselves can be contested. Show that national-level stakeholders agree broadly on the importance of restoration while differing over what restoration should ultimately mean. Therefore define restoration as a Socio-Ecological process involving collaboratively determined trajectories rather than an exclusively ecological endpoint. Local livelihoods are especially important where canal blocking changes water conditions for agriculture. Smallholder research in Sumatra shows that attitudes toward rewetting depend partly on perceived livelihood effects Studies of paludiculture and low-drainage crops indicate that wet-compatible production systems may provide alternatives, but market feasibility, farmer preferences, and local ecological conditions must be considered More recent work argues that

climate-smart peatland management can create partial synergies among climate, food-security, and livelihood objectives, while still placing peat conservation and restoration at the centre. Community participation is consequently not an optional communication exercise. Emphasise iterative and inclusive engagement demonstrate the importance of knowledge systems linking researchers and stakeholders conceptualise community acceptance in terms of a social licence to restore and embed participation throughout a “5Rs” restoration approach. Recent studies deepen this argument. Show that local representations of peatlands affect perceptions of restoration illustrate how restoration programmes interact with Changing human and non-human actor networks ; and demonstrate collaborative everyday adaptation to peatland fires. Emphasise institutional strengthening and collective action, while show that restoration actors face uneven capacities, conflicting interests, and implementation risks that require explicit management. further propose principles centred on inclusive decision-making, local context, informed consent, and fair distribution of benefits [35-49].

Method

Review Design

This study employs a qualitative literature review (QLR) rather than a systematic literature review. The objective is interpretive and integrative to bring together evidence from hydrology, fire science, restoration ecology, environmental health, remote sensing, governance, Economic, and community studies to construct a coherent explanation of how peat-fire risk develops and how policy can intervene earlier in that process. This integrative orientation is consistent with recent narrative work on tropical peatland governance, which highlights the value of combining multiple knowledge systems when analysing complex social-ecological risks. Accordingly, the review does not claim exhaustive bibliographic coverage and does not use PRISMA-style record counts. Literature was purposively identified from peer-reviewed journals published primarily between 2020 and 2026, with emphasis on Indonesia and supporting evidence from Southeast Asian tropical peat systems where the mechanisms are directly relevant [50].

Search Orientation and Evidence Selection

Literature identification used combinations of terms relating to Indonesia, tropical peatland, peat fire, groundwater table, water-table depth, canal drainage, rewetting, canal blocking, hydrological restoration, fire forecasting, drought-fire index, early warning, fire governance, community fire management, paludiculture, peat hydrological unit, haze, public health, and restoration economics. Search terms were iteratively combined and refined so that biophysical, governance, socioeconomic, and risk-management evidence could be considered within the same qualitative synthesis. Sources were prioritised when they contributed directly to at least one of six evidence domains : causal mechanisms of fire susceptibility ; hydrological intervention effectiveness ; monitoring and forecasting institutional and policy architecture ; livelihood and community dimensions ; or consequences of fire and benefits of avoided fire. Priority was given to peer-reviewed studies published from 2020 onward, with Indonesia-focused evidence preferred and wider tropical-peatland evidence included when the underlying mechanisms were directly transferable. The thematic synthesis proceeded through iterative coding rather than statistical meta-analysis. Evidence was compared for areas of agreement, conditionality, contradiction, and uncertainty. Quantitative results are therefore used as contextual evidence and are not pooled across heterogeneous study designs.

Analytical Framework

The review organised evidence along a causal sequence in which structural drivers produce hydrological deterioration, hydrological deterioration increases fuel susceptibility, and deteriorating risk indicators can activate prevention and preparedness before ignition occurs. When prevention is insufficient, the sequence proceeds through emergency suppression, recovery, and adaptive learning, allowing observed outcomes to inform subsequent thresholds and interventions. The central analytical distinction is between **upstream risk reduction** and **downstream impact management**. Neither is treated as sufficient independently.

