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Review

Reviews and Syntheses: Promoting the Advancement of Hillslope Hydrology and Stability in Taiwan from the Perspective of Critical Zone Science

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Abstract: Owing to active orogenic movement and the monsoon climate, rainfall-induced landslide disasters often occur in Taiwan. Hence, hillslope hydrology and stability have received considerable research attention. However, it remains difficult to accurately estimate the duration and consequences of hillslope instability induced by hillslope hydrology. Research on hillslope hydrology and stability is complicated by spatial heterogeneity, hydrological processes operating at various scales, spatiotemporal evolution, and geomorphological properties. Recent advances in critical zone science have provided an approach to extend geoscience studies. The "deep coupling" concept is essential for integrating physical, chemical, and biological processes on various spatiotemporal scales and for providing a macro and unified framework for evaluating internal properties and processes. Critical zone science and hillslope hydrology and stability both depend on interdisciplinary perspectives and approaches, monitoring strategies, and model analysis of integrating and coupling processes. They both share the characteristics of spatial heterogeneity, continuous evolution, and relevance to ecosystem services. To address the challenges related to hillslope hydrology and stability in Taiwan, we reviewed the progress in, relevance between, and common challenges to hillslope hydrology, stability, and critical zone science. We then presented a process-based integrated monitoring strategy, an interdisciplinary perspective, and a coupling analysis framework and model. The aim of this study was to promote the advancement of research on hillslope stability and hydrology in Taiwan.

Keywords: hillslope hydrology; critical zone science; landslide; slope stability

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1. Introduction

Taiwan is located at the junction of the Eurasian and Philippine Sea plates, and due to intense orogenic movement, approximately 70% of its surface is covered with sloping fields. Disasters such as landslides and debris flows [1,2] are frequently brought on by rain, endangering both human life and property. As a result, numerous studies on hillslope hydrology and stability have been conducted in Taiwan. These include research on the susceptibility map of rainfall-induced landslides [3–6], the correlation between rainfall and landslide erosion [7,8], the relationship between landslide size and rainfall characteristics [9–11], the use of soil moisture as an early warning signal for landslides [12], and the relationship between the development of soil–rock interface saturation and shallow collapse [13]. For various reasons (the complex geologic structure, monsoon climate, and rapid erosion in Taiwan), it remains challenging to evaluate the mechanism, timings, and effects of hillslope instability induced by hillslope hydrology.

Hillslope hydrology and stability are affected locally by tectonic, lithological, geomorphic, weathering, vegetational, and bioturbation processes as well as by spatiotemporal climatic pressures [14]. These mechanisms interact with one another and contribute to the formation and propagation of hillslope instability. Hillslope failure as a natural geomorphic process is a crucial component of the dynamic earth surface environment at different scales, from earth surface processes to deep landslides, and occurs across a variety of time frames [15]. Anthropogenic activities exacerbate these large-scale processes [16]. As a result, the research on hillslope hydrology and stability is interdisciplinary and examines the transfer and storage of water, the generation of earth surface pressure, and local instability and movement of hillslopes caused by hydrological events [17–19]. Triggering factors are the key to hillslope failure, but the causes of hillslope failure may be found in the combined effect of flows and fluxes of different scales, as well as in long-standing potential changes [20]. Understanding the relationship between the Earth's surface and subsurface processes is possible by the groundbreaking interdisciplinary subject known as critical zone science [21]. A critical zone is a heterogeneous, near-surface environment where complex interactions between rocks, soil, water, air, and living organisms maintain natural habitats and ensure the sustainability of living resources [22]. The "critical zone" concept was proposed to understand the earth's shallow subsurface environment and examine the exchange of materials and energy interacting with, and sustaining, living things between the earth's surface and subsurface, and focuses on a series of interconnected processes (such as rock weathering, soil formation, soil erosion, transportation and sedimentation, and geochemical action of water and soil) [23,24]. An interdisciplinary approach is used in critical zone studies to address the interrelated environmental issues that are relevant to several disciplines. The evolution of critical zones is closely related to human society, and the co-evolution of physical and biological systems can be investigated based on social needs combined with the critical zone perspective [25], increasing the social benefits produced by ecosystem services and understanding the supply chain concepts that emerge between them.

Hillslope hydrology and stability are commonly characterized by spatial heterogeneity, continuous development, and relevance to anthropogenic activities, and fall within the scope of the critical zone while emphasizing the understanding of mechanisms and processes. Critical zone science provides a macroscopic and unified evaluation framework that can connect and integrate hillslope hydrology and stability and their related fields [24]. Research on hillslope stability and hydrology can aid the prediction, adaptation, and management of environmental evolution in critical zones. This study reviews the progress and analyzes the application prospects of critical zone science in the study of hillslope hydrology and stability with reference to the challenges experienced in this field in Taiwan. We anticipate that the current research will facilitate research on Taiwan's hillslope hydrology and stability, promote the sustainability of research, meet real-world social demands, and provide useful policy recommendations.

