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Preliminary Geoarchaeological Sensitivity Assessment of the Proposed Ancient Opak River Diversion Site Associated with Prambanan Temple, Indonesia

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Abstract

The Prambanan Temple Complex, one of Indonesia's UNESCO World Heritage Sites, was constructed during the 9th century CE within a landscape shaped by both natural processes and human intervention. The Siwagrha Inscription suggests that the Opak River was diverted to prevent its course from intersecting the sacred temple grounds, while previous geomorphological interpretations indicate that the proposed modification may represent a form of pre-industrial anthropogenic landscape intervention. Despite its potential significance for understanding long-term human–environment interactions during the Ancient Mataram period, the proposed ancient Opak River diversion has received limited attention from geoarchaeological and geoheritage perspectives. Its potential heritage significance is particularly relevant because the proposed site is situated within the broader landscape of the Jogja National Geopark and the Bayat Purba Aspiring Geopark, where geological, geomorphological, and cultural heritage values are increasingly considered within integrated landscape management. This study presents a preliminary geoarchaeological sensitivity assessment of the proposed ancient Opak River diversion associated with the Prambanan Temple Complex. The assessment integrates geoarchaeological significance, threats, and vulnerability using inscriptional evidence, geomorphological observations, and existing archaeological studies. The proposed diversion corridor obtained a high Geoarchaeological Significance Value (76.19%), reflecting its rarity and strong association with the archaeological landscape of Prambanan. It was assessed as having moderate threat (42.30%) and moderate vulnerability (44.44%), resulting in a low Geoarchaeological Sensitivity Value (24.67%). Although the low sensitivity value indicates that the proposed feature is not currently an immediate conservation priority, its high geoarchaeological significance warrants continued attention, particularly in view of ongoing anthropogenic modification of the river corridor. The results demonstrate the potential of a preliminary sensitivity assessment to identify geoarchaeological features that may contribute to integrated geoheritage management within geopark landscapes. However, the proposed ancient Opak River diversion remains an interpretation based on currently available inscriptional, geomorphological, spatial, and archaeological evidence and requires further multidisciplinary investigation for empirical validation. This preliminary assessment therefore provides a baseline for future geoarchaeological research and for considering the proposed feature within the broader geoheritage and cultural-landscape management frameworks of the Prambanan World Heritage, Jogja National Geopark, and Bayat Purba Aspiring Geopark landscapes.

1. Introduction

The Prambanan Temple Complex, located northeast of Yogyakarta, Indonesia, is the largest Hindu temple complex in the country and has been recognised as a UNESCO World Heritage Site for its outstanding cultural significance. According to the Siwagrha Inscription, the complex was commissioned during the reign of Rakai Pikatan in the ninth century CE (Ibrahim, 1996). Since its first scientific documentation by C.A. Lons in 1733 and subsequent archaeological investigations by H.C. Cornelius and later scholars, research on Prambanan has predominantly focused on its architecture, sculpture, religion, epigraphy, and the political history of Ancient Mataram (Kempers, 1985; Soejono,

1990; Santiko, 1992). Consequently, the geoenvironmental setting that supported the construction of the temple complex has received considerably less scholarly attention.

One of the most intriguing pieces of evidence concerning the environmental history of Prambanan is preserved in the *Siwagrha* Inscription, dated to 856 CE. De Casparis (1956) used this inscription to reconstruct the chronology of the temple's construction, while Tjahjono and Widianto (1994) highlighted a particular passage, *"Lwāh ya inalih hakén apaniyānid ik palmahan"*, which has been translated as indicating that the river flow was diverted because it intersected the temple grounds. Combined with geomorphological observations, this inscription has been interpreted as suggesting that the Opak River may have been modified or diverted during the construction of the temple complex (Tjahjono & Widianto, 1994). However, the available evidence does not yet provide direct geoarchaeological verification of this proposed intervention. Thus, the ancient Opak River diversion should be regarded as a proposed and interpretable landscape modification, rather than an empirically established historical fact.

Human modification of river systems constitutes one of the most important forms of anthropogenic geomorphology, reflecting long-term interactions between societies and the abiotic environment. Ancient river diversions not only record past engineering practices and water-management strategies but also preserve evidence of landscape transformation that is valuable for understanding geoheritage, anthropogenic geomorphology, and the anthropocene (Nir, 1983; Szabó, 2010; Erlandson & Braje, 2013; Braje & Erlandson, 2013; Foley et al., 2013; Lewis & Maslin, 2015; Crofts et al., 2020). When associated with archaeological monuments, these modified landscapes may represent geoarchaeological heritage, integrating geological, geomorphological, and archaeological values within a single landscape. In the case of Prambanan, the proposed Opak River diversion is potentially significant because it may represent an example of pre-industrial anthropogenic modification of a fluvial landscape undertaken in association with monumental construction. Nevertheless, this potential geoarchaeological attribute has received little scholarly attention since the interpretation proposed by Tjahjono and Widianto (1994), particularly from the perspectives of geoarchaeological significance, vulnerability, and conservation. This knowledge gap has consequently limited its consideration in conservation planning, geoheritage assessment, and archaeological landscape management.

The potential significance of the proposed Opak River diversion is further reinforced by its geographical and heritage context. The Prambanan Temple Complex and its surrounding landscape form part of a broader region in which geological, geomorphological, and cultural heritage values are increasingly integrated within geopark-based approaches to landscape management. The proposed diversion corridor is situated within the Jogja National Geopark and within the broader landscape associated with the Bayat Purba Aspiring Geopark, linking the archaeological landscape of Prambanan with wider efforts to recognise and conserve geological and geomorphological heritage. This setting provides an important opportunity to consider the proposed river diversion not merely as an archaeological feature, but as a potential geoarchaeological heritage attribute that connects cultural remains with the physical processes and anthropogenic transformations of the landscape. However, its potential contribution to geoheritage and geopark management has not yet been systematically assessed.

From a contextual archaeological perspective, the Prambanan Temple Complex should therefore be understood not only as an assemblage of monumental structures but also as an archaeological landscape whose development was closely associated with its environmental setting, technological adaptations, and cultural practices (Hodder, 1986). The *Siwagrha* Inscription provides an important historical reference to a possible river diversion, while the geomorphological configuration of the Opak River provides a spatial and physical context for interpreting this possibility. Together, these sources of evidence provide a basis for identifying a proposed geoarchaeological feature that warrants further investigation. However, the absence of systematic geoarchaeological assessment and direct empirical validation currently limits understanding of its scientific significance, conservation condition, and potential threats.

