The Design, Development and Evaluation of GIS Applications as Decision Support Tools for Ecologically Aware Infrastructure Design

Katie McCausland

A thesis submitted in partial fulfilment of the requirements of the University of Reading for the degree of Doctor of Engineering

Technologies for Sustainable Built Environments Centre

Spring 2021

DECLARATION

I confirm that this is my own work and the use of all material from other sources has been properly and fully acknowledged.

……………………………………

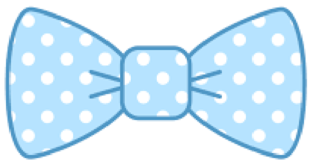
KATIE MCCAUSLAND

2021

This thesis is dedicated to

my mother, who is sadly no longer with us

and my son, who will be with us soon



ABSTRACT

The overall aim of this thesis was to critically evaluate how GIS can be applied to facilitate large infrastructure companies to reduce their impacts on biodiversity during the planning, design, construction of large infrastructure projects. The research was undertaken from the perspective of an infrastructure contractor, precisely the sponsor company, Costain Group Plc. The research aim was achieved through the development of geospatial applications to inform infrastructure design whilst adhering to national biodiversity initiatives in a construction design context. The most relevant initiative is ‘no net loss’, which calculates biodiversity value in units using a metric calculation by Defra (Department for the Environment, Food and Rural Affairs). However, these metrics face criticism for over-simplifying the complexity of the natural world, in particular the neglect of the impact of fragmentation on habitats. At present, the stages of construction do not require an initial scoping of protected and managed land, and there are no statutory requirements for reducing biodiversity loss beyond the identification of invasive species. The relevant stages of construction development for a contractor are the Concept and Developed Design, which is the contextual focus of the applications developed using GIS, referred to as the GIS simulations in this thesis. The GIS simulations include the establishment of baselines for key habitats and species, which form part of the Biodiversity Action Plan, identified as a key environmental planning procedure within the sponsor company. The GIS simulations successfully visualised baseline data. The Developed Design, which involves the refinement of the Concept Design and associated strategies, identifies the geographical placement of the design. Based on this placement, spatial planning methods were used to calculate the changes in biodiversity unit values. The applications were successfully developed, but it was recommended that changes in biodiversity unit value need to include condition, obtained through surveying, before visualising impacts. In addition, specific parameters need to be justified for implementation of the approach at different sites; these can be established based on the project type, the size of the site, and local target species. The applications are considered feasible for implementation within the sponsor company, however, there needs to be more drive from the business and client to invest in more sustainable alternatives moving forward.

ACKNOWLEDGEMENTS

The last few years have been a rollercoaster, I feel as though I have experienced a lot of life over this time and has taken me through a journey that has truly shaped who I am. There are there so many people that have influenced this journey, and I have been lucky enough to have been inspired by those people in so many ways.

I would firstly like to show my immense gratitude to my supervisors Geoff Griffiths, Dragana Nikolic, Jennifer Whyte, and Matt Blackwell that have supported the different disciplines that have not only been part of this project, and but have been understanding, and flexible. Geoff, thank you for your support and guidance, both academically, professionally, and personally. It has meant so much. Matt, the support, and flexibility you provided and continue to provide has allowed this project to flourish and progress in a way I never through imaginable. I am excited for the future of the project and my career.

My friends, colleagues, and support system at Costain have made balanced my work and academic life possible. Sophie Stouki your encouragement and support have made all this possible and has pushed my position at Costain further than I could have hoped. Geraint, Mark and Hywel for providing further opportunities and being great people to work with. Thank you, Georgia, for proof reading and to the Costain GIS Team for the support, and for just being amazing people.

Jenny Berger, you are an incredible woman. You have shown unconditional support and love through the toughest time of my life will always be appreciated and forever remembered. I cannot think about many times I sat in your office, and I would not have had the strength to persevere without you.

I have the best support system… firstly in the TSBE centre: providing fun times, deep talks and support through the hardest time of my life. Josh and Kim (to be) Eadie, Alan Halford, Nick Hollely, and Mary Pothitou, I could not have asked for better friends. My best friends Alex Cooke, Jo Wilkin, Marie Fleming, Sarah Tuttle, Jessica Berry and Sarah Stevens. Having you in my life makes me feel so complete and I am reminded every day as to why I picked you as my best girls. Laura, I seriously cannot thank you enough for reading through my chapters and nagging me.

My sister for all the love, tears, and pride. To Clive and Caroline, my wonderful in-laws for making me part of the family, and for really looking after me during the last few years.

Mum, even though you are not here, you have guided me and were always at the other end of the phone when I needed you. I owe everything I have to you.

My wonderful husband, Chris, you are one in a million. Thank you for putting with me and always looking after me. You have been my rock gotten me through the struggles over the years. This thesis would not be complete today if it were not for you. Finally, my little boy, thank goodness I got this finished before you arrived… (literally days…)

TABLE OF CONTENTS

TABLE OF FIGURES

TABLE OF TABLES

EQUATIONS

ACRONYMS AND ABBREVIATIONS

AONB	Area of outstanding natural beauty
BIM	Building Information Modelling
BM	Bid Manager
CA	Core Area
CIEEM	Chartered Institute of Ecology and Environmental Management
CLC	Corine Land Cover
CL	Contract Leader
CSRCSHEA	Contract Safety, Health and Environment Advisor
DEFRA	Department of Environment, Food and Rural Affairs
DRM	Design Responsibility Matrix
DSRM	Design Science Research Methodology
EA	Environmental Assessment
EcIA	Ecological Impact Assessment
EIA	Environmental Impact Assessment
EngD	Engineering Doctorate
ES	Environmental Statement
ESRI	Environmental Systems Research Institute
EPRSC	Engineering and Physical Sciences Research Council
EU	European Union
HS2	High Speed 2
JNCC	Joint Nature Conservation Committee
JV	Joint Venture
LCM	Landcover Map
LiDAR	Light Detection and Ranging
LNR	Local Nature Reserve
MPS	Mean Patch Size
NBN	National Biodiversity Network
NE	Natural England
NN	Nearest Neighbour
NNR	National Nature Reserve
NRW	Nature Resources Wales
OS	Ordnance Survey
PD	Patch Density

PEA	Primary Environmental Appraisal
RIBA	Royal Institute of British Architects
SAC	Special Areas of Conservation
SDSS	Spatial Decision Support System
SHE	Safety, Health, and the Environment
SPA	Special Protection Area
SSSI	Site of Special Scientific Interest
TCW	The Costain Way

1. INTRODUCTION

1.1. INTRODUCTION

This chapter introduces the research domain of impacts to the environment from large infrastructure, simulations to mitigate impacts and their business value. The chapter identifies the motivation, background and problem addressed within this thesis. Despite conservation research, countries are failing to meet global biodiversity targets every decade. Specifically, within the UK, large infrastructure projects are of critical importance for economic growth, but this industry is not considered sustainable. There is a realisation that the costs of growth to the natural environment are no longer acceptable. This thesis sets out a programme of work to review the scale and impacts of large infrastructure projects and demonstrate how their impacts can be mitigated using geospatial technology. This chapter also defines the research aim and objectives, which focused on the development and design of geospatial solutions for use within the infrastructure industry to reduce losses to biodiversity.

1.2. THE MOTIVATION

The construction and development industry are considered the least sustainable industry globally (Opoku 2019). The amount of energy and materials that are needed to sustain the construction industry has contributed to severe impacts on the natural environment including loss of species, and a reduction/loss in habitats (Opoku 2019). The allocation of new space for growing infrastructure is problematic; for example, motorways can consume as much as 10ha of land per kilometre of road, with local roads taking up less space than this. However, as local roads make up a higher percentage of the road network the collective affect is higher (Seiler 2003). Literature suggests that there is a growing body of evidence that infrastructure is major factor of biodiversity loss at both the local level and landscape level.

An example is the rail project High Speed 2 (HS2); the route (Figure 1.1.) was announced in 2013 in three different phases; Phase 1: London – West Midlands, Phase 2a: West Midlands - Crewe, and Phase 2b: Crewe – Manchester, and West Midlands – Leeds. Phase 1 was due to open in 2026, with Phase 2 scheduled for completion in 2032-2033. Although parliament approved plans for Phase I in 2017, HS2 has faced a backlash from protest groups wanting the project to halt altogether. The impacts of HS2 are both social and environmental, including the demolition of homes and natural habitats across the country. The Wildlife Trusts (TWT) completed an assessment of impacts of HS2 on the environment based on data collected from their 14 estates along the route in 2020. According to the assessment report, 106 Ancient Woodlands are in danger of damage or loss. In addition to this, sites that have been designated as protected due to their importance for wildlife are at risk, ranging from local wildlife areas to internationally designated wildlife sites. The report also states that mitigation measures have not gone far enough to avoid losses to wildlife sites.

> "*An inconsistent approach to evaluating data was found, including the use of out-of-date and incomplete data for Local Wildlife Sites. This, in combination with insufficient information on survey methodologies, results and impact assessments, leads to concerns that the Environmental Statements do not represent an accurate picture of the full impact on wildlife. In some areas, 47% of sites at risk from HS2 are understood not to have been surveyed.*" (TWT 2020, p4).

The above statement suggests that there is a failure in the reporting of biodiversity impacts. However, it is unclear from this statement whether this is due to a lack of management practices, inefficient processes, or a deliberate attempt to minimise reported loss to biodiversity.

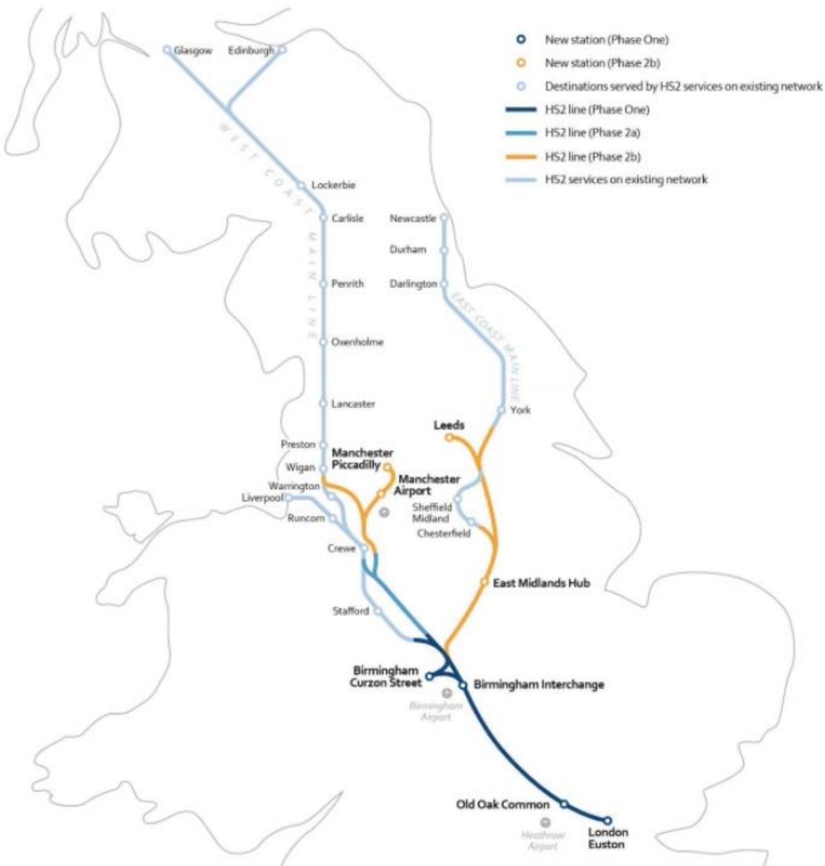


FIGURE 1.1. THE ROUTE OF HS2. SOURCE: HS2 2010

Regardless of environmental impact, the UK Government also has an investment of £37bn on UK-wide infrastructure. However, within the 2018 budget, the government have not produced any cost or yield allocations to environmental planning for conserving habitats outside of "*Tree Planting*" (HM Treasury 2018). Although the budget allocates £1.6bn to science and innovation, with an additional £7bn in the next 40 years, there is no link between infrastructure research and development, and the environment impacts increased development is causing (HM Treasury 2018). This trend continues with the release of the 2020 Budget on March 11th, 2020. The policy decisions for the environment are presented as "*Creating a Greener Economy"* which includes spending themes such as air quality, low emission vehicle grants and plastic recycling, however, does not include environmental management for large infrastructure (HM Treasury 2020).

1.3. UK CONSERVATION AND POLICY

Conservation laws and policies within the UK are fragmented; governance is separated by species and habitats that are protected under European Union (EU) law, and sites such as nature reserves, national parks and rules for hunting and fishing. The UK Government is the major actor when it comes to both national and local conservation strategies (Reid 2011). Currently, the state determines which features of the nature (i.e. habitats and species) are significant enough for attention or protection (Reid 2011). In addition to this, the government is the primary body for identification of potential sites for designation, management agreements between statutory conservation bodies, and whether a species should be reintroduced. Although the State is the major player within conservation, the voluntary role that others play is crucial to environmental law (Reid 2011). Examples of this include landowners that enter into agreements with statutory bodies, the buying of protected land for private incentives, and the management of National Nature Reserves. However, most financial incentives within forestry and agriculture are dependent on public funds, putting the government in complete control of UK conservation.

In 2018, *The 25 Year Environment Plan* was published by the Department for the Environment, Food and Rural Affairs (Defra). The plan sets out to deliver thriving plants and wildlife through actions for improved environmental policy (Curnow 2019). An action discussed within the plan is the protection and development of woodlands; £5.7m of government funding is supporting the planting of a forest along the corridor of the M62 Motorway in the North of England. While this project for developing new woodlands and protection of existing ancient woodland will enhance biodiversity and contribute to improve sustainability, the extent of protection is not discussed. The Wildlife Trusts (TWT) 2019 report introduced in Chapter 1 identified that 106 ancient woodlands are at risk of loss or damage due to the route of High Speed 2. Thus, it does not appear that these actions are embedded as legally binding actions, which raises question of the weight *The 25 Year Environment Plan* holds for environmental management in large infrastructure.

There are three major assessments relevant to large infrastructure development, the Environmental Impact Assessment (EIA), the Ecological Impact Assessment (EcIA) and the Biodiversity Action Plan (BAP). Within planning, the mitigation hierarchy begins with an EIA. The EIA was established in the UK under the EA Directive (85/377/ECC) with various categories and sets of regulations.

> "*As a planning tool, EIA serves largely to inform interested parties of the likely environmental impacts of a proposed project and its alternatives. It illuminates environmental issues to be considered in making decisions*" (Ortolano and Shepherd 2012).

The findings of these reports are then formed into an environmental statement which includes the summary of ecological impacts (Department of the Environment 1989). For projects that are likely to have substantial environmental effects, the EIA must be carried out before any development consent is given, as required by the EA Directive (CIEEM 2016). The assessment allows competent planning authorities to evaluate any impacts to the environment that could outweigh economic gains that a project may provide and increasing potential for sustainable development. Part of the EIA is the Phase I Habitat surveys, now called Preliminary Ecological Appraisal, is the method in which opportunities and constraints are first identified within an EIA or EcIA in the UK. The survey reports semi-natural vegetation in which all parcels of land are recorded and classified (Barr 2013). It is expected that a trained surveyor will visit and map each land parcel onto an Ordnance Survey (OS) 1: 10,000 or 1: 25,0000 maps. There is no official method of completing a Phase I survey and a remote sensing approach would be more cost-effective than sending a trained surveyor into the field, however remotely sensed data still cannot retrieve the level of details required for a Phase I habitat survey (JNCC 2016).

EcIAs are a systematic and repeatable process specific to habitats, species and ecosystems in their identification, quantification and evaluation of development projects or appraisals of any scale (CIEEM 2016). The EcIA fits into the UK EIA process or can stand alone as a method of ensuring planning and policy are still being adhered to by projects even when an EIA is not required (CIEEM 2016). The EcIA is the process of quantifying and evaluating impacts on ecological communities and ecosystems. There have been no reviews of the EcIA since 2000 and the document chapters lack information, continuity, and standards regarding who can write these chapters (Drayson *et al.* 2015).

The UK BAP summarises the most threatened or rapidly declining natural resources in the UK. Individual action plans were developed for habitats and species. The original publication encompassed action plans for 45 habitats and 391 species. As this developed, the most important species and habitats were referred to as "*priority species*" and "*priority habitats*". The main limitations of the BAP centre around the unknowns of the characteristics of ecological networks to individual species and the ecosystem (Gaston *et al.* 2008). Studies show that globally protected areas do capture a "*substantial level*" of biodiversity but there are gaps in knowledge that prevent researchers from assessing their performance (Gaston *et al* 2008).