2. Background of Hillslope Hydrology and Stability in Taiwan

Taiwan is located at the junction of the Eurasian and Philippine Sea plates. The Philippine Sea plate was subducted under the Eurasian plate to cause active orogenic movement on the surface with an uplift rate of approximately 5–7 mm per year [26,27]. Approximately 31% of the total area of Taiwan is made up of mountainous regions with an altitude of more than 1000 m, 40% is made up of hilly areas and tablelands with an altitude of 100–1000 m, and 29% is made up of plain areas with an altitude of less than 100 m. Hillslope areas account for approximately 70% of Taiwan's total land area. Taiwan stretches from 120° to 122° east longitude and from 22° to 25° north latitude and is dominated by a monsoon climate. The average annual rainfall is about 2500 mm, but it may be higher in mountainous areas [28]. Rainfall is influenced by the northeast monsoon during the cold season (September–April) and by the southwest monsoon during the warm season (May–August). Taiwan is situated in the path of the northwest Pacific typhoon, and typhoons frequently affect Taiwan in summer, causing intense rain. Furthermore, local afternoon showers caused by terrain and thermal convection currents are also common. The characteristic rainfall of Taiwan is usually generated either by transient subsynoptic disturbances or localized showers related to terrain or local winds [29]. From the perspective of rainfall sources, the season can be divided into winter (December–January), spring rains (February–April), May-yu season (May–June), typhoon season (July–September), and autumn (October–November). Winter is the season with the least rainfall, with an average daily rainfall of about 3 mm. Spring rainfall increases slightly, at about 5 mm per day. May-yu season and typhoon season are the most important rainfall water. The peak average daily rainfall occurs in June and August, respectively. Rainfall decreases rapidly after October [30]. It is worth noting that short-term rainfall brought by typhoons may be much higher and cause serious damage, such as Typhoon Morakot in 2009 (1623.5 mm/24 h), Typhoon Herb in 1996 (1748.5 mm/24 h), and Typhoon Lynn in 1987 (1151.9 mm/24 h). Taiwan experiences frequent regional earthquakes and heavy rainfall, with a surface erosion rate of approximately 3–7 mm per year [31]. Taiwan is especially vulnerable to hillslope disasters due to this fragile geological environment.

Figure 1 presents the statistics for natural disasters in Taiwan from 1958 to 2021 [32]. In Taiwan, natural disasters have become more frequent. Among the many different forms of disasters, including typhoons (64.95%), floods (23.97%), earthquakes (8.51%), and miscellaneous disasters (2.58%), hydro-meteorological disasters were the most common. Moreover, 97.42% of hydrometeorological disasters (rainfall- and earthquake-related disasters) directly or indirectly caused landslide hazards. Potential debris flow torrents (2021) in Taiwan have been identified by the Soil and Water Conservation Bureau (SWCB) of the Council of Agriculture (COA), while the geologically susceptible sites for landslides and landslips have been identified by the Central Geological Survey of the Ministry of Economic Affairs (Figure 2). Geologically sensitive landslides and landslips are defined as sites where landslides or landslides have occurred, and the surrounding region has been impacted by landslides or landslides. These areas are delineated by the central competent authority. Most areas in Taiwan are exposed to hillslope hazards, and these disasters tend to occur between July and September due to southwest airflow and typhoon events, with concentrated rainfall in May and June (the rainy season).

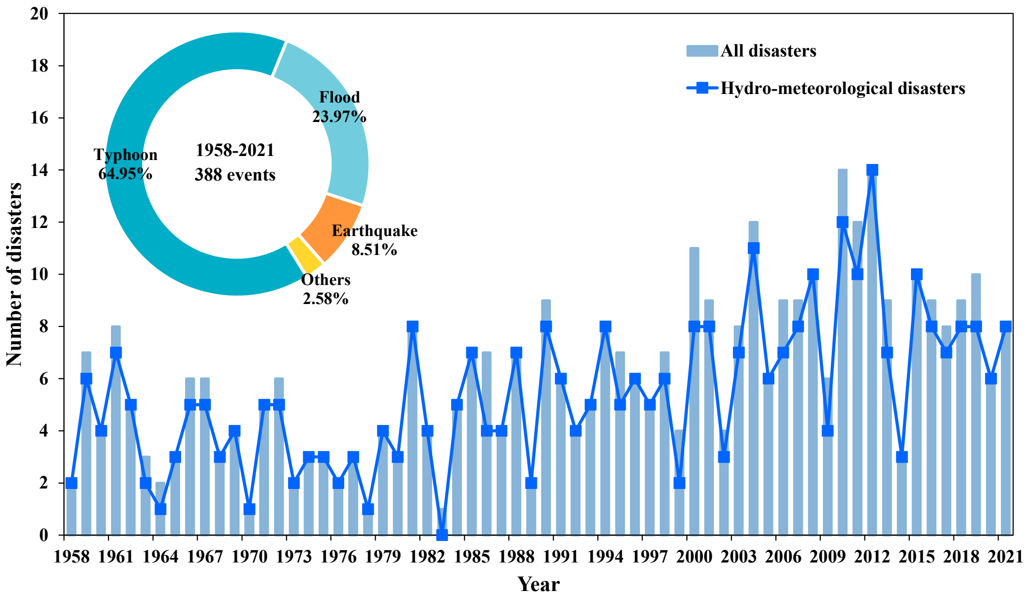

Figure 1. Number and types of natural disasters in Taiwan (1958–2021).

Typhoon Morakot in 2009, which triggered collapses (including deep and shallow collapses), debris flows, dammed lakes, and floods at varying scales in many regions, was the most recent compound debris disaster in Taiwan and caused severe casualties and property damage. To ascertain the formation mechanism and characteristics of compound debris disasters and facilitate the management of disaster prevention, the SWCB of the COA and Executive Yuan conducted a program titled "Compound Disaster Survey, Analysis, and Situation Simulation" in 2011, which included a large-scale field survey, soil hydraulic mechanism tests, numerical simulations and analyses, and process reconstruction for compound disaster time and space sequences. Internationally published studies by Taiwan's industry–government–university circles on the compound debris disasters brought on by Typhoon Morakot cover the following topics: surveys of landslide characteristics [2,33,34], reconstruction of landslide and debris disaster processes [35–39], spatial analysis of disaster telemetry [40,41], setting of rainfall warning conditions [42], and disaster management and post-disaster reconstruction [43–46].