This study therefore presents a preliminary Geoarchaeological Sensitivity Assessment of the proposed ancient Opak River diversion associated with the Prambanan Temple Complex. Rather than attempting to establish the historical certainty of the river diversion, the study evaluates the conservation significance of the interpreted feature based on the available inscriptional, geomorphological, spatial, and archaeological evidence. Specifically, the study aims to (1) assess the geoarchaeological significance of the proposed Opak River diversion; (2) evaluate the natural and anthropogenic threats affecting the interpreted geoarchaeological feature; (3) assess its vulnerability from geoarchaeological and heritage-management perspectives; and (4) integrate these components into a preliminary geoarchaeological sensitivity assessment to support future conservation and management of the Prambanan archaeological landscape. The study focuses on the river segment interpreted by Tjahjono and Widianto (1994) as the proposed diverted reach of the Opak River and adopts the conceptual perspectives of anthropogenic geomorphology (Szabó, 2010), geoarchaeological heritage, and spatial archaeology (Mundardjito, 1993). Given the provisional nature of the existing evidence, the assessment is intended as a first-order baseline for future geoarchaeological investigation rather than as definitive verification of the proposed ancient river diversion

2. The Study Area

The study focuses on a reach of the Opak River in the western part of the Kewu Plain, where Tjahjono and Widianto (1994) interpreted the river course as potentially representing an ancient diversion associated with the construction of the Prambanan Temple Complex. In this preliminary study, this interpretation is not treated as an established historical fact; instead, the proposed river diversion is considered an interpreted geoarchaeological feature for the purpose of assessing its potential significance, threats, vulnerability, and sensitivity. The Kewu Plain, also known as the Prambanan Plain, is a low-relief volcanic plain with an average elevation of approximately 140 m above sea level and extends across the Special Region of Yogyakarta and Central Java Province (Fig. 1). In archaeological studies, the Kewu Plain is recognised as an important cultural landscape of the Ancient Mataram Kingdom, containing numerous Hindu and Buddhist temples and other archaeological features. Its fertile volcanic setting, availability of water resources, and strategic topographic position contributed to the development of an important cultural centre in Central Java (Wirasanti, 2023).

The Kewu Plain represents a landscape in which geological, geomorphological, and archaeological processes have interacted over long periods. The study area is influenced by volcanic processes associated with Merapi Volcano and fluvial processes related to the Opak River system, while its archaeological landscape records long-term human engagement with these environmental conditions. The proposed Opak River diversion is therefore considered a potentially significant example of anthropogenic landscape modification that warrants preliminary geoarchaeological assessment. Its significance is not assumed from the proposed diversion alone, but is evaluated through the available archaeological, geomorphological, spatial, and historical evidence.

The heritage context further enhances the relevance of this preliminary assessment. The study area is located within the broader geopark landscape encompassing the Jogja National Geopark and the Bayat Purba Aspiring Geopark, where geological, geomorphological, and cultural heritage values provide an important basis for integrated landscape management (Figs. 1 and 2). Although the Prambanan Temple Complex is already recognised as a UNESCO World Heritage Site, the proposed Opak River diversion has not yet been formally established or explicitly recognised as a geoarchaeological heritage attribute within the surrounding geopark and archaeological landscape frameworks. Its potential scientific, educational, and conservation values therefore remain insufficiently evaluated. Accordingly, the present study provides a preliminary assessment and baseline evaluation of the proposed feature, while recognising that its interpretation requires further multidisciplinary geoarchaeological investigation and empirical validation.

3. Materials and Method

This study applies a geoarchaeological sensitivity assessment framework to the geomorphological feature interpreted as the proposed ancient diversion of the Opak River associated with the Prambanan Temple Complex. Rather than attempting to verify the historical occurrence of the river diversion itself, the assessment focuses on evaluating the geoarchaeological significance and conservation needs of the interpreted landscape feature based on the currently available inscriptional, geomorphological, spatial, and field evidence. Accordingly, the analytical framework comprises four complementary components: (1) geoarchaeological significance assessment; (2) threat assessment based on the probability and impact of potential hazards; (3) vulnerability assessment; and (4) calculation of the Geoarchaeological Sensitivity Value (GASV) through the integration of significance, threat, and vulnerability indicators. The data utilised in this study consist of previous archaeological and geomorphological studies, field observations, geomorphological and land-use maps obtained from the Indonesian Geospatial Information Agency (Badan Informasi Geospasial), and satellite imagery basemaps available through Google Earth.

The proposed assessment framework was adapted from established approaches in geoheritage evaluation and risk assessment while being modified to accommodate the specific characteristics of geoarchaeological heritage. The geoarchaeological significance assessment integrates geological, geomorphological, and archaeological perspectives to evaluate the scientific and heritage importance of

the interpreted river diversion. The assessment criteria and scoring system are presented in Table 1. Vulnerability was evaluated using the indicators presented in Table 2, reflecting legal protection, geoarchaeological integrity, and public awareness. Meanwhile, the threat assessment follows the probability–impact risk matrix proposed by Cox (2008), Levenson (2011), Arda et al. (2023), and Kubalíková and Balková (2023), thereby integrating both natural and anthropogenic hazards that may affect the interpreted geoarchaeological feature. The criteria and scoring values were adapted to reflect the objectives of this study and the characteristics of the Prambanan archaeological landscape.

The geoarchaeological significance and vulnerability scores were obtained by summing the values assigned to each assessment criterion and subsequently expressing the results as percentages of their respective ideal scores. The threat assessment was conducted through several sequential stages. First, potential hazards relevant to the study area were identified through field observations, geomorphological analysis, previous studies, and land-use interpretation. Second, each hazard was evaluated according to its probability of occurrence and potential impact, and the product of these two parameters was calculated to obtain the degree of risk following the probability–impact matrix approach (Cox, 2008; Levenson, 2011; Arda et al., 2023; Kubalíková & Balková, 2023). To ensure consistency with the significance and vulnerability assessments, the original four-level risk classification was subsequently simplified into a three-level classification by combining the original high and severe categories into a single class (3), while the moderate and low categories were assigned values of 2 and 1, respectively. The cumulative scores of both anthropogenic and natural hazards were then converted into percentages relative to the maximum possible score to derive the overall Threat Value (TV).