In addition to the above assessments, no let loss (NNL) initiatives are becoming a common theme throughout biodiversity planning, and most policy and procedures within large infrastructure development have this underlying concept in mind. The initiative is designed to rebalance any impacts on biodiversity; this is done by taking measures to minimise impacts and undertaking rehabilitation/restoration, or offsetting residual impacts to achieve no overall loss of biodiversity (Figure 1.2). This requires the quantification of biodiversity to enable post impact (losses) and offset (gains) to be estimated with the goal that gains should equal or surpass the losses. The UK's voluntary NNL scheme, piloted by Defra, is based on a framework by Treweek *et al.* (2010), with the goals of creating a framework that is precise enough to encapsulate all aspects of biodiversity while being straight forward to use and understand. The framework is intended to complement the UK BAP system and should deliver compensation that is additional to any offsets that would have occurred regardless of this initiative. This scheme has been under scrutiny since it was piloted in 2012; the pilot lasted for two years with different companies and local councils. Although this initiative by Defra is currently voluntary, the scheme is discussed in "*A Green Future: Our 25 Year Plan to Improve the Environment*" as a framework that is likely to become the mainstream NNL initiative for the UK and could become mandatory along with a press release from the UK Green Building Council stating that the government are intending to make net gains a requirement on all development projects from Spring 2019 (UKGBC 2019). In the broader context of NNL initiatives, there are potential faults when using an index to summarize a landscape (Suter 1993). For example, the combination of factors to create a single score can lead to the masking of lower scores by one high ranking variable, and that scores can be ambiguous if the user does not know if variables are "*high*" or "*low*". In addition, environmental planning and decision making can become unclear with the use of "*non-sense*" units; these are units that are not precisely measurable unlike weights, times and distances. Biodiversity units in this case are "*non-sense*" units that can be affected by its biotope value or predetermined co-efficient, which tends to be based on scientific opinion. This is a criticism that needs to be considered within environmental planning and NNL initiatives, as without clear evaluation definitions (i.e. what specifically makes that habitat "*suitable*") NNL loss and gain values have no real meaning outside of being numbers on an excel file.

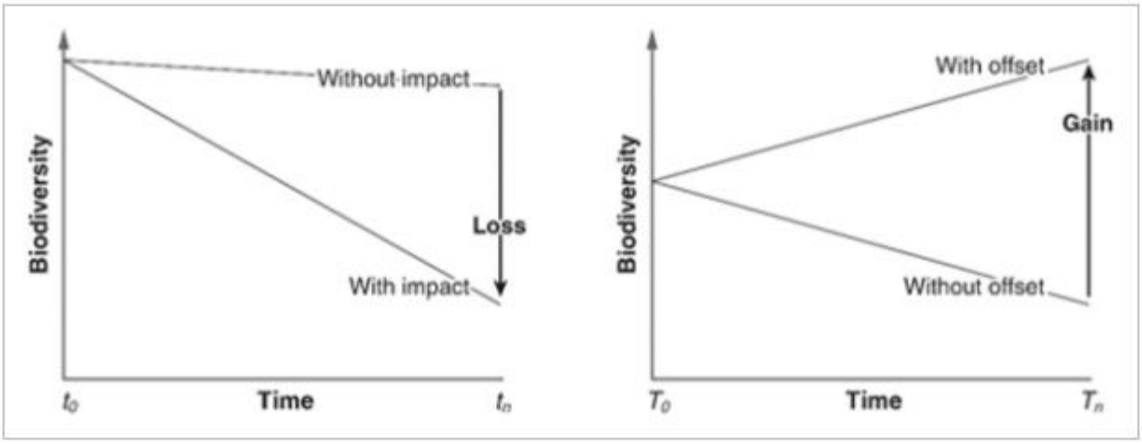


FIGURE 1.2. CONCEPT MODEL DEFINING LOSSES IN BIODIVERSITY DUE TO DEVELOPMENT (LEFT) AND BIODIVERSITY GAINS FROM OFFSETS. SOURCE: GIBBONS ET AL. 2016

NNL is discussed throughout biodiversity policy as a simple concept and has become a 'hot topic' within industry with the use of buzz words such as "*net biodiversity gains*" and "*no biodiversity loss*". The UK Government itself is guilty of this, stating that many local authorities, developers, and infrastructure companies are already implementing a "*net environmental gain*" principle. This mix of vague words and phrases tend to be used to appease the public (Rainey *et al.* 2015). However, the complexity that surrounds this concept, although seen within literature, is not always recognised within industry, and can lead to false claims of environmental protection.

1.4. SUSTAINABLE DEVELOPMENT

Sustainable development is a concept that developed in the 1970s and 1980s based on the long-term use of resources for future generations (Tomislav 2018). The concept was developed due to economic growth putting pressure on the environment that ultimately caused an exploitation of natural resources, along with an increase in pollution and illness (Šimleša, 2003). It is widely accepted among scholars, government representatives, and industry professionals that innovation is a key driver in sustainable development (Silvestre and Ţîrcă 2019). Innovation-centric approaches should be used to tackle sustainability, with further calls for organisations, educational institutions, and governments to invest in initiatives to resolve sustainability challenges (Almeida *et al.* 2013). Achieving enhanced sustainability performance requires a fundamental change in processes, management approaches and products, and this change cannot be achieved without innovations (Silvestre 2015). Specifically, for environmental sustainability, innovations for mitigating or removing impacts to the natural environment have been discussed with the consensus that organisations need to align their internal processes, particularly their decision-making processes (Joyce and Paquin

2016; Silvestre and Ţîrcă 2019). This research topic arose from the desire to understand how innovations within conservation can be used to improve environmental sustainability within the UK infrastructure industry, and to investigate the barriers and opportunities for an organisation to adopt these processes.

1.5. Geographical Information Systems

There is no shortage of conservation research; universities and institutes both in the UK and globally undertake research to provide workable solutions that will benefit our habitats and species. However, with losses continuing across the UK, it is envisaged that the results of this research will provide a viable solution that extends from an academic research setting to implementation within the large infrastructure sector. As information and technology are already used to aid in wildlife and biodiversity management (Harrison 1995), this research is going to take a data-driven approach to reduce impacts to biodiversity using Geographic Information Systems (GIS). GIS is already prevalent within conservation; applications can be used to monitor species populations, ecological networks can be established through recording of movement, distributions can be analysed and visualised using maps, and ecological databases can be stored and visualised for ongoing research (Du Puy and Moat 1998; Geneletti 2004; Michelmore 1994). Importantly for this research, GIS is a powerful technology for planning and land-use that has also become a present technology in infrastructure companies. GIS is currently used to analyse ecological constraints, collision risk modelling, feasibility studies and fly-through views of projects. GIS is also increasingly used for Environmental Impact Assessments (EIA), not only by consultancies but for large infrastructure and expansion projects (Sahi and Kurum 2002). This could provide clear and precise information to non-experts and decision-makers regarding the biological and socioeconomic environment while adhering to environmental regulations (Şahin and Kurum 2002). Data can be in the form of "*text documents, tabular databases, spatial databases (locations), image files (satellite images) … and will include topographic, environmental, species, administrative, socioeconomic and other themes*" (Salem 2003 p92). GIS can efficiently integrate these data forms (Salem 2003) and is used for analysis and monitoring purposes by international agencies such as the United National Environment Programme and the International Union for the Conservation of Nature.

Land-use planning using GIS has been used within research to identify landscape changes over time using developed indicators and indices to monitor environments (Geneletti 2002; Salem 2003). This study of spatial patterns, Landscape Ecology, is considered conservation from a different perspective; the study of spatial patterns gives the standpoint that habitats are part of a larger mosaic that affects ecological processes. The application of landscape science to natural resource management and conservation is not unknown within research. It has previously been used in different regions to conserve native ecosystems through land-use change activities (Robinson and Carson 2013). Biologists are embracing fragmentation and connectivity concepts, increasing the overlap between biology and landscape ecology in conservation (Wiens 2007). Also, Schumaker (1996) states that as habitat loss and fragmentation is linked to species decline, "*Conservation strategies now frequently consider not only amounts of habitat that must be retained, but also the spatial configurations of habitat across landscapes of concern*" (p1201). Most of the significant environmental changes occur at the landscape scale, which is the spatial scale of an entire landscape, e.g., urban sprawl, deforestation, and loss of wetlands (Riitters *et al.* 1995).

1.6. Aims and Objective

Aim: The overall project aim of this EngD, was to critically evaluate how GIS applications can be suitably designed to facilitate large infrastructure companies in sustainable development by reducing their impacts to biodiversity. The research involved in answering these questions are reflected in the following objectives:

Objective 1: To design and build geospatial models that are suitable for improving environmental management on large infrastructure development projects, including relevant context in environmental management and design.

Objective 2: To understand the limitations of environmental data, processes, and visualisation that can improve environmental management.

Objective 3: To understand the barriers, feasibility, and opportunities for the implementation of environmental GIS applications within a general corporate context and within the sponsor company.

Sponsor: This research was applied to UK engineering solutions company Costain Group Plc., introduced in Chapter 3.

1.7. Thesis structure

To answer the research question and objectives, the thesis follows a traditional format and is divided into five chapters: Introduction, Literature Review, Methodology, Results, and Discussion and Conclusion.

Chapter 2 Literature Review: details existing knowledge of environmental sustainability and management measures, cartographic modelling in a general and infrastructure context, and GIS tools for environmental management.

Chapter 3 Methodology: establishes the methodological foundations, and research approaches that address the research aims and objectives. The broader research project was developed as part of the design science research methodology, that is specific to performing research in information systems. The research project is then comprised of research inquiries, each of which have their own research paradigm, assumptions, and approaches for data collection and analysis that has influenced the choice of appropriate approach.

Chapter 4 Results: presents the findings of the research inquiries, which includes the development of context within the large infrastructure industry and the sponsor company, outputs from simulation models, and findings from implementation within the sponsor company.

Chapter 5 Discussion: presents the interpretations, implications, limitations, and recommendations of the results. This provides the meaning, importance, and relevance of the results. The discussion is structured by the three themes of the literature review and objectives: environmental management, cartographic modelling, and corporate implementation. This chapter concludes with the final remarks of the thesis.

1.8. KEY CONTRIBUTIONS

The contributions of this research are both practical and theoretical, as this research is submitted in partial fulfilment of the requirements for the degree of Doctor of Engineering through the University of Reading, it needs to address a real-world problem using an academically rigorous approach. The research attempts to contribute to theoretical knowledge by evaluating geospatial methodologies used in a policy and research context to create applications that can be used in a large infrastructure setting. The development of the proposed solutions will attempt to evaluate and analyse data and processes, and to assess the integration of landscape science within industrial applications. Theoretical deliverables of the research will provide the sponsor company with a framework on the efficient use of GIS to reduce its impact on biodiversity. The theoretical deliverables of the project will provide the company with full disclosure and access to the developed GIS applications for implementation within the business.

2. LITERATURE REVIEW

2.1. INTRODUCTION

Chapter 1 highlighted the impacts that developing infrastructure are having on natural environments within the UK. The amount of energy and materials that are needed to sustain the construction industry has contributed to severe impacts on the natural environment including loss of species, and a reduction/loss in habitats (Opoku 2019). Achieving enhanced environmental sustainability performance requires a fundamental change in processes, management approaches and products, and this change cannot be achieved without innovations. The purpose of this chapter is to examine the literature on environmental sustainability measures and practices within the UK, the use of GIS for environmental sustainability, and cartographic visualisation. This chapter sets out to achieve a better understanding of the theoretical and technical issues surrounding sustainable development, and the current practices and opportunities for implementation of innovation in the context of large infrastructure development.

2.2. ENVIRONMENTAL SUSTAINABILITY

2.2.1. INTRODUCTION

There is extensive literature discussing sustainable development since its emergence in the 1970s, a phrase now often used but very rarely defined (Lélé 1991). There is debate regarding the definition of sustainable development between individuals that support the Triple Bottom Line (TBL) concept and those supporting the concept of a human-nature relationship (Moreli 2011; Robinson 2004; Toman 1992; Vos 2007). The TBL concept, coined by Elkington (1997), is based on the pillars of economic sustainability, social sustainability, and environmental sustainability, which requires a balance between the three pillars. For example, maintaining social and human capital, human rights and equality, and the quality of our environment (Tomislav 2018). The TBL concept has been used within research as an approach for corporate reporting to assess overall levels of sustainability (Azevedo and Barros 2017; Sridhar and Jones 2012). Businesses can provide transparent accounting and evidence for economic, social and environmental sustainability through TBL reports (Raar 2002; Painter-Morland 2006; MacDonald and Norman 2007; Robins 2006). However, Sridhar and Jones (2012) point out three major limitations of the TBL approach based on past research: measurement, a non-systematic approach, and the use of TBL as a compliance mechanism. The lack of common unit of measurement, systematic prioritisation of requirements, or quantitative summary means there is a lack of aggregation across the three pillars (Robins 2006; Sridhar and Jones 2013), making this calculation of the TBL a catalyst for confusion within business. Literature shows that there is a lack of empirical research on the TBL concept, with the term TBL being used interchangeably with the term *Sustainability* and being referred to when only one or two of the three pillars are being studied (Alhaddi 2015). Thus, showing further confusion surrounding the TBL concept, therefore focusing on a single component of the TBL may help to organise the action required to improve real-life sustainable development practices (Goodland 1995).

As introduced in Chapter 1, the concept of sustainable development emerged in the 1970's, with the term being introduced at the 1980 World Commission on Environment and Development (IUCN 1980). National governments agreed to adopt Agenda 21 at the 1992 Rio Earth Summit as a commitment to sustainable development, leading to a rise in domestic policies affecting national and local governments (Howes 2005). Due to disappointing progress in this area, many countries committed to seventeen sustainable development goals (SDGs) in 2015 (UN 2015). Even with the increase of policies surrounding sustainability, there has still been a decline in environmental quality, with no country achieving environmental sustainability (Howes *et al.* 2017). Howes *et al.* 2017 analysed literature surrounding policy initiatives for sustainable development and concluded that various policy failures are due to three key factors. The first is that there is no incentive for deeper consideration of the environment when it comes to exploitation of natural resources by public and private bodies. The second is the lack of political will or capacity to implement effective policies, and the third that key stakeholders are not aware of the seriousness of sustainability issues due to poor communication. However, Elder *et al.* (2016) state that regardless of policy failures, achieving environmental sustainability is not impossible. It is the responsibility of policymakers to learn from previous mistakes in attempts to bring about change to move forward and implement effective environmental policies. Therefore, the following sections discuss the management practices within the UK policy and infrastructure business that are designed to conserve natural resources and protect ecosystems.

2.2.2. Environmental Sustainability in Infrastructure Design

2.2.2.1. Introduction

There are many phases of a construction project; however, there is a consensus about three broad phases of construction development: Design, Construction and Post-construction (Al-Rashaid 2005). The Royal Institute of British Architect's (RIBA) *Plan of Work 2013* is widely accepted in the UK as a standard method of operation in construction design and management (Cooper *2008).* Whilst RIBA has not included a biodiversity impact reduction goal in this 2030 Climate Challenge biodiversity has not been entirely ignored by the *Plan of Works 2020*. RIBA (2019) have created the *RIBA Sustainable Outcomes Guide* that directs the reader to specific desired outcomes in social, economic, environmental, and carbon whole life sustainability. For

"*Sustainable Land Use and Ecology"* the target is "*to achieve net positive species impact"* and references the design principle of "*Create habitats that enhance biodiversity*".

The *Plan of Work* documentation indicates that the contractor is responsible for stages 2-6 of the development process; *concept design, developed design, technical design, construction,* and *handover and closeout*. This section focuses on the specific theme of environmental management in infrastructure design. The Concept Design is the initial design, the Developed Design involves spatial placement of the design, and the Technical Design requires the design to be completed and signed off. As the Developed Design involves a spatial aspect, this is discussed in Section 2.3.2.1; the following sections will discuss the Concept and Technical Design.

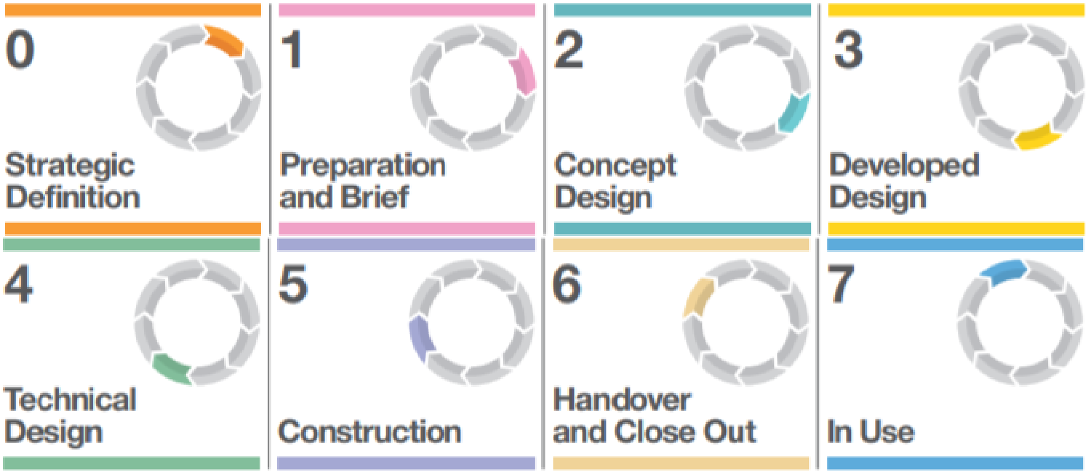


FIGURE 2.1. THE STAGES OF CONSTRUCTION DEVELOPMENT. SOURCE: RIBA 2013

2.2.2.2. THE CONCEPT DESIGN

The Concept Design is the most important stage of a project, from a design perspective, and must meet the initial project brief from the client (Sinclair 2014). The *RIBA Plan of Works 2013* suggests that strategies, including maintenance and operations, risk assessments, and the sustainability strategy, are developed here and meet any aspirations from the client in the project brief. The *Plan of Works 2013* states "*Confirm that formal sustainability pre-assessment and identification of key areas of design focus have been undertaken and that any deviation from the sustainability aspirations has been reported and agreed*" (p16), thus is the first step in sustainable development. It is also in this phase, in which the cost of changes is the lowest, making it the best phase for realising aspirations, influencing costs, and adding value in the context of project improvement (Eastman 2008; Samset 2008; Tsai and Chang 2012).

