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# Global Riverine Archaeology and Cultural Heritage: Flood-Risk Management and Adaptation for the Anthropogenic Climate Change Crisis

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**Abstract:** Significant riverine archaeological sites around the world are vulnerable to flooding associated with climate change. However, identifying sites most at risk is not straightforward. We critically review the parameters used in 22 published analyses of risk to riverine archaeology from climate change (ARRACC). Covering 17 countries globally, the ARRACC's risk parameters are highly variable. Proximity to rivers and projected changes to extreme flood frequency are the most commonly employed. However, to be robust, future ARRACC should select from a wider range of hazard parameters, including channel mobility/type, erosion/sedimentation patterns, land use and engineering works, as well as parameters for site sensitivity to flooding and heritage significance. To assist in this, we propose a basic field survey for ARRACC, to be treated primarily as a conceptual checklist or as a starting point for a bespoke ARRACC method adapted for a particular river and the objectives of local stakeholders. The framework proposes a pathway to optimal prioritisation of sites most in need of adaptation so that scarce management resources can be targeted.

**Keywords:** climate change; adaptation; risk; flood; archaeology; cultural heritage; river; erosion; cultural significance



**Citation:** Carmichael, B.; Daly, C.; Fatorić, S.; Macklin, M.; McIntyre-Tamwoy, S.; Pittungnapoo, W. Global Riverine Archaeology and Cultural Heritage: Flood-Risk Management and Adaptation for the Anthropogenic Climate Change Crisis. *Climate* **2023**, *11*, 197. https://doi.org/10.3390/cli11100197

Academic Editor: Jim Perry

Received: 6 August 2023
Revised: 11 September 2023
Accepted: 20 September 2023
Published: 25 September 2023



## 1. Introduction

Globally, river valleys contain rich archaeological records, having supported human occupation since Palaeolithic times. The attractions remain numerous: water, game, rock shelters, riparian plants and timber, stone quarries, transport and trade routes, arable soil, agricultural irrigation, strategic/military advantage and manufacturing power. As a result, rivers were, and still are, fundamental to human social and technological development [1].

Rivers are also potentially at risk from more frequent extreme precipitation and flooding resulting from anthropogenic climate change. Global projections for flooding under a warming climate, however, involve uncertainty [2]: results differ markedly for particular regions and climate scenarios (Representative Concentration Pathways). The IPCC have projected high risk of riverine flooding in the Small Islands Developing States, Arctic and High Mountain regions and medium risk in Africa, Central and South America, Europe and North America. Direct flood damage is projected to increase by four to five times at 4 °C compared to 1.5 °C [3].

### 1.1. Impacts

More frequent, extensive, fast-moving and long-lasting floods pose a risk of damage to, or loss of, riverside and in-channel archaeological resources. Accelerated by human landscape modification, extreme flooding induces inundation and saturation and causes erosion, drainage change and sedimentation of subsurface and surface structures, artefacts and petroglyphs/petrographs.

Inundation and saturation are a catalyst for various deterioration mechanisms, including pH changes, algal growth, salt intrusion and freeze-thaw weathering. Erosion may structurally degrade, disintegrate or redistribute archaeological resources. It can destabilise an entire floodplain through channel incision and lateral migration [4,5]. Fast-moving floods can subject sites to water-born, high-impact projectiles. Migrating channels may flood sites once distant from the river, while formerly waterlogged sites may become dry, causing oxidation and decay of organic material [6]. Erosion can also destabilise higher riverine terraces [7,8], and saturation and drainage changes may cause surface structures to subside or collapse. Erosion produces sediment that can bury sites under fast-moving, abrasive alluvium [9], making detection, excavation or reconstruction challenging.

The effects of climate change will be amplified by past and future landscape modification [1,10]. Intensive agriculture increases sedimentation, while deforestation removes deep-rooted, consolidating woody plants [11]. Sites may be protected by waterway engineering, such as dams where these consider archaeology, but construction may impact archaeological resources, and unless dams are future-proofed, they may become overwhelmed by more extreme flooding [12]. Urbanisation, paved surfaces and inadequate urban drainage increase the risk of flash flooding [13].