Finally, the Geoarchaeological Sensitivity Value (GASV) was calculated using Formula (1), which integrates geoarchaeological significance (SgV), threat value (TV), and vulnerability value (VV). This composite index was designed to provide a first-order evaluation of the relative conservation sensitivity of the interpreted geoarchaeological feature. The framework does not seek to demonstrate the historical validity of the proposed Opak River diversion; rather, it provides a systematic approach for assessing the conservation significance of a geoarchaeological interpretation derived from currently available evidence. Consequently, the resulting sensitivity values should be interpreted as a decision-support tool for geoheritage management and archaeological landscape conservation, while recognising that further geoarchaeological

Formula 1. Geoarchaeology sensitivity value equations

$$\mathrm{GASV} = \frac{\mathrm{TV}^{*}\mathrm{VV}}{\mathrm{SgV}}$$

1

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Table 1
Criteria, Indicator, and Value of Geoarchaeological Significance

No	Criteria	Indicator	Value
1	Geological-geomorphological Rarity Value	The geoarchaeological site is rare in area of interest according to its geological-geomorphological point-of-view	3
		The geoarchaeological site is not so rare in area of interest according to its geological-geomorphological point-of-view	2
		The geoarchaeological site is common in area of interest according to its geological-geomorphological point-of-view	1
2	Archaeological Rarity Value	The geoarchaeological site is rare in area of interest according to its archaeological point-of-view	3
		The geoarchaeological site is not so rare in area of interest according to its archaeological point-of-view	2
		The geoarchaeological site is common in area of interest according to its archaeological point-of-view	1
3	Geological-geomorphological Representativess Value	The geoarchaeological site is able to represent the distinctive geological and geomorphological aspects of the earth	3
		The geoarchaeological site is able to represent the distinctive geological and geomorphological aspects of a country	2
		The geoarchaeological site is able to represent the distinctive geological and geomorphological aspects of a region in some of country	1
4	Archaeological Representativess Value	The geoarchaeological site is able to represent the distinctive archaeological aspects of the earth	3
		The geoarchaeological site is able to represent the distinctive archaeological aspects of a country	2
		The geoarchaeological site is able to represent the distinctive archaeological aspects of a region in some of country	1
5	Geological-geomorphological Scientific Value	There is international scientific papers which discusses the Geoarcheological Site	3
		There is national scientific papers which discusses the Geoarcheological Site	2
		There is no published paper which discusses the Geoarcheological Site	1
6	Archaeological Scientific Value	There is archeological national scientific papers which discusses the Geoarcheological Site	3

No	Criteria	Indicator	Value
		There is archeological international scientific papers which discusses the Geoarcheological Site	2
		There is no published scientific papers which discusses the Geoarcheological Site	1
7	Geoarchaeological Relatedness Value	The main geoarchaeological object are directly related with geological, geomorphological, and archaeological aspects in certain areas	3
		The main geoarchaeological object are indirectly related with geological, geomorphological, and archaeological aspects in certain areas	2
		The main geoarchaeological object is not related with geological, geomorphological, and archaeological aspects in certain areas	1

Table 2
Criteria, Indicator, and Value of Vulnerability of Geoarchaeological Significance

No	Criteria	Indicator	Value
1	Legal Protection	There is national legislative protection	3
		There is regional legislative protection	2
		No legal protection	1
2	Geoarchaeological Integrity Value	The main geoarchaeological object (related with geological, geomorphological, and archaeological aspects) is well preserved	3
		The main geoarchaeological object (related with geological, geomorphological, and archaeological aspects) not so well preserved because of some minor degradation	2
		The main geoarchaeological object (related with geological, geomorphological, and archaeological aspects) is completely altered	1
3	Community Awareness	The geoarchaeological site is known by public	3
		The geoarchaeological site is known by some of certain community (eg. Scientific community)	2
		The geoarchaeological site is unknown	1

investigations, including sedimentological, stratigraphic, geophysical, and chronological analyses, are required to strengthen the empirical basis of the interpreted river diversion

4. Theory and Calculation

4.1. The Geoecological Requirement to Build a Temple

Natural resources were among the primary considerations in temple construction (Mundardjito, 2002; Wirasanti, 2023). According to Mundardjito (2002), the establishment most of temples in the Yogyakarta region took into account a range of geoecological aspects. These considerations were guided by the Manasara Silpasastra and Silpaprakasa texts, which state that only fertile land, with permeable soils capable of absorbing water and located near a water source, particularly at the confluence of two rivers (*tempuran* in Javanese), was deemed suitable for the construction of sacred structures. The Silpaprakasa text further prohibits temple construction on dry land or in areas far from water sources. This reflects the traditional understanding that temples are sacred edifices (Soekmono, 2017). Soekmono (1974, 2017) also asserted that a sacred place possesses inherent sanctity due to its own natural potential, implying that the selection of land holds a position of great importance in temple construction. Mundardjito (1993, 2002) reinforced this notion, emphasising that the choice of land was of paramount importance. It indeed even more significant than the temple itself.

From the perspectives of Soekmono (1974, 2017) and Mundardjito (1993, 2002), it can be understood that a sacred structure must be established upon land considered equally “sacred”. Such land, regarded as sacred, embodies (geo)ecological characteristics capable of supporting both the material and spiritual needs of human life. Beyond the availability of land resources, the concept of worship within sacred architecture is intrinsically linked to the management of water resources, viewed as both a sacred and purifying entity. Therefore, the geomorphological characteristics of the landscape played a crucial role in determining the location and establishment of sacred buildings.

4.2. Geoarchaeology and Geoarchaeological Heritage

Geoarchaeology is an interdisciplinary field that integrates the study of archaeology and geomorphology, aiming to understand how natural and human processes have shaped and transformed landscapes over time (French, 2003; Christopher & George, 2014). One of the principal objectives of geoarchaeology is to apply empirical approaches from the natural sciences to the archaeological record (Christopher & George, 2014). Through this, an integrated model of the interactions between human and environmental systems can be established, enabling a deeper understanding of how both natural and anthropogenic factors influence landscape evolution (French, 2003; Christopher & George, 2014).

Heritage that embodies both natural and cultural characteristics from the past is referred to as geoarchaeological heritage (Fouache & Rasse, 2009; Fouache et al., 2012; Melelli et al., 2016; Reynard & Giusti, 2018; Filippo et al., 2019; Piau et al., 2023). This concept encompasses heritage that is significant not only for its cultural or historical human value but also for its geological and natural dimensions, aligning closely with the principles and definitions of geoarchaeology. The sites that exemplify such interactions are known as geoarchaeosites or geoarchaeological sites (Fouache & Rasse, 2009; Piau et al., 2023).

Geoarchaeological heritage reflects the outcomes of past interactions between humans and their natural environments, providing valuable insights into how human societies have adapted to, utilised, and even modified their surrounding landscapes. This interplay has resulted in a rich and complex legacy that endures today. Through the diversity of sites it encompasses, geoarchaeological heritage offers a distinctive perspective on understanding the past—one that tells not only the story of humankind but also the story of the Earth itself, which served as the stage upon which civilisations developed.

4.3. Anthropogenic Geomorphology

Anthropogenic geomorphology is a branch of geomorphological study that focuses on artificial landforms, emphasising their material composition, origin, evolution, and spatial distribution (Nir, 1983; Panizza, 1996; Szabó, 2010). This field is closely associated with human interventions in the natural environment. Human intervention is defined as a disturbance to the existing equilibrium of nature (Nir, 1983). Such disturbances manifest in various forms, including interference with gravitational processes, the acceleration or deceleration of natural geomorphic dynamics, the concentration of human activities within limited areas yet of high intensity, and the degradation of existing ecosystems (Nir, 1983).