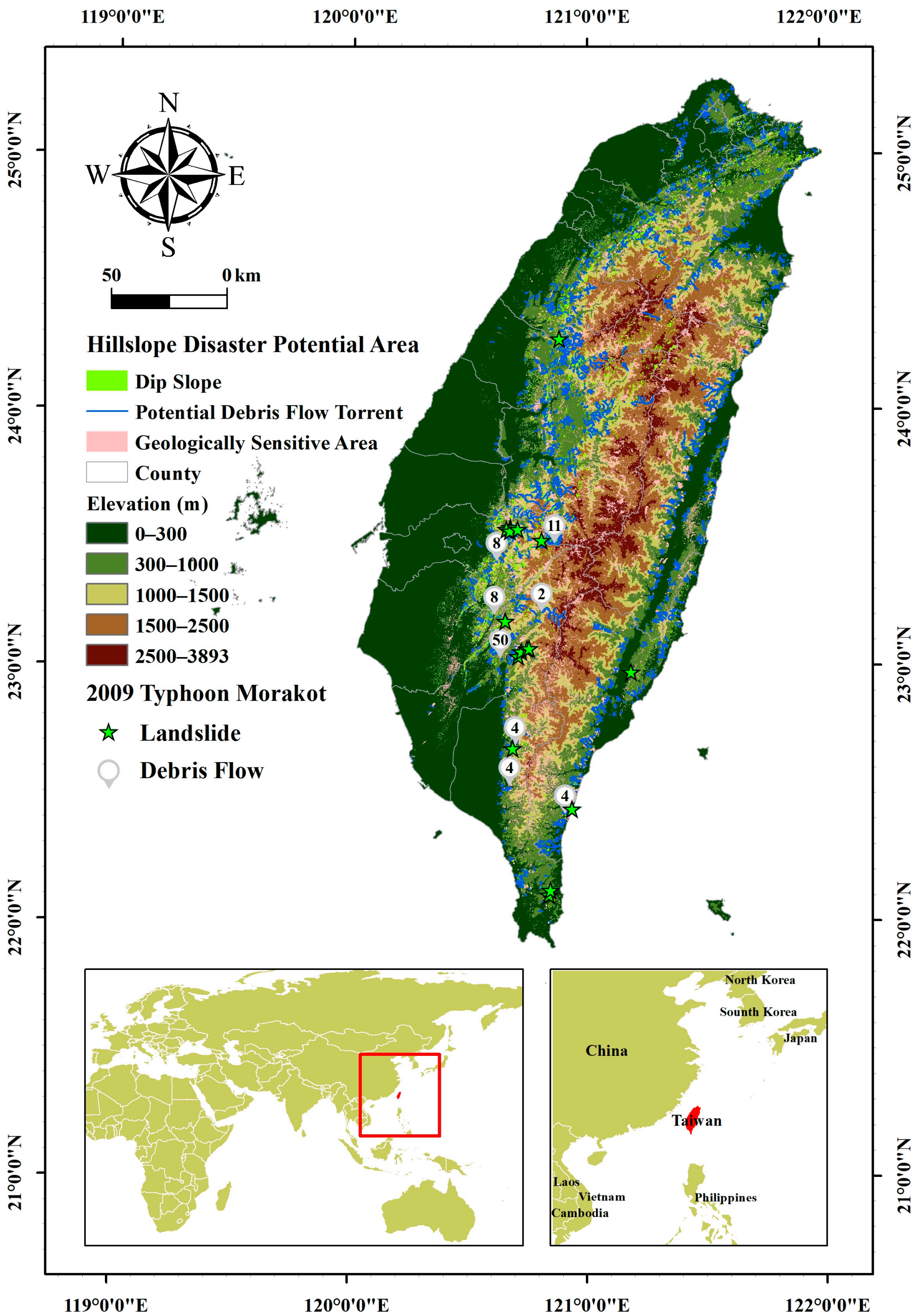

Figure 2. Hillslope disaster potential in Taiwan (2021).

Taiwan has developed an increasingly mature mechanism for debris disaster prevention; related studies include the rainfall thresholds for shallow landslides [47–49], hydro-meteorological thresholds (soil moisture and rainfall) for large-scale collapses [50], a rainfall threshold model for debris flows [51], and an emergency response system for potential large-scale landslides [52]. Lee (2009) [53] proposed the landslide hazard analysis (LHA) method as a workable approach to disaster prevention after reviewing the development and research progress of analytical methods for landslides and debris flow disasters around the world. Studies on the duration and consequences of hillslope instability induced by hillslope hydrology, however, are currently limited to observational tools and analysis methods. Aimed at slope surfaces, catchment areas, and watersheds, the National Science and Technology Centre for Disaster Reduction (NCDR) of Taiwan promulgated the Action Plan for Large-scale Collapse Disaster Prevention and Control in 2015. The action plan specified the following key measures: (1) strengthening potential analysis and database development, (2) developing appropriate evaluation methods for the collapse mechanism and influence, and (3) developing multi-scale observation or monitoring information integration methods and applications (note that a few measures are still at an initial stage). An interdisciplinary approach facilitates an easier comprehension of the causes, mechanisms, processes, spatiotemporal scales, observational methods, and numerical models of landslide disasters in a complex hydrological system because it generates complementary conceptual models, spatiotemporal scales, models, and observational methods. To better understand the functions and processes of hillslope hydrology, this approach aids in the development of a unified evaluation framework and model [54].

3. Critical Zone Science

The dynamic interface between the solid earth and its fluids, which involves complex interactions between different physical, chemical, and biological processes in the atmosphere, biosphere, hydrosphere, pedosphere, and lithosphere, as well as the flow of various mass and energy fluxes, is an example of a critical zone [21]. The change in mass and energy flows within a critical zone drives its evolution [55,56]; regulates soil development, water quality, and flow; and facilitates chemical cycling and the regulation of energy and mineral resources on Earth, as well as providing the necessary resources to sustain various forms of life. Internal environmental processes in critical zones are crucial for maintaining biodiversity and human development [57,58]. Understanding the characteristics and mechanisms that govern critical zones, comprehending their roles and evolution, and increasing ecosystem services are all made possible by the "critical zone" concept [58].