Although requirements and theories are discussed frequently within the research domain of sustainability, there is a lack of requisite techniques and tools for achieving sustainability in construction (Chong *et al.* 2009). Tsai and Chang (2012) developed a framework for developing construction sustainability items, based on requirements of the Leadership in Energy and Environmental Design (LEED), the Global Reporting Initiative (GRI) and relevant literature, that should be considered in the earliest of design stages. There is a total of 60 items discussed by the authors (listed in Figure 2.2), categorised into 14 category types including “*Geometrics and Alignments*”, “*Earthworks*”, “*Drainage*” and “*Slope protection*”.

1. Geometrics & Alignments
1) Reduction in volume or weight
2) Mild curves
3) Mild slopes

2. Earthworks
1) Earthwork balance
2) Minimum excavation and fills
3) Topsoil recycling
4) Waste reuse (m)

3. Pavement
1) Reduction in volume or weight
2) Permeable materials (m)
3) Recycled materials (m)
4) Noise reduction materials (m)
5) Fiber materials (m)

4. Drainage
1) Runoff reduction
2) Vegetated or gravel ditches
3) Rainwater catchments
4) Infiltration trenches or catch basins
5) Sediment ponds
6) Regional materials (m)

5. Retaining walls
1) Reduction in volume or weight
2) Vegetation
3) Grinding stones or soft reinforcing

6. Slope protection
1) Vegetation
2) Reinforced slopes
3) Waste reuse (m)

7. Landscape & Ecology
1) Avoidance of natural preservation sites
2) Embankments or cuttings replaced by bridges or tunnels
3) Native trees
4) (Treasure) Tree transplanting
5) Vegetation
6) Topsoil recycling
7) Culverts for wildlife crossings
8) Ecological ponds
9) Habitat connectivity
10) Biological porous environment
11) Reduction in landscaping facilities
12) High bridges

8. Transportation facilities
1) Reduction in volume or weight
2) Multi-function poles

9. Transportation maintenance
1) Reduction in path changes

10. Bridges
1) Reduction in volume or weight
2) Long-span bridges
3) Pre-casting techniques
4) Temporary bridges for construction
5) Hollow railings
6) Reinforced materials (m)
7) High strength concrete (m)
8) Self-compacting concrete (m)
9) Lightweight concrete (m)
10) Steel (m)

11. Sound insulation
1) Reduction in volume or weight
2) Landscaping

12. Tunnels
1) Reduction in volume or weight
2) Vegetation
3) Reduction in ventilation facilities
4) Waste reuse (m)
5) Fiber materials (m)

13. Electrical & Mechanical work
1) Reduction in transportation controlling facilities

14. Lighting
1) Reduction in lighting equipment
2) Renewable energy
3) Shading board (m)

FIGURE 2.2. THE DEVELOPED SUSTAINABLE ITEMS FOR HIGHWAYS DESIGN. SOURCE: TSAI AND CHANG 2012

The category relevant to this research is “*Landscape and Ecology*", containing 12 items. The items listed in the paper are broad, and the authors provide little specification on the techniques that should be involved in that item. The most relevant item listed in this category are part of Item 9 of the Landscape and Ecology category is "*Habitat connectivity*", this shows that incorporating environmental sustainability concepts such as fragmentation and connectivity as part of a sustainability strategy in early design is not a new concept, at least in academic study.

2.2.2.3. THE TECHNICAL DESIGN

The technical design is the final stage of the design work for a project, with all aspects of the main design completed. Minor queries regarding the design may arise in the construction stage and works within this final design stage may be concurrent with the construction stages when specialist sub-contractors are contributing to the design (RIBA 2013). The technical design stage finalises the refinements of the designs and strategies developed through the previous two design stages. The technical design needs to be in accordance with the Design Responsibility Matrix (DRM). For each element of the design, the DRM sets out the responsibilities and level of detail (RIBA 2013) in every design stag. Of the ten responsibilities for *Flora and Fauna Systems*, the most relevant is *SS_45_70 Animal Conservation Systems*.

This responsibility is broken down into three subcategories *Species Protection, Species Introduction and Animal Road Crossings*. The NBS does not offer any further information for *Animal Road Crossings*, however, states the purpose of this responsibility for *Species Protection* and *Species Introduction* in development stages 2-4 (Figure 2.3). This information is the same for both subcategories and requires visual information as a means of support for construction. In Stage 2, the requirement for graphic representation of the element allows for dimensional inaccuracy, which is reasonable considering spatial coordination happens in Stage 3. However, there is no visual requirement outside of access and maintenance zones. In Stage 3, the requirements are in greater detail; however, the visual information is pertinent to refining the design of the construction element and the relationship between elements. For example, dimensional coordination, performance requirements and qualities of finish. Stage 4 requires that visual information be coordinated between all professionals involved, for representations for general size, and relationships between elements, and installation details that link the models to adjacent constructions. The purposes and requirements for *Animal Conservation Systems* are vague and does not specify terms that are not commonly used within conversation or biodiversity planning. The use of the terms "*dimensional coordination*", "*performance requirements*" and "*qualities of finish*" confuses the context of the information, as this would be a description for a construction element rather than a conservation system. Also, the term "*visual information*" although a positive requirement, is vague and could incorporate a variety of different technologies and software, thus further confusing the design process. This highlights the need for more in-depth requirements and descriptions for the DRM, including the specification of Geographical Information Systems (GIS) integrated with BIM for visual representation, and risk assessments for both habitats and species.

2

Requirement

Graphical representation of element, dimensionally inaccurate.

Purpose of information

To provide a visual indication of proposals at a Concept stage identifying key requirements such as access and maintenance zones etc.

Information to be suitable for zonal spatial coordination of primary systems / elements.

3

Requirement

Visual information to provide developed principles of the design to a greater level of detail. Developed coordination between all professions. Visual development showing coordination for general size and primary relationships between different elements of the construction.

Can form a brief for a specialist sub-contractor or fabricator to progress with their technical design, fabrication and installation. This would be expected to include critical dimensional coordination, performance requirements and qualities of finish.

Purpose of information

To provide a visual representation of proposals, confirming brief for technical Design stage supporting full spatial coordination.

4

Requirement

Visual information to provide fixed principles of the design supporting procurement. Developed coordination between all professions. Visual representations showing coordination for general size and relationships between different elements of the construction.

Graphical representation of system, dimensionally accurate indicating primary performance characteristics.

Graphical information represented may alter dependant on visual information to be produced, eg: Scope of work drawings, setting out, floor loading etc

Typical / Installation details separately produced linked to model element and adjacent constructions.

Purpose of information

To provide a visual representation of proposals at a Technical Design stage supporting full spatial coordination.

FIGURE 2.3. THE REQUIREMENTS AND PURPOSE OF INFORMATION FOR ANIMAL CONTROL SYSTEMS IN THE DESIGN RESPONSIBILITY MATRIX. SOURCE: NBS

2.2.3. THE ENVIRONMENTAL IMPACT ASSESSMENT

Environmental policy within the UK was introduced in Chapter 1, defining the Environmental Impact Assessment (EIA), the Ecological Impact Assessment (EcIA), and the UK Biodiversity Action Plan (BAP). These assessments are undertaken to inform stakeholders of the environment and ecology that is surrounding the site, any potential risks to threatened habitats and species, and to potential improve environmental sustainability.

Ortolano and Shepherd (2012) discussed the EIA as a tool across numerous countries; they state that while there are few systematics studies on how a government's EIA framework has affected decision-making procedures although there have been many case studies on how EIAs are used and conducted on projects. The most common positive outcomes of an EIA are recommendations for mitigation measures; however, other positive influences include improved site selection, redefinition of goals and responsibilities, and the legitimation of "*sound*" projects (Ortolano and Shepherd 2012). However, the authors state that aspects of the EIA are too heavily reliant on the judgement of experts and professionals, this can be problematic when predicts of impacts are either too vague to be validated, or the basis for these predictions are not clear. Furthermore, the EIA is subject to further subjectivity through the evaluation of the predicted impacts. There have been attempts to avoid this through the development of algorithms which can combine predictions and subjective values of affected parties to relate to an overall index, however, there are no indices that are universally embraced. In addition to this, Ortolano and Shepherd (2012) even state that comments have been made about EIAs in various countries being a bureaucratic exercise that is subsequently filed and ignored rather than integrated. The authors criticize this integration and state that EIA serves as a tool to suggest mitigation for a project that has already been selected, this failure to integrate has been termed "*the integration problem*". The documentation of the EIA has also been criticized, in addition to the amount of in information within the EIA potentially overwhelming even the most tenacious reader, the authors stating a need for clearer formatting and a set standard for display.

Within literature, many authors have contributed to the knowledge of effects caused by fragmentation on animal and plant species. Geneletti (2003) states that although there is this vast knowledge, it is focused on the response to fragmentation rather than how to determine the impacts at a risk assessment stage. There has been a call for the use of landscape spatial parameters within EIAs or EcIAs that can predict the disturbance caused by fragmentation based on ecosystem size, distribution and shape by Seiler and Eriksson in 1995. Byron also concluded this in 1999, stating that the effect on biodiversity from fragmentation can, and should, be thoroughly measured. These statements from the 1990s still hold true today, with Jaeger stating in 2017 that landscape scale effects of road-networks have not been studied very well and neglected by EIAs yet are highly important for wildlife populations. The author compiled points to improve EIAs when building roads based on reviews of EIAs in Europe, the USA, and the UK, with the take home message that wildlife crossing structures, and fences do not mitigate all the impacts of fragmentation from building roads.

2.2.4. The Ecological Impact Assessment

Although there have been changes in legislation regarding planning and biodiversity, there have been no reviews of UK EcIAs since 2000 (Drayson *et al.* 2015). Drayson *et al.* (2015) also concluded that the EcIA, broken down into chapters, lack information, continuity, and standards regarding who can write these chapters, thus providing a need for a more coherent and up to date procedure for EcIAs.

In January 2016, the Chartered Institute of Ecology and Environmental Management (CIEEM) published a second edition of EcIA guidelines. These guidelines were revised by a Technical Review Group that was comprised of CIEEM members. As mentioned above, it has been suggested in literature that guidelines needed to be updated, and this second edition of guidelines aims to:

"…promote good practice, promote a scientifically rigorous and transparent approach to EcIAs, provide a common framework to EcIA in order to promote better communication and closer cooperation between ecologists involved in EcIAs, and provide decision makers with relevant information about the likely ecological effects of a project." (CIEEM 2016, p5).

The expansion and updating of the 2006 policy also consider legislation changes from 2006. The guidelines are split into the following sections: *Introduction, Scoping, Establishing the Baseline, Important Ecological Features, Impact Assessment, Mitigation Compensation and Enhancement,* and *Consequences for Decision Making.* Due to the recent release of these guidelines, there is little literature analysing the expansion and updating of the guidelines. However, Drayson *et al*. (2017) completed an evaluation of EcIA procedure over the years; the authors have outlined the six major published chapter reviews of EcIAs, which are from 1988-2011 (Figure 2.4).

Review Authors	Publication Year	EcIA Year Range	No. of EcIAs	Geographic Distribution of EcIAs	Planning Application Status	Comments
Spellerberg & Minshull	1992	1988–1989	45	UK	All	N/A
Treweek et al.	1993	1989–1991	37	UK	All	Road EcIA chapters only
RSPB	1995	1988–1994	37	UK	All	N/A
Thompson et al.	1997	1988–1993	179	UK	All	N/A
Treweek & Thompson	1997	1988–1993	194	UK	All	Mitigation only
Byron et al.	2000	1993–1997	40	UK	All	Road EcIA chapters only
Current Review	N/A	2000–2011	112	England	Granted permission	N/A

FIGURE 2.4. THE FEATURES OF THE SIX MAIN ECIA CHAPTER REVIEWS IN COMPARISON WITH THE CURRENT REVIEW. SOURCE: DRAYSON ET AL 2017

The authors state the following appear to be limitations within EcIAs that have provided a need for the published chapter reviews:

1. Lack of consultation
2. Poor baseline survey
3. Lack of quantification
4. Inadequate cumulative impact assessment
5. Vague mitigation measures
6. Low-level of commitment to mitigation and follow-up

The limitations that are relevant to this thesis are: "*the lack of quantification*" as this is regarding ecological baselines and impact predictions; "*Vague mitigation measures*" as strong mitigation measures are linked with a more effective biodiversity offsetting program and no net loss initiatives; and "*low-level of commitment to mitigation and follow-up*". In terms of follow-up, the authors briefly mention the 2^{nd} edition of the EcIA guidelines published by CIEEM in 2016. They state:

> "*A further important change has been the release of the second edition of the EcIA Guidelines (CIEEM, 2016), a decade after the first edition was published. One of the improvements in the Guidelines is a greater acknowledgement of the importance of follow-up*" (p62).

This is the only statement within the paper that is made on the new guidelines, despite the paper being published in 2017, suggesting that this is the most significant change to the published guidelines. The EcIA states:

> "*The EcIA should identify where monitoring is required for mitigation, compensation and enhancement measures. It should set out the methods to be used, the criteria for determining success/failure, appropriate timing, mechanisms for implementation, frequency and duration of monitoring, and frequency of reporting*" (p47).

In the above quotation mention is made about the importance of follow up but there is no description on how this can be implemented or whether this has influenced any follow-up. This could be because the guidelines were only published in January 2016 and there has been no data on the effectiveness of the new guidelines.

2.2.5. No Net Loss (NNL)

In the broader context of NNL initiatives, Suter (1993) identified potential faults when using an index to summarize a landscape. For example, the combination of factors to create a single score can lead to the masking of lower scores by one high ranking variable, and that scores can be ambiguous if the user does not know if variables are "*high*" or "*low*". The author also states that environmental planning and decision making can become unclear with the use of "*non-sense*" units; these are units that are not precisely measurable unlike weights, times, and distances. Biodiversity units in this case are "*non-sense*" units that can be affected by its predetermined co-efficient, in this case habitat distinctiveness, which tends to be based on scientific opinion. This is a criticism that needs to be considered within environmental planning and NNL initiatives, as without clear evaluation definitions (i.e., what specifically makes that habitat "*suitable*") NNL loss and gain values have no real meaning outside of being numbers on an excel file.

However, there is an argument that no net loss of biodiversity can be calculated on paper in a detailed fashion (Gibbons *et al.* 2016). Another 'successful' example of NNL this is taken from a 2016 paper by Gibbons *et al.* in which they provide the scenarios in which a no net loss of biodiversity can occur. The authors use a BVM approach and give variety of parameters and multipliers to quantify impacts and calculate restoration methods to reach no net loss of biodiversity. For example: by using cavity nests as a biotope, the authors could estimate the loss and compensation for a protected bird. The development predicted an impact of 50 nests lost over two years, which was the "*present value loss*". To achieve a no net loss in this scenario, the authors state that 300 artificial nest boxes need to be built as this protected bird only has an occupancy rate of 0.2. Over a three-year period, this equates to 55 nests for the protected bird, which is the "*present value gain*". This means that there is a net gain of 7.9 nest cavities for this development project. This paper uses a "*like for like*" for offsets, using specific attributes such as nesting cavities. Even using an occupancy rate, these nest boxes may not provide as an adequate "*gain*" due to potential differences in species preference for nest boxes, surrounding habitat and the geographical location of the nest box placement. There is a grey area when it comes to establishing and defining "*gains*" in this way; for example, a planted vegetation can have ecosystem benefits, it will ultimately not perform the same as native vegetation (Salt *et al.* 2004). Cunningham *et al.* (2004) provide a more specific example of this when comparing habitats that are greater than 20 years old as suitable habitat for reptiles and mammals compared to planted vegetation and remnant native vegetation. The authors concluded that the planted vegetation was inferior and that restoration efforts should be put into improving existing remnant vegetation. Gibbons and Lindenmayer (2007) state that a key limitation in NNL initiatives is the "*amount of gain that can be achieved relative to the loss from clearing, the time lag between the loss and gain, and adequate compliance*" (p28). Relating back to the definition of this concept, if a restoration attempt is unable to compensate for the loss, then NNL cannot be achieved.

Curran *et al.* (2014) addressed the question of whether there is empirical support for NNL initiatives. The authors extracted data through an intensive literature review of quantitative assessments of species diversity of old-growth and secondary growth habitats, observed indicators of alpha diversity, predator variables, and a simplified biome classification to understand the evidence base that could provide a more informed debate on NNL and offsets. The authors specifically assess whether conditions are met for restoration success, whether offsets through restoration projects are robust in preventing NNL of biodiversity. The results of the study support that "*species diversity indicators are initially impacted by disturbance and converge to old-growth reference values over time*" (p618). It is concluded overwhelmingly that there is little support to suggest that current theory in offsets practically leads to an NNL of biodiversity; the authors compiled results from three other studies that conclude that out of an 87 active restoration projects 6% fully recovered (Pimm *et al.* 1995), there is only an ~23% success rate in species composition from a review of 240 studies (Jones and Schmitz 2009), and that the overall success rate in replacing lost biodiversity is < 30% (Suding 2011). This is a bleak outlook for offsets and their ability to provide a NNL of biodiversity, although Curran *et al.* (2014) state that species can converge to old-growth references over time, establishing a new or restored habitat will involve a time lag to maturity; even if the developed habitat fully offsets the original ecosystem, the time involved for the ecosystem to reach maturity may have incurred some loss to biodiversity. Moreno-Mateos *et al.* (2015) states that this over-simplification of habitats for NNL purposes can lead to not only a time lag in the maturity of that habitat but the lack of realisation that affected ecosystems may take centuries or longer to fully recover, which is beyond any type of planning or prediction.