### 1.2. Analysis of Risks to Riverine Archaeology from Climate Change (ARRACC)

In the last two decades, a growing number of pioneering studies have sought to conduct an ARRACC. The following nine examples provide a global overview.

In Africa, a tributary wadi of the Nile River that becomes a flood path during extreme rainfall threatens the 1600–1100 BC painted tombs of the Valley of the Kings, Egypt. Ogiso et al. [14] found that increasingly intense rain storms will likely breach defences built after the 1994 flash flood that damaged most of the 30 open tombs.

In Asia, the circa 1300–1700 AD Buddhist temples and monasteries of Ayutthaya City, Thailand, are increasingly inundated by the Chao Phraya River. Vojinovic [15] undertook adaptation planning in response to an inundation event lasting over four weeks and registering depths of 4 m in places. In Cambodia, the 800–1600 AD Khmer temples of the Angkor Wat Archaeological Park are on the banks of the Siem Reap River and connected to historic canals. Liu et al. [16] found that the elevated frequency of extreme floods and urbanisation heighten the risk to nine of the Park's fifty-two monuments.

In mainland Europe, a 500–1400 AD site in Albenga, Italy, containing a Roman bath and early Christian church, is regularly inundated by the River Centa. Previtali et al. [17] found that floods associated with increasing daily precipitation rates are eroding and structurally degrading the site.

In the British Isles, the circa 5000 BC Megalithic passage graves of Brú na Bóinne are close to the River Boyne, Ireland. Daly [18] found an increase in high magnitude floods (projected 47% increase in the 50 year flood by 2099), combined with land use change, threatening 10% of site monuments.

In the Middle East, the 9 BC–40 AD tombs, temples, reliefs and inscriptions of Petra, Jordan, line the Wadi Musa. Akasheh [19] found flash flooding influenced by climate change, urbanisation, goat herding and loss of ancient flood-management infrastructure is increasing the erosion of inscriptions/reliefs and may lead to some sites' destruction.

In North America, pre- and post-European contact archaeology is close to rivers and streams in the environs of Houston, Texas. Reeder-Myers et al. [20] found sites more than 1000 m from inland streams were inundated during a high-intensity hurricane, which is an increasingly common phenomenon.

In Oceania, the Cadell River escarpment in Arnhem Land, Australia, contains significant, undated pictographs, with pictographs elsewhere in the region dating from the Pleistocene. Carmichael et al. [21] found evidence of flood damage to pictographs and assessed 22 rock galleries to be at risk from increased daily precipitation rates.

Finally, in South America, 8000 BC–1800 AD artefacts, structures and historic buildings along the Quebrada de Humahuaca, Argentina, line the Rio Grande. Marcato et al. [22] found increasing frequency of extreme flooding will continue breaching protective flood levees, which in 1984 saw damage to 30 colonial-era structures.

### *1.3. Aims*

We note that the above examples of ARRACC used a variety of parameters to assess the risk of site loss or damage, which begs the question, 'what is the appropriate set of risk-analysis parameters that should be used?'. To address this pressing question, we present the results of a critical review of all published ARRACC. Following an exploration of the parameters used in these studies, we propose a new ARRACC site survey/framework that combines these parameters. This study responds to calls [18,21,23] to integrate multiple exposure parameters for archaeological sites to climate change risks and develop a more holistic approach that includes assessment of sensitivity and significance and involves risk management by local stakeholders.

## 2. Materials and Methods

We searched the Web of Science for peer-reviewed studies and conference papers containing the following keyword set: archaeology, cultural heritage, river, climate change, global warming, flood and risk analysis. We excluded studies that considered (a) sites as one asset among a broad range of others; (b) pluvial flooding; (c) sensitivity risk alone, and not exposure risk; and (d) the risks to artworks within ancient buildings, not the buildings themselves. We included studies that did not use the term 'climate change' or 'global warming' if they were responding to increased flooding.

