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The Historic Garden Climate Risk Management Framework (HG-CRMF): A Multi-Scale Heritage-Centered Methodology for Integrating Climate Risk into Conservation Management Plans

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Abstract

Historic gardens are among the cultural heritage assets most vulnerable to climate change because their significance depends on the continuous interaction between living ecological systems, designed landscapes and cultural values. Although international policies increasingly advocate the integration of climate adaptation into heritage management, operational methodologies capable of systematically incorporating climate risk into the conservation planning of historic gardens remain limited. This paper develops the Historic Garden Climate Risk Management Framework (HG-CRMF), a multi-scale, heritage-centered methodological framework designed to integrate climate risk management within existing Conservation Management Plans (CMPs). The framework was developed through the synthesis of international heritage conservation principles, climate adaptation policies, environmental risk assessment methodologies and adaptive governance approaches. Its principal innovation lies in combining strategic conservation planning at the scale of the historic garden with operational implementation through Garden Conservation Units (GCUs), spatially coherent heritage entities that enable site-specific assessment of heritage values, climate hazards, exposure, vulnerability, adaptation measures and monitoring indicators. The HG-CRMF provides a structured workflow linking heritage significance, climate risk assessment, adaptation planning, monitoring and adaptive governance within a single decision-support methodology. Rather than constituting a stand-alone adaptation strategy, the framework strengthens existing conservation planning by embedding climate-informed decision-making into routine management processes.

Keywords: historic gardens; climate risk management; Conservation Management Plans; Garden Conservation Units; heritage-centered conservation

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1. Introduction

Climate change has become one of the most significant challenges facing cultural heritage conservation in the twenty-first century. Rising temperatures, altered precipitation patterns, prolonged droughts, more frequent heatwaves, flooding, severe storms, wildfires and the spread of biological threats are progressively transforming the environmental conditions under which cultural heritage has evolved and has been managed for centuries [1–5]. These changes are no longer regarded as distant scenarios but as measurable processes already affecting heritage sites worldwide, requiring conservation approaches capable of responding to increasing environmental uncertainty while safeguarding cultural significance [1,2].

Among the diverse categories of cultural heritage, historic gardens represent one of the most climate-sensitive and management-intensive typologies. Unlike monuments or archaeological remains, historic gardens are living heritage systems whose significance derives from the continuous interaction between designed landscapes, vegetation, water systems, biodiversity, built elements and cultural practices [6–9]. Their material fabric is inherently dynamic, requiring continuous ecological renewal and horticultural management to preserve historical identity, spatial composition and aesthetic character. Consequently, climate change affects historic gardens simultaneously as ecological systems and as cultural artefacts, challenging conventional conservation approaches based on relatively stable environmental conditions [6,10–14].

This dual ecological and cultural character has long been recognised in international conservation doctrine. The Florence Charter defines the historic garden as an architectural and horticultural composition whose principal material is living vegetation and which therefore requires continuous care, renewal and management [6]. Subsequent conservation theory has reinforced the values-based nature of heritage management, recognising that authenticity and integrity in living heritage cannot be understood solely through the preservation of original material fabric but also through the maintenance of historical design, ecological function, cultural meaning and long-term continuity [15–20]. Climate change intensifies this challenge by modifying the environmental conditions that historically sustained these living systems, requiring conservation strategies capable of accommodating change while preserving heritage significance.

During the last two decades, international organisations have progressively incorporated climate adaptation into cultural heritage policy. UNESCO has emphasised the need to integrate climate action, disaster risk reduction and resilience into World Heritage management [2–4], while ICOMOS has identified climate change as one of the defining challenges for contemporary heritage conservation and has advocated interdisciplinary, values-based adaptation strategies [5]. At the European level, the European Union Strategy on Adaptation to Climate Change and related policy initiatives increasingly recognise cultural heritage as a vulnerable sector requiring proactive adaptation [21]. National adaptation frameworks, including those adopted in Spain and France, similarly acknowledge the need to strengthen the resilience of historic landscapes and gardens under changing climatic conditions [22,23].

Parallel to these policy developments, scientific research has significantly improved understanding of climate impacts on cultural heritage. Studies have analysed vulnerability assessment, climate hazards, ecosystem-based adaptation, nature-based solutions, adaptive governance and environmental monitoring across a wide range of heritage contexts [7–16]. Within the field of historic gardens, increasing attention has been devoted to vegetation resilience, water management, biodiversity conservation, species selection and long-term adaptation planning [24–41]. Collectively, these contributions provide an essential scientific foundation for climate-informed conservation.

Nevertheless, an important methodological gap remains. Although climate risk assessment is now well established in environmental and heritage-related research, its application to historic gardens remains limited and fragmented within routine conservation planning [7–17]. Existing approaches have largely been developed for infrastructure, buildings, or heritage sites treated as relatively stable entities, whereas historic gardens are living and heterogeneous landscapes in which ecological processes, designed form, cultural meaning, and visitor experience are inseparably linked [6,10–14,23–29]. As a result, standard risk terminology is insufficient unless it is translated into a framework capable of connecting heritage significance, climate-related threats, spatial variability, and management decision-making within a single conservation process [1,16,25–29]. This limitation is particularly

evident in Conservation Management Plans, which generally include historical research, significance assessment, maintenance policies, and visitor management, but rarely integrate climate-informed analysis in a systematic and operational manner. It is also evident at the spatial scale of intervention, since historic gardens contain sectors with distinct values, vulnerabilities, and adaptation requirements that cannot be adequately addressed through site-wide assessment alone [6,14,35–45]. In response, this paper develops the Historic Garden Climate Risk Management Framework (HG-CRMF), a heritage-centred, multi-scale methodology that integrates climate risk management into Conservation Management Plans and operationalises this process through Garden Conservation Units (GCUs).

The objectives of this research are therefore fourfold: (i) to examine the theoretical and policy foundations linking climate adaptation and historic garden conservation; (ii) to identify the methodological limitations of current approaches to climate-informed conservation planning; (iii) to develop the Historic Garden Climate Risk Management Framework (HG-CRMF) as a transferable, heritage-centred methodological framework; and (iv) to propose Garden Conservation Units (GCUs) as the operational mechanism through which climate risk assessment, adaptation planning and monitoring can be systematically integrated into Conservation Management Plans.

2. Theoretical Foundations for Climate-Informed Conservation of Historic Gardens

2.1. Historic Gardens as Living Heritage Systems

Historic gardens constitute one of the most complex and dynamic categories of cultural heritage because they combine living vegetation, built structures, hydraulic systems, topography, biodiversity and cultural meaning within an integrated designed landscape. Unlike monuments or archaeological sites, whose material fabric is generally expected to remain relatively stable over time, historic gardens are characterised by continuous ecological transformation resulting from biological growth, seasonal cycles, natural succession and long-term environmental change. Their conservation therefore requires the management of dynamic ecological processes while simultaneously preserving historical design, cultural significance and landscape character [6,8–12].

Historic gardens should be understood as living heritage places in which botanical, spatial, aesthetic, and cultural values are sustained through continuous care and management rather than through static preservation alone. In this sense, they are comparable to botanical gardens as living museum-like landscapes, because their significance depends on the ongoing stewardship of living collections, designed compositions, ecological processes, and visitor experience. Unlike inert heritage objects, historic gardens require renewal, adaptation, and interpretation to maintain historical character and meaning over time. This living quality makes them especially vulnerable to climate change, but it also places them within a conservation logic that values continuity through managed change rather than strict material fixity.

The recognition of historic gardens as living heritage has progressively influenced international conservation theory over the last four decades. The Florence Charter defines the historic garden as an architectural and horticultural composition of interest to the public from the historical or artistic point of view whose constituent material is primarily vegetal and therefore living, perishable and renewable [6]. This definition remains one of the fundamental conceptual references for historic garden conservation because it acknowledges that biological change is an intrinsic characteristic of the heritage asset rather than a threat to be eliminated.