2.2.6. No Net Loss in the UK

The limitations of the UK NNL scheme by Defra are like those mentioned above such as simplifying landscapes, the limitations of quantifying biodiversity, and the lack of empirical support for NNL initiatives. The UK's biodiversity offsetting scheme is no different: the metric considered simple in terms of calculating biodiversity units. However, there are some limits and risks that are included with biodiversity offsetting. Currently, biodiversity offsetting does not consider any location parameters in its calculation, so factors such as slope, aspect, and bedrock are not taken into consideration. Also, varying weather, such as temperature, amount of sunlight and rainfall across the UK means that an improved grassland in Cornwall will grow and develop differently from an improved grassland in Cumbria. In addition to this, single time to maturity metrics is considered too simplistic, especially if the time between the negative impacts and the offset reaching the required maturity results in biodiversity loss during a period of time (Defra 2012). For example, establishing a new or restored habitat will involve a time lag to maturity; even if the developed habitat fully offsets the original ecosystem, the time involved for the ecosystem to reach maturity may have incurred some loss to biodiversity.

As nature is complex and can be unpredictable; with distinctive habitats responding to restoration and environmental factors differently, predicting the probability of success is somewhat challenging as restoration techniques and management need to be incorporated (McKenney and Kiesecker 2010). It has been discussed that current frameworks do not offer guidance regarding the ratio of lost, mitigated, and replaced habitats; this is mainly due to the absence of detailed guidance for quantifying natural and unnatural land (McKenney and Kiesecker 2010). This lack of documentation hinders the predictions for success and comes from the scheme being voluntary and therefore no policies put in place to ensure that developers are using the scheme correctly. Coralie *et al.* (2015) expresses that biodiversity offsetting could lead to the 'commodification' of biodiversity; thus scientists, planners, and conservationists need to take care. This concern is not only discussed within academia, but there have also been public news headlines such as "*Biodiversity offsetting will unleash a new spirit of destruction on the land*" from the Guardian on 7th December 2012, and "*Biodiversity offsetting and net gain: licence to trash nature*" from Friends of the Earth on 29th November 2018. A concept such as NNL through biodiversity offsetting or net gains is already unpopular within academia; negative news reports can potentially hinder the perception of the public and reducing support for infrastructure developers that are adopting this scheme.

Finally, as biodiversity offsetting is based on habitats rather than sustaining a protected species, a developer may construct on one type of habitat, but may lean towards the restoration of a habitat that provides a larger number of offset biodiversity units. In practice, this may benefit a new set of species within the area but fail to adequately protect the original species of interest that are closely associated with the local complement of species.

2.3. CARTOGRAPHIC MODELLING

2.3.1. INTRODUCTION

The generalisation of information is an inherent characteristic of all geographical data, with the derived dataset that is a less complex representation of reality (Bell 2001). This could be a set of geometries can be rendered with symbols and associated texts to provide a perspective to the viewer (Chaudhry *et al.* 2009). Chaudhry *et al.* (2009) states:

"…*the viewer does not see a twisty blue line but sees a meandering river as it snakes through the delta on its way to the sea. The viewer does not see a dense collection of small angular polygons, but sees a collection of buildings, performing many different but related tasks that all contribute to the idea of urban space and the city*" (p349).

Generalising information allows for the data analysis at varying degrees whilst reducing storage requirements, however, can lead to errors and discrepancies within data transformation (Bell 2001). Bell (2001) states that GIS is a sophisticated analysis tool that can control data transformations to avoid errors in data accuracy.

GIS has been associated with the construction industry for decades (Palve 2013). Authors such as Wiley (1997) state that GIS should be used not only as an operational process to provide information for the user's immediate needs but should be approached as an evolutionary tool that allows for the gradual organisation and workflow changes. In the 1990's more GIS based articles were being published in civil engineering and construction journals and conference proceedings. Palve (2013) states that in the context of construction management, people think of GIS as a data visualisation tool, overlooking the opportunity for data analysis and decision support. The authors suggest that GIS can be used for:

- Progress monitoring system
- 3-D data analysis
- Comparison of data
- Construction scheduling and progress control
- Government regulations

Countinho-Rodrigues *et al.* (2011) discusses the use of GIS in decision support. The author states that this support is key for infrastructure investments to successfully implement changes in urban areas. Kouziokas and Perakis (2017) reviewed the use of decision support systems and stated that many studies have proposed the use of decision support systems that incorporate geospatial systems. This need to integrate spatial information in decision problems gave rise to the Spatial Decision Support System (SDSS), integrating analytical models with database management (Densham 1991). The following sections discussed the implementation of an SDSS in large infrastructure sectors, and within construction design.

2.3.2. Approaches in Infrastructure Development

2.3.2.1. Design

The spatial coordination of a design takes place during the Developed Design stage of construction development. The developed design involves the refinement of the Concept Design and associated strategies. This will involve multiple tools and iterations of the design until spatial coordination exercises are complete (RIBA 2013). This stage should complete any research and development aspects, and the strategies developed in the Concept Design as developed in detail sufficiently enough for the client to sign them off. This stage aims to test the Concept Design and add spatial coordination, the to-scale placement of the design. The spatial coordination of a design is discussed within a Building Information Modelling (BIM) environment. BIM is a three-dimensional representation of a building or infrastructure design and its inherent characteristics.

In 2013, the UK Government released *"Industrial Strategy: Construction 2025"* outlining its vision, ambition, and commitments for 2025. The Government has committed to the BIM Programme:

"*Government will mandate BIM for all centrally procured Government contracts from 2016. Industry must therefore meet the challenge – only through the implementation of BIM will we be able to deliver more sustainable buildings, more quickly and more efficiently." (p9)*

Evident by the mandate of BIM by the government, an added requirement of geospatial placement can also be achieved at this stage of construction as a standard of operation on all contracts by the government. The integration of GIS and BIM is not novel (Fosu *et al.* 2015). There have been many approaches suggested by authors to integrate the two technologies. For example, Seo (2005) developed a data flow diagram (Figure 2.5) that incorporates CAD drawings into ArcGIS and integrated with both spatial and non-spatial data. The authors implemented this in 2005 as part of a project to improve road construction planning. In addition, there are platform extensions available between the two technologies such as Geo BIM (Laat and Berlo 2011).

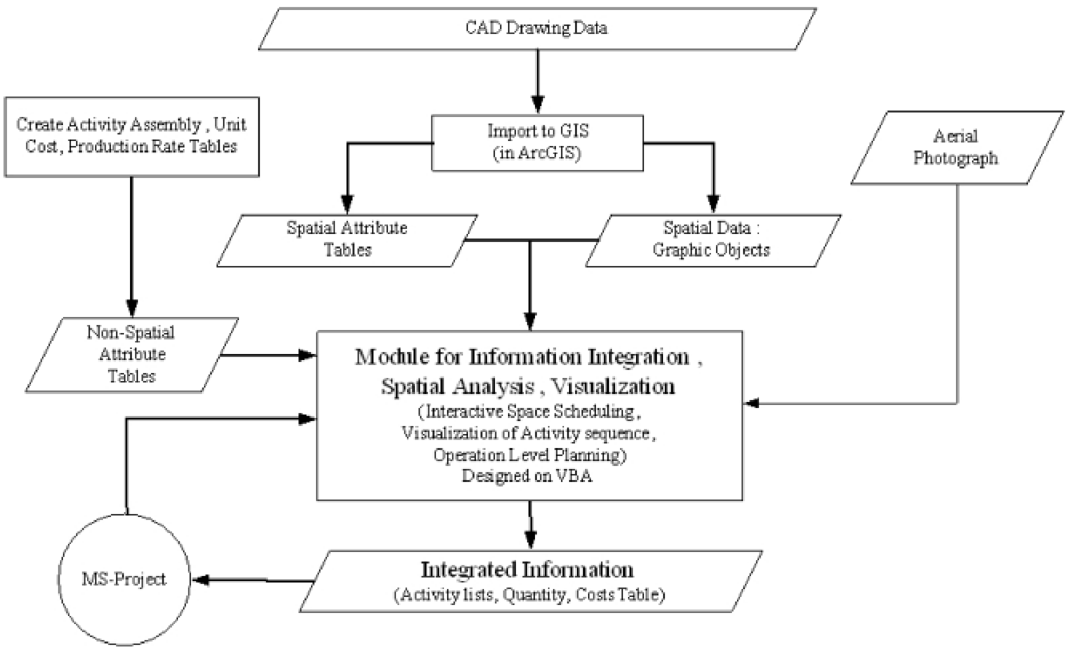


FIGURE 2.5. MODEL OF INTEGRATION OF CAD DRAWING DATA INTO GIS. SOURCE: SEO 2005

This integration comes with advantages, the integration of GIS and BIM can provide a geographical context to highly detailed building models (Fosu *et al.* 2015). This can allow for planning questions to be addressed throughout the project stages including design, including construction, and operation and facility management (Kolbe *et al.* 2011; Kurwi *et al.* 2017). Within design, the applications of a GIS and BIM integration include traffic planning, optimal number and location of tower cranes, and management of fire response (Isikdag *et al.* 2008; Izharry and Karan 2012). Izharry *et al.* 2013 used a GIS and BIM integration within the construction stage for managing the supply chain. Finally, applications in operation and facility management include flood damage assessments, the evaluation of construction performance and detection of pipe networks (Amirebrahimi *et al.* 2015; Elbeltago and Dawood 2011; Lui and Issa 2012). Panday and Shahbodaghlou (2016) developed a model to measure the contribution BIM brings when developing sustainability goals in construction. As part of their conclusions, the authors state that "*Further research needs to be done on integration of land, landscape and building ecology into BIM capabilities*" (p382). This may be because a collaborative delivery method of this nature requires a change in processes, structures, and attitudes (Eriksson and Pesämaa 2007).

2.3.2.2. Linear Assets: Rail and Highways

The demand for more efficient construction has increased over the last few decades, with GIS being considered an approach to meet the needs of "*doing more with less*" (Kurwi *et al.* 2017 p47). In many countries, the rail sector is struggling to be efficient despite being considered a mature industry in the developed world (Bank 2015; Kurwi *et al.* 2017). GIS has been used in the rail sector route optimisation, rail track design, and identification of rail infrastructure improvements (Ebright-McKeehan and Murtha 2009; Kang *et al.* 2014; De Luca *et al.* 2012). Guler *et al.* concluded that GIS can be used to analyse relationships between assets or events that ultimately improve decision making. A framework by Wei (1996) showed that using a GIS system in the selection of a railway line was more efficient than the traditional manual method with an insufficient difference in results. Specifically, within the UK, the value of GIS has been highlighted within industry standards (Boyes *et al.* 2017). In the context of High Speed 2 (HS2), it is suggested that GIS can streamline information produced to meet the requirement of *"delivering the right piece of information to the right person at the right time"* (Floros *et al.* 2020).

The use of GIS in the highways sector is widespread and has made it possible to solve problems that were previously difficult to tackle (Daneshgar *et al.* 2018). Example tools and applications include short-path analysis, vehicle routing, trip investigation and accident analysis (Aultman-Hall 1998; Despande *et al.* 2011; Kim *et al.* 2011; Pons and Perez 2003; Xu 2005). Daneshgar *et al.* (2018) discusses the use of GIS for roadway networks, using a spatial join and linear referencing approach to combine roadway datasets. The authors were successful in their methodologies, but state that there are imperfections within GIS datasets that need to be considered when integrating different types of geospatial information and stresses the importance of data pre-processing. In addition to the technical limitations of implementing GIS in highways network management, Ye *et al.* (2014) has highlighted five general limitations in the uptake of GIS into the highways sector. These are the lack of communication between highways engineers and GIS professionals, a lack of standards for data consistency, insufficient data availability, a lack of knowledge of GIS and a lack of awareness of benefits to using GIS. Understanding these barriers will allow further research into how these can be addressed at the organisational level, and ultimately improve uptake of GIS to improve operations and decision making.

The collaboration of GIS and BIM (Section 2.3.2.1.) is also discussed in the context of the rail sector. While the opportunities of GIS and BIM integration discussed within literature are positive, there are limitations. Kenley *et al.* (2016) studies BIM interoperability issues in the context of the rail sector. The authors concluded that digital data collection and transformation does not always provide a sufficient reduction in effort and time. This is due to CAD data being referenced with local markers such as street names, whereas GIS location identifiers tend to be based on a global or national reference system. A manual translation between the two data types may be needed due to the difference in scale, thus creating a complex and time-consuming task. Floros *et al.* 2020 state that the integration and interoperability of GIS and BIM is not simple. Noardo *et al.* (2019) documented and analysed existing software to facilitate the integration of the dominant standards with GIS and BIM; CityGML and Industry Foundation Classes (IFC). The results of the study show that there were errors in height and volumes calculations, missing or misshaped geometries, and a lack of customisation of the export (Noardo *et al.* 2019). These limitations, and the importance of the collaboration of GIS and BIM, more research needs to be completed both within and beyond the rail sector for improved decision-making (Kurwi *et al.* 2017).

2.3.2.3. ENERGY SECTOR

Energy infrastructure manages and directs energy flow, enabling the transportation of energy from the producer to the consumer. Within the energy sector, authors have developed frameworks to integrate GIS for data visualisation and decision support. Using geospatial data on elevation, buildings, infrastructure and land-use, GIS has been used within the energy sector as a tool to identify areas suitable for wind and solar farm development (Aydin *et al.* 2013; Connolly *et al.* 2010; Janke 2010) as well as the mapping of current energy resources (Kaundinya *et al.* 2013; Ramachandra and Shruthi 2007; Van Hoesen 2010; Zambelli *et al* 2012). A framework developed Kucuksari *et al.* (2014) used Light Detection and Ranging (LiDAR) data to find the optimal location and size of solar photovoltaic plants within a campus environment. However, this framework should only be considered as a basis for a more comprehensive study that can integrate non-static data, such as weather, solar radiation, and wind (Resch *et al.* 2014). Another example of GIS integration within energy infrastructure is related to heat-network planning by (Nielsen and Möller 2012). This integration used economic and administrative data to assess the feasible expansion of the heating network. However, Resch *et al.* 2014 states that the authors did not identify the most effective use of GIS in this case, which would be to assess the location of energy storage from individual houses, which would influence the overall cost of the supply. Other authors, including Aydin *et al.* (2013), Omitaomu *et al.* (2012) also use GIS as an SDSS for site selection for renewable energy systems.

Standard user interfaces and data exchange makes GIS a key component of energy infrastructure planning (Medrano *et al.* 2008). However, Resch *et al.* 2014 states that the most essential limitation in the integration of GIS with energy systems is that topographical parameters are considered within research but not within real-world planning activities. In addition to this, Oldewurtel (2012) states that combining geospatial models and energy system models with numerous parameters to represent the real-world is highly complex and could require too much simplification. The authors state this is due to fine-grained results requiring an increase in the model's complexity and number of datasets necessary. However, advancements in this area include approaches that use a small area of interest, or a regional resolution (Resch *et al.* 2014). Other limitations within this area include a lack of relevant or detailed data. Datasets such as types of home-heating systems, energy production, heat demands, and heat-grid topologies do not contain a geospatial reference or are owned by private energy providers that are not willing to provide these datasets (Resch *et al.* 2014). In addition, data that is crucial to energy calculations may not be available, such as number of floors in a dataset of buildings within a study area (Medrano *et al.*2008). Medrano *et al.* 2008 states that this be more complex when a study site involves different public institutions expanding across different administrative boundaries.

2.3.2.4. Water Sector

The management of water resources is complex, the growing public awareness of environmental issues has led to more rigorous legislation, which poses a challenge to water utilities when addressing chemicals and pollutants in the waste stream (Romero *et al.* 2017). The pressure is on to establish water conservation strategies whilst meeting our water requirements, this includes turning storm water or urban wastewater into a sustainable water supply (Garrido-Baserba *et al.* 2020). The application of Big Data and Artificial Intelligence (AI) is emerging within the water sector, with an estimated 80% of utilities in developed countries undergoing digital transition, and 50% of utilities in developing countries by 2025 (Jones *et al.* 2014). Garrido-Baserba *et al.* (2020) states this transformation of strategy and decision-making is due to the advancements in communication technologies, social media, and affordable high-resolution remote sensing. There are many applications in water resource management and flood mitigation, in which GIS plays a crucial role (Wang and Xie 2018).

Wang and Xie (2018) states that within the water sector, GIS is used in conjunction with other tools and data such as Landsat satellite imagery, ground-penetrating radar, and frequency domain reflectometry for cutting edge hydrologic models. Specifically, GIS is used in this area for data processing, spatial analysis, and results maps. Applications include water resources mapping, rainfall measurements, rainfall runoff prediction for flood forecasting, and water body and flood mapping (Li *et al.* 2017; Sharif *et al.* 2017; Tekeli 2017; Wang *et al.* 2017,).