## 3. Results

Our search found 22 ARRACC (see Table 1).

**Table 1.** The 22 ARRACC.

| | | Lead Author | Site | River | Archaeology/Cultural Heritage |
|---|---|---|---|---|---|
| AFRICA | 1. | Ciampalinia [24] | The Royal Hill of Ambohimanga MADAGASCAR | Tributary creeks of Ikopa River | Merina tombs, pavilions, walled village<br>• 17th–20th century AD |
| | 2. | Ogiso [14] | Valley of the Kings EGYPT | Tributary wadi of the Nile River | Pharaonic tombs and temples<br>• 1600–1100 BC |
| ASIA | 3. | Li [25] | Mogao Grottoes CHINA | Daquan River | Buddhist cave temples and pictographs<br>• 5th13th century AD |
| | 4. | Liu [16] | Angkor Wat CAMBODIA | Siem Reap River | Khmer temples<br>• 9th–15th century AD |
| | 5. | Vojinovic [15] | Ayutthaya City THAILAND | Chao Phraya River | Buddhist temples and monasteries<br>• 14th century AD |
| | 6. | Wang [26] | New Taipai City TAIWAN | Tamsui, Xindian, Keelung and Dahan rivers | Archaeology, historic buildings, monuments<br>• 7000 BC to present |

**Table 1.** *Cont.*

| | | Lead Author | Site | River | Archaeology/Cultural Heritage |
|---|---|---|---|---|---|
| EUROPE | 7. | Ardielli [2] | Ostrava old city CZECH REPUBLIC | Odra River | churches, historic buildings, monuments<br>• 13th–20th century AD |
| | 8. | Boinas [27] | 397 protected sites PORTUGAL | All major Portuguese rivers | Historic buildings<br>• Dates not specified |
| | 9. | Daly [18] | Brú na Bóinne IRELAND | River Boyne | Megalithic passage graves<br>• Circa 5000 BC |
| | 10. | Hapciuc [28] | Sucevita River Valley ROMANIA | Sucevita River | Monastery, churches pottery, frescos<br>• Neolithic, Late Bronze Age, Iron Age, 16th century |
| | 11. | Howard [29] | Derwent Valley Mills UK | River Derwent | Industrial and associated sites<br>• 18th–19th century AD |
| | 12. | Iosub [30] | Jijia River Valley ROMANIA | Jijia River | Cucuteni tumuli and necropolis<br>• 5500 BC–16th century AD |
| | 13. | Kincey [7] | Ouse and Trent valleys UK | Ouse and Trent rivers | Unidentified archaeological sites<br>• potentially Mesolithic to 20th century AD |
| | 14. | Lanza [31] | Genoa old city ITALY | Eight urban streams | Palaces, fortifications, churches, villas<br>• 16th–20th century AD |
| | 15. | Miranda [32] | Guimarães old town PORTUGAL | Couros River | Historic buildings<br>• 10th–19th century AD |
| | 16. | Ortiz [33] | Seville old city SPAIN | River Guadalquivir | Churches, Gothic, Mudejar, Renaissance and Baroque<br>• 13th –18th century AD |
| | 17. | Previtali [17] | San Clemente Church ITALY | River Centa | Roman bath house and early Christian church<br>• 5th–13th century AD |
| | 18. | Tutunaru [34] | Bahlui River Basin ROMANIA | Bahlui River | Cucuteni tumuli and necropolis<br>• 5500 BC–16th century AD |
| MIDDLE EAST | 19. | Akasheh [19] | Petra JORDAN | Wadi Musa | Tombs, temples, reliefs, inscriptions, ancient water channels<br>• 6th century BC–12th century AD |
| NORTH AMERICA | 20. | Reeder-Myers [20] | Houston environs UNITED STATES | Various rivers/streams | Archaeological sites<br>• pre- and post-European contact |

**Table 1.** *Cont.*

| | | Lead Author | Site | River | Archaeology/Cultural Heritage |
|---|---|---|---|---|---|
| OCEANIA | 21. | Carmichael [21] | Djelk Indigenous Protected Area AUSTRALIA | Cadell River | Australian Aboriginal pictographs<br>• Undated, but potentially from 30,000 years BC |
| SOUTH AMERICA | 22. | Marcato [22] | Quebrada de Humahuaca ARGENTINA | Huasamayo Stream and Rio Grande | Structures, historic buildings, artefacts<br>• 8000 BC–colonial period |

The 22 ARRACC used a wide variety of parameters and combinations of parameters. We tabulated the parameters used by each study (see Table 2).

