Shared Landscapes, Shared Futures: Visual Landscape Evolution Modelling for Community Stewardship

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Abstract

Landscapes are living systems whose long-term trajectories carry profound cultural, spiritual, and resource significance for Indigenous communities worldwide. Yet the tools capable of simulating long-term landscape change, such as numerical landscape evolution models, remain largely inaccessible outside specialist research communities, constraining their potential contribution to community-led stewardship and land management decision-making. This paper introduces LandEvolve, a landscape evolution modelling framework developed entirely within a free and open-source software ecosystem, designed to extend process-based geomorphic simulation into community-accessible settings. Built upon the Landlab platform, it integrates a Python-based graphical user interface developed using the Qt framework and supporting libraries, enabling users to configure and execute simulations such as fluvial incision, hillslope diffusion, and sediment transport without requiring programming expertise or specialist technical knowledge. The tool and its source code will be made publicly available to enable reuse, modification, and community-driven development. As a primary case study, LandEvolve is co-developed with Māori Indigenous communities of Aotearoa New Zealand through an iterative participatory process in which Indigenous knowledge directly informs scenario design and model configuration. This engagement is grounded in geoethical principles and data sovereignty frameworks, ensuring that culturally sensitive information remains under community governance and that communities retain meaningful agency throughout the modelling process. Interactive two-dimensional and three-dimensional visualisation capabilities further support accessible, dialogue-based exploration of landscape futures, illustrating how open-source geospatial tools can be repositioned as instruments of intergenerational stewardship that place long-term landscape futures in the hands of the communities who depend on, and hold responsibility for, them.

1. Introduction

Indigenous communities worldwide maintain multigenerational relationships with their ancestral lands, oriented toward long-term stewardship rather than short-term utility (Berkes and Berkes, 2008). The *Māori* communities of Aotearoa New Zealand exemplify this depth of engagement. Through *kaitiakitanga* (guardianship of the natural world for future generations) and *whakapapa* (the relational genealogy linking people, land, and ecological processes), *Māori* knowledge systems have long engaged with landscape change across timescales extending well beyond individual lifespans (Harmsworth and Awatere, 2013, Tipa and Teirney, 2006). Rivers, hillslopes, and coastal margins are understood as dynamic, living entities whose behaviour through time carries direct implications for cultural continuity, resource availability, and the integrity of *wāhi tapu* sacred sites (Salmond, 2014, Te Awa Tupua (Whanganui River Claims Settlement) Act, 2017).

This multigenerational perspective aligns with geomorphological reality: landscapes are not static, and the processes that shape them, including fluvial incision, hillslope diffusion, sediment transport, and tectonic adjustment, operate continuously across timescales spanning decades to millennia (Willgoose, 2005). These processes reorganise drainage networks, redistribute sediment, and alter erosion regimes in ways that govern long-term water quality, flood hazard, land productivity, and the preservation of culturally significant landforms (Tucker and Hancock, 2010). Non-linear feedbacks inherent to coupled geomorphic systems mean that short-term observations are often insufficient to anticipate long-term trajectories, particularly under changing climatic and land-use conditions (Murray et al., 2009), underscoring the need for physically based modelling tools that remain interpretable and usable by non-specialists.

Numerical landscape evolution models (LEMs) simulate physical processes such as erosion, sediment transport, deposition, and tectonic uplift using elevation data and process-based formulations, enabling investigation of landscape evolution under varying environmental conditions through time (Coulthard, 2001, Tucker and Hancock, 2010). Platforms developed for this purpose range from flexible, modular frameworks such as Landlab (Hobley et al., 2017) to more integrated systems such as CAESAR (Coulthard et al., 2013) and SIBERIA (Willgoose et al., 1991), each differing in process representation, coupling strategy, and user interaction design. Although most are publicly accessible, their use remains largely confined to specialised research communities (Temme et al., 2022): development is typically driven by specific research groups centred on the original developers, and the resulting familiarity and accumulated expertise reinforce continued use of established models while raising the barrier for new users.