2.3.3. BARRIERS TO IMPLEMENTATION

The previous sections have shown the integration of GIS for both operational and decision-making tasks within different sectors within infrastructure. Due to the multidisciplinary nature of GIS technology, many domains have not adopted this integration of GIS, addressed the need for the technology, or have not yet delivered it to its full potential (Ventura 1995; Ye *et al.* 2014). However, understanding the barriers to implementation is the first stage in promoting further use of GIS for advanced applications (Göçmen and Ventura 2010). Over the years researchers have investigated the direct and indirect barriers that hinder the adoption rate of GIS and have distinguished them into two groups: *Organisation Barriers* and *Technical Barriers* (Brown 1996, Esnard 2007, Göçmen and Ventura 2010). Ye *et al.* 2014 define organisation barriers as "*department factors, such as lack of staff (e.g., constraints by size of the team or funding), lack of purpose or mission to promote GIS application and lack of collaborators and networking*" (p19) and technical barriers as "*lack of context, insufficient software and tools, lack of reliable data and lack of technical knowledge*" (p19). Skidmore (2017) states that the key books and papers regarding GIS implementation (Figure 2.6) show that the trend of barriers in the 1980s appears to be technical (e.g., software, hardware etc.), whereas the barriers tend to be more organisational from the 1990's, with current barriers being data availability, data quality, and suitable applications.

Year	Author	Problems in implementing GIS
1986	Burrough	Technical requirements (hardware, software and data structures); cost; expertise; embedding GIS in the organization
1989	Aronoff	Technology; database creation; institutional barriers; expertise
1991	Atenucci *et al.*	Software (data structures, hypermedia, artificial intelligence); hardware (PC performance, mass storage); communications and networking; system implementation
1993	Van Oosterom	Software (data structure)
1995	Huxhold and Levinsohn	Embedding GIS technology in organizations; managing GIS projects
2001	Bregt *et al.*	Data availability and quality; model applicability and development

FIGURE 2.6. THE KEY BOOKS AND PAPERS THAT IDENTIFY BARRIERS TO IMPLEMENTING GIS FROM 1986 – 2001. SOURCE: SKIDMORE 2017

Ye *et al.* 2014 compiled a literature review and survey questionnaires to identify the barriers within government, transportation, commercial and public domains (summarised in Figure 2.7). The barriers range from awareness of the tools and understanding of the technology, to insufficient resources and costs, showing there are still a range of organisational and technical barriers among the different domains that were prevalent in the 1980s. Göçmen and Ventura (2010) state that the most significant barriers for GIS implementation in planning are organisational, although planning departments are faced with a range of organisational and technical barriers. The authors suggest the major organisational barriers are training, funding, and data issues. The study concludes with suggestions of improving implantation barriers, including training in internet GIS-based tools to enhance public participation, accessibility to workshops, and increased networking opportunities such as conferences and user group meetings.

Domain	Application areas	Identified barriers
Government	▪ *land management* ▪ *coastal monitoring* ▪ *environment protection* ▪ *census statistics* ▪ *fire management* ▪ *military* ▪ *administration* ▪ *surveying*	▪ *insufficient programs* ▪ *lack of awareness of tools* ▪ *lack of initiatives/mandates* ▪ *lack of support from managers* ▪ *understanding technology*
Transportation	▪ *short path analysis* ▪ *vehicle routing* ▪ *trip investigation* ▪ *road navigation* ▪ *dynamic routing* ▪ *accident analysis*	▪ *insufficient tools* ▪ *lack of expertise* ▪ *lack of professional staffs* ▪ *training* ▪ *understanding technology* ▪ *lack of communication*
Commercial Sectors	▪ *banking* ▪ *insurance* ▪ *logistics* ▪ *media* ▪ *real estate* ▪ *retail*	▪ *expensive cost* ▪ *lack of expertise* ▪ *lack of data*
Public & Education	▪ *libraries* ▪ *museums* ▪ *nature centres* ▪ *high schools* ▪ *Universities*	▪ *lack of cooperation* ▪ *insufficient software and data resources* ▪ *lack of proficient teachers* ▪ *acceptance of new technology*

FIGURE 2.7. SUMMARY OF IDENTIFIED BARRIERS AND APPLICATION DOMAIN. SOURCE: YE ET AL. 2014

2.3.4. DATA VISUALISATION

2.3.4.1. THE POWER OF MAPS

In this age of computer progress, in both power and storage capacity, the amount of data created is continually growing. Although select software tools are used to analyse and organise data, it can sometimes be messy and inconsistent, and hinders decision makers from selecting the relevant and essential information they need. There is an opportunity to turn an overload of information into an opportunity to enable decision makers to make informed decisions through data visualisation (Keim *et al.* 2006). Harris and Hazen (2006) use the term "power of maps" about early literature from the 1980's and 1990's and state that the power of maps is rooted in knowledge. The literature poses questions as to how what is not only represented on a map affects interpretation, but the implications of the absence of that map (Edney 1997; Harley 1989). Harris and Hazen (2006) applied the findings of this literature to also look to understand:

"*How does mapping suggest that certain spaces can, or should be protected for conservation? How does the relative "mappability" of different areas or landscapes encourage the protection of certain features of others? How do maps allow readers to imagine certain spaces as uninhabited and appropriate protection, or successfully 'protected?'*" (p101)

2.3.4.2. DATA VISUALISATION: MAP READABILITY

There are three types of information that are relevant to visualisation, these are:

1. Syntactic – this refers to the relationship among symbols
2. Semantic – this refers to the meaning of the symbols
3. Pragmatic – this refers to the application of symbols

The semantic and pragmatic types of information are specific to the individual reader and could be influenced by opinions, preferences, social/cultures factors, or previous knowledge (Harrie and Stigmar 2010). The readability, defined as the ability to discern map symbols and the ease of reading and interpreting a map, is a major issue within cartography (Harrie *et al.* 2015; Harrie and Stigmar 2010). The term was originally introduced in the 1920's in which user tests were used to validate formulas that could predict the difficulty of a text based on its contents. These tests focused on readership, reader persistence, and reading efficiency. It has been suggested that the digital revolution and the internet has allowed more freedom to cartographers to adapt to specific usability requirements but has also been suggested that cartographers have a decreasing amount of control of map readability (Harrie *et al.* 2011; Harrie and Stigmar 2010). The measures used to understand map readability have two main purposes, the first is to set specific dataset provisions, including minimum and maximum sizes/lengths for objects appearing on the maps. Cartographers have aimed to reduce visual complexity by eliminating excess items (distractors) that lead to the decrease in user performance (Harrie and Stigmar 2010). Map readability is related to these visual distractors. He *et al.* (1996) concluded that the distractors increase the visual complexity, especially when there are multiple distractors, however having no distractors could limit perception of objects by the visual resolution. Wolfe and Horowitz (2004) suggest that distractors should be different from the target objects by differences in size, orientation, or colour. Harrie *et al.* (2015) identified that certain factors influence and determine the level of readability in a map, they are as follows:

1. Amount of information: The number of objects of a particular type, the number of vertices, the number of nodes, links and areas, the total length of links, and occupied space

2. Spatial distribution: the distribution of objects, object symmetry and organisation, entropy measures for objects and points, homogeneity and number of neighbours, density of object and congestion measures

3. Object complexity: sinuosity, total angularity, and line connectivity

4. Graphical resolution: minimum size of points (on paper and on screens); minimum width of lines; and minimum separation of objects.

5. Additional measures include aspects of colours (e.g., contrast) of the visualised objects.

The readability measures discussed are mainly used with vector data rather than raster. Fairbairn (2006) identified that there have been more studies on the use of measures on vector maps, and it is more advantageous to do so. Spiess *et al.* (2005) and Alfredsson *et al.* (2014) state that there are few rules regarding specifications, especially with raster maps. Harrie *et al*. 2015 also claim that there are no map specifications that include the use of a combination of readability measures, thus providing no rules or justifications when selecting readability measures, or a composite of measures. There have been many studies that have aimed to define readability measurements; however, these studies do not target the applicability or usability of these measurements. It is stated that determining which readability measures to include in a composite is useful for the map generalisation process. (Harrie *et al*. 2015).

Trends within cartographic research show that most readability measures are geometrically oriented (Harrie *et al.* 2015). Brewer *et al.* (1994) states the significance of symbol style; the use of symbol style changes could not only improve the quality of a map but could decrease the work involved in maintaining multiple scale databases. An example of this could be increasing the transparency of an object that lies adjacent or on top of another object, which reduces the need to move the objects away from each other to allow the user to see both objects.

With that being said, Harrie *et al*. (2015) states that literature has placed an emphasis on syntactic measures rather than semantic. The semantic measures are harder to measure as they relate to the perception of the individual user. Because of this, it has been debated that full readability of a map cannot be measured due to the unmeasurable semantic factors (MacEachren 2004). Factors that affect perception could be pieces of information that are not viewed on the map, such as intelligence or previous knowledge. Roth *et al.* (2011) claims that cartography needs readability measures that focus on symbol styles that include semantic factors. This includes the adjustment of patterns, iconicity and colours that adhere to semantic rules, such as related themes having similar colours. This could specifically include water being shown as blue, grasslands as green, and roads as grey.

The second use of measures of map readability is the control of the generalisation process. Relating back to the question of how much information to put on a map, Biderman (1986) stated that when reading or interpreting a map, the human brain puts significance on the object points. Thus, providing the need to understand what constitutes an object point and applying the correct readability factors. Harrie and Stigmar (2010) concluded from a study that object points, line lengths and number of objects influenced the judgement of the reader rather than the area of an object itself.

Landscape planners have relied on two dimensional visualisations, however non-experts can be confused by abstract and graphically sparse, presenting a need for coherent yet still stimulating data visualisations (Lange 1999; Paar 2006). The field of computer graphics has grown and has provided opportunities for landscape visualisations but just in a two-dimensional form, with predictions that more people will use 3D landscape simulations (Orland *et al.* 2001; Sheppard 2001). Appleton *et al.* 2002 concluded that there is no "universal landscape solution" in the visualisation of landscapes, however Steintiz (1992) and Ervin (2001) state that environmental research should concentrate on the specifications of their required technology and efficient representation of data, rather than specific software, tools and technology.

The authors identified that even though there has been progression to overcome limitations such as incorporating local people into conservation management and the reduction of sharp edges in conservation boundaries, there is no comprehensive answer to these questions, however it is possible to engage experts to help identify these issues.

2.4. GIS IN ENVIRONMENTAL MANAGEMENT

2.4.1. INTRODUCTION

There are three key components for successful environmental and natural resource management: policy, participation, and information (Skidmore 2017). Policy within the UK has been introduced in Chapter 1 and discussed in Section 2.2. Skidmore (2017) states that "*Better spatial information and maps leads to improved planning and decision making at all levels and scales, and hopefully generates harmony between production and conservation across a landscape"* (p1). The following sections discusses information, particularly spatial information, and its use within the fields of land-use change, risk assessments, NNL and fragmentation.

2.4.2. PATTERNS IN LAND-USE CHANGE

Frequent monitoring of land use and land cover patterns are useful for the sustainable use of land (Singh Bijender *et al.* 2014). Datasets such as aerial and satellite imagery in conjunction with GIS plays an important role in the detection of land-use changes and ultimately in the protection and maintenance of natural resources (Prashad *et al.* 2014). Landscape metrics, patch mosaic models that quantify the structure and configuration of a landscape, are a widely understood quantitative technique that are suited for landscapes that are frequently disturbed (i.e., fire disturbances, felling, etc.) or undergo anthropomorphic change or are within a built environment (McGarigal *et al.* (2009). Landscape metrics have also been used to analyse changes in urban land-use over time; Seto and Fragkias (2005) completed the first comparative analysis of land-use change through spatial and temporal patterns. The authors used landscape metrics to analyse changes through 10 maps created from RS satellite imagery spanning 10 years for four cities in China. The conclusions state that the use of metrics was successful in the analysis (Seto and Fragkias 2005). In addition to this, Liu and Yang (2015) used the integration of satellite imagery, GIS and landscape metrics as part of an urban mapping and land cover change study. The authors concluded that the integration of these tools: GIS, satellite imagery, and landscape metrics were useful for landscape mapping and change understanding over time. Other authors over time have established the use of landscape metrics, also known as spatial metrics outside the field of landscape ecology in mapping and modelling land-use change (Herold *et al.* 2005). For example, Parker *et al.* (2001) stated the usefulness of spatial metrics is assess urban landscape patterns by linking them to economic processes. In addition, Alberti and Waddell (2000) also stated the importance of spatial metrics in complex spatial patterns as they provide a representation of heterogeneous characters of land-use cover and potential impacts on ecological impacts. Finally, Geoghegan *et al.* (1997) implied that people care about landscape patterns and spatial metrics by linking these patterns to house prices. The mapping and modelling of spatial metrics already has a variety of applications, but the research of these applications is only beginning (Herold *et al.* 2005). Most of the case studies point out that applications of spatial metrics need further systematic investigations (Herold *et al.* 2005).

In 1998, Hargis *et al.* stated that landscape metrics can provide useful interpretation of the landscape if the limitation of using metrics is understood. Firstly, Gustafson (1998) stated that applying numerous metrics without a clear hypothesis could result in a 'fishing trip', which could confirm a desired outcome by just selecting certain metrics. Although Liu and Yang (2015) stated above that the integrated use of landscape metrics was useful in landscape mapping and analysis, they discussed some limitations. Firstly, the authors stated that the quantification of changes does not address or explain the causality behind these changes, and that studies should include ancillary data and qualitative methods to fully understand the underlying processes associated with the consequences of landscape changes. In addition, the authors state that quantifying changes at different scales may lead the way to a need for specific measures, and more specific metrics for habitat fragmentation rather than vague indicators, such as "*total edge*".

2.4.3. Environmental Risk Assessments

The use of GIS for assessing habitats for EIA's is considered highly relevant, and a versatile platform for efficient data collection, enhanced system requirements and smoother operations (Gontier *et al.* 2010; Yadav and Mishra 2014). The concept of integrating GIS to assess environmental risk is not recent, with both Erickson (1994) and Eedy (1994) identifying applications and benefits for this integration. Erickson (1994) identified the following ways in which GIS can be used for the EIA: the overlaying of different layers over the study site, the categorisation of environmental components and attributes, the reporting of specific types of impacts that are related to specific project activities and identifying project activities and the network of possible impacts. Eedy (1995) describes the benefits of the integration of GIS and EIA. The author states that this integration allows for the evaluation of changes over time, can be updated and used for multiple projects, can store large multidisciplinary datasets, and can used to analysed relationships between environmental characteristics. In addition, the author also claims that the use of GIS and the EIA serves the interests of the public through more accurate reporting of impact assessments whilst aiding processes for technical analysts. In more recent research, Yadav and Mishra (2014) state that using GIS for impact assessments allows for a more realistic approach for habitat descriptors and opportunity to analyse their interrelationships. The authors also detail the specific actions a user can complete when GIS is used to visualise environmental data from an impact assessment. This includes the querying of a specific location, the selecting of a point which allows the user to see the corresponding attributes and any supporting photographs or documents, the suer can also search and query the data and export results and perform data management and configuration (Yadav *et al.* 2014).

The use of GIS is not as simple and developing applications without methodological structure. Gontier *et al.* 2010 discusses criteria for the selection of modelling method for impact assessments. These include technical reliability and user-friendliness of the platform, the types of outputs/results required, the possibility to test alternative scenarios, and data requirements and data format. A key component is environmental data as this is the subject of GIS analysis and visualisation (Gharehbaghi and Scott-Young 2018). There has been an increase in the amount of relevant digital environmental data published and being made available by governments, and private companies via remote sensing or environmental monitoring (Kogan *et al.* 2010). However, data heterogeneity can be a challenge in environmental data integration with varying accuracy and precision depending on the data source and subsequent processing (McAfee and Brynjolfsson 2012). Examples of environmental data that has been integrated with GIS for environmental assessments within research include weather patterns, topography, land-cover, and species distributions/presence data (Gontier *et al.* 2010; Vitolo *et al.* 2015). However, Vitolo *et al.* (2015) state that limitations, particularly with large environmental datasets, are a lack of structure which increases the complexity, few standardised definitions of domain variables, and metadata that has not been integrated with the dataset. Therefore, it is important to understand data restrictions and limitations when integrating environmental data into decision-making, ensuring that data requirements should be identified early as data availability and accessibility may be influenced if further data collection is needed (Glasson and Therivel 2013; Gontier *et al.* 2010; Johnson and Gillingham 2005)

2.4.4. GIS to Implement No Net Loss

There is no shortage of literature surrounding NNL and biodiversity offsetting, zu Ermgassen *et al.* (2019) reviewed NNL literature capturing over 15,000 articles, 32 of which observe ecological outcomes from NNL policies. The authors highlight the key themes of policy relevance, achieving NNL, and compliance with NNL policies, however there is no mention of techniques or technologies to aid NNL implementation. In addition, GIS is not mentioned within the entire global NNL review. It appears that research within this field is either based within policy, or physical management for NNL. Yu *et al.* (2018) used GIS spatial analysis methods to aid in identifying offsetting areas in the Yellow River Delta due to increased land reclamation on the coast. Spatial analyst tools such as interpolation of habitat attributes across the study area, natural breaks classifications for ranking suitability, and Euclidean Distance allowed the researchers to locate offsetting sites. Although the methodology and use of GIS was successful, ultimately the results are that NNL in this case is unachievable as too much land reclamation has taken place and there is not enough area within the Delta to offset like-for-like. The authors conclude by stating that the focus of NNL policies should be placed on minimising of land-use change for development.