Studies in a variety of fields, such as soil science, hydrology, biogeochemistry, geomorphology, geophysics, and ecology, are necessary for the advancement in critical zone science [21,57,59–63]. The Weathering System Science Workshop, which initially focused on the advancement of weathering system science and integrated itself with disciplines such as chemistry, biology, physics, and geology launched critical zone science studies in 2003 [64]. The Weathering System Science Consortium (WSSC) was founded the following year—it was renamed the "Critical Zone Exploration Network" (CZEN) in 2006—to develop a global community of researchers and educators. A global network of critical zone observations (CZO) and CZO-like stations encompassing climatic, biological, ecological, geological, and human contexts has recently emerged [65]. High-density, temporally continuous instrument arrays at CZO stations conduct dynamic coupling experiments, particularly in zones with biological–hydrological interactions (for example, weathering and erosion zones) [66]. Multi-scale and interdisciplinary field observation data acquired by CZO stations were jointly studied by various interdisciplinary CZO teams. To predict future scenarios, they researched the evolution and functions of critical zones and developed critical zone evolution models [67]. These models served as a guide for land-use decision making and management [67]. Critical zone science involves temporal scales, depth scales (or spatial scales), and a deep connectivity between diverse fields and disciplines [57,63]. This illustrates the unique contribution of critical zone studies to the environment and ecology and emphasizes the importance of integrating physical, chemical, and biological processes in multiple temporal and spatial dimensions [63,65].

Many previous critical zone studies focused on geophysics and biology connections within critical zones [55,68,69]. In recent years, critical zone studies have covered diverse topics, including the water cycle and nutrient and material transfers (for example, the transformation of carbon and water between the atmosphere and land) [70,71], soil water content [72], transformation of surface water [73], chemical weathering and groundwater [74–76], long-term soil evolution and other processes [77–83], water ecology and economy in watersheds [84], and hillslope subsurface structure and runoff in cold regions [85]. Researchers have also attempted to promote studies of deep critical zones through scientific advancements [86]. Moreover, they provided a review and analysis and detailed the prospects of critical zone studies in their respective disciplinary fields, such as hydrology [87], multifunctional landscape science [88], dynamic earth system modeling including hillslope hydrology [89], and biogeography [90].

Critical zone studies must ultimately return to ecosystem services to address the changes and depletion of natural resources brought about by human activity, thus promoting sustainable development [91]. Banwart et al. (2012) [92] proposed the concept of "energy and mass flow" in critical zones to identify the supply chains necessary for human behaviors and to facilitate the integration of critical zone studies and practical management applications. By linking critical zone studies with ecosystems and quantifying the evolutionary process of critical zones, researchers can perform environmental, social, and economic evaluations of critical zones. The objective is to investigate the co-evolutionary and interdependent relationship between the human economy and its associated natural ecosystems on various spatiotemporal scales and to assess the long term sustainability of these relationships in response to climate change and increased human disturbance [58,63,90,92]. Montanarella and Panagos (2015) [93] discussed critical zone-related problems in soil management policies (including climate change, water management, biodiversity, air quality, water quality, waste management, and environmental management) and highlighted the significance of the response of critical zone studies to related management policies.

4. Research Progress in Hillslope Hydrology and Stability

As basic landscape units, hillslopes can vertically and horizontally control hydrological processes that describe the form of water movement. Hillslope hydrology comprises rainfall, evaporation, transpiration, runoff, infiltration, and saturated groundwater flow at different scales (for example, pores, hillslopes, and catchments). These physical processes are dynamic and interrelated, influenced by the location, morphology, climatic environment, and geological materials of the hillslopes [15]. They are also characterized by highly heterogeneous flow fields and preferential flow paths [94]. These interacting physical processes can drive spatiotemporal changes in hillslope stress, resulting in landslides or landslips.

Mass movement describes a natural geomorphic process that involves the downward movement of geological materials under the influence of gravity. This activity changes the geomorphic landscape and contributes intermittently or continuously to the sediment input of downstream rivers [95]. It is a crucial process in the dynamic earth surface environment on various scales. Mass movement ranges from earth surface processes to deep landslips and occurs on various temporal scales, usually in a hillslope environment [96]. The causes of hillslope failure can be classified into triggering and susceptibility factors. Triggering factors constitute the ultimate impetus for hillslope instability [97] and rainfall is the most common triggering factor for hillslope failure [17,98]. Hillslope failure risk factors relate to long-term potential changes, which are usually associated with large-scale spatiotemporal processes [99–102].