Despite the presence of graphical user interfaces (GUIs) in some platforms, such tools are often tailored to specific workflows and insufficiently flexible for generalised use. Their application therefore tends to be concentrated in domains such as mining (Hancock et al., 2000, Evans and Willgoose, 2000, Hancock et al., 2015, Hancock and Martin Duque, 2024), where established workflows, calibration datasets, and domain expertise support routine use. Outside these contexts, transferring and adapting LEMs to new environments or management questions is often non-trivial, requiring site-specific parameterisation. Effective application of LEMs therefore still typically demands substantial expertise in programming, numerical methods, and geomorphic processes, with usability remaining secondary to numerical rigour and constraining broader adoption in land management and planning.

Addressing these limitations requires not only improved usability, but a more fundamental reconsideration of how LEMs are developed and for whom. Participatory and co-produced modelling approaches offer a path forward by incorporating situated, place-based, and Indigenous knowledge directly into the modelling process (Lopez, 2020, Zellner, 2024), enabling stakeholders to shape key stages of model development, including research questions, landscape drivers, and future scenarios, rather than only interpreting outputs. Interactive tools such as scenario-based visualisation and participatory mapping interfaces further support this by allowing communities to explore alternative landscape trajectories iteratively and dialogically (Sheppard, 2015, Miller et al., 2020). Evidence from applied environmental management suggests that integrating local and Indigenous knowledge within modelling workflows improves the credibility and contextual realism of long-term projections while strengthening the legitimacy of resulting management strategies (Hemmerling et al., 2020, Brown and Gabrys, 2026).

Building on these approaches, this study investigates how community engagement can be integrated into landscape evolution modelling, focusing on Indigenous communities and the stewardship of ancestral lands. It aims to move beyond conventional model–user separation by embedding co-production principles into the modelling process, supporting community-informed representations of landscape change and enhancing the applicability of LEM outputs for land management and decision-making. To operationalise this, we develop LandEvolve, a GUI-based landscape evolution modelling framework that extends process-based LEMs beyond specialist research environments into more accessible, interactive settings. The framework is built on Landlab, selected for its modular, component-based architecture, active open-source community, and demonstrated applicability across diverse geomorphic contexts (Hobley et al., 2017, Barnhart et al., 2020). Its Python-based implementation enables individual process components, including hydrological routing, fluvial incision, sediment transport, and hillslope diffusion, to be flexibly combined and reconfigured without modifying the underlying codebase, supporting adaptable, scenario-driven exploration. The graphical user interface is implemented using Qt for Python, chosen for its seamless integration with the Python ecosystem, enabling direct coupling with Landlab and integrated interaction within a single application environment (Summerfield, 2013).

The application provides a user-centred interface for configuring and running landscape evolution simulations without programming expertise, while integrated 2D and 3D visualisations further enhance accessibility beyond specialist research communities. Community engagement is undertaken in Aotearoa New Zealand, particularly with Māori iwi (tribal nations) and hapū (kinship-based sub-tribal groups with enduring relationships to specific landscapes), through a staged, iterative co-production process culminating in a freely accessible community tool that communities can use independently to explore landscape change scenarios without advanced technical knowledge. This dialogical, collaborative framework embeds geoethical principles throughout, including respect for Indigenous knowledge systems, recognition of Indigenous authority over ancestral landscapes, and support for intergenerational stewardship, positioning landscape modelling as a shared interpretive and decision-support practice rather than a unidirectional technical exercise.