Results

Theme 1: Peat Fires are Largely Produced Before Ignition

The literature converges on the conclusion that fire susceptibility is built over time. Drainage changes groundwater behaviour, drying expands the combustible unsaturated peat layer, land-cover alteration modifies microclimate and fuel characteristics, drought amplifies moisture deficits, and human activities provide ignition. Provide especially clear recent evidence that drainage density interacts with land cover to shape hotspot occurrence. This process means that “fire season” is partly the visible endpoint of conditions established months or years earlier. Canal networks constructed for land development can continue drawing water from peat through successive seasons. Hydrological degradation therefore persists outside the months in which fire agencies traditionally mobilise. Restoration that begins only during the dry season may consequently face a landscape whose vulnerability is already structurally embedded. Add a longer-term perspective by demonstrating interactions among climate, fire, floods, human disturbance, peat formation, and carbon dynamics in West Kalimantan. Similarly synthesise how drainage and land conversion transform biogeochemical processes. The resulting picture is not of a single cause but of a coupled social-hydrological system in which climatic stress and land-management decisions jointly condition fire risk [51-.52].

Theme 2: Groundwater Is a High-Value Risk Indicator, But Not a Stand-Alone Universal Trigger

Water-table position is consistently important because it mediates the moisture conditions of near-surface peat. Yet the literature also warns against reducing complex fire risk to one number. Link deep water tables to elevated fire risk, whereas demonstrate substantial spatial variation produced by drainage configuration and rainfall. Fire forecasting improves when groundwater and soil moisture are considered jointly with meteorological information.

The practical implication is to treat groundwater thresholds as part of an escalating decision matrix. A groundwater level approaching a locally calibrated critical range could trigger increased monitoring; continued decline combined with rainfall deficit could trigger canal inspections, targeted rewetting, patrol intensification, and restrictions on risky activities; additional hotspot or smoke signals could then escalate the system toward emergency response [53].

Figure 4 translates this principle into an illustrative monitoring-to-action ladder. It links escalating risk states to progressively stronger monitoring, preventive, preparedness, and emergency measures so that information is connected to pre-agreed institutional responses.



Figure 4: Monitoring-to-Action Trigger Ladder Source : Author's synthesis based on the reviewed literature

The ladder deliberately does not assign fixed centimetre values. Empirical calibration should determine locally appropriate thresholds using historical fire records, peat properties, land cover, drainage configuration, groundwater observations, and weather information. This prevents an administrative threshold from being mistaken for a universal physical constant.

Theme 3: Rewetting Reduces Risk, But Design and Maintenance Determine Effectiveness

The literature strongly supports hydrological repair while simultaneously revealing substantial heterogeneity. Rewetting can raise groundwater, reduce oxidation, lower subsidence, and decrease fire susceptibility. However, restoration structures are not equivalent. Canal location, density, dam integrity, surrounding topography, peat characteristics, and connectivity of rewetted areas influence outcomes. The large counterfactual evaluation by indicates that canal blocks with overlapping rewetting influence were most effective in their study landscape. This supports treating canal blocking as a network-design problem rather than a simple count of infrastructure units. Add an important temporal qualification : restoration effects were evident in the higher-fire 2019 conditions but not in the lower-fire conditions of 2023. The absence of a detectable effect during a lower-risk year does not necessarily mean restoration ceased functioning ; it illustrates how treatment effects depend on climatic background conditions and the amount of fire risk available to be reduced. This heterogeneity has policy implications. Performance evaluation should not rely solely on the number of canal blocks constructed, wells installed, or hectares formally treated. More meaningful indicators include groundwater response, duration of rewetting, spatial continuity of hydrological influence, maintenance status, reduction in hotspot density, avoided burned area, subsidence, carbon outcomes, and community acceptance [54].