The majority of studies on the hydrological processes that cause hillslope failure have focused on the effects of small-scale hydrological processes and soil hydraulic properties, including theoretical development, soil hydraulic tests, geotechnical engineering, and physical model modeling techniques [96]. In extensive mountainous slope studies, rainfall thresholds are frequently analyzed according to statistical data [103,104]. Limited monitoring data are included in empirical models for regional potential analysis using remote sensing- and GIS-based technologies [105–107]. Increasing attention has recently been given to spatiotemporal potential analyses of hillslope stability based on physical processes [108,109]. Potential analyses based on physical processes rely on parameters related to the hydrology, geomorphology, and hydraulic properties of the geotechnical materials. However, the translation of indoor test data into hillslope scale or catchment scale data is often challenged by heterogeneity and large-scale hydrological processes and is influenced by spatiotemporal evolution and geomorphic properties. Emerging hydrogeomorphology [110] and hydrology [111] have gradually examined the influence of these mechanisms in dynamic earth models. Bogaard and Greco (2016) [20] provided an interdisciplinary summary of landslide hydrology at various scales (pore, hillslope, and catchment scales), contending that the understanding and quantifying of hydrological processes of landslides depend on determining the mechanisms of water filling, storage, and drainage on hillslopes. Based on observational data, many studies have investigated the hydrodynamics of hillslope soil and development, as well as the distribution of groundwater response during rainfall events [13,112–115]. However, determining the physical causality between hydrological processes on various scales and triggering mechanisms (such as spatial variation, long-term geomorphic change and weathering processes, and geomorphic features), as well as discussing the influence of vegetation and species on subsurface runoff, is a challenge in studies of rainfall-induced hillslope failure [54]. To gain insight into the mechanisms and processes of hillslope hydrology and stability, investigations on these topics include a variety of disciplines and technologies (such as field surveys, theoretical development, experimental methods, and analytical and modeling techniques) [15].

5. Challenges of Hillslope Hydrology and Stability

Rainfall-induced landslides are typically characterized by rapid or prolonged infiltration and relatively slow drainage, and the hydrological processes operating at different spatiotemporal scales have an impact on how frequently these landslides occur [116]. Landslides can change the hydraulic behavior of hillslope geological materials, including both shallow and deep movement. Integrated erosional processes (such as sediment transport of surface soil) that alter the subsurface structure and geomorphology are key to the evolution of mountainous environments [117]. Hillslope hydrology and stability have traditionally been the focus in hillslope research. The hillslope response is based on the dynamic earth system and ecological processes [14], atmospheric movement, soil and weathering layer environments, ecosystems, and tectonic and geomorphic evolution, which directly or indirectly affect the hillslope hydrology and stability at various spatiotemporal scales. Hillslope hydrology and stability are among the primary processes in critical zones [96].

There have been numerous studies on hillslope hydrology, including the conceptualization of hydrological runoff processes on hillslopes [118–120] and the analysis of forms and functions of hillslope hydrology based on flow observation [94,121]. However, understanding the mechanism underlying hillslope hydrology that triggers landslides remains a challenge [20]. This challenge is primarily due to the dynamic nature of hydrological processes, which depend on the complex interactions between rainfall characteristics, soil and bedrock properties, local geomorphology, and biosystems (Figure 3). Hillslope instability is promoted by such dynamic behaviors, specifically interactions between multiple features that have co-evolved on diverse spatiotemporal scales [14,20]. Rainfall infiltration and impermeable or permeable bedrock are local factors triggering hillslope failure [122]. Geohydrological processes are influenced by dominant flows and bedrock topography [123–126], and hillslope failure often occurs during hydrological interruptions. Therefore, to ensure hillslope stability, hydrological monitoring should focus on changes in soil moisture and pore water pressure. Early warning mechanisms and evaluation models should be developed for hillslope hydrology processes and stability. However, there have been no models in which hillslope stability is associated with complex hydrological processes, mainly because the hydrological mechanisms are distinct from those for landslides [20] and because of spatial variability. In situ monitoring of landslide regions is also challenging [127].