Recent developments in Heritage Science have further expanded this understanding by interpreting historic gardens as complex socio-ecological systems. From this perspective,

historic gardens are not merely designed landscapes containing vegetation, but dynamic systems in which ecological processes, cultural values and management practices continuously interact across multiple temporal and spatial scales.

2.2. Climate Change and the Conservation of Historic Gardens

Climate change is increasingly recognised as one of the principal long-term drivers of transformation affecting both natural and cultural heritage. Historic gardens are particularly exposed because their living components respond directly to changes in temperature, precipitation, atmospheric composition and the frequency and intensity of extreme weather events. Consequently, climate change has become a critical factor influencing the long-term conservation, management and resilience of designed landscapes [1–5].

Prolonged drought and increasing water scarcity represent some of the most significant threats to historic gardens. Many gardens were designed under climatic conditions characterised by greater water availability and lower evapotranspiration rates than those projected for the coming decades. Reduced water resources affect irrigation systems, ornamental ponds, fountains and wetlands while simultaneously increasing physiological stress in mature trees and ornamental plant collections [30–32].

Extreme precipitation, flooding, heat stress, pests and diseases interact with existing conservation pressures. These cascading interactions create complex risk profiles that cannot be adequately addressed through isolated management actions. Conservation planning therefore requires integrated approaches capable of simultaneously considering multiple hazards, ecological responses and heritage values.

2.3. Climate Risk Management and Heritage Conservation

Climate risk management provides a structured basis for identifying, evaluating, and responding to climate-related threats, commonly through the interaction of hazards, exposure, and vulnerability within a broader process of review and treatment [1,25]. In heritage contexts, however, this logic cannot be applied as a purely technical exercise, because what is at risk is defined not only by physical condition but also by cultural meaning, historical continuity, and values-based conservation priorities [17–20]. This is particularly relevant in historic gardens, whose significance derives from the interaction between living vegetation, built elements, ecological processes, spatial design, and cultural experience [6,17–19].

The principal challenge, therefore, is not the definition of risk itself, but its adaptation to a heritage-centred framework capable of evaluating climate threats in relation to significance [1,17,19–25]. If climate risk assessment is detached from heritage values, adaptation measures may reduce environmental pressure while compromising authenticity, design intent, or cultural meaning [17–19]; conversely, conservation planning that ignores future climate conditions may preserve short-term integrity while increasing long-term vulnerability [7–14]. Climate-informed conservation of historic gardens therefore requires an approach that retains the analytical clarity of risk management while embedding it within the decision-making logic of living heritage [6,17–19,24,25].

2.4. Existing Approaches to Climate Adaptation in Historic Gardens

During the last two decades, climate adaptation has progressively become embedded within the policies and management strategies of organisations responsible for cultural heritage and historic landscapes. UNESCO, ICOMOS, European institutions and national heritage agencies have developed guidance on climate action, disaster risk reduction, resilience and adaptive management [2–5,17–19].

At the site level, several heritage organisations have implemented innovative adaptation initiatives. The National Trust in the United Kingdom has developed long-term

climate adaptation strategies for historic estates [36,37], Historic England has produced technical guidance on climate adaptation [28,29], and Royal Botanic Gardens Victoria has incorporated climate projections into living collections management [30,31]. Comparable approaches to historic-garden conservation and management have addressed restoration, cultural sustainability and long-term stewardship [32–35]. Within Spain, the Plan Director de la Alhambra y Generalife provides an important example of integrated planning for a major historic garden and cultural landscape [38], while national initiatives have progressively incorporated meteorological emergencies, cultural landscape planning and risk management into heritage conservation [39–41]. Despite these advances, existing approaches remain largely project-specific and institutionally fragmented. Most initiatives have been developed in response to local environmental conditions, organisational priorities or individual management challenges. Consequently, while they provide valuable examples of good practice, they rarely offer a transferable methodological process capable of systematically integrating climate risk assessment into conservation planning.

2.5. Knowledge Gaps and the Need for an Integrated Framework

The review presented in the preceding sections demonstrates that significant advances have been achieved in heritage conservation, climate adaptation and environmental risk management. Nevertheless, these fields have largely evolved independently, resulting in limited integration of their respective concepts and methodologies within the conservation of historic gardens.

A critical examination of current approaches reveals two principal gaps. First, most climate adaptation studies remain hazard-oriented and rarely connect environmental analysis with heritage values and conservation priorities. A critical examination of current approaches reveals three related gaps. First, although value-based and hazard-based approaches have been combined in other heritage contexts, their application to historic gardens remains limited, particularly in relation to climate-change-related hazards. Second, existing Conservation Management Plans rarely incorporate structured methodologies that systematically connect heritage significance, climate risk assessment, and adaptation priorities. Third, most approaches do not adequately address the internal heterogeneity of historic gardens at the landscape scale. The HG-CRMF has been developed to respond to these limitations through a heritage-centred, multi-scale framework operationalised through Garden Conservation Units.

The HG-CRMF has been developed to address these methodological needs. It provides a heritage-centred methodology through which climate risk management can be systematically integrated into Conservation Management Plans and operationalised through Garden Conservation Units.

3. Materials and Methods

3.1. Research Design

This study adopts a methodological research approach aimed at developing a structured framework for integrating climate risk management into the conservation planning of historic gardens. Unlike empirical studies that seek to test predefined hypotheses through experimental or observational methods, methodological research focuses on the systematic development of conceptual and operational tools capable of addressing identified gaps within existing scientific knowledge.

The research design followed an iterative and interdisciplinary process that combined qualitative literature review, comparative analysis of international conservation policies, synthesis of existing climate adaptation approaches and conceptual integration

of established principles from heritage conservation, climate science, landscape ecology, environmental risk management and adaptive governance.

3.2. Development of the HG-CRMF

The conceptual development of the HG-CRMF was guided by the premise that climate adaptation in historic gardens cannot be addressed exclusively through environmental assessment nor solely through conventional conservation planning. Instead, effective adaptation requires a methodology capable of integrating environmental risk analysis with the values-based principles that underpin heritage conservation.

The development of the HG-CRMF was guided by six methodological principles: heritage-centred decision-making, systems thinking, climate-informed conservation, risk-based prioritisation, adaptive management and transferability. Together, these principles define the conceptual philosophy underlying the HG-CRMF and ensure consistency throughout the different stages of framework implementation.

The HG-CRMF was developed through four stages: (i) identification and review of theoretical foundations relevant to climate-informed conservation of historic gardens; (ii) comparative analysis of existing methodologies and institutional approaches; (iii) conceptual synthesis of concepts derived from reviewed disciplines; and (iv) framework design and internal validation.

3.3. Definition and Delimitation of Garden Conservation Units (GCUs)

One of the methodological innovations of the Historic Garden Climate Risk Management Framework (HG-CRMF) is the introduction of Garden Conservation Units (GCUs) as the operational scale for climate-informed conservation planning. Historic gardens are inherently heterogeneous socio-ecological systems in which heritage values, ecological characteristics, spatial structures, and climate-related vulnerabilities vary considerably across space. For this reason, assessing the garden as a single homogeneous entity may obscure localised risks and overlook the specific conservation needs of different landscape sectors. A GCU is defined as a spatially coherent heritage entity that groups landscape components sharing similar historical, ecological, functional, management, and experiential characteristics. Rather than being determined exclusively by geometric boundaries, GCUs are delineated by considering historical design, vegetation structure, hydrological systems, built heritage, topography, patterns of use, visual relationships, sensory qualities, and maintenance requirements. In this sense, GCUs capture not only the physical organisation of the garden but also the ways in which its components contribute to aesthetic experience, symbolic meaning, and public appreciation. Depending on the characteristics of each historic garden, GCUs may correspond to formal parterres, tree masses, specimen trees, hydraulic systems, woodland sectors, terraces, circulation networks, viewpoints, or public-use areas. The adoption of GCUs enables the HG-CRMF to operate simultaneously at two complementary spatial scales. At the strategic scale, the historic garden is managed through an integrated Conservation Management Plan. At the operational scale, each GCU is independently analysed through the complete HG-CRMF workflow, allowing climate risks, heritage values, adaptation priorities, and monitoring programmes to be tailored to the specific conditions of each conservation unit. The aggregation of all GCU assessments subsequently provides an integrated climate risk profile for the historic garden as a whole.