**Table 2.** Parameters used by 22 ARRACC.

| | | Risk Management Parameters Used | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Site Exposure | | | | | | | | Site Sensitivity 1 | | | | | | | Site Significance 2 | | | | | | |
| | ARRACC | Modelled Flood Risk | River Channel Pattern | Vertical Tendency of Channel | Lateral Tendency of Channel | Channel/Floodplain Erosion/Sedimentation | Land Use | River Engineering | Future Climate Adaptation Impact | Situation/Location | Material Character | Complexity/Form | Substrate Type | Condition | Heritage Status/Age 3 | Land Use 4 | Scientific/Archaeological | Social/Cultural | Cosmological/Spiritual | Historic | Aesthetic | Economic | Stakeholder Input |
| 1. | Akasheh [19] | ✔ | | ✔ | | | ✔ | | | | | | | | | | | | | | | | |
| 2. | Ardielli [2] | ✔ | | | | | | | | | | | | | | | | | | | | | |
| 3. | Boinas [27] | ✔ | | | | | | | | | ✔ | ✔ | | | | | | | | | | | |
| 4. | Carmichael [21] | ✔ | | | | | | | | | | | | ✔ | | | | ✔ | ✔ | ✔ | | | ✔ |
| 5. | Ciampalinia [24] | | | | ✔ | ✔ | ✔ | | | | | | | | | | | | | | | | |
| 6. | Daly [18] | ✔ | ✔ | | | | | ✔ | | ✔ | ✔ | ✔ | ✔ | | | | ✔ | | | | ✔ | | ✔ |
| 7. | Hapciuc [28] | ✔ | | | | ✔ | | | | | | | ✔ | | | ✔ | | | | | | | |
| 8. | Howard [29] | | | ✔ | ✔ | | ✔ | | | | | | | | | | | | | | | | |
| 9. | Iosub [30] | ✔ | | | | | | | | | | | | | | | | | | | | | |
| 10. | Kincey [7] | ✔ | | | ✔ | | | ✔ | ✔ | | | | | | | | | | | | | | |
| 11. | Lanza [31] | ✔ | | | | | ✔ | | | | | | | | | | | | | | | | |
| 12. | Li [25] | ✔ | | | | | | | | | | | | | | | | | | | | | ✔ |
| 13. | Liu [16] | ✔ | | | | ✔ | | | | | | | | | | | | | | | | | |
| 14. | Marcato [22] | | ✔ | | ✔ | | ✔ | | | | | | | | | | | | | | | | |
| 15. | Miranda [32] | ✔ | | | | | | | | | ✔ | | | | ✔ | | | ✔ | | ✔ | | | |
| 16. | Ogiso [14] | ✔ | | | | ✔ | | | | | | | | | | | ✔ | | | | ✔ | ✔ | |
| 17. | Ortiz [33] | ✔ | | ✔ | | | ✔ | | | | ✔ | ✔ | | | | | | | | ✔ | | | |
| 18. | Previtali [17] | ✔ | | | | | | | | ✔ | ✔ | | | ✔ | | | | ✔ | | | | ✔ | |
| 19. | Reeder-Myers [20] | ✔ | | | | ✔ | | | | ✔ | ✔ | | ✔ | | | | | | | | | | |
| 20. | Tutunaru [34] | ✔ | | | ✔ | ✔ | | | | | | | | | | | | | | | | | |