Theme 4: Prevention Can Deliver Benefits Beyond Fire Avoidance

The value proposition for hydrological prevention extends beyond firefighting budgets. Rewetting can reduce greenhouse-gas emissions and subsidence while creating conditions for vegetation recovery. Repeated fires can reduce biodiversity and modify carbon stocks, making avoided fire ecologically valuable. Carbon implications are particularly important document substantial trace-gas and particulate emissions from peat fires, while demonstrate

the importance of building national capacity for credible fire-emission estimates. Further show how peat-fire emissions can be underestimated when accounting systems insufficiently represent smouldering combustion, and show that disturbance can progressively mobilise very old peat carbon. New radar-based work also indicates that spatially explicit peat-subsidence measurements can improve carbon-accountability systems by providing scalable estimates of peat motion and associated emissions. The public-health dimension strengthens the preventive case. Estimate major health impacts from Indonesian peat fires, while conclude that diverse epidemiological and health-risk approaches consistently identify potential health harm from Southeast Asian fire haze, although methodological uncertainties remain. Similarly reviews the atmospheric processes and impacts associated with peat-fire haze. Economic assessments show why these externalities should be included in investment decisions. Estimated that hypothetical restoration of 2.49 millions hectares before historical fire events could have reduced cumulative losses and damages across the analysed years by billions of US dollars, while Januar, found that enhanced conservation and restoration can produce higher long-run societal welfare than less sustainable management scenarios. A recent systematic review of the economics of Indonesian peatland restoration likewise concludes that economic evidence remains limited and fragmented, with substantial uncertainty around trade-offs, opportunity costs, and the distribution of restoration benefits [55,56].

Theme 5: Seasonal Emergency Institutions Are Insufficient for A Year-Round Hydrological Problem

Hydrological deterioration does not follow the administrative calendar of emergency mobilisation. A system dominated by temporary dry-season task forces risks creating a mismatch between the temporal scale of the ecological process and the temporal scale of institutional action. Show that Indonesian fire-management interventions have differed substantially among government, civil-society, and industry actors and have not always targeted risk effectively. Similarly demonstrate that combinations of interventions operate differently across landscape contexts. These findings discourage reliance on a universal programme package and favour adaptive, context-dependent governance. Find that local governance arrangements can constrain adaptive restoration responses, while identify problems of policy coherence across multiple sectors. Recent multilevel-governance evidence from

Riau similarly identifies coordination gaps, actor-network tensions, and power struggles that can reduce programme effectiveness and equity. The implication is that anticipatory governance requires durable coordination mechanisms and permanent institutional capacity rather than merely a larger emergency budget.

Theme 6: Restoration Succeeds Only When Compatible with Social Systems

Hydrological restoration can create trade-offs. Raising water tables may support ecological objectives but affect crops or land-use systems developed under drained conditions. demonstrate that smallholder acceptance of canal blocking depends on perceived consequences for agricultural livelihoods. Uda, Hein and identify several lower-drainage or paludiculture options but also emphasise profitability, market scalability, and farmer acceptance. show that indirect costs associated with addressing social challenges can represent a substantial share of total restoration costs, while financing uncertainty can threaten programme durability. Consequently, budgeting only for physical structures systematically understates the real costs of successful restoration. Community engagement must therefore be integrated into project design, monitoring, livelihood adaptation, conflict resolution, and benefit distribution. The 5Rs approach proposed by is useful because participation is embedded across restoration rather than relegated to an isolated “community” component. Likewise emphasise informed consent and equitable distribution [58].

Discussion and Analysis

The Required Policy Correction is Temporal, Not Merely Technological

The central proposition derived from the evidence is that peatland-fire management should intervene at the earliest tractable point in the risk-production chain. Much public attention naturally concentrates on dramatic emergency actions—aircraft dropping water, cloud-seeding operations, firefighting teams, arrests, and emergency coordination. Yet these are activated after the landscape has already entered an elevated-risk state. This does not make emergency measures unnecessary. The academically defensible distinction is between first-line prevention and last-line containment. Once a peat fire is established, water bombing and ground suppression may save ecosystems, settlements, and infrastructure. However, if those instruments are repeatedly required on the same landscapes, the recurrence itself indicates that upstream risk production has not been adequately controlled. Figure 1 therefore represents an institutional inversion. The largest share of managerial attention should ideally be concentrated before ignition: maintaining hydrological function, monitoring deterioration, reducing ignition pressure, preparing response capacity, and securing budgets. Emergency response remains essential but is no longer expected to compensate for prolonged pre-fire hydrological degradation.