The final step of the framework is a cross-unit synthesis that consolidates GCU findings into a site-level heritage risk profile, thereby reconnecting unit-level assessments into an integrated understanding of the historic garden as a whole.

3.4. Scope and Intended Application of the Framework

The HG-CRMF is intended as a conceptual and methodological framework rather than a prescriptive management protocol. Its primary purpose is to support heritage professionals in integrating climate risk management into existing Conservation Management Plans while maintaining consistency with internationally recognised conservation principles.

3.5. Study Site

The case study is located in Aranjuez, in the southern part of the Community of Madrid, central Spain, at the confluence of the Tajo and Jarama rivers within the fertile alluvial landscape of the Tajo valley. From a biogeographical perspective, the site lies in a Mediterranean continental climate zone characterised by hot, dry summers, cold winters, and marked seasonal variability in precipitation. Average annual precipitation is approximately 470 mm, with a pronounced summer drought and most rainfall concentrated in autumn and spring. Mean monthly maximum temperatures reach about 35 °C in July, while winter minimums frequently fall below freezing. These climatic conditions place the garden in a transition zone between Mediterranean and continental influences, with strong implications for plant selection, irrigation demand, and seasonal stress.

In terms of plant selection, the site falls within USDA Plant Hardiness Zone 9a, which corresponds to average annual extreme minimum temperatures between −6.7 °C and −3.9 °C. This hardiness zone is typical of the central Iberian plateau and reflects the combination of a Mediterranean climate with continental influences, including cold winter minima and hot, dry summers. The zone provides a useful reference for understanding which perennial species can persist under current climatic conditions, and which are likely to experience increasing stress as minimum temperatures shift and summer drought intensifies [45].

Within this context, the vegetation of the Jardín de la Isla y del Parterre has historically combined species adapted to the riverine environment of the Tajo with ornamental taxa introduced for formal and scenic purposes. The climate zone therefore plays a decisive role in determining which species can persist under low summer water availability and high thermal exposure, and which require intensive irrigation or microclimatic protection. The case study uses this geographical and climatic framing to interpret the vulnerability of different Garden Conservation Units, particularly those dominated by vegetation, and to justify adaptation measures related to species compatibility, irrigation management, and soil improvement.

4. Results

4.1. Formal Definition of the Historic Garden Climate Risk Management Framework

The principal outcome of this research is the development of the Historic Garden Climate Risk Management Framework (HG-CRMF), a multi-scale, heritage-centred conceptual and methodological framework designed to support the systematic integration of climate risk management into the conservation planning of historic gardens.

The HG-CRMF functions as an integrative methodology (Figure 1) that enables climate risk considerations to become an intrinsic component of existing Conservation Management Plans. Unlike conventional climate risk methodologies, which generally begin with the identification of climatic hazards, the HG-CRMF begins by identifying heritage values, character-defining elements and cultural attributes that require long-term conservation.

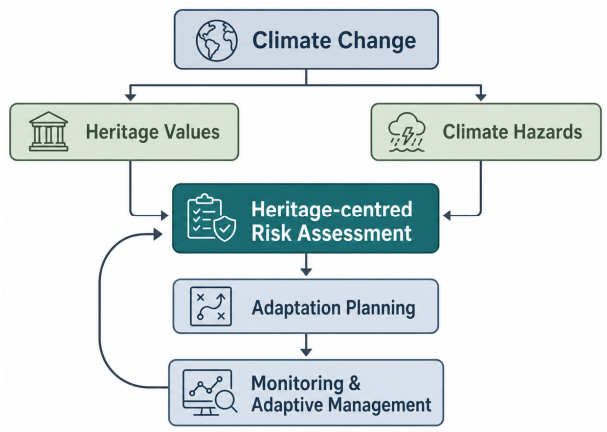


Figure 1. Conceptual model underpinning the HG-CRMF. (Source: Own elaboration).

4.2. Conceptual Scheme of the HG-CRMF

The HG-CRMF is organised around five interconnected methodological modules: Heritage Characterisation, Climate Risk Assessment, Adaptation Planning, Monitoring and Evaluation, and Adaptive Governance (Figure 2). These modules are not independent phases but complementary components of an iterative management cycle in which information generated during implementation continuously informs subsequent decision-making.

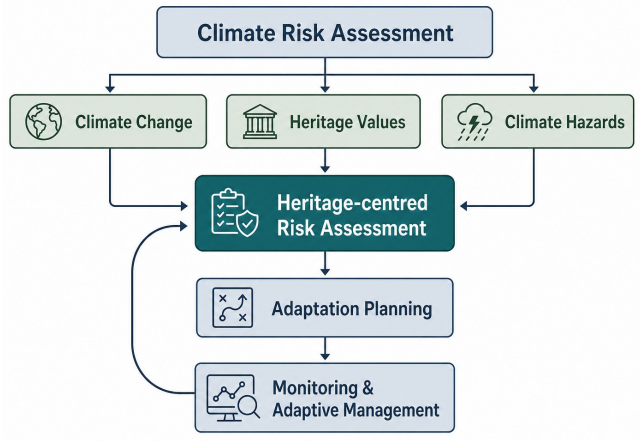


Figure 2. Conceptual scheme of the HG-CRMF. (Source: Own elaboration).

The HG-CRMF translates the conceptual scheme into an operational workflow (Figure 3) that supports climate-informed conservation planning through a structured sequence of decision-making stages. The sequence begins with heritage characterisation, followed by climate characterisation, hazard identification, exposure assessment, vulnerability assessment, heritage-centred climate risk assessment, adaptation planning, implementation, monitoring and adaptive governance.

4.3. Operational Application Through Garden Conservation Units

The HG-CRMF was spatially operationalised through Garden Conservation Units (Figure 4). A GCU is characterized as a heritage unit with spatial coherence, encompassing landscape elements that exhibit similar historical, ecological, functional, and management traits. Instead of relying solely on geometric borders, GCUs are outlined by considering factors such as historical design, vegetation layout, water systems, architectural heritage, terrain, usage patterns, and upkeep needs. Based on the specific features of each historic garden, GCUs might align with formal parterres, clusters of trees, individual specimen

trees, water management systems, wooded areas, terraces, pathways, or zones designated for public use.

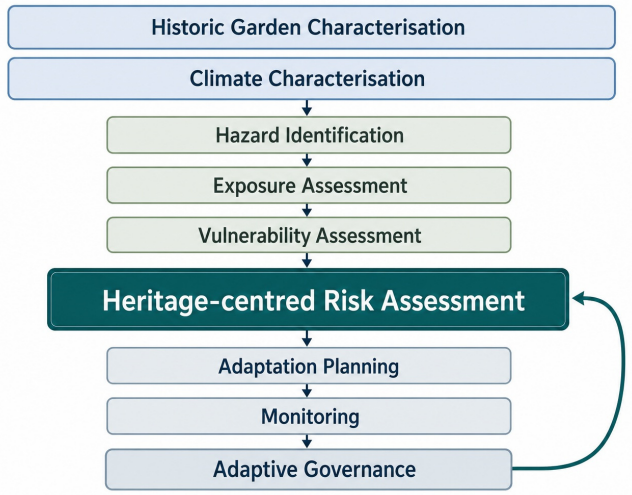


Figure 3. Operational workflow of the HG-CRMF. (Source: Own elaboration).