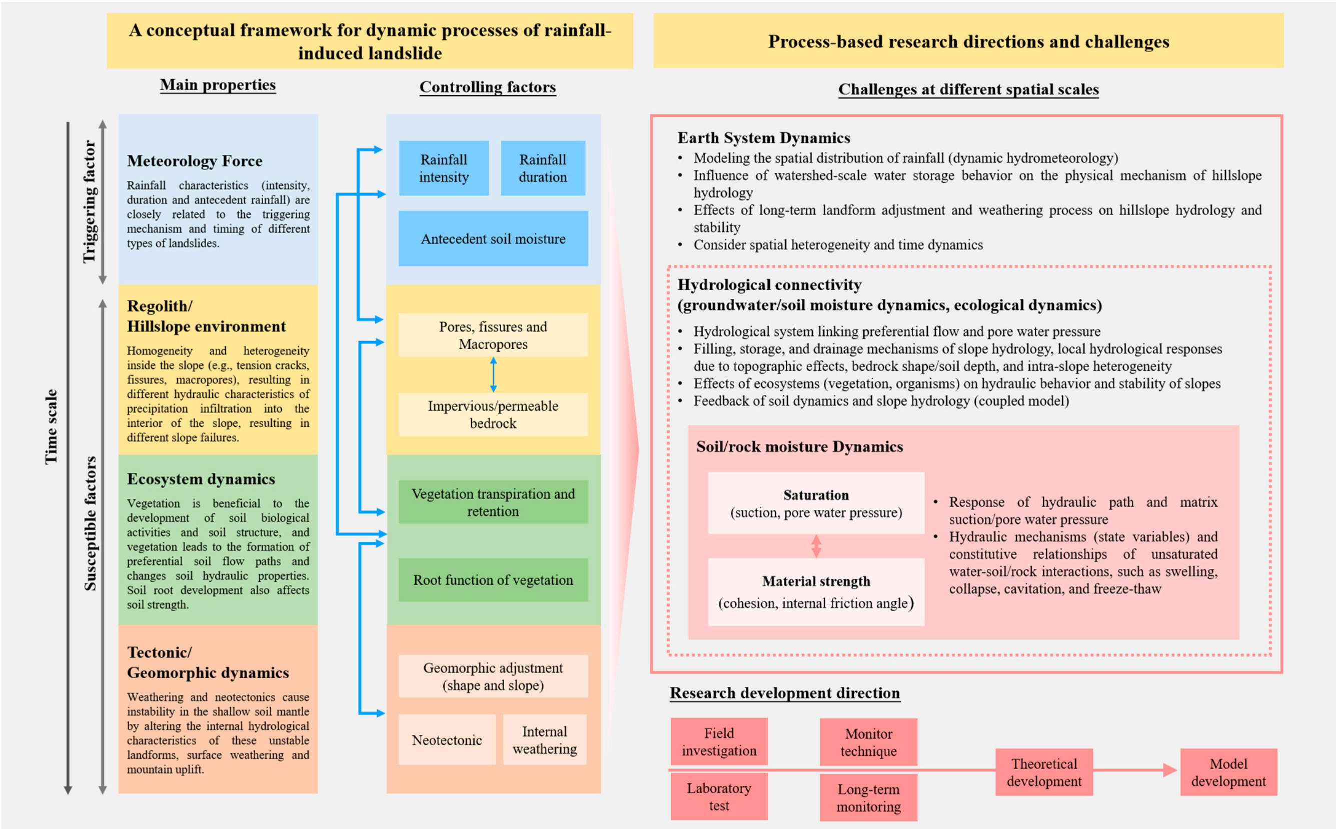

Figure 3. Dynamic processes and research challenges for hillslope hydrology and stability.

As a key determinant of hillslope hydrology, topography influences the formation of soil and weathering layers, the distribution of plants, and contributes to the spatial variation of regional energy and water. The degree of weathering of hillslopes determines the formation of soil, the structure of weathered rock debris [128], and the expansion of internal fissures [129], thus impacting the flow, path, and hydrochemical characteristics of water within hillslopes. Vegetation affects hillslope hydrology and runoff redistribution [130,131]. The development of plant roots affects soil biological activities and structure, promoting the formation of dominant flow paths in soil and changing the hydraulic properties of soil [132,133]. Additionally, the development of plant roots affects soil strength [134]. Plant roots can improve soil hydraulic conductivity, and thick vertical roots can greatly increase soil cohesion and shear strength, indicating that the impact of plant roots on hillslope stability is a result of the hydraulic conductivity and shear strength of soil–root complexes [135]. Vegetation plays a crucial role in changing the soil water content and geohydrology and can reinforce shallow soil [136]. The transformation of hillslope vegetation may have long-term effects on hillslope stability [116,137]. Existing studies on vegetation and hillslope stability have been conducted on a small scale, focusing on species, and vegetation has rarely been considered in the long-term evaluation of hillslope stability.

Hillslope hydrology can effectively control the timing, location, and scale of landslides and is influenced by small- to large-scale dynamic processes. It is therefore necessary to understand the interactions among atmospheric motion, soil and weathering layers, ecosystem dynamics, and tectonic or geomorphic dynamics. Moreover, the implications of hydrologic processes at appropriate scales on hillslope hydrology and stability must be assessed. Spatial rainfall patterns can be combined with hillslope evaluation models to improve landslide warnings and potential analyses [138–140]. The spatiotemporal resolution of rainfall events can be increased by combining a limited number of rainfall stations with suitable monitoring technologies (such as radar, infrared, and microwave monitoring) [141–143]. Changes in soil moisture and near-surface unsaturated soil make it easier to understand hydrological fluxes and flow pathways and their effects on biogeochemical dynamics [63,144,145]. Moreover, many studies have demonstrated that surface–subsurface runoff connectivity drives the hydrological response of hillslopes [146–149]. Small-scale geo-hydraulic behavior studies must be strengthened and integrated with in situ information to facilitate a better understanding of the physical mechanism underlying water–soil interactions in near-surface partially saturated areas and aid in the resolution of geotechnical issues [150]. Despite the challenges in the description of physical mechanism variables (such as matric suction, effective stress, and independent stress variables), a breakthrough in basic concepts allows attention to be given to the description of behaviors such as soil classification, swelling, collapse, cavitation erosion, and freeze–thaw [151]. Studies on water flow and reserves in mountain systems have recently been initiated; quantifying water fluxes provides insight into the hydrological balance of hillslopes as well as the hydraulic paths of landslides [54].

Consistently monitoring and collecting sufficient data over a suitable spatial range and time is necessary to identify the key processes affecting hillslope hydrology and stability [152]. Key processes can be incorporated into physical evaluation models to improve hillslope stability evaluation and landslide prediction. Hillslope safety and stability have always been the focus of attention in hillslope studies because they are important to the safety of human life and property. It is therefore crucial to determine the mechanism and causes of hillslope hydrology and stability, to accurately identify potential landslide-sensitive areas, and to provide a reference for landslide warnings and evaluation [96].

6. Promoting the Research of Hillslope Hydrology and Stability in Taiwan

Critical zone science is process-orientated and highlights structures, functions, and evolution [63]. However, studies on critical zone functions and services are still in the theoretical exploration stage [58,68]. Hillslope hydrology and stability are associated with surface and subsurface hydrological processes [15]. Their interactions with and effects on slope stability are crucial for human safety. Critical zone science and hillslope hydrology and stability share the common ground of spatial heterogeneity, continuous evolution, and relevance to ecosystem services. Both also rely on interdisciplinary perspectives and approaches, monitoring strategies, and model analyses of integrating and coupling processes. Comprehensive studies of these issues contribute to the progress in critical zone science and hillslope hydrology and stability, as well as breakthroughs in the studies of hillslope hydrology and stability in Taiwan.