Methodological transparency is ensured through a fully reproducible workflow implemented exclusively using free and open-source software, with no proprietary dependencies. Model code, configuration files, and non-sensitive demonstration datasets are made publicly available under the permissive MIT License to support independent verification and reuse; the source code is openly accessible at (Piyathilake, 2026). This openness is, however, qualified in accordance with Indigenous data sovereignty principles articulated in frameworks such as Te Mana Raraunga and the CARE Principles (Te Mana Raraunga, 2018, Carroll and Garba, 2020): data derived from Māori ancestral lands, cultural knowledge, and community engagement processes remain under the governance and authority of participating communities. Public dissemination is therefore limited to the generalised modelling framework and non-sensitive materials, maintaining transparency and accessibility without compromising cultural authority, data sovereignty, or community stewardship.

The remainder of this paper is structured as follows: Section 2 reviews participatory modelling for land management decision support; Section 3 outlines the methodology; Section 4 describes the development of LandEvolve; Section 5 presents initial results through a case study; and Section 6 discusses limitations, future work, and conclusions.

2. Related Work

Participatory modelling is increasingly established in environmental and landscape science as a means of integrating stakeholder knowledge into simulation-based decision support (Voinov and Bousquet, 2010, Gray et al., 2018). Approaches range from facilitated group model building to co-produced scenario development, improving model legitimacy, transparency, and uptake among non-specialist audiences (Eker et al., 2018, Hare et al., 2003). Most participatory modelling applications are implemented within Geographic Information Systems (GIS) or agent-based modelling (ABM) frameworks, whose relatively low technical barriers and visual interfaces suit collaborative work (Bousquet and Le Page, 2004, Laniak et al., 2013). Systems dynamics models, Bayesian belief networks, and ABMs have all been employed within participatory contexts to support land management and catchment planning (Voinov et al., 2016, Prell et al., 2007), while physically based simulation models, particularly those representing complex geomorphic processes, have remained almost entirely outside this paradigm.

Physically based LEMs such as CAESAR-Lisflood (Coulthard et al., 2013), Landlab (Hobley et al., 2017), and SIBERIA (Willgoose et al., 1991) are capable of reproducing long-term catchment dynamics through the mechanistic coupling of fluvial erosion, hillslope processes, sediment transport, and hydrological response. Their strengths lie in process-based realism, spatially distributed prediction, and the capacity to simulate geomorphic responses to forcing perturbations such as climate or land-use change (Tucker and Hancock, 2010, Coulthard and Van De Wiel, 2017). Nevertheless, these models have been developed primarily as research instruments, calibrated and operated by specialist scientists, with interaction beyond wider user communities typically limited to expert consultation or post-hoc sensitivity analysis (Skinner et al., 2018); there are very few documented instances of LEMs deployed in genuinely participatory or co-produced modelling exercises. Where stakeholder engagement has been attempted in geomorphic or catchment modelling, it has generally been mediated through simplified model surrogates, reduced-form emulators, or GIS overlays rather than direct engagement with full-process LEM frameworks (Baartman et al., 2013, Oreskes et al., 1994).

The gap between participatory modelling practice and physically based LEMs reflects structural and epistemological barriers that have received insufficient critical attention. Computationally, most LEMs impose substantial runtime demands and require careful parameterisation of physically meaningful quantities—hydraulic roughness, erodibility coefficients, grain-size distributions—that are neither intuitive nor accessible to non-specialist stakeholders (Tucker and Hancock, 2010). Equally significant is the epistemological mismatch between the qualitative, place-based, tacit knowledge stakeholders contribute to participatory processes and the quantitative, spatially continuous representations underpinning physically based geomorphic simulation (Voinov and Bousquet, 2010, Prell et al., 2007). Most LEM frameworks also lack graphical user interfaces, interactive scenario-testing environments, or real-time visualisation capabilities that would facilitate collaborative engagement (Hobley et al., 2017, Gray et al., 2018). Unlike the broader environmental modelling community, where tools such as Open Modelling Interface (OpenMI) and QGIS plugin ecosystems have lowered barriers to interdisciplinary use (Laniak et al., 2013), LEM development has prioritised computational performance over accessibility—a significant, largely unaddressed opportunity for interactive, co-production-ready LEM frameworks that preserve physical process integrity while enabling meaningful stakeholder participation in scenario development and landscape management planning (Eker et al., 2018, Voinov et al., 2016).