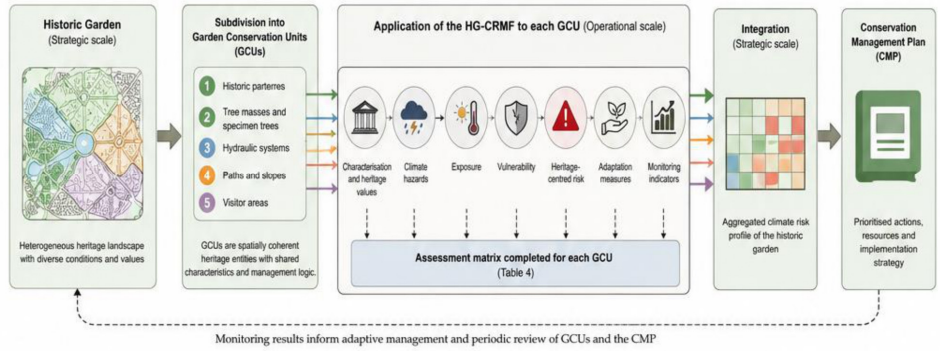


Figure 4. Spatial operationalization of the HG_CRMF through Garden Conservation Units (GCU). (Source: Own elaboration).

The HG-CRMF is operationalised through the systematic assessment of each Garden Conservation Unit (GCU) using a standardised analytical matrix (Table 1). While the conceptual scheme and operational workflow remain consistent across the historic garden, the assessment is conducted independently for each GCU to capture the spatial variability of heritage values, climate hazards and management priorities.

Table 1. Operational assessment matrix for Garden Conservation Units (GCUs) within the Historic Garden Climate Risk Management Framework (HG-CRMF). (Source: Own elaboration).

Garden Conservation Unit	Heritage Values	Climate Hazards	Exposure	Vulnerability	Heritage-Centred Risk	Priority Adaptation Measures	Monitoring Indicators
Historic parterres	geometric design, planting composition, formal legibility, visual order, scenic experience.	Extreme heat, drought, intense rainfall	High if exposed to solar radiation and soil compaction	High if species are sensitive or irrigation is insufficient	High	Soil improvement, mulching, irrigation adjustment, review of compatible species	Water consumption, plant decline, cover, surface temperature

Table 1. *Cont.*

Garden Conservation Unit	Heritage Values	Climate Hazards	Exposure	Vulnerability	Heritage-Centred Risk	Priority Adaptation Measures	Monitoring Indicators
Tree masses and specimen trees	botanical value, landscape identity, shade, enclosure, visual prominence, symbolic and emotional associations.	Wind, storms, heat, pests, drought	High along exposed edges and axes	High due to age, pathology or lack of structural soil	High to very high	Phytosanitary inspection, compatible pruning, soil improvement, root and irrigation management	Branch failure, mortality, vigour, wind-related incidents
Hydraulic systems	functional, aesthetic, and sensory value, including sound, movement, visual reflection, and spatial character.	Drought, intense rainfall, flooding, siltation	High in low-lying areas or obsolete infrastructure	Medium to high due to obsolescence and maintenance needs	Medium to high	Cleaning, hydraulic restoration, leakage control, storage and drainage improvement	Water level, pumping failures, overflow events
Pavements, slopes and routes	Material integrity, historic accessibility, legibility of layout	Intense rainfall, erosion, runoff, frost	Variable according to slope and use	Medium to high due to fragile materials or poor drainage	Medium to high	Drainage improvement, stabilisation, preventive maintenance, runoff control	Erosion, deformation, slipperiness, use incidents
Public-use areas	social use, legibility, comfort, atmosphere, accessibility, and visitor experience.	Extreme heat, wind, storms	High due to occupation and permanence	Variable according to shade, refuge and management	High for safety	Closure protocols, signage, climate refuges, visitor-flow management	Activated alerts, closures, safety incidents

For every GCU, the framework evaluates complementary dimensions: heritage values, climate hazards, exposure, vulnerability, heritage-centred climate risk, priority adaptation measures and monitoring indicators. This structured assessment ensures methodological consistency while allowing conservation actions to respond to the specific ecological, historical and functional characteristics of individual landscape sectors.

To reflect the different conservation logics of historic gardens, the operational matrix is divided into vegetation-dominated units, mineral/built units, hydraulic systems, and public-use/circulation areas, each of which responds differently to climate stress.

4.4. Application of the HG-CRMF to the Case Study

The HG-CRMF was applied to the Jardín de la Isla y del Parterre in Aranjuez, through the identification of Garden Conservation Units corresponding to its principal spatial and functional components. The units were delineated according to the riverine structure of the landscape, the distribution of tree masses, planted compartments, hydraulic relationships, and circulation areas. Table 2 was used to assess the vegetation-dominated units, Table 3 the mineral and built units, Table 4 the hydraulic systems, and Table 5 the public-use and circulation areas.

Table 2. Vegetation-dominated units.

Garden Conservation Unit	Heritage Values	Climate Hazards	Exposure	Vulnerability	Heritage-Centred Risk	Priority Adaptation Measures	Monitoring Indicators
Historic parterres	Geometric design; planting composition; formal legibility; visual order; scenic experience	Extreme heat; drought; intense rainfall	High if exposed to solar radiation and soil compaction	High if species are sensitive or irrigation is insufficient	High	Soil improvement; mulching; irrigation adjustment; review of compatible species	Water consumption; plant decline; cover; surface temperature
Tree masses and specimen trees	Botanical value; landscape identity; shade; enclosure; visual prominence; symbolic and emotional associations	Wind; storms; heat; pests; drought	High along exposed edges and axes	High due to age; pathology; lack of structural soil	High to very high	Phytosanitary inspection; compatible pruning; soil improvement; root and irrigation management	Branch failure; mortality; vigour; wind-related incidents
Shrub borders and hedges	Spatial definition; compositional continuity; enclosure; habitat value	Heat; drought; frost; pests	Medium to high depending on exposure	Medium to high due to water stress and pruning sensitivity	Medium to high	Species review; pruning adjustment; mulching; irrigation optimization	Dieback; density; regrowth; pest incidence
Lawns and herbaceous displays	Seasonal aesthetics; legibility; visitor experience; texture and colour	Heat; drought; heavy rainfall	High in open areas and compacted soils	High where irrigation or drainage is insufficient	Medium to high	Reduce water demand; soil aeration; reseeding with compatible taxa; irrigation management	Coverage; colour retention; water use; surface temperature

Table 3. Mineral and built units.

Garden Conservation Unit	Heritage Values	Climate Hazards	Exposure	Vulnerability	Heritage-Centred Risk	Priority Adaptation Measures	Monitoring Indicators
Paths and pavements	Material integrity; historic accessibility; legibility of layout	Intense rainfall; erosion; runoff; frost; heat	Variable according to slope and use	Medium to high due to fragile materials or poor drainage	Medium to high	Drainage improvement; stabilisation; preventive maintenance; runoff control	Erosion; deformation; slipperiness; use incidents
Terraces, retaining walls and steps	Topographic legibility; structural stability; historic construction techniques	Intense rainfall; runoff; freeze–thaw; subsidence	High on slopes and edges	Medium to high where joints or foundations are vulnerable	Medium to high	Structural inspection; joint repair; drainage; stabilisation	Cracking; displacement; dampness; instability

Table 3. *Cont.*

Garden Conservation Unit	Heritage Values	Climate Hazards	Exposure	Vulnerability	Heritage-Centred Risk	Priority Adaptation Measures	Monitoring Indicators
Statues, ornaments and garden architecture	Artistic value; iconography; focal points; historical layering	Heat; wind; rainfall; pollutants; biological colonisation	Variable according to position and material	Medium to high depending on stone, metal or composite material	Medium	Cleaning; material repair; protective treatment; microclimate control	Surface decay; staining; loss of detail; movement

Table 4. Hydraulic systems.