Anthropogenic interventions can be categorised as either primary or secondary, depending on the motivation behind human activities (Szabó, 2010). For instance, agricultural terraces created through planation for cultivation purposes represent a form of primary anthropogenic intervention, whereas mounds of material left over from planation activities constitute secondary anthropogenic intervention (Szabó, 2010). Anthropogenic landforms may also be classified based on whether their impacts are direct or indirect, as human-induced geomorphic processes do not always act independently within the Earth system (Szabó, 2010). Direct anthropogenic interventions are those driven by processes distinct from natural ones and are undertaken with explicit intent or purpose (Szabó, 2010). In contrast, indirect anthropogenic interventions refer to human influences that accelerate or decelerate natural geomorphic processes without necessarily having a clear or deliberate motive (Szabó, 2010). A comprehensive classification of anthropogenic interventions is thus based on the motivation or nature of human activity (Szabó, 2010). These categories include: montanogenic (related to mining or excavation), industrogenic (industrial activity), urbanogenic (urban development), traffic-related, water management, agrogenic (agricultural modification), warfare-related, and those associated with tourism and recreation (Szabó, 2010).

4.4. Considerations of Abiotic and Cultural Environment in the Construction of Prambanan Temple

The phrase “Lwāh ya inalih hakén apaniyānid ik palmahan,” meaning “thus the river’s course was diverted because it touched the temple courtyard,” implies that the river was intentionally redirected westward (Tjahjono & Widianto, 1994). Tjahjono and Widianto (1984) discussed this passage in conjunction with palaeogeomorphological evidence derived from geomorphological mapping conducted by the Japan International Cooperation Agency (JICA). According to their analysis, the river that was diverted lies to the west of the Prambanan Temple, identified as the Opak River. Originally, the Opak River flowed across

the temple courtyard before being redirected westward in a straight course for approximately one kilometre, then turning eastward for about 500 metres, before meandering back westwards (Tjahjono & Widianto, 1994). Contemporary geomorphological observations (Figs. 4) confirm the existence of this diverted river segment west of the Prambanan Temple, corresponding to the Opak River. In other words, both the inscriptional evidence and modern geomorphological data refer to the same spatial phenomenon.

When this analytical framework is applied to recent geomorphological data at a scale of 1:50,000, it is evident that a section of the Opak River indeed flows westward in a straight channel before turning east. The meandering pattern of the river only appears further south of the Prambanan Temple Complex. Referring back to the inscriptional phrase “Lwāh ya inalih hakén apaniyānid ik palmahan” from the Sivagrha inscription, it can be determined that an ancient anthropogenic intervention took place in the Prambanan–Opak River system.

Based on the analysis of Tjahjono and Widianto (1984) and the corresponding spatial review, it can thus be confirmed that the river diversion formed an integral part of the Prambanan Temple’s construction process. In addition to the river being redirected, the same inscription mentions that the outer enclosure wall and the third courtyard of the Prambanan Temple were “rotated” in position (Fig. 3) (Jordaan, 2009). This realignment of the wall is consistent with the redirection of the Prambanan–Opak River, as both actions were undertaken to protect the temple from erosion while maintaining its proximity to the water body. However, at present, the third enclosure wall has suffered damage and has been cut through by the course of the modern Opak River.

5. Result

5.1. Geoarchaeological Significant Value (SgV)

The geoarchaeological significance assessment was undertaken using seven criteria: geological–geomorphological rarity, archaeological rarity, geological–geomorphological representativeness, archaeological representativeness, geological–geomorphological scientific value, archaeological scientific value, and geoarchaeological relatedness. These criteria were applied to the geomorphological feature interpreted as the proposed ancient diversion of the Opak River associated with the Prambanan Temple Complex. The assessment is therefore directed toward the potential heritage significance of the interpreted feature, rather than toward establishing the historical certainty of the proposed river diversion.

The interpreted Opak River diversion received the maximum score for both geological–geomorphological rarity and archaeological rarity. These scores reflect the apparent scarcity of comparable geoarchaeological features within the Kedu–Kewu cultural landscape and the broader Indonesian context. A broadly comparable example is the Gomati Canal associated with the Tarumanegara Kingdom in West Java, which represents an ancient form of large-scale anthropogenic

modification of a water system. Within this context, the proposed Opak River diversion may represent a comparatively uncommon type of anthropogenic landscape modification associated with monumental architecture in Indonesia.

Both geological–geomorphological and archaeological representativeness received a score of 2. The interpreted feature does not represent a globally unique geological, geomorphological, or archaeological process; however, it potentially represents a significant example at the national scale of the interaction between landscape modification and monumental architecture during the Ancient Mataram period. Its representativeness therefore lies primarily within the Indonesian archaeological heritage and geoheritage context. This assessment reflects the potential representativeness of the feature and does not imply that the proposed river diversion has been conclusively demonstrated.

The geological–geomorphological scientific value received a score of 1 because no published geological or geomorphological studies specifically addressing the interpreted river diversion were identified in the available literature. In contrast, the archaeological scientific value received a score of 2, reflecting the limited archaeological discussion of the feature, particularly the interpretation proposed by Tjahjono and Widianto (1994). The difference between these scores indicates that the proposed river diversion has received greater attention from an archaeological perspective than from geological, geomorphological, or explicitly geoarchaeological perspectives. This limited body of research further highlights the preliminary nature of the current interpretation and the need for additional multidisciplinary investigation.

The geoarchaeological relatedness criterion received the maximum score (3), reflecting the strong spatial and conceptual association among the interpreted geomorphological feature, the Siwagrha Inscription, and the archaeological landscape of the Prambanan Temple Complex. Importantly, this score represents the degree of relatedness among the available lines of evidence and should not be interpreted as direct validation of the proposed river diversion. Rather, the convergence of inscriptional, spatial, geomorphological, and archaeological evidence provides a reasonable basis for treating the feature as a potential geoarchaeological heritage attribute for preliminary assessment.

The proposed Opak River diversion obtained a total score of 16 out of 21 (76.19%), corresponding to a high geoarchaeological significance within the adopted assessment framework. The high SgV indicates that the interpreted feature possesses substantial potential as a geoarchaeological heritage attribute within the Prambanan cultural landscape. This result is primarily associated with its apparent rarity, its close relationship with the monumental landscape of Prambanan, and the strong spatial and conceptual connections among the available geomorphological, archaeological, and inscriptional evidence. Its significance therefore extends beyond the possible modification of a river channel itself, as such an intervention, if subsequently verified, could provide insights into the interaction between ancient society, geomorphological processes, water management, and monumental construction. In this context, the proposed diversion may represent a form of pre-industrial anthropogenic landscape modification in which the physical environment was intentionally adapted to accommodate cultural and religious objectives. Nevertheless, the high SgV represents an assessment of geoarchaeological heritage

potential rather than confirmation of the historical river diversion. Given the preliminary and yet-to-be-validated nature of the interpretation, the result primarily establishes the proposed feature as a priority for further geoarchaeological investigation and conservation consideration. Additional empirical evidence, particularly direct evidence of channel modification, may subsequently strengthen, refine, or revise the present interpretation and provide a more robust basis for recognising the feature within the broader geoheritage and archaeological landscape of Prambanan.