Reinterpreting the six Propositions in the Initial Infographic

The source infographic contrasts six conventional practices with proposed preventive alternatives. The literature supports the direction of this correction but requires greater nuance.

First, water bombing after large fires versus maintaining shallow groundwater throughout the year should not be interpreted as an either/or choice. Maintaining wet peat lowers the probability of deep smouldering, while water bombing remains necessary when fires nevertheless occur. The correct hierarchy is prevention first and suppression second.

Second, weather modification versus canal blocking likewise involves different stages of risk management. Weather modification may provide emergency support under suitable meteorological conditions but cannot repair long-term drainage. Canal blocking addresses a more structural cause by changing the hydrological system, although its effectiveness depends on spatial design and maintenance. Third, seasonal task forces versus permanent monitoring networks is strongly supported by the evidence. Groundwater dynamics and drainage operate continuously, which favours permanent observation systems capable of detecting risk months before peak fire periods. Fourth, post-fire enforcement versus predefined drought thresholds should also be understood as complementary. Enforcement addresses prohibited behaviour and accountability; trigger-based risk management improves timing. One does not eliminate the other. Fifth, public appeals not to burn versus financed preparedness highlights a classic implementation problem. Behavioral appeals have limited effectiveness when households, firms, or local agencies lack viable alternatives or operational resources. Preparedness therefore requires personnel, equipment, maintenance, incentives, livelihood support, and contingency funding. Sixth, seasonal restoration versus year-round hydrological restoration is well supported because canal networks and peat oxidation do not switch off during the wet season. Hydrological management should therefore be treated as permanent landscape infrastructure rather than an annual emergency project.

The Hydrological Safety Envelope

A key contribution of this review is the concept of the Hydrological Safety Envelope (HSE). It provides a decision-support concept for integrating several pre-fire indicators rather than relying on a single threshold. Operationally, the HSE is the locally calibrated combination of water-table position, soil moisture, recent rainfall, expected weather, drainage pressure, land-cover characteristics, and ignition exposure within which the probability of severe peat combustion remains comparatively constrained. It should be interpreted as a decision-support concept rather than as a universal statutory threshold, because the relative importance of its indicators changes across landscapes and climatic conditions. The concept avoids two extremes. One extreme assumes that only visible fire matters; the other assumes that a single groundwater value is sufficient for decision-making. The HSE treats risk as multivariate and dynamic. This approach follows naturally from the literature. Demonstrate strong relationships among drought, groundwater, hydraulic properties, and fire ; demonstrate groundwater heterogeneity ; and show that combining hydrological variables with forecasting improves predictive performance. Further show that drainage density and land cover alter risk. Together, these studies indicate that operational decisions should incorporate multiple interacting indicators rather than a single static threshold. The HSE could be operationalised through locally estimated risk bands. These could begin with a “normal” state, followed by “watch,” “alert,” “severe,” and “emergency” states. Movement among states would depend on combinations of indicators rather than a single measurement.

From Early Warning to Early Action

Many environmental systems possess warning information without corresponding anticipatory authority. A weather service may identify drought, groundwater stations may detect recession, and satellites may show drying or initial hotspots, yet action can remain delayed because institutional rules do not specify what should happen next. The solution is a trigger-action protocol. Each risk band should be linked to predefined action, responsibility, and

finance. At normal conditions, agencies and communities maintain canals, monitoring stations, access routes, and databases. At watch level, monitoring frequency increases and anomalous locations are verified. At alert level, targeted rewetting and patrols intensify while personnel and equipment are pre-positioned. Severe conditions trigger restrictions on particularly risky activities, rapid fund release, intensified community outreach, and high-frequency surveillance. Emergency status activates suppression, incident command, smoke-health measures, evacuation where necessary, and post-fire hydrological repair.

This structure has a practical advantage: it narrows the gap between science and administration. Information becomes actionable because a prior agreement establishes who acts when a threshold is crossed.

Governance at the Peat Hydrological Unit scale

Figure 5 proposes an integrated architecture in which monitoring, analytics, decision thresholds, institutional actors, interventions, outcomes, and learning are explicitly connected. The architecture treats governance as a feedback system in which data inform action and Observed outcomes are used to revise thresholds, financing arrangements, and intervention design.