According to Bull *et al.* (2018) there are no "*peer-reviewed multi-national assessments concerning the implementation of no net loss policies to date*" (p64). The authors state that barriers to transparency in this area are the lack of regulatory requirements and clarity surrounding the requirements, lack of political will, no protocol for combining sub-national datasets, and heterogeneous data formats. An increase in the transparency of assessments would further inform the debate regarding the suitability of NNL policies but would also set standards for good practice towards evidence-based conservation, and ultimately consistent techniques and technology for decision-making and implementation. In conclusion to their global review of NNL outcomes, zu Ermgassen *et al.* (2019) states "*If we are to achieve NNL of biodiversity, it is an urgent priority to develop the evidence base to understand what works, and when*" (p14), providing a gap for investigation into the use of technology and innovation in NNL initiatives.

2.4.5. Habitat Fragmentation and Landscape Indices

Almenar *et al.* (2019) use landscape metrics to analyse fragmentation and habitat loss in Luxembourg from 1999 to 2007 by calculating values for both years regarding specific species. The authors concluded these analyses can be easily replicated and would be suitable for coupling with least-cost path models, which would be applicable to the development of new linear infrastructure (e.g., roads, pipelines, etc.). In addition, it was recommended that similar spatial exercises would support nature conservation and could provide a value insight into the impacts of future land-use change. However, actions for biodiversity in *The 25 Year Environment Plan* do not appear to be legally-binding, and there is no requirement as part of the Contract BAP or EIA to include analyses such as this.

Corry and Nassauer (2005) tested the validity and reliability of metrics using small mammals in the corn belt of Iowa, USA. The authors measured four different indices that asked: *How much habitat is there? How big are the patches? How many habitat types are there?* And *how clumped or dispersed are the patches.* Using literature, the authors hypothesized that smaller, and more diverse patches were more suitable for small mammals. The analysis of landscape patterns gave habitats in the study a rank from 1-5 of suitability for small mammals, this was then compared to published values. The authors concluded that patterns within the landscape are not always good indicators of habitat quality. Corry and Nassauer (2005) also identified some other limitations and challenges faced when using this tool, along with advice to planners and designers. First, the authors found that from their study, applying landscape metrics on to fine-scale habitat patterns does not provide valid information when the landscape is already highly fragmented. This authors state that this may be because fine habitat patches may be considered as "*linear elements*" rather than polygon patches (i.e., hedgerows). Therefore, the user should not rely solely on compositional metrics such as mean nearest neighbour, as this tool is not valid with linear elements. To avoid fine-scale habitat patterns, the habitat classes can be aggregated to create larger habitat parcels of a similar characterisation, if appropriate for the goals of the study (i.e., broadleaf wood and mixed woodland) However, this increases contiguity within the landscape. The authors recommend using a habitat classification scheme.

Martinez and Castillo (2015) identified ten individual metrics that can be used to indicate fragmentation and connectivity. In another study, the degree of fragmentation was measured as a value between zero and one, as used by Reza and Abdullah (2011) and originally by Penghua *et al.* (2007). These studies look at fragmentation across an entire landscape to assess the vulnerability of that landscape to anthropogenic change. As a development site is composed of dynamic factors, Andreasen *et al.* (2001) allows for the degree of fragmentation to be assessed over time as proposed landscape changes emerge. There have been reviews of the use of landscape health and composition indices from as early as 1993. Suter (1993) reports that some components within environmental indices have "*non-sense units*" which have no real-world value. For example, the biodiversity units discussed by Defra (2012) are a compilation of determined values for habitats. The use of "*unreal properties*" for ecological indices may obscure the basis for decision making (Suter 1993). This critique further supports the use of landscape metrics as “*real properties*” that are not only measurable in the field but are not combined into an index of “*non-sense units*”. Other indices, such as Karr’s (1993) Index of Biotic Integrity (IBI) and Costanza’s (1992) Health Index (HI) both use an integration of factors into a single index to summarize the health of an ecosystem. Suter (1993) claims that a single unitary response implies that there is only one type of response. For example, Karr’s (1993) 12 metrics of fish communities implies that there are 12 different responses to a disturbance; it is then compiled into a single index, which implies a simple linear scale response, which, due to diverse components of an ecosystem, are not generally comprehensible.

Experiments in understanding the predicted impacts on landscapes by linear infrastructure is discussed by authors. Geneletti (2004) used spatial indicators to assess ecosystem fragmentation caused by roads and developed a methodology to compare changes in landscape configuration caused by road projects, and to encourage good practice in spatial planning. The author created a flow diagram for impact assessment for habitat loss and fragmentation (Figure 2.8). The methodology differs from previous landscape analysis is also applied to individual patches in addition to the wider landscape. Geneletti (2004) states that while landscape configuration metrics such as mean patch size and patch density are useful in evaluating changes at the landscape-level, highlighting the patches that are going to be affected by infrastructure design should be a prerequisite for an infrastructure impact assessment. Geneletti (2004) concludes by stating “*is an urgent need to provide reasonable estimates of impacts such as fragmentation, whose ecological implications cannot be ignored during the design of transportation infrastructure*” (p13). However, outside of linear infrastructure, experts in this field are yet to reach an agreement regarding how to measure fragmentation patterns within a landscape, making findings experimental and blurring the translation into management guidelines (Bogaert 2003).

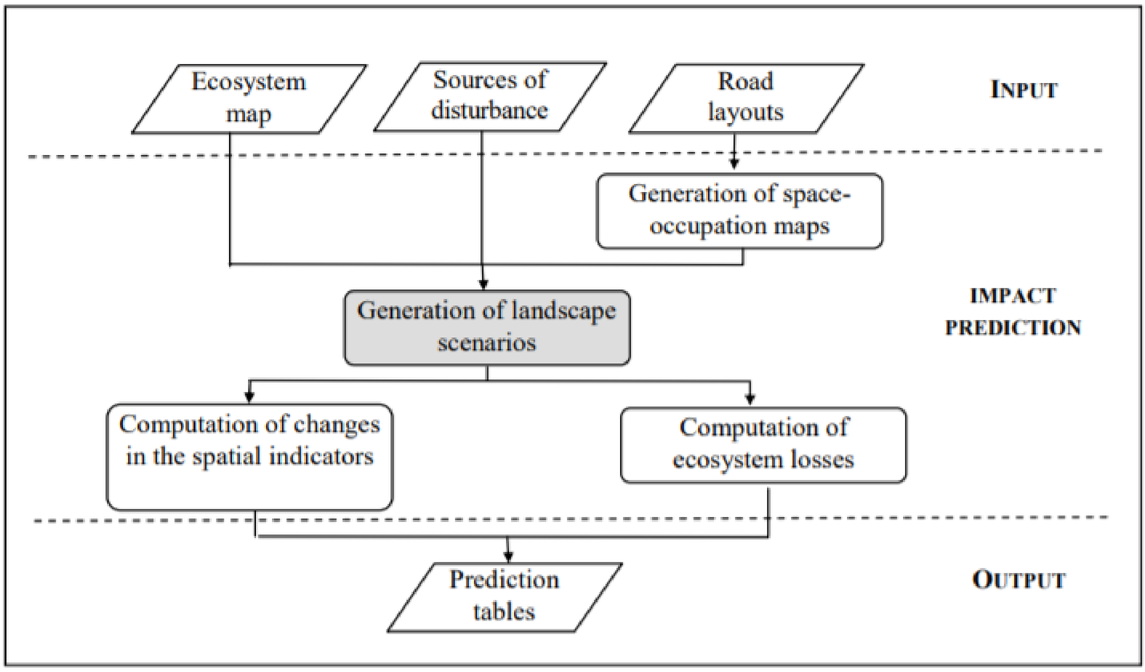


FIGURE 2.8. SCHEMATIC OF IMPACT PREDICTION. SOURCE: GENELETTI 2004

2.5. CHAPTER SUMMARY

This chapter has discussed the three themes of environmental sustainability and management, cartographic modelling in an infrastructure context, and geospatial solutions in environmental management. There have been many attempts to push sustainable development policies worldwide since the 1980s with little success. Current environmental policies within the UK are considered arduous tasks that require subjective expert opinions which are not always integrated throughout the entire lifecycle of a development project. These limitations are despite the relevant integration of GIS with the EIA in literature, including data collection, data analysis, and visualisation. Furthermore, procedures for impact assessments lack a consistent review in monitoring methodologies, and do not assess the impact of fragmentation. The prominent ecological initiative, no net loss, allows for the commoditisation of nature into biodiversity units that can be lost or gained on a site. There is currently no mandate for official reporting of biodiversity losses and gains or required targets. In addition, there is limited literature on the application of geospatial technologies to improve the process of NNL calculations and further inform decision making. Finally, there are no requirements for assessing biodiversity in the form of NNL calculations or a Contract BAP within the design phases of construction development despite sustainability goals needing to be set within the concept design. There is a clear knowledge gap that provides an opportunity for further research into the integration of biodiversity management tools into the concept and developed design. In addition, there Is an opportunity to further research and develop GIS applications that incorporate NNL calculations to inform the Contract BAP and the EIA. Finally, there is a need to establish whether fragmentation can be included as part of the Contract BAP or the EIA using landscape pattern analysis to predict impacts.

GIS applications are an established tool within the context of large infrastructure research and has been demonstrated across multiple sectors for asset visualisation and in decision support. However, there is no requirement for use of GIS at the technical design phase of construction development, which is the stage in which the design is given spatial coordination. Literature surrounding barriers to GIS implementation suggest that uptake of the technology is based around data quality and availability, and organisational factors. These factors include a lack of knowledge and awareness of the benefits, no political will to implement the technology, and a general lack of expertise. There is an opportunity to investigate the practical applications of GIS outside of research to understand how GIS is used as a decision support tool for environmental management, using the sponsor company as a case study. There is also an opportunity to assess the feasibility of implementation of GIS for environmental management to improve the uptake of GIS and reduce the barriers, thus improving environmental management and sustainability in large infrastructure development.

3. METHODOLOGY

3.1. INTRODUCTION

Chapter 2 highlighted the need for a new approach to help the infrastructure industry to increase their biodiversity protection and sustainability. Delivering this approach is challenging as methodologies discussed in the literature review, such as no-net loss, are considered over-simplified and out-dated. This chapter explains and justifies the combination of methodologies to address the challenges uncovered in the literature review and to achieve the research objectives.

The aim of this chapter is to establish the methodological foundations, and research approaches that address the research aims and objectives. The broader research project was developed as part of the design science research methodology, that is specific to performing research in information systems. The research project is then comprised of research inquiries, each of which have their own research paradigm, assumptions, and approaches for data collection and analysis that has influenced the choice of appropriate approach.

The chapter is comprised of nine sections; the first investigates the research design and describes the design science research approach. The second presents the setting and participants of the research; this is focused on the details of the sponsor company. The third through seventh sections explore the specific research enquiries. The eighth discussion ethical considerations, and the ninth concludes the chapter.

3.2. RESEARCH PARADIGM AND DESIGN

3.2.1. RESEARCH PARADIGM

This research project is concerned with the broader context of biodiversity loss due to infrastructure development. The research, therefore, focuses on a pragmatic approach. This type of approach allows the researcher to understand "*what works*" rather than reaching a conclusion that is objectively "*real*" or "*true*" (Mackenzie and Knipe 2006). Pragmatists "*rejected the scientific notion that social inquiry was able to access the truth about the real world solely by virtue of a single scientific method*" (Mertens, 2005, p.26). Therefore, pragmatists tend to include a mixed-method approach in research design. In this case, the purpose is to understand if GIS can support infrastructure companies reach their biodiversity goals while minimising their impact on the surrounding environment, and to develop a simple approach to be implemented within infrastructure design and implementation.

3.2.2. DESIGN SCIENCE RESEARCH APPROACH

Research design is a systematic plan to "*understand, describe, predict or control an educational or psychological phenomenon or to empower individuals in such contexts*"

(Mertens, 2005, p.2). The objectives in this thesis used mixed methods; however, the overall research follows a pragmatic approach for performing research in information systems, such as GIS, based on the Design Science Research Method (DSRM). This proactive research methodology "*focuses on creating and evaluating innovative IT artefacts that enable organisations to address important information-related tasks*" (Hevner et al., 2004 p33). Design science is regarded as a problem-solving process in information systems. Knowledge and understanding of a design problem are a fundamental principle of design science research, and the solution is the development and application of an artefact (Hevner *et al.* 2004). In this case, the artefact being the human/computer interface.

The DSRM approach is comprised of three cycles, the Relevance Cycle, Rigor Cycle, and Design Cycle (Figure 3.1.). The Relevance Cycle is based around the understanding of the problem. For this research the literature review, and contextual studies provide the domain in which the artefacts are placed. The Rigor Cycle grounds the design of the artefact in a knowledge base, for this research the knowledge base is cartographic communication. In addition to this, spatial planning methodologies shape the artefact and are used in the identification of parameters within the artefact. Finally, the Design Cycle is the key research activity. Objective 3 is based around the design and development of the geospatial applications to aid in reducing biodiversity loss. The framework for the artefact is grounded by the knowledge base of cartographic communication, and influenced by existing UK biodiversity policies, construction design, and practices within the sponsor company. This cycle also encompasses evaluation. Supporting methods of evaluation include a technical discussion, business opportunity discussion, and a discussion based around the DSRM.

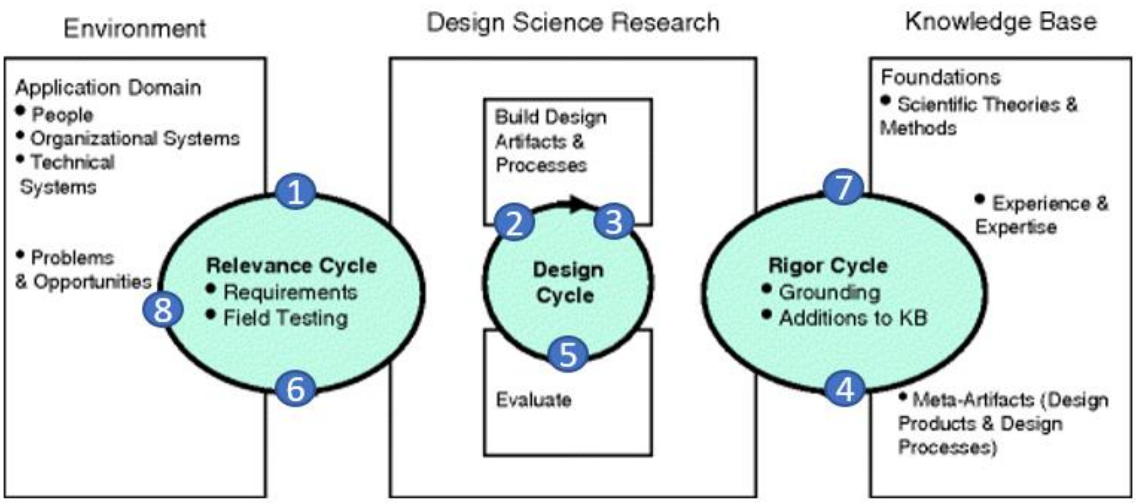


FIGURE 3.1. THE THREE RESEARCH CYCLES WITH NUMBERS THAT LINK TO THE DSRM CHECKLIST QUESTIONS. ADAPTED FROM HEVNER AND CHATTERJEE (2010)

A design science research in information systems methodology was developed by Peffers *et al.* (2007), legitimising design science research by creating a commonly accepted framework for researchers. The methodology recognises the objectives, processes, and outputs in six stages: "*Identify the problem and motivation*", "*Define objectives of a solution*", "*Design and development*", "*Demonstration*", "*Evaluation*" and "*Communication*". This is presented in Figure 3.2.

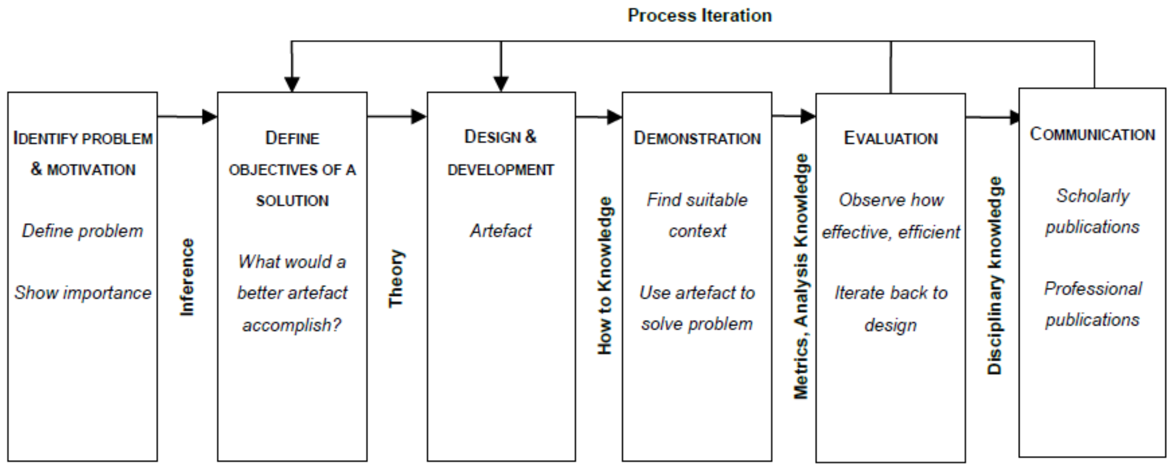


FIGURE 3.2. THE PROCESS MODEL FOR DESIGN SCIENCE SOURCE: PEFFERS ET AL 2007

In the first stage, the "*Identify problem and motivation*" is defined and investigated in the introduction and literature review, which identifies the research problem and the value of a solution. The introduction explores the impacts that infrastructure has on surrounding environment. The motivation is that the UK government is increasing its investment in infrastructure development but are not funding sustainability for the wider environment. The literature review established that environmental policies do not force or incentivise developers to invest in further conservation methods outside of the requirements of an Environmental Impact Assessment (EIA), and results are not integrated throughout a project life cycle. Whilst this presents a challenge, a geospatial toolkit may provide a solution. Therefore, this research proposes the development of geospatial applications that can be integrated with current procedures to aid decision making and provide relevant data.