**Table 2.** *Cont.*

| ARRACC | | Risk Management Parameters Used | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Site Exposure | | | | | | | | Site Sensitivity [1] | | | | | | | Site Significance [2] | | | | | | |
| | | Modelled Flood Risk | River Channel Pattern | Vertical Tendency of Channel | Lateral Tendency of Channel | Channel/Floodplain Erosion/Sedimentation | Land Use | River Engineering | Future Climate Adaptation Impact | Situation/Location | Material Character | Complexity/Form | Substrate Type | Condition | Heritage Status/Age [3] | Land Use [4] | Scientific/Archaeological | Social/Cultural | Cosmological/Spiritual | Historic | Aesthetic | Economic | Stakeholder Input |
| 21. | Vojinovic [15] | ✔ | | | | ✔ | | | | | ✔ | ✔ | | | ✔ | | | ✔ | ✔ | ✔ | ✔ | | ✔ |
| 22. | Wang [26] | ✔ | | | | | | | | | | | | | | | | | | | | | |

A tick [✔] indicates the use of the given parameter. [1] Sensitivity parameters differed somewhat amongst the reviewed articles: where the terms differed marginally, we allocated them to their nearest equivalence, understanding that interpretation will vary from case to case and be decided by the surveyor/risk manager. [2] Significance categories utilised in the reviewed articles most frequently used ICOMOS categorisation; where the terms differed marginally, we allocated them to their nearest equivalence. [3] Where reviewed articles used 'heritage status/age' as a Sensitivity parameter, in our proposed field survey [Table 3] we allocate these to the Sensitivity parameter 'degree of intervention/conservation status', to distinguish this parameter from the Significance parameter 'historic'; [4] and where reviewed articles used 'land use' as a Sensitivity parameter, in our proposed field survey we treat this as an Exposure parameter.

**Table 3.** ARRACC Site Survey/Framework.

| | VALUE OPTIONS (Numerical Score in Brackets) | | |
|---|---|---|---|
| **PARAMETERS** | **Option A (2 pts)** | **Option B (1 pt)** | **Option C (0 pts)** |
| **1.1 Exposure parameters** | | | |
| Modelled flood risk | high [✓] | medium | low |
| River channel pattern | single-channel rivers: braided<br>anabranching rivers: braided [✓] | single-channel rivers: meandering<br>anabranching rivers: meandering | single-channel rivers: straight<br>anabranching rivers: island form<br>single-channel rivers: stable sinuous<br>anabranching rivers: stable sinuous |
| Vertical tendency of channel | aggrading [✓] | incising | stable |
| Lateral tendency of channel | highly mobile | mobile | stable [✓] |
| Channel/floodplain erosion/sedimentation | high | medium | low [✓] |
| Land use | urban growth | high intensity agriculture/forestry<br>urban [✓] | low intensity agriculture/forestry<br>non-urban |
| River engineering | no flood embankments | partially embanked | fully embanked [✓] |
| Future climate adaptation impact | high [✓] | medium | low |
| **1.2. Sensitivity Parameters** | | | |
| Complexity | tall/complex structure | low/simple structure [✓] | artefact |
| Situation/location | above surface [✓] | surface | subsurface |
| Material characteristics | low [✓] | medium | high |
| Degree of intervention/conservation status | no conservation [✓] | partially conserved | highly conserved, adapted |

**Table 3.** *Cont.*

| | VALUE OPTIONS (Numerical Score in Brackets) | | |
|---|---|---|---|
| **PARAMETERS** | **Option A (2 pts)** | **Option B (1 pt)** | **Option C (0 pts)** |
| Condition | good | medium | poor [✓] |
| Substrate i.e., soil type | soft | medium [✓] | hard |
| | | | **(A) Total Exposure and Sensitivity Score = [17]** |
| **2 Significance Parameters** | | | |
| Social | high [✓] | medium | low |
| Scientific | high | medium [✓] | low |
| Cosmological/spiritual | high | medium [✓] | low |
| Historic | high [✓] | medium | low |
| Aesthetic | high | medium [✓] | low |
| Economic | high [✓] | medium | low |
| | | | **(B) Total Significance Score = [9]** |