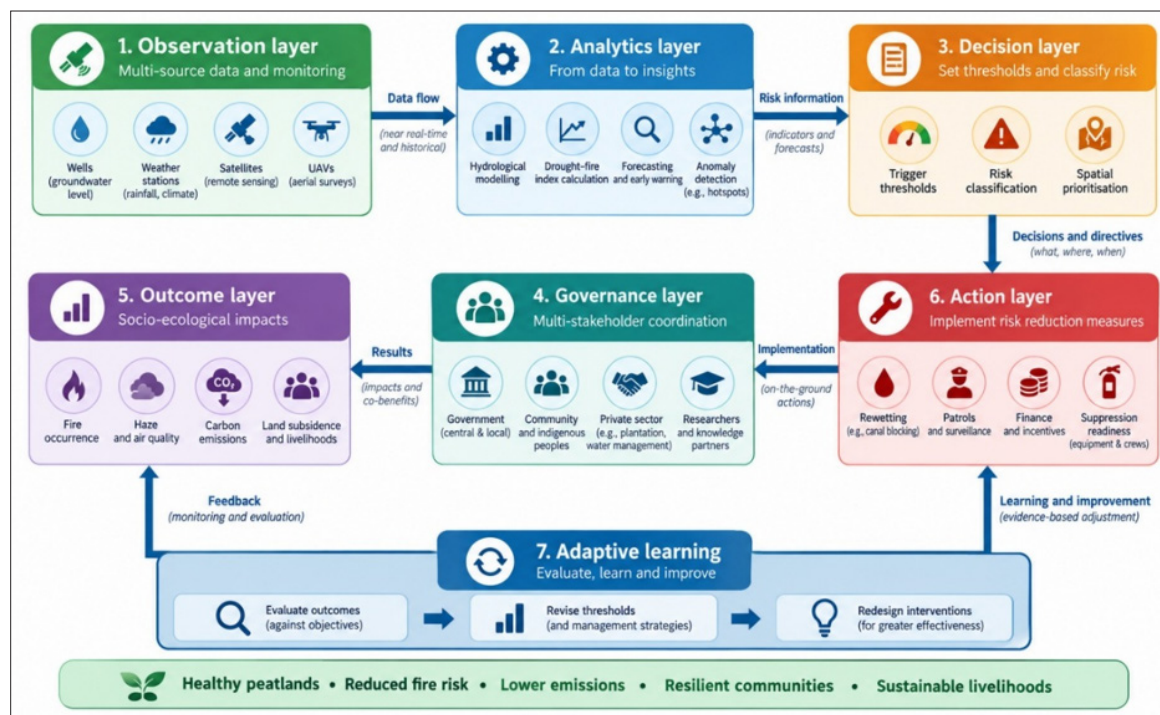


Figure 5: Integrated Peat Hydrological Unit (PHU/KHG) Governance Architecture. Source : Author's Synthesis Based on the Reviewed Literature. The hydrological character of peatlands creates a jurisdiction problem. Water flows across village, district, plantation, and concession boundaries. A canal on one landholding can alter groundwater on neighbouring areas. Consequently, local fire prevention undertaken independently by individual actors may be undermined by drainage elsewhere within the same hydrological unit. Cahyono, explicitly emphasise hydrological-unit approaches to restoration prioritisation. Policy-coherence research similarly demonstrates that fragmented spatial and sectoral rules can impede implementation while adaptive-governance scholarship highlights the importance of institutional flexibility, local ownership, and learning across governance levels. These findings support governance arrangements that follow hydrological connectivity while remaining responsive to administrative and community realities. The appropriate governance unit is therefore not necessarily identical to the administrative unit. Indonesia's Kesatuan Hidrologis Gambut (KHG), or Peat Hydrological Unit, provides an analytically relevant landscape scale because it recognises hydrological connectivity. Within each unit, risk governance should ideally integrate surface and groundwater monitoring, canal maps, land cover, fire history, concession boundaries, community land use, infrastructure, and response capacity. The essential feature of Figure 5 is the feedback loop. Monitoring is not complete when data have been collected, and restoration is not complete when infrastructure has been built. Outcomes must return to the decision system so that ineffective thresholds, locations, canal-block configurations, financing procedures, and community-engagement models can be revised.