3. Methodology

The study adopts an iterative, participatory methodology to develop a landscape evolution modelling framework with GUI capabilities, integrating technical development with community-informed co-design (see Figure 1).

The initial phase focuses on building a stable LEM framework that incorporates physically based landscape evolution processes within an accessible GUI, reducing the technical barriers of conventional LEMs and enabling interactive exploration of landscape change scenarios by non-specialist users.

Once a functional prototype is established, it will be introduced to Indigenous communities through existing relationships, trusted networks, and academic collaborations, to demonstrate the tool's capabilities, limitations, and potential applications in an accessible, exploratory manner rather than to initiate full co-development.

Engagement will proceed only where there is mutual interest and willingness to participate. Early collaboration will involve joint work between communities and researchers on model use, parameterisation, and scenario development, recognising the technical complexity of LEMs; rather than independent configuration, the emphasis will be on guided interaction and collaborative interpretation of outputs. Discussions will focus on locally relevant environmental concerns, landscape histories, future aspirations, and culturally significant factors that inform scenario design and refinement.

Feedback from these engagements will inform iterative improvements to usability, interface design, scenario representation, visual communication, and modelling functionality, refining the framework over time to support progressively more accessible and autonomous use.

Overall, the methodology follows an iterative co-design approach in which technical development and community engagement continuously inform one another, producing a freely available, community-oriented tool for exploring landscape change scenarios and engaging with environmental planning in locally meaningful ways.

4. Technical Implementation of the Modelling Framework

LandEvolve is a modular, desktop-based landscape evolution modelling framework built entirely from free and open-source scientific and geospatial software libraries. It adopts a layered architecture separating user interaction, application logic, and numerical simulation to enhance maintainability, extensibility, and long-term reuse of the core modelling engine independent of the graphical interface.

4.1 System Architecture

The framework follows a layered design comprising the user interface, controller, service, engine, and data layers (Figure 2), enabling independent development, testing, and extension of system components.

The user interface layer, implemented using PyQt6 (Riverbank Computing Limited, 2021), provides functionality for configuring simulations, executing model runs, and visualising outputs; user inputs are passed to the controller layer, which translates interface events into structured application requests. The service layer coordinates application workflows, including simulation setup, execution, and retrieval of results, ensuring consistent handling of modelling operations across the system.

At the core of the framework is the simulation engine, fully decoupled from the interface and persistence layers and built on the Landlab landscape evolution modelling library, implementing key geomorphic processes such as erosion, sediment transport, flow routing, and hillslope diffusion (Barnhart et al., 2020). This separation ensures the numerical engine remains reusable outside the application context.

4.2 Data Management and Persistence

Data persistence is managed using an object-relational mapping approach via SQLAlchemy (Bayer, 2012), with SQLite (Hipp, 2024) as the underlying database, supporting reproducible storage of simulation configurations, parameter sets, and outputs. Geospatial data handling is supported through Rasterio (Gillies et al., 2013) and GeoPandas (Jordahl et al., 2020), enabling processing of raster (GeoTIFF) and vector (Shapefile) formats commonly used in geomorphic and spatial analysis workflows.