**3 Adaptation-priority matrix**

In this hypothetical survey, (A) Total Exposure and Sensitivity Score of 17 and (B) Total Significance Score of 9 converge on a 'very high' adaptation priority.

| | | **(B) Total Significance Score** | | |
|---|---|---|---|---|
| | | 0–4 pts | 5–8 pts | 9–12 pts [✓] |
| **(A) Total Exposure and Sensitivity Score** | [✓] 17–24 | medium | high | **[very high]** |
| | 9–16 | low | medium | high |
| | 0–8 | very low | low | medium |

**RESULT: Site Adaptation-Priority Level = VERY HIGH**

Eleven ARRACC exclusively used exposure parameters, i.e., parameters assessing the likelihood of flood impacts [7,16,19,20,22,24,26,29–31,34].

Nine ARRACC combined exposure parameters with site sensitivity parameters, i.e., the relative sensitivity of sites to flood impacts [15,17,18,20,21,27,28,32,33]. Seven ARRACC combined exposure parameters with site significance parameters, i.e., the relative value of sites or elements within them [14,15,17,18,21,32,33]. Five ARRACC combined exposure, significance and sensitivity parameters [15,17,18,21,32].

While the exposure parameters most used were based on flood modelling—often using a Geographic Information System (GIS) framework—in relation to predicted changes in the frequency and severity of flooding affecting the site (19 ARRACC), only one of these studies incorporated climate-change projections into modelling [18]. Four ARRACC exclusively used GIS-flood-modelling exposure parameters [2,25,26,30].

Other ARRACC incorporated the following exposure parameters:

- Land use [14–16,20,24,28,34];
- River engineering works [19,22,24,29,31,33];
- Channel and floodplain erosion and sedimentation [7,22,24,29,34];
- Current vertical and/or lateral channel mobility [19,29,33];
- The impact of future climate change adaptation works, as well as future heritage adaptation works [7].

The sensitivity parameter most used was material character [15,17,18,20,27,32,33]. Others used include the following:

- Complexity/form [15,18,27,33];
- Situation/location [17,18,20];
- Substrate type [18,21,28];
- Condition [17,21];
- Heritage status/age [15,32];
- Land use [28].

The significance parameters most used were social/cultural [15,17,21,32] and historic [15,21,32,33]. Others used include the following:

- Aesthetic [14,15,18];
- Scientific/archaeological [14,18];
- Cosmological/spiritual [15,21]; and
- Economic [14,17].

Four ARRACC collaborated with site stakeholders to gain local knowledge or assist with site-significance assessment [15,18,21,25].

## 4. Discussion

In the following sections, we argue that ARRACC should give consideration to a wide range of exposure parameters and not rely on flood modelling alone. As Schroter et al. state:

> "Comparison of model predictive performance shows that additional explanatory variables besides the water depth improve the predictive capability in a spatial and temporal transfer context, i.e., when the models are transferred to different regions and different flood events" [35]

We note the failure of previous conventional defences (concrete flood barriers) undertaken to protect riverine cultural heritage sites from flooding, including at the Valley of the Kings, Egypt [14], Ayutthaya City, Thailand [36], Mogao Grottoes, China [25] and Quebrada de Humahuaca, Argentina [22]. We seek to align our approach with that of the IPCC: undertaking a complete risk assessment requires an in-depth understanding of the full range of possible elements of risk, including the potential hazards, the exposure and sensitivity (also called vulnerability) of defined values/attributes to those hazards and the capacity for adaptation or resilience of the system to bounce back. The IPCC's definition of risk states:

> "In the context of climate change impacts, risks result from dynamic interactions between climate-related hazards with the exposure and vulnerability of the affected human or ecological system to the hazards. Hazards, exposure and vulnerability may each be subject to uncertainty in terms of magnitude and likelihood of occurrence, and each may change over time and space due to socio-economic changes and human decision-making" [37]

In Table 3, we propose a site survey/framework for ARRACC that includes (1) exposure parameters, (2) sensitivity parameters, and (3) significance parameters. Adaptive capacity is not evaluated separately but is considered at several points, e.g., the exposure parameters 'modelled flood risk' and 'river engineering'; the sensitivity parameters 'complexity', 'situation/location', 'condition' and 'degree of intervention/conservation'; and during stakeholder engagement.