5.2. Threat Value (TV)

The interpreted geoarchaeological feature associated with the proposed ancient Opak River diversion is situated within a landscape exposed to both anthropogenic and natural hazards. The threat assessment was conducted to evaluate the present and potential pressures affecting the conservation of the interpreted feature, rather than to assess the historical certainty of the proposed river diversion. Based on field observations, geomorphological analysis, land-use interpretation, and previous studies, eleven major threats were identified: mining, agricultural activities, urban development, water-management interventions, transportation infrastructure, lahar flows, volcanic ash fall, earthquakes, flooding, erosion, and sedimentation (Table 4). These hazards reflect the combined influence of ongoing human activities and natural geomorphological and volcanic processes operating within the Opak River corridor.

Among the anthropogenic hazards, mining activities were assigned a moderate probability (3) and low impact (1), resulting in a minor risk level (3). The relatively low risk reflects the limited extent of extraction activities within the study area, although local disturbance of soil structure and potential archaeological deposits remains possible. Agricultural activities received a high probability score (4) and significant impact score (3), producing a major risk level (12). Intensive cultivation, irrigation, and associated land-management practices may modify soil properties and local hydrological conditions and may consequently disturb subsurface archaeological deposits. Urban development was assigned an extremely high probability (5) and significant impact (3), resulting in a major risk level (15). Expansion of settlements and infrastructure may permanently alter the geomorphological characteristics of the interpreted river corridor through land levelling, excavation, and construction activities. Water-management interventions represent another major pressure, with a very high probability (5) and significant impact (3), producing a severe risk level (15). Modern interventions, including riverbank reinforcement, retaining structures, and channel modification, may alter or obscure geomorphological characteristics potentially relevant to the interpretation of past landscape modification. Transportation infrastructure represents a comparatively lower threat, although bridges and associated infrastructure may locally contribute to disturbance through construction activities and repeated vibration.

Natural hazards also contribute to the overall threat profile of the interpreted feature. Lahar flows originating from Merapi Volcano have a moderate probability (3) and significant impact (3), resulting in a moderate risk level (9), while volcanic ash fall receives the same probability and impact scores. These processes may bury, modify, or physically affect geomorphological and archaeological evidence preserved along the river corridor. Earthquakes have a moderate probability (3) but severe potential impact (4), producing a major risk level (12), particularly through riverbank instability and the

acceleration of geomorphological processes. Flooding has a high probability (4) and relatively low impact (2), resulting in a moderate risk level (6). Although its effects may be temporary, recurrent flooding may contribute to localised erosion and disturbance of potentially significant deposits. Erosion and sedimentation both exhibit very high probability (5) and moderate impact (3), producing major risk levels (15). These processes may progressively remove, bury, or redistribute geomorphological and archaeological evidence within the interpreted river corridor.

The integrated assessment produced an anthropogenic threat score of 45.45% and a natural threat score of 40.00%, yielding an overall Threat Value (TV) of 42.30%, which corresponds to the medium threat class within the adopted classification scheme. The slightly higher anthropogenic score indicates that current human activities constitute a somewhat greater potential pressure than the aggregated natural hazards. In particular, water-management interventions and urban development are important because they can directly modify the physical characteristics of the river corridor, while erosion and sedimentation represent persistent natural processes capable of altering or obscuring potential geoarchaeological evidence.

The medium TV indicates that the proposed geoarchaeological feature is exposed to ongoing but not yet critical levels of pressure. The result is particularly important in the context of this preliminary assessment because the potential loss is not limited to the physical form of the river corridor; continued modification may also reduce the availability and integrity of evidence required to evaluate the proposed ancient diversion in the future. Thus, the principal concern is not that the medium threat level currently demonstrates degradation of a confirmed archaeological feature, but that continued river engineering, urbanisation, agriculture, erosion, and sedimentation may progressively diminish the geomorphological context within which the proposed interpretation can be tested. The medium TV therefore supports a preventive rather than emergency conservation approach, in which monitoring and documentation of the river corridor should accompany future geoarchaeological investigations. This is particularly relevant because preservation of the present geomorphological context may increase the possibility of identifying direct evidence capable of strengthening, refining, or revising the proposed interpretation of the ancient Opak River diversion.

5.3. Vulnerability Value (VV)

The vulnerability assessment comprises three indicators: legal protection, geoarchaeological integrity, and community awareness. These indicators evaluate the current conservation condition and capacity for protection of the interpreted geoarchaeological feature associated with the proposed ancient Opak River diversion, rather than the degree of certainty regarding its historical origin. The legal protection criterion received the lowest score because the interpreted Opak River diversion has not yet been formally recognised as an integral component of the Prambanan Temple Complex or the broader archaeological landscape of the Kewu Plain. Consequently, its potential geoarchaeological value is not yet explicitly incorporated into existing cultural heritage, geoheritage, or landscape-management frameworks, potentially increasing its exposure to future landscape modification.

The geoarchaeological integrity and community awareness criteria were both assigned a score of 2. The geoarchaeological integrity score reflects the presence of relatively minor geomorphological degradation, particularly riverbank erosion observed along the southern section of the interpreted river corridor. Although these processes have not substantially altered the overall geomorphological configuration of the area, their continued occurrence may progressively remove, disturb, or obscure sedimentary and archaeological evidence that could be relevant to

Table 3
Value of geoarchaeological significant value (SgV) from Opak river relocation geoarchaeological attributes of prambanan temple complex

No	Criteria	Value from certain sites
1	Geological-geomorphological Rarity Value	3
2	Archaeological Rarity Value	3
3	Geological-geomorphological Representativess Value	2
4	Archaeological Representativess Value	2
5	Geological-geomorphological Scientific Value	1
6	Archaeological Scientific Value	2
7	Geoarchaeological Relatedness Value	3
Total: 16/21; Percentage: 76.19%		
Class: High		

Table 3
Threat class of Opak river relocation geoarchaeological attributes of prambanan temple complex

Threats		Probability	Impact	Degree of Risk	Class (4)	Reclass (3)
Anthropogenic Threats	Montanogenic (mining)	3	1	3 (minor)	1	1
	Agrogenic	4	3	12 (major)	3	3
	Urbanogenic	5	3	15 (major)	3	3
	Water Management	5	3	15 (major)	3	3
	Traffic	3	1	3 (minor)	1	1
Natural Threats	Lahar Flow	3	3	9 (moderate)	2	2
	Ash Fall	3	3	9 (moderate)	2	2
	Earthquake	3	4	12 (major)	3	3
	Flood	4	2	6 (moderate)	2	2
	Erosion	5	3	15 (major)	3	3
	Sedimentation	5	3	15 (major)	3	3

Table 4
Threat value of Opak river relocation geoarchaeological attributes of prambanan temple complex

Threat		
Anthropogenic Threat	5/11	45.45%
Natural Threat	6/15	40.00%
Total	11/26	42.30%
Class	**Medium**	

future geoarchaeological investigations. The community awareness score similarly reflects the limited recognition of the proposed Opak River diversion as a potential geoarchaeological heritage attribute. Knowledge of the interpretation appears to remain concentrated primarily within archaeological and heritage research communities, while its potential geoarchaeological significance has received limited public recognition. This condition may constrain community engagement in conservation and contribute to the continued underrepresentation of the feature in broader heritage-management initiatives.