Permanent Preparedness and Anticipatory Finance

Institutional timing depends heavily on finance. Emergency funds released only after major escalation are poorly aligned with a risk system in which the most cost-effective intervention may occur weeks or months earlier. Show that restoration costs include substantial social and institutional components and that long-term financing remains a critical challenge. Demonstrate that avoided damages can make restoration economically attractive, while Januar, show the potential long-term welfare gains from sustainable peat management. additionally estimate positive economic returns for well-performing rewetting interventions in some locations. Recent economic synthesis nonetheless finds that the evidence base remains thin relative to the scale of restoration investment and that opportunity costs, distributional trade-offs, and valuation methods require more systematic attention. This supports a tiered financing architecture. Baseline funding should support permanent monitoring and maintenance. A second funding tier should be released automatically when predetermined watch or alert conditions are reached. Additional contingency funds should support severe and emergency stages.

Such an arrangement would reduce administrative delay between recognising deteriorating conditions and mobilising preventive resources. Crucially, preventive finance must cover mundane activities. A canal block that fails because of poor maintenance can reverse hydrological benefits. A monitoring well without calibration provides weak evidence. A weather station without data integration contributes little to decision-making. A community fire programme that ends when external project funding stops may not provide lasting prevention. Preventive governance therefore depends on recurrent operating expenditure rather than only capital construction [57].

Social legitimacy is infrastructure

A major insight from recent peatland research is that community engagement should be treated with the same seriousness as hydrological infrastructure. Canal blocks alter water. Water alters farming possibilities. Farming affects income. Income affects acceptance. Acceptance influences maintenance, compliance, fire use, and programme durability. And distributional outcomes are central determinants of restoration success. Participatory action research in Indonesia further indicates that sustained political support, local leadership, social capital, functioning institutions, and viable business models are needed if community-based fire prevention and restoration are to persist beyond individual projects. This leads to a useful reframing: social legitimacy is a form of restoration infrastructure. Like a dam, it must be built, maintained, monitored, and repaired. Technical programmes that neglect it may generate resistance, non-maintenance, or adaptation strategies that undermine hydrological objectives. Paludiculture and wet-compatible livelihoods are consequently important not because they constitute a universal economic solution, but because they address a structural contradiction: asking communities to maintain high water tables while depending economically on production systems requiring drainage. Research on paludiculture shows plausible alternatives, although markets, skills, profitability, and local suitability remain constraints [59].

Redefining Successful Restoration

A further implication concerns performance indicators. Restoration is frequently reported through inputs: hectares targeted, dams constructed, wells drilled, seedlings planted, communities trained, or funds disbursed. These measures indicate activity but not necessarily outcome. A stronger performance system would distinguish five connected levels of evidence. These levels should be interpreted as a results chain linking implementation outputs to hydrological response, fire-risk reduction, ecosystem outcomes, and social legitimacy rather than as independent reporting categories. At the implementation level, indicators track whether infrastructure and programmes were delivered. At the hydrological level, groundwater response, drainage reduction, and soil-moisture recovery are measured. At the fire-risk level, indicators examine hotspot density, ignition probability, burned area, and severity. At the ecosystem level, subsidence, carbon emissions, vegetation recovery, and biodiversity are assessed. Finally, the social level evaluates livelihood security, participation, equity, compliance, and programme legitimacy. Illustrate the value of this outcome-oriented approach by measuring water-table change, subsidence, and vegetation recovery rather than merely reporting dam Numbers, while evaluate avoided fire outcomes rather than assuming constructed canal blocks are effective. The need for multidimensional evaluation is reinforced by whose synthesis of Indonesian restoration studies shows that monitoring systems remain disproportionately focused on short-term biophysical indicators and would benefit from stronger social, governance, equity, and resilience metrics [60].