### *4.1. Exposure Parameters*

With respect to appropriate exposure parameters related to assessing the impact of increases in flood frequency and magnitude on sites, the following parameters gathered from our literature review are considered of primary concern:

(a) Modelled flood risk—hydraulic modelling of current and future flood risk (e.g., frequency of events, areal extent, depth and duration of inundation), ideally with a GIS, using US Army Corps of Engineers free-to-use HEC-RAS software [38];
(b) River channel pattern—classification of river pattern at the site, using standard protocols, into single-channel and anabranching forms, and into laterally inactive and laterally active channels (Nanson and Knighton, 1996). This will identify site risk related to river channel activity that controls rates of bank erosion, flooding and deposition on floodplains;
(c) The vertical tendency of the channel—documenting the vertical (stable, incising or aggrading) tendency of river channel(s) using field survey, serial cartography, aerial photography or remote sensing;

(d) The lateral tendency of the channel—documenting the lateral (stable or mobile) tendency of river channel(s) in the same way as for the vertical tendency of the channel (above);
(e) Channel/floodplain erosion and/or sedimentation—documenting the degree of sedimentation and erosion in the same way as for the vertical tendency of the channel (above);
(f) Land use—documenting the degree of urbanisation and/or intensity of agriculture or forestry;
(g) River engineering—an evaluation of current and planned river engineering operations and flood control measures from the perspective of whether a site is likely to be protected or compromised by these works;
(h) Future climate adaptation impact—a process-based assessment of any (non-cultural heritage) adaptation works for river-related climate change impacts.

Parameter '(a) modelled flood risk' is likely the most specialised, technical and costly to engage, whereas (b)–(f) can be generally assessed through direct observation, making their addition potentially a cost-effective add-on.

*4.2. Sensitivity Parameters*

The characteristics of the archaeological resource affect its degree of sensitivity to exposure. In situ preservation of the archaeological record occurs when deterioration mechanisms are slowed due to an equilibrium being reached between the artefact and the environment. Where this equilibrium is disturbed, deterioration is likely to accelerate [39]. The degree of sensitivity will also be influenced by the environment in which it is preserved. For example, organic materials in waterlogged environments will have low sensitivity to low-impact inundation, while those in arid environments will be highly sensitive.

Existing studies primarily addressing sensitivity are generally limited to studies of historic buildings [32,40,41]. However, the following parameters gathered from our literature review should be considered of primary concern:

(a) Situational location—whether subsurface or surface;
(b) Material character—the nature and resilience of the material/fabric;
(c) Complexity/form—such as whether the record is an individual artefact or a potentially disaggregated composite;
(d) Substrate type—its potential to protectively encase or support the site;
(e) Condition—any deterioration that reduces resilience or makes the heritage more susceptible to the effects of climate hazards;
(f) Degree of intervention—conservation status, including adaptive measures undertaken. Where reviewed articles used 'heritage status'/'age' as a Sensitivity parameter, we allocate these here to distinguish between the Significance parameter 'historic'.

One reviewed article used 'land use' as a Sensitivity parameter [28]; we consider this better considered an Exposure parameter.

*4.3. Significance Parameters*

The assessment of relative risk to multiple sites across a given landscape may seek to rank them in order of the magnitude of risk for purposes of targeting scarce adaptation resources. However, dedicating conservation efforts to sites at 'very high' risk may make less sense than to sites at 'high' or 'medium' risk if the latter have greater heritage significance. Therefore, combining significance assessment with risk assessment is an important part of site risk *management*. In the late 20th and early 21st centuries, value-based approaches to heritage management became widely accepted [42,43].