6.1. Process-Based Integrated Monitoring Strategy

The vertical cycle of bottom groundwater to the top of the vegetation canopy is specifically covered by critical zone research, along with the hydrological processes connected to surface and subsurface structures formed across geologic time scales. Critical zone studies involve time scales associated with pedological, geomorphological, and geological processes [68]. Based on a review of watershed hydrological, hydrochemical, hydrogeological, and eco-hydrological studies, Brooks (2015) [87] identified that these subdisciplines of hydrology share a common knowledge gap in groundwater runoff and retention time. They argued that critical zone science can deepen the understanding of hydrologic regionalization processes and meet the following four challenges in the development of hydrological models: (1) determining the interactions between topography, lithology, vegetation, and water that control subsurface weathering and predict the subsurface structure; (2) quantifying the amount, retention time, and action paths of groundwater to better predict the availability of water for plants and the formation of rivers; (3) evaluating the role of topographic complexity when microclimatic change affects water demand; and (4) conducting goal-oriented observations on larger spatial scales to facilitate area-specific work on a regional scale. Critical zone hydrology combined with different sub-disciplines of hydrology can serve as a catalyst for new theories, observation techniques, and closure schemes across various spatiotemporal scales [153]. Cross-regional comparisons of groundwater reserves, hydrogeological structures, and climate in critical zones can improve long-term hydrological predictions for future climate scenarios. The question of common concern should be "how is the biogeophysical structure of critical zones associated with the volume, flow paths, and retention time of subsurface water?"

In situ observational data and interdisciplinary theories and tools are needed to measure the processes in critical zone science [62,154]. Scientific interest in critical zone studies is increasing as a result of advancements in remote sensing technologies and geophysical methods that have provided diverse ways of examining cross-scale critical zone studies [21]. Harpold et al. (2015) [155] reviewed the applications of Lidar technology in extracting three-dimensional surface features, as well as the feedback regarding its applications in identifying hillslope hydrological and ecological processes and its co-evolution on a landscape scale [156]. Parsekian et al. (2015) [157] reviewed the unique contribution of geophysical methods in capturing the features associated with the interactions between subsurface structure and properties, particularly in deep critical zone studies [86]. In addition to overcoming the limits of conventional direct measurements, remote sensing technologies and geophysical methodologies are characterized by their non-destructiveness, high spatial density, and temporal continuity. As a result, they can facilitate the understanding of cross-scale coupled processes and act as a tool for validating critical zone models. Despite this, they face the following technological challenges: (1) analyzing the relationship between measurement results and hydrogeological characteristics and (2) developing numerical methods for integrating various types of data to improve evaluation models [158–160].

Geophysical approaches have been widely used in studies of hillslope hydrology and stability [161,162] because of their advantages in spatial coverage and compatibility with remote sensing technologies and current monitoring systems [163]. In recent years, the integration of geophysical approaches has been universally applied in hillslope studies, specifically to evaluate the types of internal geological materials and structural properties [164–166], surface features and influence scope of landsides [167,168], surface tension properties [169], and hydrological processes inside hillslopes [170,171]. Whiteley et al. (2019) [172] reviewed the applications of geophysical methods in monitoring hydrologically induced hillslope failure and found that advancements in observation instruments, analysis methods, and modeling significantly improved the spatiotemporal variation in soil moisture dynamics and characteristics. Many studies have discussed how to calibrate geophysical measurement results based on hillslope-scale geotechnical data [173,174] and have directly evaluated landslide potential and thresholds based on calibration results. By integrating geomorphology and geophysical methods, landslide modeling approaches have been developed [175] to improve hillslope-scale monitoring and early warning capabilities. Geophysical methods face various problems, such as technological deficiencies (data inversion and signal processing), installation and monitoring costs, and quantitative associations with traditional geotechnical survey data [176]. However, hillslope-scale experiments and case studies remain the cornerstone for the continuous development of this science [177]. Process-based monitoring strategies and interdisciplinary monitoring technologies continue to have immense development potential because they can facilitate data collection and mechanistic analysis for studies of hillslope hydrology, stability, and critical zone processes.

In addition to interdisciplinary integration for critical zone monitoring, hydrogeochemical analysis techniques facilitate a better understanding of regional hydrological conditions [178–181]. The consistency of the variables can be observed by comparing the measurement results obtained using different techniques [182]. Hydrochemical observations of hillslope runoff show that studies of the hillslope C–Q relationship contribute to a better understanding of the structural evolution of critical zones [183]. However, the use of different measurement devices and calibration methods may produce different values for the same variable, thereby adversely affecting data comparisons. Data homogeneity (including data quality and format) is therefore crucial for data sharing [184]. CZO stations have used a theory–model–data integrated framework to supply open critical zone datasets, thus increasing the accessibility of critical zone data. However, the exchange of information across different data sharing systems has yet to be improved. Although monitoring resources are allocated to a few CZO stations, high-quality critical zone datasets can still provide the framework for conceptualizing experience-based processes and facilitating data sharing [185], such as a hydrology data sharing framework [186]. Moreover, developing data exchange standards is the goal of ongoing research.

6.2. Interdisciplinary Perspective

Interdisciplinary studies provide insights into critical zones and hillslope hydrology and stability. The driving factors for the response to hillslope hydrology and stability are interrelated [54], particularly in the atmosphere–vegetation–soil system. For example, vegetation influences hillslope hydrology and stability processes in a variety of ways, yet the majority of experiments and models for hillslope hydrology and stability did not take vegetation into account because it was not considered a dominant influencing factor in the past. Eco-hydrology provides a new perspective for investigating the hydrological mechanisms of ecosystem patterns, evaluating the potential relationship between spatial patterns in hydrological dynamics and ecosystems [187] and investigating the potential connection between isotopic observations of landscape features and hydrological responses [188]. Based on hydrology, this interdisciplinary integration connects pedology, landscape science, and other disciplines to promote studies and find solutions to soil- and water-related problems [111,189,190].