The combined assessment indicates a moderate level of vulnerability for the interpreted geoarchaeological feature. This result suggests that its current vulnerability is influenced less by extensive physical degradation than by limited institutional recognition, incomplete integration into heritage-management frameworks, and low public awareness. The absence of formal recognition is particularly important because the geomorphological context may constitute an essential component of the evidence required to evaluate the proposed ancient river diversion. If this context is progressively modified before further geoarchaeological investigation is undertaken, opportunities to identify and interpret potential evidence of past anthropogenic river modification may be reduced.

The moderate VV indicates that the proposed feature occupies an intermediate position between effective protection and substantial vulnerability. Its relatively preserved geomorphological condition provides an opportunity for future investigation, but this opportunity is not necessarily secured by existing protection mechanisms. In this respect, vulnerability should be understood not only as physical susceptibility to degradation but also as vulnerability arising from insufficient recognition and knowledge. The combination of limited legal protection and public awareness may allow ongoing river management, land-use change, and other landscape interventions to occur without consideration of the potential geoarchaeological value of the feature. Therefore, although the preliminary assessment does not indicate an immediate condition of severe vulnerability, early documentation, scientific investigation, heritage interpretation, and consideration within relevant geopark and archaeological landscape-management frameworks would be appropriate. Such measures would help preserve the present context while allowing future research to test, strengthen, refine, or potentially revise the proposed interpretation of the ancient Opak River diversion.

Table 5
Vulnerability value of Opak river relocation geoarchaeological attributes of prambanan temple complex

No	Criteria	Value from certain sites
1	Legal Protection	1
2	Geoarchaeological Integrity Value	2
3	Community Awareness	2
Total: 5/9; Percentage: 55.55%		
Class: Medium		

5.4. Geoarchaeological Sensitivity Value (GASV)

The Geoarchaeological Sensitivity Value (GASV) was derived by integrating the Geoarchaeological Significance Value (SgV), Threat Value (TV), and Vulnerability Value (VV) following Formula (1). The interpreted Opak River diversion attained a high geoarchaeological significance value of 76.19%, whereas both the threat (42.30%) and vulnerability (44.44%) values were classified as moderate. The resulting GASV of 24.67% places the interpreted geoarchaeological feature within the low sensitivity

class. This result indicates that, under the present conditions and within the adopted assessment framework, the feature does not constitute an immediate conservation priority when compared with geoheritage resources experiencing higher levels of threat and vulnerability. Importantly, however, the low sensitivity classification should not be interpreted as indicating low scientific, archaeological, or geoheritage significance. Rather, it reflects the current balance between the feature's high potential significance and its moderate levels of threat and vulnerability. Thus, the interpreted Opak River corridor retains considerable potential geoarchaeological value while currently exhibiting a comparatively limited degree of conservation sensitivity.

The relatively low GASV primarily reflects the moderate levels of existing threats and vulnerability rather than a lack of heritage importance. Nevertheless, the current condition should not be interpreted as evidence that the feature is permanently resilient to future landscape change. Continued river engineering, urban expansion, agricultural intensification, erosion, and sedimentation may progressively alter the geomorphological context of the river corridor and potentially obscure or remove evidence relevant to testing the proposed ancient diversion. Preventive management is therefore important even in the absence of an immediate need for intensive conservation intervention. Management priorities should include reducing anthropogenic pressures, particularly those associated with river engineering and land-use change, improving legal and institutional recognition, strengthening public awareness, and maintaining the geomorphological characteristics of the river corridor. These measures would help preserve the contextual integrity of the interpreted feature while creating more favourable conditions for future geoarchaeological investigation.

From a geoarchaeological perspective, the GASV result also demonstrates the importance of distinguishing heritage significance from conservation sensitivity. A feature may possess high scientific or heritage significance while exhibiting relatively low sensitivity when current threats and vulnerability remain moderate. In the present case, the high SgV indicates that the interpreted Opak River diversion warrants continued scientific attention, whereas the low GASV indicates that immediate conservation intervention is not presently justified by the combined threat and vulnerability conditions. The appropriate management response is therefore better characterised as preventive conservation and continued investigation, rather than either intensive intervention or neglect. This distinction is particularly relevant for the proposed Opak River diversion because its historical interpretation remains provisional and the preservation of its present geomorphological context may be critical for obtaining direct evidence in future studies.

The GASV should be regarded as a first-order decision-support indicator for conservation prioritisation rather than a measure of historical certainty. The assessment identifies the interpreted Opak River diversion as a geoarchaeological feature with substantial potential heritage significance that merits continued protection, documentation, and scientific investigation. However, the assessment does not establish that the Opak River was historically diverted as proposed. Future sedimentological, stratigraphic, geomorphological, geophysical, archaeological, and chronological investigations will be necessary to test the interpretation and determine whether the geomorphological configuration

represents anthropogenic river modification associated with the construction of the Prambanan Temple Complex. Such evidence may strengthen, refine, or potentially revise the current interpretation, while simultaneously providing a more robust basis for evaluating the feature's geoarchaeological and geoheritage significance.

Table 4
Geoarchaeology sensitivity value of Opak river relocation geoarchaeological attributes of prambanan temple complex

Value	Percentage	Class
SgV	76.19%	**High**
TV	42.30%	**Medium**
VV	55.55%	**Medium**
GASV	30.84%	**Low**

6. Discussion

The geoarchaeological sensitivity assessment indicates that the geomorphological feature interpreted as the proposed ancient Opak River diversion possesses high geoarchaeological significance (76.19%), despite its low overall sensitivity (GASV = 24.67%). This distinction reflects the difference between heritage significance and current conservation sensitivity. The high significance is associated with the feature's rarity and its spatial and conceptual relationship with the Prambanan archaeological landscape, potentially representing an important record of long-term human–environment interaction during the Ancient Mataram period. The proposed diversion is supported by a convergence of inscriptional, archaeological, spatial, and geomorphological evidence, particularly the interpretation of the Siwagrha Inscription by Tjahjono and Widianto (1994). However, these lines of evidence remain complementary rather than conclusive. The proposed river diversion should therefore be regarded as an interpreted geoarchaeological feature, rather than a historically confirmed intervention.