Garden Conservation Unit	Heritage Values	Climate Hazards	Exposure	Vulnerability	Heritage-Centred Risk	Priority Adaptation Measures	Monitoring Indicators
Ponds, canals and ornamental water bodies	Water presence; visual reflection; sound; spatial identity; ecological support	Drought; intense rainfall; flooding; siltation; eutrophication	High in low-lying areas or with limited inflow	Medium to high due to water imbalance and maintenance needs	Medium to high	Cleaning; water-level control; sediment management; quality monitoring	Water level; clarity; algae growth; overflow events
Fountains and basins	Aesthetic focal points; hydraulic heritage; sensory character	Drought; flooding; siltation; pump failure; water loss	High where supply or drainage is constrained	Medium to high due to mechanical and hydraulic dependence	Medium to high	Leakage control; pump maintenance; storage improvement; seasonal management	Flow continuity; pump failures; water loss; overflow
Irrigation and drainage networks	Functional support for vegetation; soil moisture regulation; site resilience	Drought; intense rainfall; flooding; blockage; leakage	High across planted and low-lying zones	High where infrastructure is obsolete	High	Network inspection; cleaning; repair; capacity adjustment	Pressure; blockages; leakage; drainage performance

Table 5. Public-use and circulation areas.

Garden Conservation Unit	Heritage Values	Climate Hazards	Exposure	Vulnerability	Heritage-Centred Risk	Priority Adaptation Measures	Monitoring Indicators
Entrance zones and gathering areas	Accessibility; legibility; visitor orientation; social use	Extreme heat; wind; storms	High due to occupation and permanence	Variable according to shade, refuge and management	High for safety	Closure protocols; signage; climate refuges; visitor-flow management	Activated alerts; closures; incidents

Table 5. *Cont.*

Garden Conservation Unit	Heritage Values	Climate Hazards	Exposure	Vulnerability	Heritage-Centred Risk	Priority Adaptation Measures	Monitoring Indicators
Circulation routes and rest areas	Movement; sequence; scenic experience; comfort	Heat; storms; rainfall; erosion	High along main routes and exposed nodes	Variable by exposure and surface condition	Medium to high	Shade provision; drainage; route rerouting; preventive maintenance	Use incidents; overheating; congestion; slippery surfaces

4.4.1. Vegetation-Dominated Units

The vegetation-dominated units showed the highest dependence on irrigation, soil condition, and species resilience. In the Jardín de la Isla y del Parterre, (Figure 5) tree masses and planted compartments presented a complex relationship between ecological resilience and heritage significance, since plant material contributed both to spatial identity and historical character. The analysis identified soil improvement, irrigation optimisation, species compatibility, and canopy monitoring as priority measures.

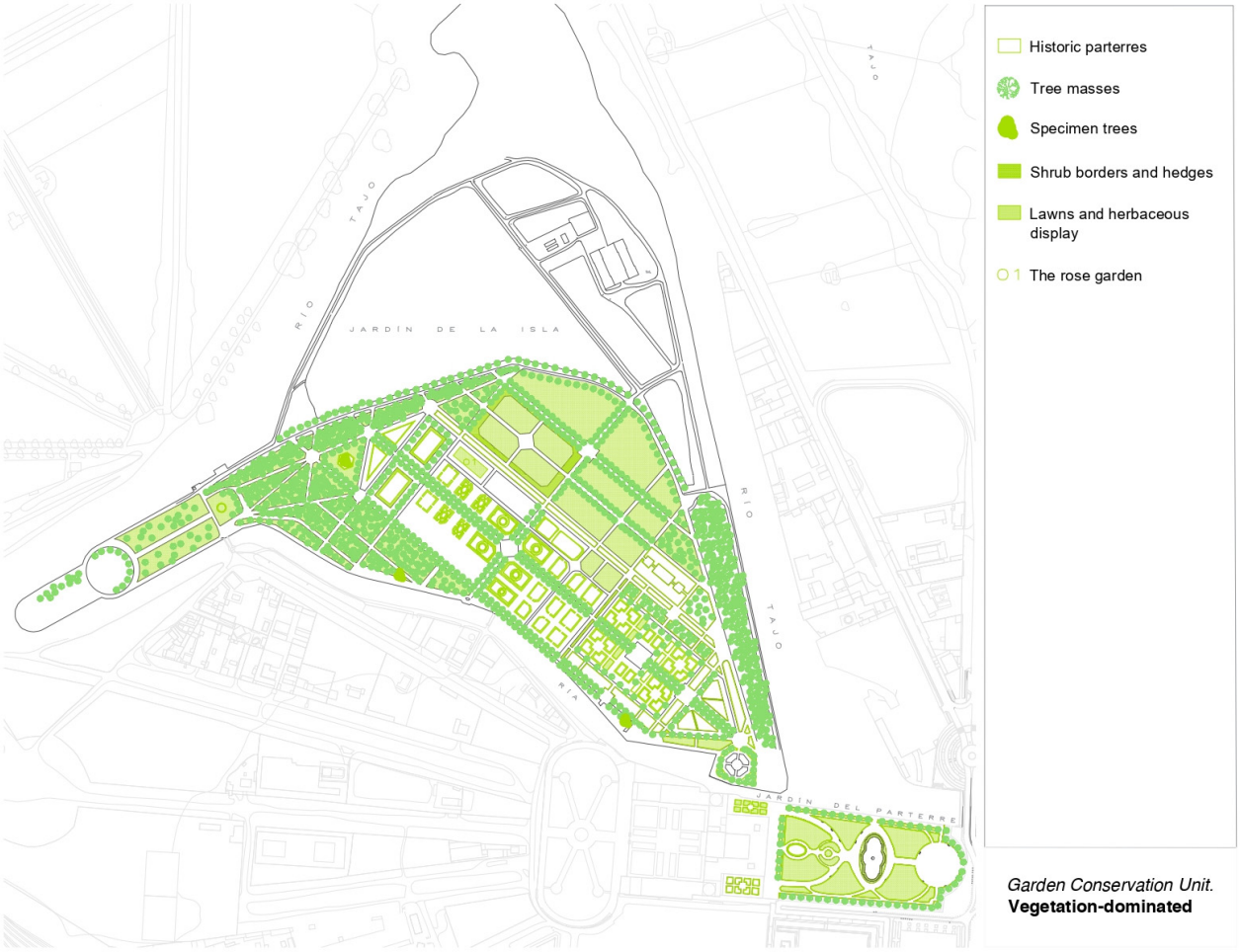


Figure 5. Vegetation Units. El Jardín de la Isla y del Parterre (own elaboration).

4.4.2. Mineral and Built Units

The mineral and built units in the Jardín de la Isla y del Parterre (Figure 6) displayed a different risk profile, with vulnerability concentrated in erosion, thermal stress, drainage failure, and material decay. Paths, pavements, terraces, and retaining structures were especially sensitive to intense rainfall and runoff, particularly in sloping or heavily used areas. These elements required conservation through repair, stabilisation, and preventive maintenance rather than through renewal of living material.