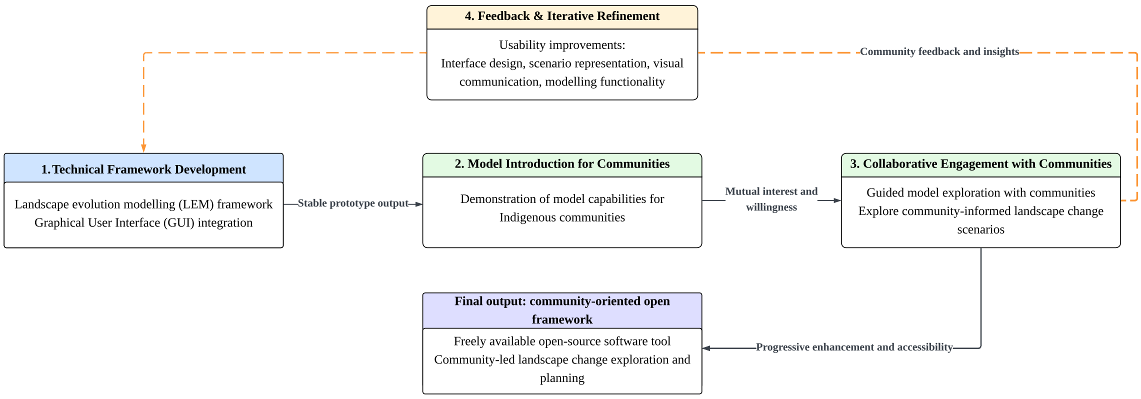
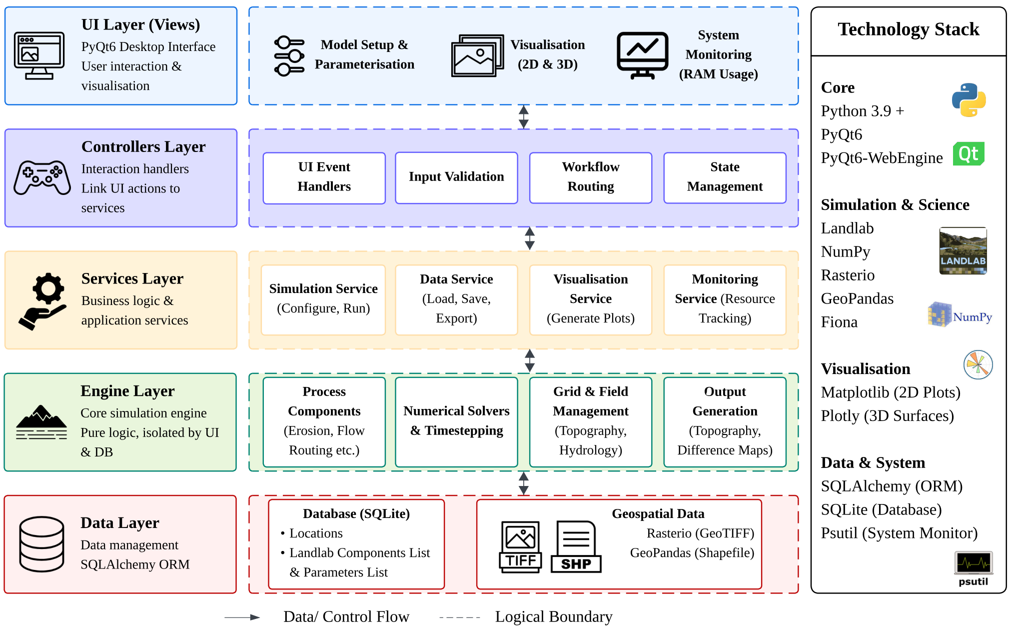


Figure 1. Conceptual Methodology Framework.



User Interface (UI), Database (DB), 2-Dimensional (2D), 3-Dimensional (3D), Random Access Memory (RAM), Object-Relational Mapping (ORM)

Figure 2. LandEvolve V1 (Version 1) Modelling Framework - Layered Architecture.

4.3 Scientific Computing and Model Components

Numerical computations are performed using NumPy (Harris et al., 2020) for efficient array-based representation of terrain surfaces and model states. The framework leverages Landlab components to simulate key landscape evolution processes, including fluvial incision, sediment transport, hydrological routing, and diffusive hillslope processes, operating on structured grids across spatial and temporal scales ranging from short-term landscape adjustments to long-term geomorphic evolution.