The "*Define objectives of a solution*" stage is defined by the research problem and the expected output of the research. This is where the research objectives are defined, in this case by the problem and motivation discussed in the first stage. The research is from the perspective of an infrastructure developer; thus, the research objectives should consider the industrial context, and ultimately the development of an artefact. Furthermore, the objectives should explore how the methods and proposed solution will be evaluated. In this research, the problem is how to reduce losses to biodiversity in infrastructure projects, and the solution is to develop geospatial applications that developers can implement. Therefore, the objectives should describe activities including investigating the literature on current policies and procedures for planning development; industrial procedures in planning and biodiversity management; the design and development of a proposed solution and methods of evaluation.

The "*Design and Development*" stage is the creation of the artefact, in this case the geospatial applications. The design of the applications needs to meet the requirements of the research objectives; therefore, the application is based on current biodiversity frameworks used within the infrastructure industry, with a defined scope and end-user.

The "*Demonstration*" stage is when the artefact is used to solve an instance or multiple instances of the problem. The GIS applications can be used in two aspects: quantifying biodiversity using value metrics and calculating biodiversity units and simulating habitat loss and fragmentation in surrounding landscapes. The models developed here are piloted on two test sites: the A465 and the A14 trunk roads.

The "*Evaluation*" stage measures and observes how well the proposed solution is supported by the artefact. The models piloted in the demonstration stage are then each validated and verified based on the functionality of the model and the representation of the visual outputs. If a model is invalidated or not verified alternatives will be discussed. In addition, the entire solution is assessed as suitable for business implementation a discussion of the themes associated with a value proposition, including profitability, uniqueness, and persuasiveness.

In the "*Communication*" stage, the research is concluded. The key findings as discussed in each chapter, along with research contributions and future research.

3.3. Research Setting

3.3.1. Introduction

The research setting can be described as the geographical location of the research, or the details of the participants that are taking part in the study. As the Engineering Doctorate seeks to combine academic research with real-world industry requirements (AEngD 2016), this research has been in collaboration with an industry sponsor. Therefore, for this section, the research setting describes the sponsor company and the context in which the research was applied.

3.3.2. Introduction to Sponsor Company

The sponsor for this research is Costain Group Plc. (referred hereafter as 'Costain'), an engineering solutions company established in 1865 in the building trade. The company started by building accommodation in the north west of England, and then moved south to London in

1920 to build houses, beginning the expansion of the company. In 1930 the company undertook work overseas, which included the building of an 11-mile section of the Trans-Iranian Railway (Figure 3.3.), a 10-million gallon-per-day water distillation plant in Kuwait and airports in Bahrain and Dubai. Within the UK, Costain have been part of infrastructure development, which has included iconic projects such as the Thames Barrier (Figure 3.4.), and the Channel Tunnel (Costain 2015).

FIGURE 3.3. CONSTRUCTION OF THE TRANS-IRANIAN RAILWAY. SOURCE: COSTAIN 2015

FIGURE 3.4. THE THAMES BARRIER. SOURCE: COSTAIN 2015

Today Costain is an established company in infrastructure delivery, their revenue (including the Group's share of joint ventures) for 2017 was £1.7 billion, which is an increase of 4% from 2016 (Costain 2017). Costain's head office is based in Maidenhead, Berkshire, with twelve supplementary offices across the country, including London, Manchester, Birmingham, Worle, and Aberdeen (Figure 3.5). The company is comprised of six infrastructure sectors: Rail, Nuclear, Highways, Water, Oil and Gas, and Power. Each sector within Costain deals with different clients, sub-contractors, suppliers, and joint-venture partners.

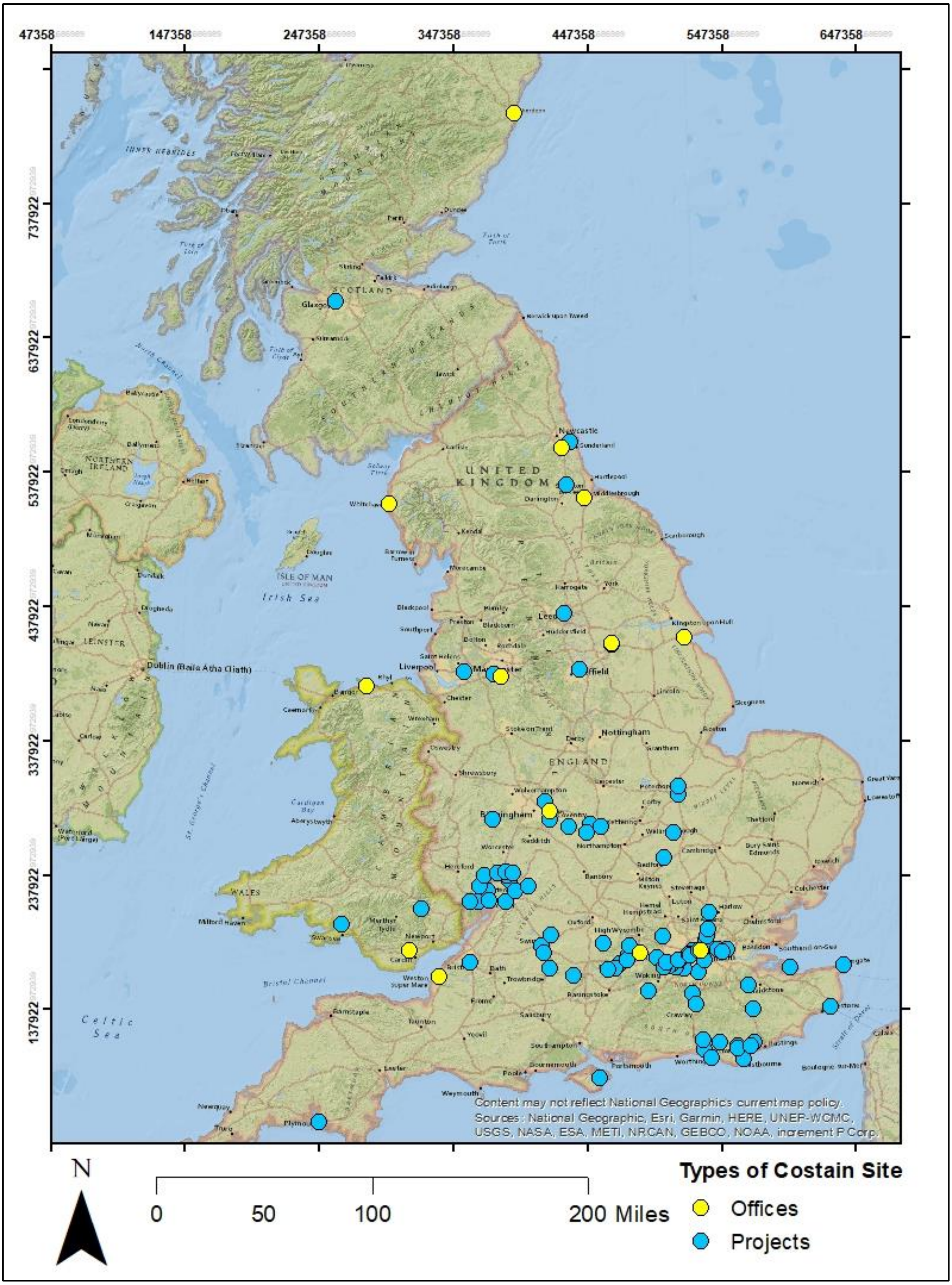


FIGURE 3.5. THE OFFICES AND PROJECT SITE OF COSTAIN GROUP PLC AS OF OCTOBER 2020. SOURCE: COSTAIN 2020

3.3.3. The Business and Sustainability

In the last five years, Costain have been transitioning their business perspective from project delivery to providing technology consultancy. The company outlines in its in its 2017 Sustainability Report the nature of this transition under three headings (Figure 3.6): "*sources of competitive advantage*", "*how we create value*", and "*how we maximise value*". Costain (2017) states that it uses its known reputation within the industry, its previous successes and financial strength along with skilled employees and smart technology specifically within the energy, water, and transportation markets. The company wants to integrate technology through consultancy, complex delivery, and asset optimisation to bring value to stakeholders and clients. By doing this, Costain intends to grow as a "*smart infrastructure solutions company*".

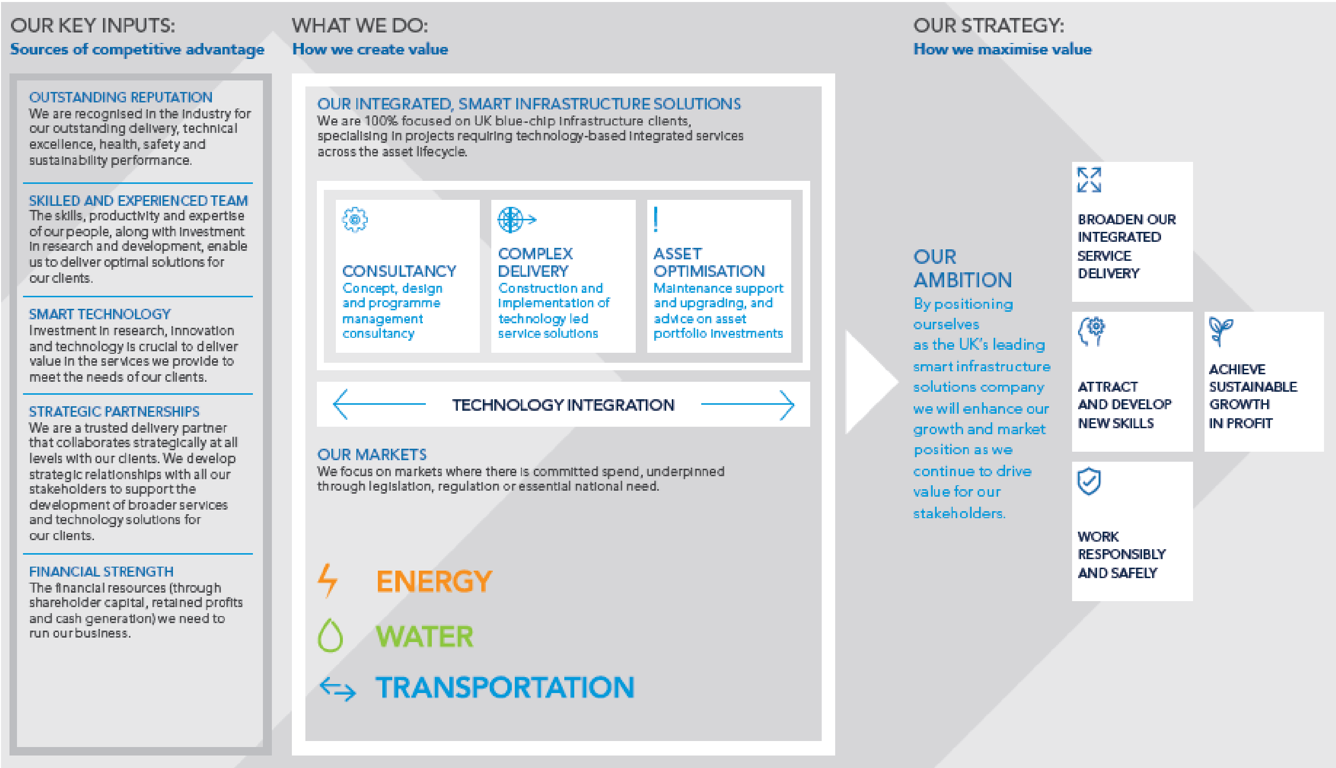


Figure 3.6. Infographic of Costain's strategy for its business transition Source: Costain 2017

Costain published a sustainability report in 2017, titled "*Smart Thinking, Improving Lives*", is a 44-page document with the mission statement: "*Our purpose is to improve people's lives by deploying technology-led programmes to meet urgent national needs in the UK's energy, water and transportation infrastructures*" (Costain 2017 p2). The report accounts for several different aspects of sustainability such as carbon footprint and community engagement. This is relevant to this research as the investment in smart infrastructure includes the use of geospatial technology. The report outlines current initiatives and its strategies for 2025 goals, based on the United Nations (UN) Sustainable Development Goals. The goals that specifically relate to biodiversity loss are under the category "*Creating a Better Environment*". The company makes the commitment to "*Enhancing biodiversity*" with the goal of "*All projects have a net positive biodiversity impact*" (Figure 3.7). This goal aligns to No Net Loss concept that was introduced in Chapter 1 and discussed within the literature review.

	Commitment	By 2025
Creating a better environment	Enhancing biodiversity	All projects have a net positive biodiversity impact
	Using natural resources efficiently	Collaborating to contribute towards a successful circular economy
	Reducing our carbon emissions	Leading the industry in low carbon engineering solutions and operations
	Protecting the environment	No direct harm to the environment from our operations

FIGURE 3.7. THE COMMITMENTS FROM COSTAIN FOR "CREATING A BETTER ENVIRONMENT" BY 2025. SOURCE: COSTAIN 2017

This section shows that Costain is experienced with corporate social responsibility with social and Science, Technology, Engineering and Mathematics (STEM) initiatives. The benefits of sponsoring research such as this increases technology capability and integration across sectors whilst adhering to sustainability commitments and upholding their reputation.

3.3.4. STUDY SITES

As part of the sponsorship, Costain provided data relation to study sites for use within the thesis, Site 1: A465, and Site 2: A14 (Figure 3.8). For consistency, the study sites were selected from a single sector, in this case the Highways Sector, as requested by the sponsor company.

FIGURE 3.8. THE LOCATION OF SITE 1 (A465 – SECTION 2) (BLUE) AND SITE 2 (A14) (YELLOW)

Site 1 is Section 2 of the A465 managed by the Welsh Government (Figures 3.9 and 3.10). The route is an 8km long road expansion from Brynmawr to Gilwern in South Wales. The scheme aims to reduce journey times for private and commercial road users and facilitate economic regeneration within the area. The expansion was due to finish at the end of 2019; however, the scheme is currently the subject of a dispute between Costain and the Welsh Government causing a delay to completion, potentially until 2021.