The results further demonstrate that the feature has moderate threat (42.30%) and vulnerability (44.44%), resulting in relatively low conservation sensitivity. This does not imply limited scientific or geoheritage importance but rather indicates that the current combination of threats and vulnerability does not yet warrant intensive conservation intervention. Nevertheless, ongoing river engineering, urban development, agriculture, erosion, and sedimentation may progressively alter the geomorphological context and obscure or remove evidence required to test the proposed diversion. Preventive management is therefore important, particularly through documentation, monitoring, preservation of geomorphological integrity, improved legal recognition, and greater public awareness. Such measures should be integrated with archaeological and geopark landscape-management approaches to balance

contemporary river-management requirements with the preservation of potential geoarchaeological evidence.

The findings also demonstrate the value of the Geoarchaeological Sensitivity Assessment as a first-order decision-support framework for interpreted geoarchaeological features where direct empirical validation remains incomplete. The GASV should be used for conservation prioritisation rather than as evidence of historical authenticity. The principal limitation of this study is the absence of direct geoarchaeological evidence, including sedimentological and stratigraphic data, geophysical investigation, archaeological excavation, and chronological dating. Future multidisciplinary research integrating these approaches is therefore required to test whether the present geomorphological configuration reflects intentional ancient river modification. Such investigations may strengthen, refine, or potentially revise the current interpretation while providing a more robust basis for recognising the proposed Opak River diversion as a geoarchaeological and geoheritage attribute of the Prambanan cultural landscape.

7. Conclusion

This study evaluated the geoarchaeological sensitivity of the geomorphological feature interpreted as the proposed ancient diversion of the Opak River associated with the Prambanan Temple Complex. The assessment does not seek to verify the historical occurrence of the diversion but evaluates its potential conservation importance based on available inscriptional, geomorphological, spatial, and archaeological evidence. The interpreted river corridor obtained a high Geoarchaeological Significance Value (SgV) of 76.19%, reflecting its rarity and strong relationship with the Prambanan archaeological landscape. The feature recorded moderate threat (42.30%) and vulnerability (44.44%), resulting in a low Geoarchaeological Sensitivity Value (GASV) of 24.67%. This low sensitivity indicates that the feature does not currently require immediate intensive conservation intervention, but it should not be interpreted as indicating low scientific or geoheritage significance. Preventive management, documentation, monitoring, and maintenance of the geomorphological integrity of the river corridor remain important, particularly in response to river engineering, urban development, agriculture, erosion, and sedimentation.

The proposed Geoarchaeological Sensitivity Assessment provides a preliminary, first-order decision-support framework for evaluating interpreted geoarchaeological features where direct empirical validation remains incomplete. The GASV is therefore intended to support conservation prioritisation rather than demonstrate historical authenticity. Its application to the proposed Opak River diversion highlights the importance of distinguishing between geoarchaeological significance, conservation sensitivity, and historical verification. Nevertheless, the proposed ancient Opak River diversion remains a provisional interpretation requiring further multidisciplinary investigation. Sedimentological, stratigraphic, geomorphological, geophysical, archaeological, and chronological studies are needed to determine whether physical evidence supports intentional ancient river modification. Future evidence may strengthen, refine, or potentially revise the current interpretation, while providing a more robust

basis for recognising the Opak River corridor as a geoarchaeological and geoheritage attribute of the Prambanan cultural landscape.

Declarations

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used NotebookLM/Gemini Notebook, DeepL, ChatGPT, Scopus AI, and Microsoft 365 Copilot in order to finding references, translate and increase the readability of this paper. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

Consent to Participate

Not applicable.

Consent to Publish

Not applicable.

Competing interest

declarations

Author Contribution

Conceptualization: A.A.I., S.R., H.P., B.D.T; Methodology: A.A.I., B.D.T; Data Curation: S.R., H.P.; Formal Analysis: A.A.I., B.D.T; Visualization: A.A.I.; Writing—Original Draft: A.A.I., S.R., H.P., B.D.T; Writing—Review & Editing: A.A.I., S.R., H.P., B.D.T; Supervision: S.R., H.P., B.D.T.

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Data Availability

The data supporting the findings of this study are not publicly available due to the sensitive nature of the information, particularly concerning the location and characteristics of cultural heritage objects.

However, the data may be made available from the corresponding author upon reasonable request, subject to ethical considerations and the protection of the research sites.

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Figures



Figure 1

The Prambanan Temple. Photo taken by BPCB DIY.