4.4 Visualization and Interaction

Model outputs are visualised using Matplotlib (Hunter, 2007) for static representations of elevation change and terrain evolution, and Plotly (Plotly Technologies Inc., 2015) for interactive three-dimensional exploration of evolving landscapes. Interactive outputs are embedded within the desktop interface using PyQt6-WebEngine to support iterative model exploration.

4.5 System Monitoring and Performance

System performance and memory usage are monitored using Psutil (Rodola, 2009), enabling runtime tracking that is particularly important for high-resolution grids and long-duration simulations, ensuring stability under computationally intensive workloads.

5. Preliminary Results & Analysis

5.1 Overview of LandEvolve Version. 1

LandEvolve Version 1 implements a click-and-configure graphical workflow for landscape evolution simulations, enabling users to define and execute model scenarios without programming expertise. Upon launching the application, users select a study area through a region-of-interest interface, after which an appropriate digital elevation model (DEM) is automatically retrieved from a curated set of pre-registered datasets, managed via a local SQLite database that stores file locations and metadata and dynamically loads them into the interface as selectable options. Users can then choose from available spatial resolutions and define key simulation controls, including total simulation duration (years) and model timestep, which governs the temporal discretisation of geomorphic process updates. The selected terrain is visualised in both 2D and 3D, with DEM boundary conditions also displayed to support informed model setup (interface screenshots and a short demonstration video are provided in Section A.2 of the supplementary material (Piyathilake et al., 2026)).

Simulation configuration is achieved through the selection and coupling of Landlab process components, including flow routing, erosion, and sediment transport modules. Version 1 integrates several core Landlab components, notably the SPACE (Stream Power with Alluvium Conservation and Entrainment) Large-Scale Eroder (Shobe et al., 2017), the Depth-Dependent Diffuser (Johnstone and Hilley, 2018), and the Flow Accumulation component (Braun and Willett, 2013). SPACE represents fluvial incision and sediment entrainment, transport, and deposition, while the Depth-Dependent Diffuser simulates hillslope sediment transport as a function of soil depth, and Flow Accumulation computes drainage pathways and upstream contributing areas from the DEM to enable hydrological routing. Although Version 1 requires users to explicitly specify model parameters, introducing some configuration complexity, this design prioritises transparency and flexibility during early-stage development; future iterations will reduce this burden through more guided, scenario-driven parameterisation.

The framework further supports spatially targeted analysis through shapefile-defined sub-regions, enabling users to track localised landscape change within larger catchments and generate time-series outputs of elevation change to quantify geomorphic evolution over time. After each simulation, input and output topographies are stored and compared, with elevation differences and surface change visualised in both 2D and 3D. Overall, LandEvolve Version 1 provides an interactive environment that abstracts key landscape evolution processes while preserving user control over model structure and parameterisation for exploratory analysis.

5.2 Modelling Workflow

Once the application achieved stable core functionality, initial experimental simulations were conducted. The following sections describe the initial analysis phase, including case study area selection, data acquisition and preprocessing, landscape evolution modelling, and community engagement.

5.2.1 Case Study Area Selection: Whiria Pā was selected as the case study area for the initial stage of the analysis due to the direct ancestral connection of one of the authors with the site and its people, which also facilitated meaningful community engagement. Whiria Pā is located on a conical hill approximately 19 m above sea level near Pakanae, along the Hokianga Harbour in the North Island of New Zealand, covering 0.189 km² at 35.491844°S, 173.411379°E (NZ Topo Map, 2025).

Culturally, Whiria Pā holds significant importance for Ngāpuhi (the largest Māori iwi in New Zealand) as a wāhi tapu (sacred place) and tūrangawaewae (ancestral place of belonging) strongly associated with ancestral identity and leadership, including the chief Pōmare I and his role in key early Māori–Pākehā interactions (Crosby, 2017, Orange, 1997, Salmond, 2014). Rather than an archaeological site alone, it is understood here as a living cultural landscape where historical narratives, identity, and connection to tūpuna (ancestors) remain embedded in place, embodying mana (prestige and authority) and the enduring legacy of Ngāti Manu.