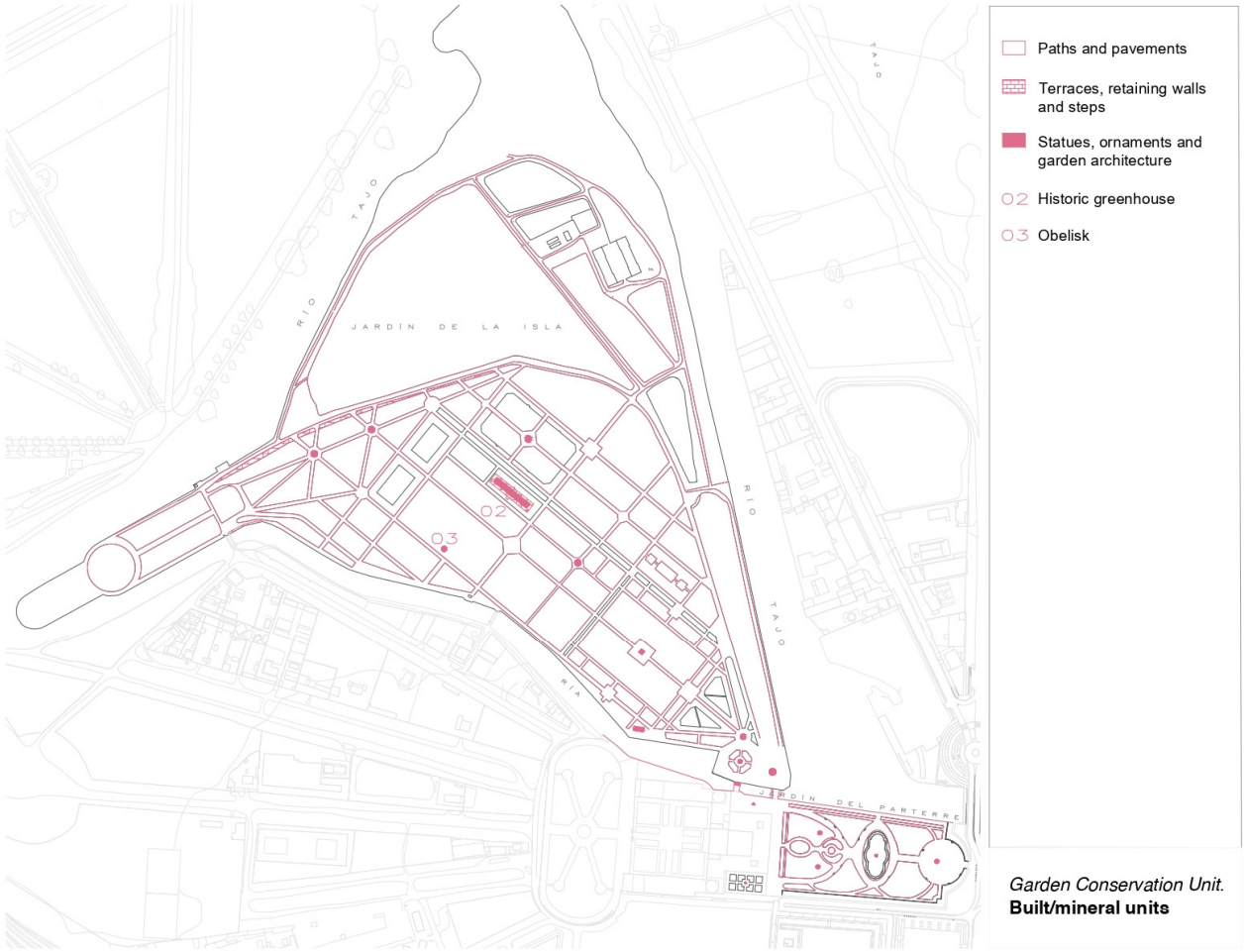


Figure 6. Mineral and built Units. El Jardín de la Isla y del Parterre (own elaboration).

4.4.3. Hydraulic Systems

Hydraulic systems emerged as a critical component of the garden because water functioned not only as a material feature but also as a structuring principle of its historical design. In the Jardín de la Isla y el Parterre (Figure 7), canals, ponds, and water-related spaces were especially important because of their relationship with the Tajo landscape and the sensory identity of the garden. The analysis showed that drought, siltation, flooding, and hydraulic malfunction affected both technical performance and heritage character, making water management a central adaptation priority.

4.4.4. Public-Use and Circulation Areas

Finally, the public-use and circulation areas in the Jardín de la Isla y del Parterre, (Figure 8) were assessed in relation to safety, legibility, comfort, and visitor experience. These areas were particularly exposed to extreme heat, wind, and storm events, requiring measures related to shade, signage, closure protocols, and visitor-flow management.

The results confirmed that a single site-wide assessment was insufficient and that Garden Conservation Units provided a more precise operational basis for climate-informed conservation planning.

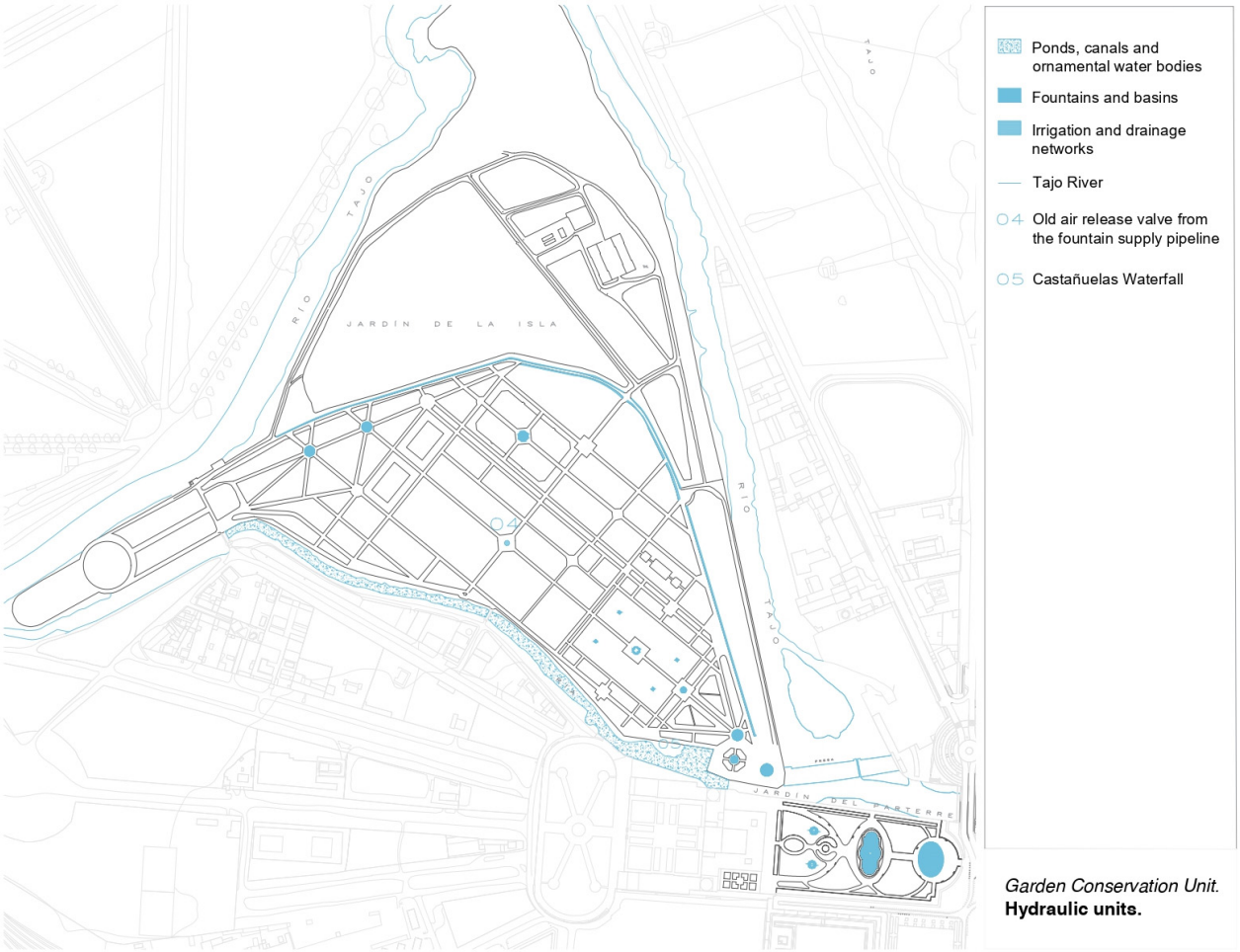


Figure 7. Hydraulic systems units. Jardín de la Isla y del Parterre (own elaboration).