Recovery Must Close the Hydrological Loop

Post-fire recovery is often interpreted as rehabilitation after damage. In the proposed framework, recovery also becomes diagnosis. A burned site provides evidence that prevention failed somewhere in the risk chain. Post-fire assessment should therefore ask whether groundwater levels were already critically low, whether canal structures failed, whether monitoring detected deterioration, whether thresholds were inappropriate, whether warnings reached decision makers, whether resources were released, whether suppression was delayed, and whether livelihood pressures contributed to ignition. Such diagnostic review can identify where the prevention-to-response chain failed and provide evidence for recalibrating thresholds, responsibilities, maintenance schedules, and financing arrangements. This learning function is particularly important because peat landscapes and climatic conditions are changing. No trigger architecture will be optimal permanently, so adaptive recalibration must be an explicit governance function. Recent work on adaptive and transformational peatland governance similarly emphasises iterative learning, the integration of multiple knowledge sources, and institutional capacity to revise strategies as climate risks and stakeholder needs evolve.

Remaining Uncertainties and Research Agenda

Several important uncertainties remain, and they should be treated as a research agenda rather than as reasons to delay prevention. The most important gaps concern causal evaluation, locally calibrated thresholds, infrastructure durability, social distribution, and credible carbon accounting. First, long-term causal evaluations of restoration remain relatively scarce. The 2026 studies by Salmayenti et al. and Castro et al. Represent major methodological advances, but more counterfactual evaluations across different islands, peat types, land uses, and intervention designs are needed. Second, greater research is required on locally calibrated thresholds. Groundwater depth is important, but its relationship with combustion changes according to peat hydraulic properties, drainage density, vegetation, and weather. Multi-indicator models should therefore be validated operationally rather than merely statistically.

Third, maintenance deserves more empirical attention. Restoration infrastructure is commonly evaluated near the time of installation, while degradation of dams, wells, sensors, and access infrastructure over longer periods may affect performance. Fourth, social and distributional effects require longitudinal evaluation demonstrate that programmes can alter complex local actor networks over time. Restoration success should therefore be assessed not only immediately after consultation but across livelihood transitions. Fifth, fire-risk reduction should be integrated more systematically with carbon accounting. And highlight the importance and complexity of estimating peat-fire carbon consequences. Emerging L-band InSAR approaches provide an additional pathway for scalable monitoring of peat motion and emissions, potentially strengthening monitoring, reporting, verification, and performance-based restoration finance Reliable avoided-emission methodologies could therefore connect fire-risk reduction more directly with climate-finance accountability.

Conclusion

Indonesia's peatland-fire problem begins long before smoke becomes visible. Drainage, declining groundwater, peat desiccation, vegetation change, climatic drought, and ignition pressures jointly create the conditions in which manageable land-fire events can become persistent peat fires. By the time large-scale water bombing, emergency weather interventions, and intensive suppression are required, much of the underlying

risk trajectory has already developed. The evidence reviewed here therefore supports a rebalancing of peatland-fire governance from predominantly reactive suppression toward year-round hydrological prevention and anticipatory risk management. This does not imply abandoning firefighting, law enforcement, water bombing, emergency command systems, or other response instruments. Those measures remain essential when preventive systems fail or extreme conditions exceed preventive capacity. The proposed Hydrological Safety Envelope–Anticipatory Governance Framework places hydrological integrity at the center of prevention but integrates it with monitoring, forecasting, trigger-action protocols, permanent preparedness, financing, community participation, livelihood compatibility, residual suppression, recovery, and adaptive learning. Its defining principle is temporal: institutions should intervene while risk is still comparatively inexpensive and technically manageable.

The resulting Policy architecture can be Summerville as a continuous cycle : keep peat hydrologically resilient, observe conditions continuously, detect deterioration, act before ignition, prepare before crisis, suppress residual fires rapidly, repair hydrology, and learn from outcomes. This sequence emphasises that emergency response remains essential, but that the highest leverage is achieved when institutions detect and alter the risk trajectory before severe combustion is established. The deepest correction is therefore not simply replacing one fire-management technology with another. It is moving the centre of governance from the moment after peat has begun to burn to the much longer period before the peat becomes capable of sustaining severe fire.

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