Morphologically, the pā is characterised by a terraced landscape typical of human-modified hilltop settlements in the region, with terraces arranged along the slopes of the conical hill reflecting historical occupation and land-use patterns. The underlying geology is relatively uniform, consisting predominantly of micritic limestone bedrock (Mahurangi Limestone Group) (GNS Science, 2014). Detailed soil data are not available; land cover is primarily herbaceous vegetation (Manaaki Whenua - Landcare Research, 2016).

5.2.2 Data Aquisition: For the selected site, spatial boundaries were carefully delineated. The *.las* point-cloud data (the binary standard for storing LiDAR point clouds) were downloaded from OpenTopography and processed into 1 m resolution DEMs in GeoTIFF format using QGIS's *LAS to Raster* tool. The resulting DEMs are single-band 32-bit floating-point rasters referenced to the New Zealand Geodetic Datum 2000 within the NZTM 2000 projected coordinate system, with pixel values representing elevation in metres and embedded metadata including projection, extent, cell size, and band-level statistics. These DEMs serve as the primary topographic input for the Landlab modelling framework.

5.2.3 Landscape Evolution Modelling: At Whiria Pā, the distinctive human-made terraced landscape represents an important expression of cultural heritage, and the long-term evolution of these features under natural geomorphic processes was explored across multiple simulation durations (100, 1,000, and 10,000 years) using a 10-year timestep to capture progressive morphological evolution.

The site's evolution was simulated through erosion, hillslope diffusion, and flow-routing processes using the Landlab components described above, detailed further in Section A.1 of the supplementary material (Piyathilake et al., 2026), with flow routing incorporating a constant runoff rate under a uniform rainfall regime. Although this initial presentation of the findings has been received with interest, they cannot be presented here without further and wider permission granted by the Indigenous Māori community at this stage.

5.2.4 Community Engagement: Once preliminary modelling results were obtained, engagement was conducted with Indigenous communities associated with Whiria Pā through online meetings, due to logistical constraints on travel. During these sessions, model capabilities were demonstrated and key simulation outputs were presented, including the long-term evolution and gradual smoothing of the terraced landscape.

Strong interest was expressed in the modelling approach and its potential applications. The next step involves a collaborative process in which the model is further developed and applied jointly, particularly regarding land management implications, including how different vegetation conditions may influence the persistence of terraced forms, for example whether maintaining open grass-dominated surfaces versus allowing woody vegetation establishment alters landscape longevity. This process will support community use of the modelling tools while incorporating local knowledge, feedback, and priorities into future simulations and scenario design.

6. Discussion

This study presents an approach to Indigenous land stewardship that integrates geomorphic modelling within an accessible, community-led tool for exploring long-term landscape change. By embedding landscape evolution simulations within an interactive framework, the work demonstrates how scientific modelling can extend beyond technical analysis to become a medium for dialogue on intergenerational stewardship, placing long-term landscape futures more directly in the hands of the communities that live with, depend on, and care for these environments.

The first version of the tool demonstrates stable model performance and successfully captures key geomorphic processes governing long-term landscape evolution, reproducing meaningful landscape trajectories under simplified forcing conditions, establishing the initial technical viability of the system as both a modelling and communication platform and providing a foundation for scenario-based exploration and participatory engagement.

However, several limitations remain. A central challenge concerns parameter selection and calibration, particularly in community-facing contexts where users may lack specialist modelling expertise, so parameters must be both scientifically robust and intuitively interpretable. The current implementation also relies on simplified process representations and relatively basic visualisation outputs, which may constrain interpretability for non-technical users. Future work will address these issues through more intuitive, dynamic 3D visualisation and accessible parameterisation strategies, such as guided calibration tools and scenario presets co-designed with expert and community input, with continued engagement remaining critical to iteratively align the tool’s design and outputs with local knowledge systems, decision-making practices, and stewardship priorities.

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