4.5. Integrated Climate Risk Profile

The application of the HG-CRMF produced a differentiated climate risk profile for the Jardín de la Isla. Vegetation-dominated units were most affected by drought and thermal stress, mineral and built units were more exposed to erosion and material degradation, and hydraulic systems were particularly vulnerable to water imbalance, blockage, and seasonal variability. Public-use and circulation areas were primarily affected by extreme heat and storm events, with safety and comfort as the main concerns. The results confirmed that a single site-wide assessment was insufficient and that Garden Conservation Units provided a more precise operational basis for climate-informed conservation planning.

4.6. Integration into Conservation Management Plans

One of the principal innovations of the HG-CRMF is that it is not conceived as an independent climate adaptation plan but as a methodological layer integrated within existing Conservation Management Plans (Figure 9). Climate considerations are introduced at each principal stage of the conservation planning cycle, allowing adaptation to become a cross-cutting component of management rather than an isolated environmental activity.

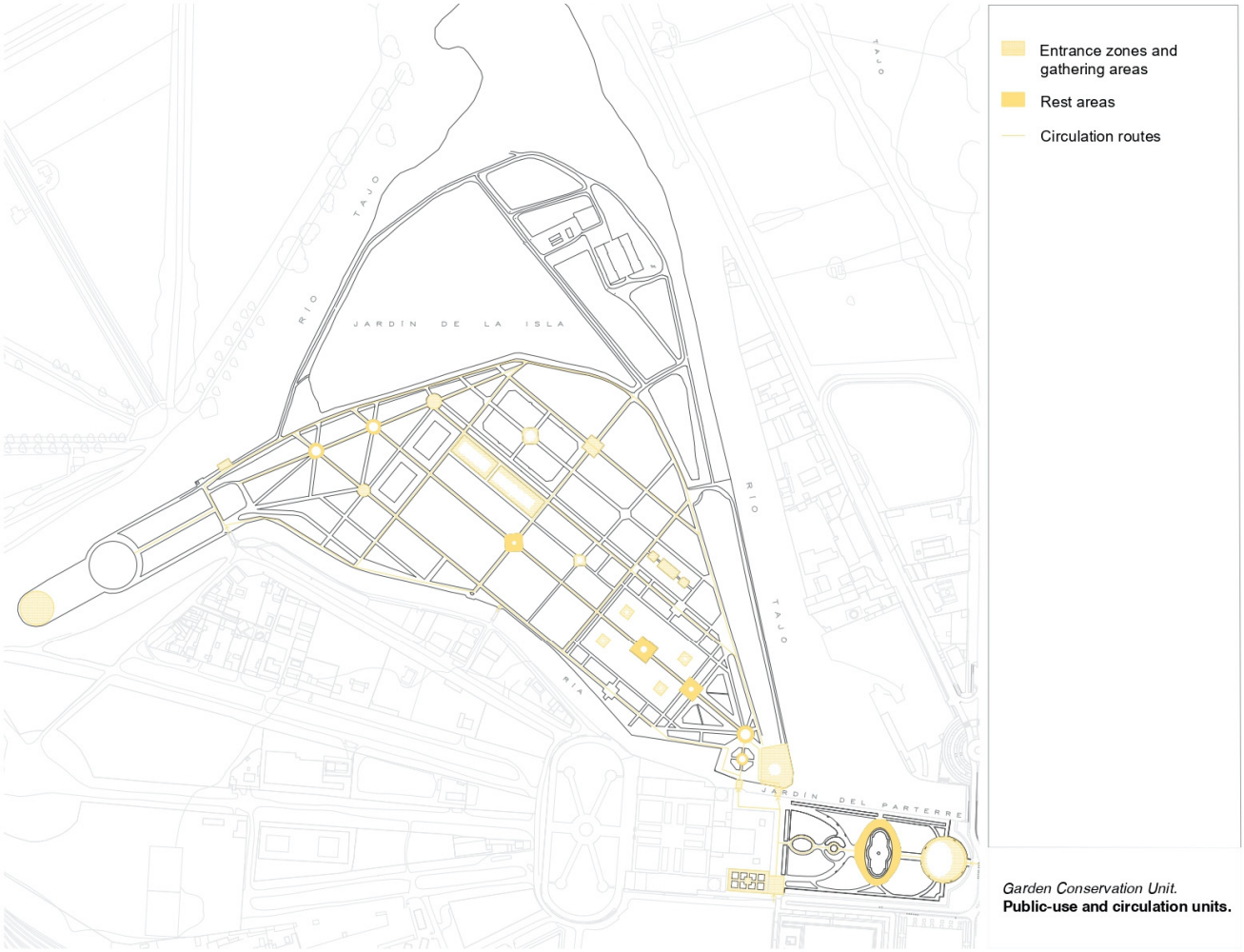


Figure 8. Circulation areas units. Jardín de la Isla y del Parterre (own elaboration).

One of the principal innovations of the HG-CRMF is that it is not conceived as an independent climate adaptation plan but as a methodological layer integrated within existing Conservation Management Plans. Climate considerations are introduced at each principal stage of the conservation planning cycle, allowing adaptation to become a cross-cutting component of management rather than an isolated environmental activity. The cross-unit synthesis considers spatial relationships, continuity of views, circulation patterns, and experiential coherence, enabling adaptation priorities to be established at both the GCU scale and the scale of the historic garden as a whole.

The HG-CRMF adopts adaptive management as the guiding principle for long-term conservation under climate change. The implementation of the framework is expected to generate a heritage value assessment, climate risk profile, hazard inventory, exposure and vulnerability maps, heritage-informed risk register, adaptation strategy, monitoring framework and adaptive governance programme.

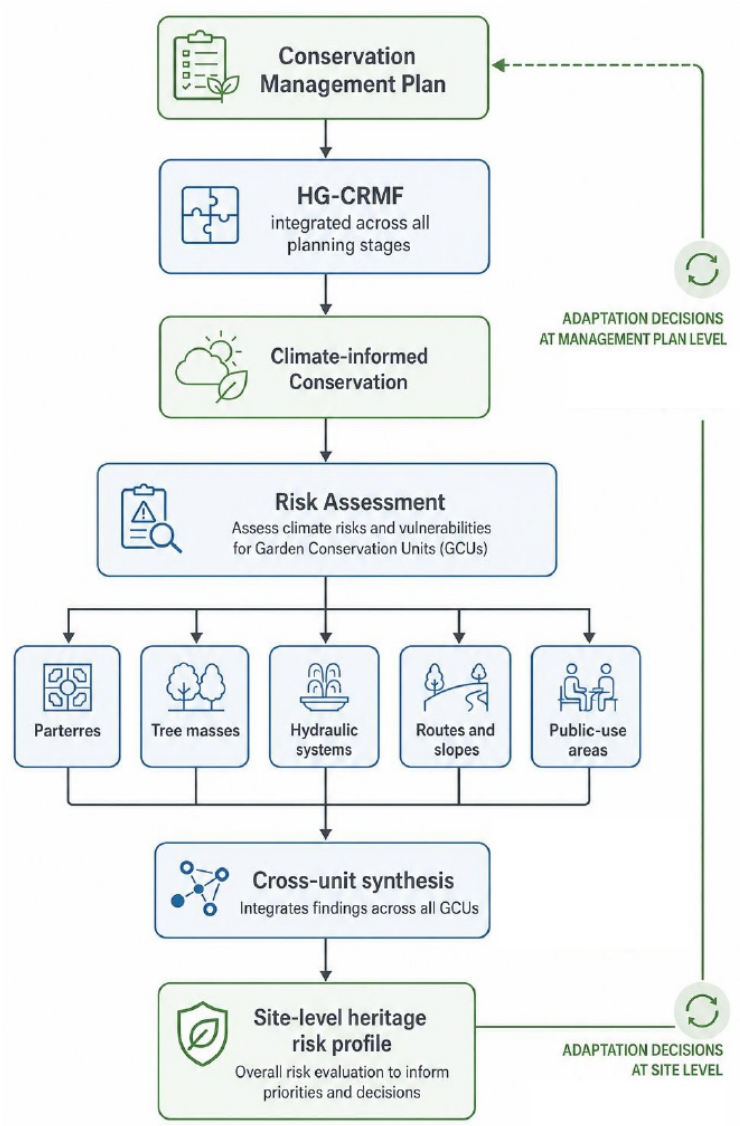


Figure 9. Integration of the HG-CRMF into a Conservation Management Plan. (Source: Own elaboration).