Numerous methodologies have been developed to describe hydrological processes [191,192]. Owing to the over-reliance on particular hydrological process theories and the absence of a single theory to explain inter-process interactions and feedback, numerous complex hydrological models have emerged and are now subject to a high level of parameter uncertainty [193,194]. In recent years, studies on hillslope hydrology have tended to unify hydrological processes [193,195,196]. As a thorough analysis of the interactions and feedback between hydrologic systems has been conducted, spatial heterogeneity is now accepted as a normal state rather than characterizing or identifying the heterogeneity and complexity of rainfall runoff and mass movement. This implies that spatial heterogeneity arises from the action of a certain mass, energy, and fluxes, rather than certain stochastic processes [68,197].

The "unified system" concept in critical zone science expands the in situ observation scale to a larger spatial scale, and this deep coupling feature provides a new approach for the development of frontier sciences [57,63]. A study by Vogel et al. (2013) [198] has focused particularly on hydrodynamics based on physical processes, emphasizing the fundamental role of water in numerous soil processes (such as the correlation between soil type, soil structural characteristics, vegetation, and use and cycling of organic matter), and argues that the relationship between hydrology and other disciplines can serve as a bridge between different disciplinary fields. Using dissolved organic matter, Jansen et al. (2014) [199] established relationships between terrestrial and aquatic systems in critical zones, including nutrient cycling, microbial action, and diagenesis. The development of critical zone science demonstrates the growing interest in the interactions and feedback between anthropogenic and environmental processes. A good understanding of such interactions necessitates interdisciplinary collaborations.

The integration of scientific studies is the key to future research. Innovations in critical zone science have broadened the range of disciplines and encouraged the exploration of scale impacts [21]. Novel concepts and approaches can jointly facilitate the advancement in critical zone science as well as studies of hillslope hydrology and stability [96]. It is therefore imperative to develop new mechanisms to encourage interdisciplinary integration and an integrated system to explore the interactions between mechanisms and their processes in critical zones.

6.3. Developing a Scalable and Coupled Analysis Framework and Model

On the critical zone scale, studies on hillslope hydrology and stability merely emphasize observation instruments, site conceptual models, and simulations [89]. On the hillslope scale, highly complex physics-based finite models are dominant among the models for hillslope hydrology and stability, and they can describe the interactions between processes and predict the time and form of hillslope failure. However, nonlinear matrix-dominant flow processing is extremely complex and requires a description of dynamic hydrological responses through different conceptual models [200]. Many dominant flow models have been developed [201,202] and applied to the evaluation of hydrological responses to dominant flows [203]; however, such models use unmeasurable calibrated parameters. Moreover, associating the hydraulic paths of dominant flows with the pore water pressure is challenging [20]. Although researchers have realized the significance of dominant flows in hillslope hydrology and stability, studies on dominant flows and their effects on landslides are scarce, which restricts our understanding of hillslope failure mechanisms. Coupled soil deformation and hydraulic properties have always been controversial research topics [204–208]. In geotechnical applications, existing physical models can be applied to the study of fissures by adjusting the mesh and boundary conditions [209–211]. However, this simplified analysis pattern can barely address complex fissure systems and higher order analysis models are urgently required.

Complex physical models frequently struggle with uncertainty, in situ application, and model parameter selection, largely because the integration of experimental and modeling efforts needs to be improved [212]. Simple models can represent hillslope hydrology and stability for a single rainfall event, but complex models can better describe the dynamic behavior within hillslopes [213]. To calibrate and validate these models, long-term experimental and monitoring data are essential.

Critical zone studies require coupling models with spatiotemporal scaling and process interactions to improve understanding and management of near-surface systems [24]. The fundamental goal of the scaling of the model is to illustrate the interactions between processes at various scales, which are typically highly nonlinear and dynamic [214]. Each scaling process has its own restrictions and thresholds, and scaling is performed by introducing rules and algorithms into a system [215–217]. Model coupling directions contain process-based, dimension-based, and systematic coupling guidance frameworks [88]. Earth system models (ESMs) are crucial for investigating and predicting Earth systems [218]. ESMs are mainly built on large, simulated grid cells (grid scale: 20–200 km), which can simulate the interactions between the atmosphere, land, and oceans in physical, chemical, and biological ways, but cannot describe the fundamental processes of slope hydrology on a finer scale. ESMs are derived from the general circulation model. Hence, Clark et al. (2015) [219] suggested ways to improve hydrological processes in ESMs. The fundamental goal of CZ-ESMs is to investigate how the hillslope structure affects large-scale water, energy, and biogeochemical fluxes, determine these mechanisms through ESMs, and identify key knowledge gaps while extending the hillslope scale [89]. Although many hypotheses are yet to be verified and many questions are yet to be answered through further studies [86], this two-way exchange of knowledge is beneficial to scientific progress and provides the impetus for the investigation of critical zone science and hillslope hydrology and stability. Recently, researchers have used large-scale models to evaluate social issues, such as soil and water safety and management [220], proving the significance of scalable coupling models.

7. Conclusions

Owing to its complex geological structure, monsoon climate, and rapid weathering and erosion, rainfall-induced hillslope failure is a common type of hillslope disaster in

Taiwan. Ascertaining the mechanisms of hillslope hydrology and stability and identifying the time and scope of influence of landslides remains a challenge. Hillslope hydrology and stability are two key processes in critical zone science that link surface and subsurface processes. They are distinguished by their dynamic nature, high heterogeneity, and continuous development, and are closely related to ecosystem services. To address the challenges of hillslope hydrology and stability in Taiwan, we reviewed the advancements, applicability, and common problems related to hillslope hydrology, stability, and critical zone science. We also presented a process-based integrated monitoring strategy, an interdisciplinary perspective, and a coupled analytical framework and model, thus contributing new knowledge and insights based on monitoring data, mechanisms, and processes. This study enriches the body of knowledge on hillslope hydrology and stability and facilitates the management of hillslope safety through knowledge integration and model-based prediction.

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