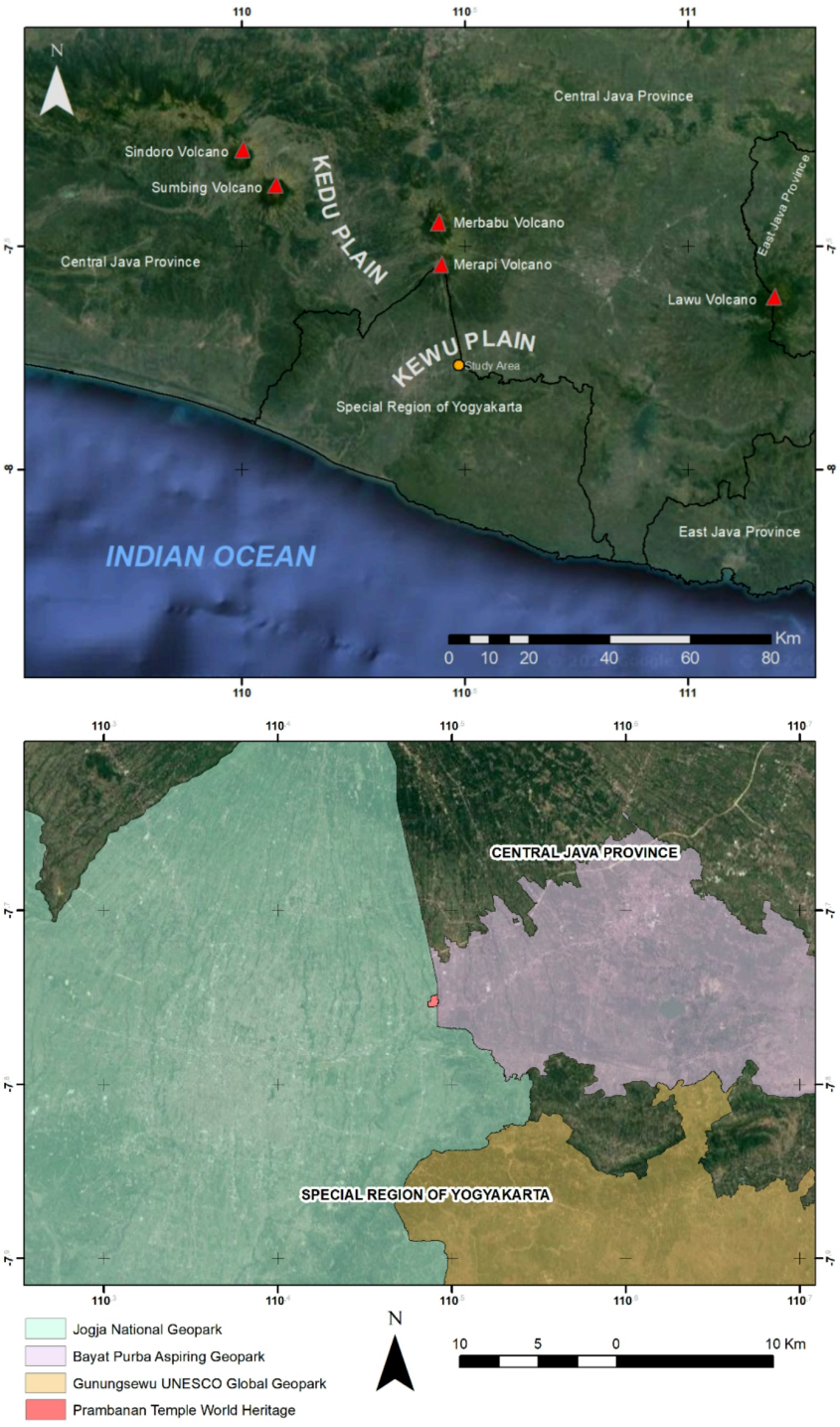


Figure 2

Study area within the Kewu Plain and its surroundings (top). The lower map shows the location of the Prambanan Temple World Heritage Site and the surrounding geoparks, highlighting its proximity to the Jogja National Geopark and Bayat Purba Aspiring Geopark. Basemap data from Google Earth.



Legend

Prambanan Temple Courtyard Fences

- First Courtyard Fences
- Second Courtyard Fences
- Third Courtyard Fences (Rotated 10 Degrees to the east)
- Third Courtyard Fences (If not rotated 10 Degrees to the east)

Other Features

- Third Courtyard Fences Rotating Shaft, Near Shiva Temple (Largest and Main Temple of Prambanan)

Inset



Figure 3

Prambanan Temple and its three courtyards configuration. Source: Jordaan, 2009 wit modifications

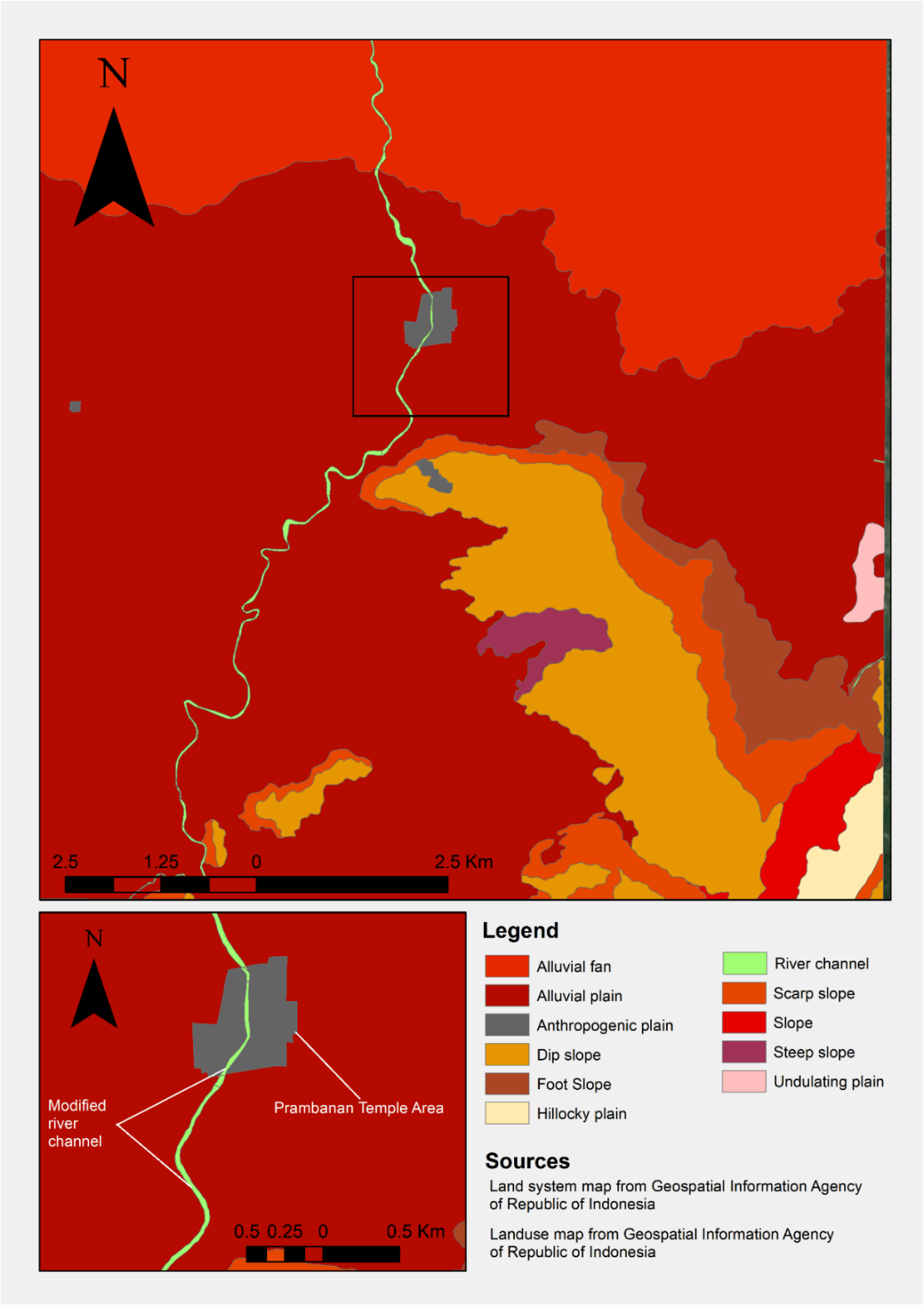


Figure 4

Prambanan Temple and Opak River relocation geoarchaeological attributes of the Prambanan Temple Complex shown in Geomorphological Map. This map corroborates the previous findings by Tjahjono & Widianto (1984) that utilize geomorphological map from JICA. Source: Land Sytem and Landuse Map from Geospatial Information System of Republic of Indonesia