Australia ICOMOS [43] conceives of five cultural significance values, all of which appeared across our literature review:

(a) Scientific (including archaeological);
(b) Social/cultural;

(c) Cosmological/spiritual;
(d) Historic;
(e) Aesthetic

In addition, sites may also have a sixth parameter, (f) economic significance, predominantly through tourism [44].

### *4.4. Stakeholder Engagement*

Local stakeholders (i.e., cultural custodians, local governments, 'citizen scientists' or landowners) can potentially provide details on past flood impacts and help devise adaptation strategies. Their involvement in risk management can build skills and the adaptive capacity of the site, and their early 'buy in' results in better outcomes during adaptation-option identification, appraisal and implementation [45].

### *4.5. Damage or Loss from Societal Adaptation to Climate Change*

Sites may be indirectly impacted by climate change, i.e., by climate change-induced agricultural land use changes or large-scale climate change adaptation infrastructure projects such as new hydro-electric schemes and flood-alleviation projects [46]. For example, the construction in Australia of a new pumped hydroelectric energy storage scheme on Snowy River tributaries aims to assist Australia in meeting international $CO_2$ emissions reduction obligations. In 2018, rescue scoping began for over 190 surface-found, early-Holocene Indigenous stone artefacts within the construction path of the scheme [47].

### *4.6. A Site Survey/Framework for ARRACC*

A basic field survey for ARRACC is set out in Table 3. While it takes the form of a survey, it should be treated primarily as conceptual checklist or as a starting point for a bespoke ARRACC for a particular river and the objectives of local stakeholders. The role of local stakeholders is important. They will undoubtedly bring values to bear, and over time, changing values will lead to new iterations of the framework. The site survey proposes a pathway to optimal prioritisation of sites most in need of adaptation so that scarce conservation resources can be targeted. It seeks to assist non-specialists in adding to more specialised modelling of flood risk and to assist them in addressing threats to 'emerging' heritage not yet academically investigated. It combines exposure and sensitivity values—to determine relative site risk of loss or damage—with relative site significance. A scoring system, if used, might be adjusted or locally calibrated through collaboration with stakeholders.

1. The site survey is applicable to components of composite sites or for multiple sites within a broad landscape.
2. Assessments should be regularly reviewed/updated over time as new information becomes available, or climate change projections change.
3. If scoring, the survey/assessor selects a Value Option for each parameter. Each Value Option has a corresponding numerical score (A = 2, B = 1, C = 0). Total scores are calculated for (1) Exposure, (2) Sensitivity and (3) Significance, then registered on the corresponding axes of the Adaptation-Priority Matrix.
4. For illustrative purposes, ticks [✔] and [scores] have been added to Table 3 to replicate a hypothetical survey. Ideally, flood-related climate change risk analysis will be integrated with other risks, i.e., vandalism/theft, fire, invasive species, site remoteness, etc.

## 5. Conclusions

Direct flood damage is projected to increase by four to five times at 4 °C compared to 1.5 °C [3]. ARRACC can inform site adaptation but also inspire further global action to reach carbon neutrality if the risks to significant sites are publicly known. ARRACC might serve as a monitoring or auditing system for the costs of damage and loss and to inform reparation claims. To be robust, however, risk management should consider and select from a wide range of parameters, justifying the exclusion of those not used and leveraging insights from local stakeholders. Cost-benefit analyses for new riverine climate change adaptation infrastructure, such as hydro dams, should account for the cost of loss or rescue of heritage. The level of uncertainty around regional flood projections requires further down-scaling research. While current ARRACC focus on Europe and Asia, the projections for the Americas and Oceania, combined with a paucity of studies, suggest a particularly urgent need for ARRACC in those regions. Earth's endangered riverine archaeological resources need climate change adaptation planning because they are often of high significance—socially, scientifically, cosmologically, historically, economically and aesthetically.

**Author Contributions:** Conceptualization, methodology, writing, review and editing: B.C., C.D., S.F., M.M., S.M.-T. and W.P. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research received no external funding.

**Data Availability Statement:** No new data were created or analyzed in this study. Data sharing is not applicable to this article.

**Conflicts of Interest:** The authors declare no conflict of interest.

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