5. Discussion

Climate change has fundamentally altered the context within which historic gardens are conserved and managed. While international organisations and national heritage agencies increasingly recognise the need to integrate climate adaptation into heritage management, practical methodologies capable of translating these recommendations into operational conservation planning remain limited. The HG-CRMF addresses this methodological gap by providing a structured, heritage-centred framework specifically designed for historic gardens.

Prior research has already demonstrated the value of combining value-based and hazard-based approaches in heritage risk assessment, including a conceptually related application is Gociman et al.'s (2015) [46] multihazard assessment of a protected urban area in Bucharest, which combined cultural-significance scoring with threat, vulnerability, and functional analyses. The contribution of the HG-CRMF is not to claim novelty for this general principle, but to extend it to historic gardens as living heritage systems exposed to climate-change-related hazards and characterised by strong spatial, ecological, and experiential heterogeneity. In contrast to building-scale applications, historic gardens require a landscape-scale and multi-scale approach that can account for the interaction

between heritage values, living vegetation, designed spatial composition, and visitor experience. Within this context, the HG-CRMF adapts the combined value-based and hazard-based logic to Conservation Management Plans through the operational use of Garden Conservation Units, thereby offering a heritage-centred framework specifically tailored to the conservation needs of historic gardens under climate change.

A principal contribution of the HG-CRMF lies in its integration of climate risk management within existing Conservation Management Plans rather than proposing climate adaptation as a parallel planning instrument. Existing conservation plans generally include comprehensive historical research, significance assessments and management policies, yet climate-related issues are frequently addressed through separate environmental assessments or emergency response plans. This separation limits the capacity of conservation planning to anticipate long-term environmental change and may result in fragmented decision-making.

The framework also contributes to the development of climate-informed conservation by repositioning heritage significance as the principal reference for climate risk assessment. Conventional risk assessment methodologies generally follow a hazard-centred logic in which hazards are identified first and their consequences subsequently evaluated through exposure and vulnerability. In historic gardens, adaptation measures cannot be evaluated exclusively according to their capacity to reduce physical risk because interventions must simultaneously safeguard authenticity, integrity, historical design, ecological processes and cultural significance.

Perhaps the most distinctive methodological innovation introduced by the HG-CRMF is its hierarchical spatial organisation through Garden Conservation Units (GCUs). Historic gardens are intrinsically heterogeneous systems composed of landscape elements that differ substantially in their historical significance, ecological characteristics, exposure to climate hazards and management requirements. Treating the garden as a single analytical entity inevitably masks this spatial variability and may lead to adaptation strategies that are either overly general or insufficiently responsive to local conservation needs.

The introduction of GCUs addresses this limitation by establishing a dual-scale methodological structure. At the strategic level, the historic garden is considered as an integrated cultural landscape managed through the Conservation Management Plan. At the operational level, the garden is subdivided into coherent conservation units that constitute the basic spatial entities for climate risk assessment, adaptation planning and monitoring. The aggregation of all GCU assessments subsequently provides a comprehensive climate risk profile for the historic garden while preserving the spatial complexity that characterises living heritage.

The HG-CRMF also recognises that heritage significance in historic gardens is not limited to physical form, but includes the experiential, aesthetic, and cultural meanings produced through human interaction with the landscape. By defining Garden Conservation Units through both material and experiential characteristics, the framework captures how different garden components contribute to visual composition, sensory qualities, spatial perception, and public appreciation. This approach strengthens the values-based basis of the method and ensures that climate-informed conservation addresses not only ecological and physical integrity, but also the lived heritage qualities that give historic gardens their significance.

The HG-CRMF is designed not only to analyse historic gardens through their constituent units, but also to reassemble those findings into an integrated understanding of the garden as a whole heritage place. While Garden Conservation Units provide a necessary operational scale for identifying spatially specific values, hazards, and vulnerabilities, the framework ultimately treats the historic garden as a relational system in which meaning

arises from the interaction among components, spatial sequences, views, circulation, vegetation, water, and built elements. In this sense, the purpose of subdivision is analytical rather than reductive: it makes it possible to capture local variation while preserving the garden's overall character, legibility, and experiential unity. The aggregation of GCU assessments therefore supports a garden-wide synthesis that reflects not only the condition of individual elements, but also the combined heritage qualities that shape the experience of "being in a garden."

The cross-unit synthesis further reassembles GCU-level findings into a site-level heritage risk profile, considering spatial relationships, continuity of views, circulation patterns, and experiential coherence so that adaptation priorities can be defined both at the scale of individual units and at the scale of the historic garden as a whole.

The framework has been intentionally designed to remain flexible and transferable. It does not prescribe specific adaptation measures or quantitative risk indices but instead provides a methodological structure capable of incorporating local environmental data, institutional priorities and management capacities. Future research should focus on comparative case studies representing different climatic regions, landscape typologies and institutional contexts, as well as the refinement of GCU delimitation through spatial analysis and geographic information systems.

6. Conclusions

Historic gardens are among the most climate-sensitive categories of cultural heritage because their significance depends upon the continuous interaction between living ecological systems, designed landscapes and historical continuity. Climate change therefore challenges not only the conservation of their physical components but also the preservation of the cultural values, spatial compositions and ecological processes that define their heritage significance.

This paper has presented the Historic Garden Climate Risk Management Framework (HG-CRMF) as a heritage-centred methodological framework specifically designed to integrate climate risk management into the Conservation Management Plans of historic gardens. Rather than functioning as a separate climate adaptation strategy, the framework establishes a coherent methodological process through which climate characterisation, hazard identification, vulnerability assessment, adaptation planning, monitoring and adaptive governance become integral components of conservation planning.

The HG-CRMF makes three principal methodological contributions. First, it provides a structured methodology for integrating climate risk management within existing Conservation Management Plans while maintaining compatibility with internationally recognised conservation principles. Second, it adopts a heritage-centred approach in which heritage significance constitutes the primary reference for climate risk assessment. Third, it introduces Garden Conservation Units (GCUs) as the operational spatial scale of the framework, enabling strategic planning at the level of the historic garden while supporting detailed climate risk assessment, adaptation planning and monitoring within coherent conservation units.

Ultimately, climate adaptation and heritage conservation should no longer be understood as separate management processes. The long-term resilience of historic gardens depends upon their capacity to adapt to changing environmental conditions while preserving the historical, ecological and cultural values that justify their conservation. The HG-CRMF provides a structured and transferable methodology for achieving this objective.

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Abbreviations

The following abbreviations are used in this manuscript:

(GCUs)	Garden Conservation Units
HG-CRMF	Historic Garden Climate Risk Management Framework
ICOMOS	International Council on Monuments and Sites
MITECO	Ministerio para la Transición Ecológica y el Reto Demográfico
UNESCO	United Nations Educational, Scientific and Cultural Organization

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