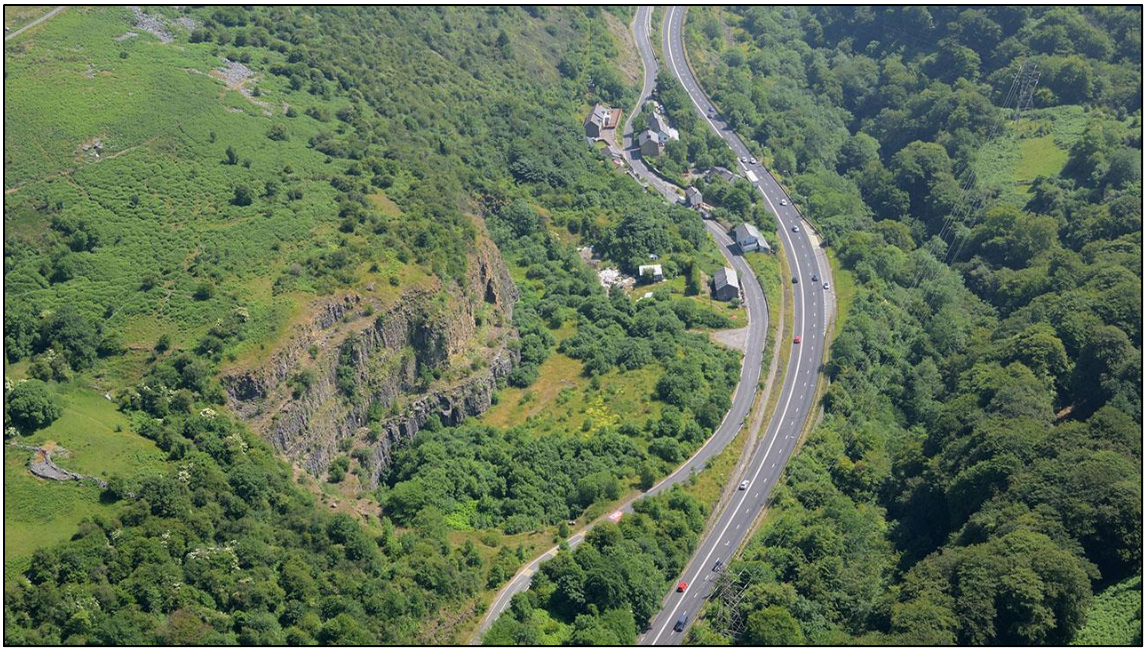


FIGURE 3.9. PHOTOGRAPH OF THE A465 SOURCE: COSTAIN 2011

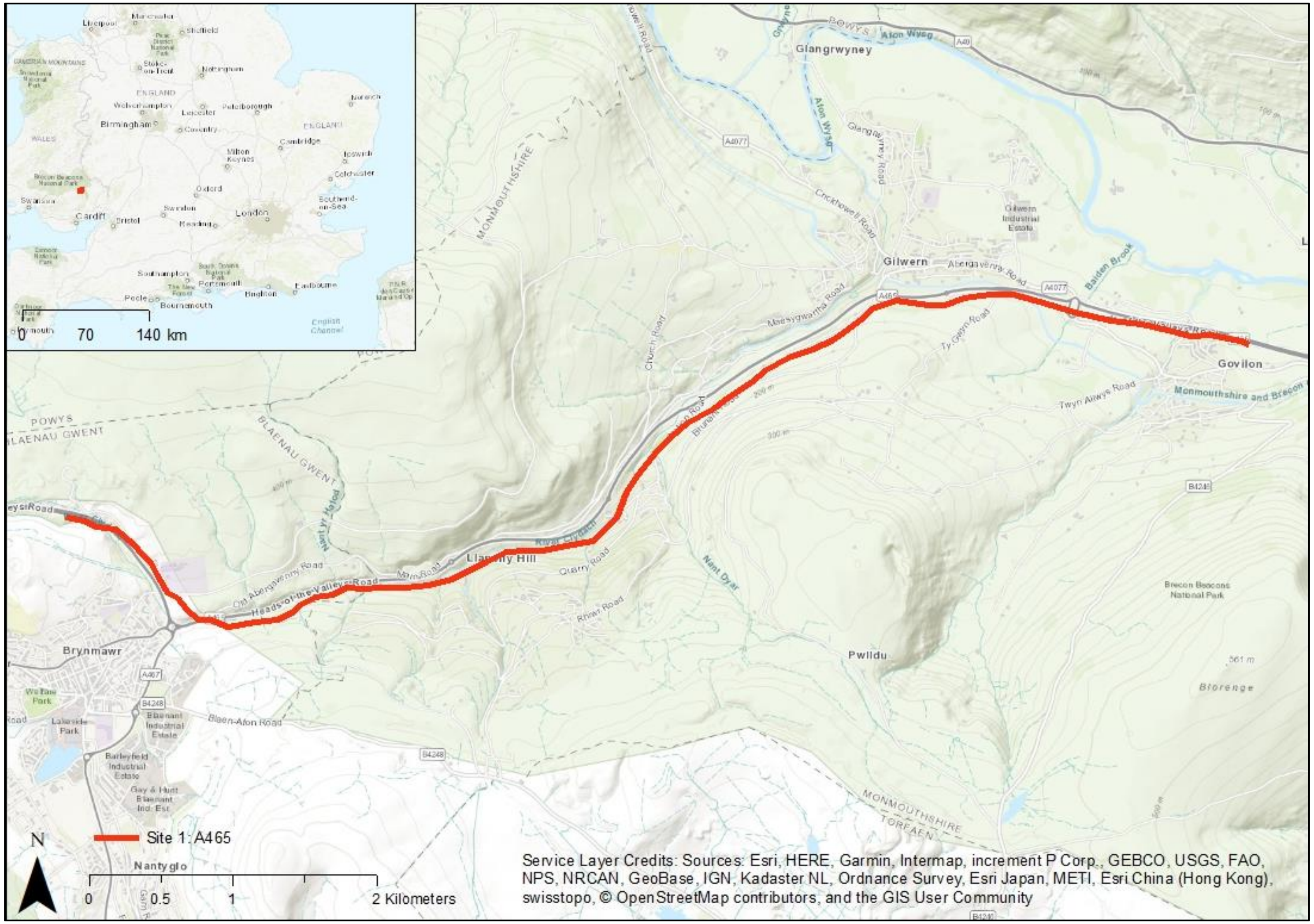


FIGURE 3.10. THE ROUTE OF SITE 1: THE A465 (RED

Site 2 is the A14 (Figures 3.11 and 3.12), managed by Highways England, a governmental company that manages approximately 4300 miles of road networks in England. Costain (2019) states that the new bypass runs between Ellington and Swavesey as part of an upgrade joint venture project costing £1.5 billion. This section of the route between Huntingdon and Cambridge is approximately 27km long and was due to be opened in spring/summer 2020. However, the road opened in December 2019, six months ahead of schedule.

FIGURE 3.11. PHOTOGRAPH OF THE A14. SOURCE: COSTAIN 2019

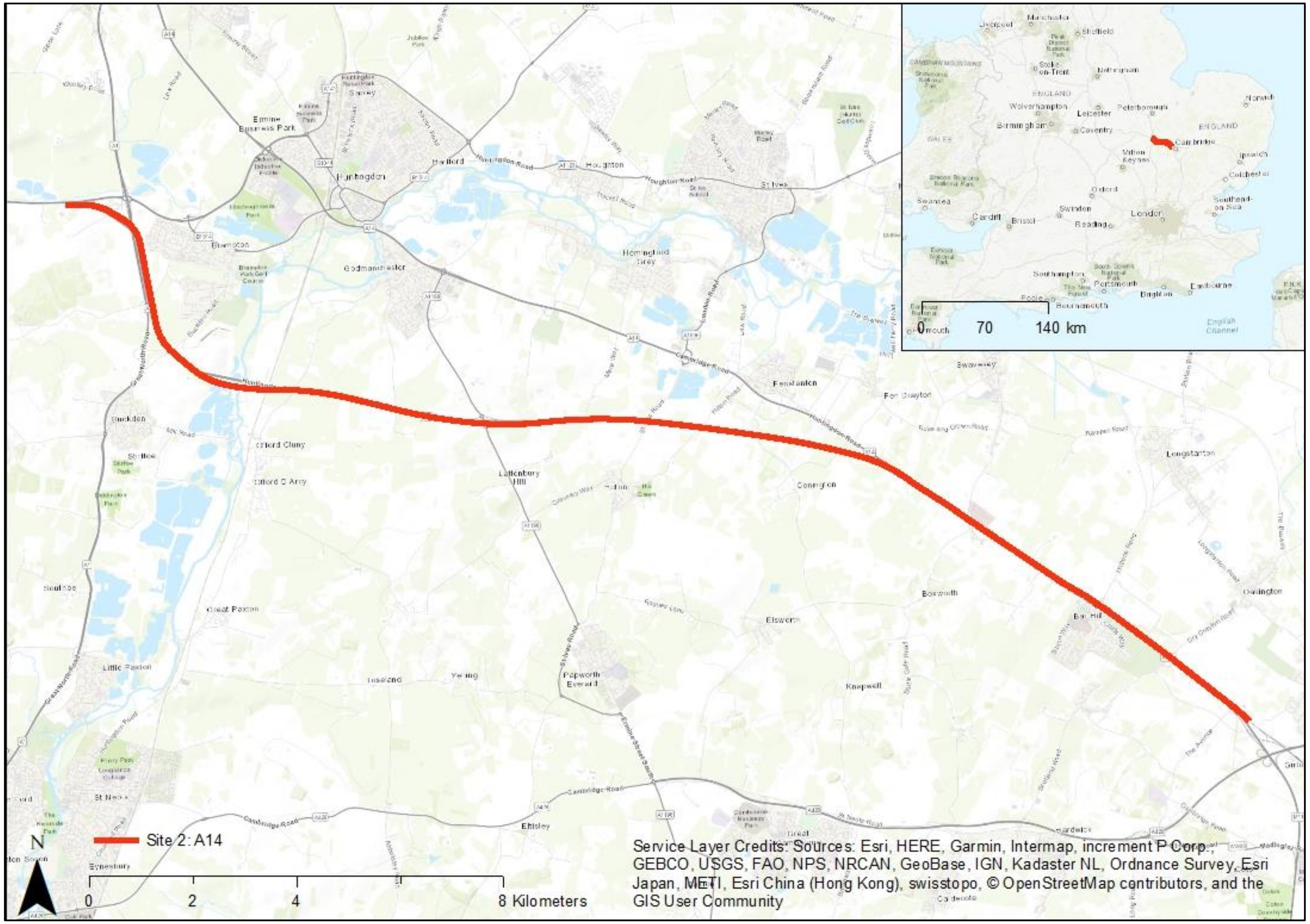


FIGURE 3.12. THE ROUTE OF SITE 2: A14 (RED). SOURCE: COSTAIN 2015

The specific sector of Highways and the study sites were selected by Costain. This did mean that a method of site selection was not needed and shows the potential application on a real site. However, having no method of site selection does come with its own impacts. Site selection bias has been studied within the context of biodiversity sampling, with influences including "*data availability and analyses that are possible, including over- or underrepresentation of geographic regions, land - use types, and taxonomic groups*." (Mentges *et al.* 2020 p2). In addition, the justification for this specific site selection cannot be made clear, for both the sector and the individual sites. For example, it is unclear whether the sites were chosen based on their environmental constraints, the availability of engaged environmental staff, or to win favour with the client, Highways England.

The study site boundary pertained to the guidelines of the PEA set out by the Chartered Institute of Ecology and Environmental Management (CIEEM). The virtual boundary for the habitat and species baselines was set at 5km from the route, fully containing all polygons that intersected the boundary. This was initially selected to include impact zones from infrastructure on all types of protected species (mammals, birds, amphibians, etc.). The boundary is adaptable within the habitat and species baseline based on the requirements of the project for scoping and screening purposes.

3.4. Method – Study of the End-User

3.4.1. Introduction

The Study of the End-User biodiversity management practices, using the sponsor company as a case study. This was done by reviewing documentation regarding biodiversity management that is available across the Costain group. Specifically, this section includes relevant definitions, the document review methodology, the results and summary, and an analysis and discussion.

3.4.2. Costain's Environmental Policy

In January 2020, the Chief Executive Officer (CEO) of Costain, Alex Vaughan, signed a one-page environmental policy. The document discusses the aspirations of the CEO for Costain to "*go beyond merely minimising harm on the environment, to working with our customers to provide environmental enhancement and sustainable solutions*" (Costain 2020 p1). The policy pledges to become carbon neutral by 2035 along with nine other action points to achieve "*environmental excellence*". Of the nine action points, two are relevant to this research. Therefore, in addition to understanding the end-user for the GIS applications, this study also aims to understand how Costain is going to meet the following commitments:

1. Continually review and improve the environmental management system to ensure all operations comply with environmental legislation and target higher levels of performance

2. Eliminate damage to the environment and promote environmental enhancement through working with our customers to achieve no net loss and target a net gain in biodiversity

Regarding the first commitment, the literature review discussed the improvements needed in EIAs, EcIAs and NNL. However, Costain as a contractor should be compliant with environmental legislation regardless and should have the procedures in place to do so. However, a commitment such as this indicates the opposite and a further need for a review of management procedures and technology integration in environmental planning and design. Moreover, a commitment to eliminate damage to the environment by implementing NNL initiatives also indicates that a framework or procedure should be in place. Therefore, a document review will provide an overview of biodiversity management within Costain compared with the policy limitations discussed within the literature review. This comparison is important to fully understand why the industry is not meeting their biodiversity goals if they are incorporating the findings from the literature, and how this can be improved. Using Costain as the case study.

3.4.3. METHODOLOGY

This study focuses on discussing GIS and environmental planning in the context of large infrastructure. This was done through a document review. The broad methodology for a document review, was taken from Wach *et al.* (2013) and described setting the criteria for documents, data collection, identifying the key areas for analysis and the analysis of the data (Figure 3.13). These results then form the model framework for the GIS simulations. This methodology section discusses the criteria for document selection and the collection and analysis of data.

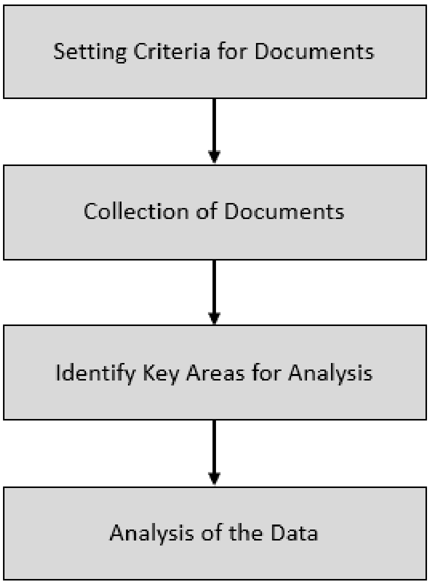


FIGURE 3.13. FLOW CHART OF THE METHODOLOGY FOR THE DOCUMENT REVIEW. SOURCE: WACH ET AL. 2013

The setting of the document criteria is linked to the research aims and objectives of this thesis. The document review is using the sponsor company as a case study for determining the key roles, aspects, and procedure for biodiversity management. This is to identify end-users and roles for the implementation of GIS applications. In addition, this review aims to discuss any limitations and shortcomings from the documentation that require improvement. Therefore, the documents for this review need to meet the criteria that documentation is accessible to any Costain employee in any sector of the company. The documents review is further refined by two themes: the first in this case, the documentation must be relevant to environmental aspects, impacts and hazard to understand how biodiversity is managed. The second theme of GIS was applied to the document review to understand both the internal geospatial capabilities of the business, and whether GIS is required as part of any environmental management. In summary, the criteria for the document review are as follows:

1. Be accessible internally for any Costain employee

And

2. Must be relevant to biodiversity and environmental management

To meet the criteria of internal accessibility within Costain, the data was collected from the internal intranet "*The Costain Way*" (TCW). TCW is "*Costain's Business Assurance System, a risk-based, integrated management system that provides instructions and advice on how to promote best practice and reduce risk across the Group*" (Costain p2). TCW contains all internal documentation for the business from company car lists, permits, and supplier verification. There are 3816 documents available on TCW and are broken down into four processes: "*How We Do it*" (2417 documents), "*How We Manage Our Business*" (561 documents), "*What We Do*" (238 documents) and "*Working for Costain*" (276 documents). Documentation is referenced and identified by a unique code that is made up of three parts: the department, the document type, and document number. There are 40 departments; examples include "*WWG – Work Winning*", "*QUA – Quality Control*" and "*AOR – Corporate Accounts and Reporting*". The full list of departments can be viewed in Appendix C. The document type will either be "*H – How to*", "*T – Tool*" or *"G – Gate*". For example, the document "*WWG-T-018 – Joint Venture Negotiation Strategy*" is a tool in the Work Winning department. The documents were further refined based on their relevance to the document criteria

Bowden (2009) states that a wide array of documents is advantageous; however, the quality of the document is more important than the quantity. Therefore, the documents collected will be refined based on theme and relevance to UK policy and impact themes. Documents were collected based on a search, with the term "*Biodiversity*" typed into the search bar. The documents and results were categorised into the five groupings based on the purpose of the document, "*Approvals"* (AP)*, "Checklists"* (CKL)*, "Guides"* (G)*, "Plans and Templates"* (PT) *and "Tools"* (T). The definitions for each category type are summarised in Table 3.1.

TABLE 3.1. THE DOCUMENT TYPE, ACRONYM, AND DEFINITION FOR THE FIVE CATEGORIES OF DOCUMENTATION WITHIN THE DOCUMENT REVIEW

Type	Acronym	Definition
Approval	AP	Official approval document with "*Approval*" in the document title
Checklist	CKL	A series of questions requiring comments or evidence
Guide	G	Documents containing process maps that link to detailed documents
Plans and Templates	Pt	Example client plans, and documents that require information to fill
Tools	T	A document that used to implement or carry out a function

There is no recommendation on the number of documents for an effective document review; however, Bowen (2009) states that a document review should focus on the quality of documents rather than the quantity. Therefore, the review sought to narrow the selection of documents by categorising into environmentally and non-environmentally focused documents. A document would be considered of environmental focus if the document title contained any variations of the terms "*Biodiversity", "Environment",* or "*Ecology".* The most systematic way to have completed this would be to use department classification. However, as environmental documentation is broadly placed within, SHE, this categorisation would be too vague and would include other health and safety documentation not relevant to the study. Any titles that contained "*Environment"* as part of SHE, it was not considered of environmental focus. The full list of documentation results for the biodiversity search can be found in Appendix C.

The analysis aligns with the objective to establish the context of biodiversity management in the industry to recommend where geospatial technology can be integrated. There are three types of techniques for analysing document content: interview, content analysis, and thematic analysis (Bowen 2009; O'Leary 2014). The interview technique sees the researcher "*ask*" questions and highlight those answers within the text. The content analysis technique sees the research quantify the use of selected words or phrases (O'Leary 2014). The thematic analysis categorises emerging theme for further analysis. There were two types of analysis in this study: the first uses the noting occurrences technique to refine the selection documentation and identify trends; the second uses the interview technique to highlight information that is relevant to research aims (O'Leary 2014).

The first analysis categorised and quantified the documentation that is relevant to the current UK biodiversity policy. The documents subject to a keyword search, a widely popular process for querying datasets to extract useful information (Li *et al.* 2008). The keyword search used terms and phrases that were highlighted themes in the literature review (summarised in Table 3.2). Documents were manually searched using the "*search features*" function available in Microsoft Word, Excel, and Adobe file formats. Each document underwent a pilot search to ensure that the content was searchable. The pilot searched for the first three words in the main body text of that document. Any non-searchable documents were recorded as such. Any documents that were referenced in any Env focused documentation (known as linked documents) that had not been reviewed in the original search was also classified by focus and categorised. The linked documents that were classified as Env focused also underwent the search for terms and phrases themed within the literature review. This was to ensure that all relevant documentation was retrieved.

TABLE 3.2. THE THEME AND WORDS SEARCHED WITHIN THE DOCUMENT REVIEW

Theme	Word(s) searched
Mitigation Hierarchy	*Mitigation*
Environmental Impact Assessment	*Environmental impact assessment, assessment of impacts, EIA*
Ecological Impact Assessment	*Ecological impact assessment, EcIA*
Biodiversity Action Plan	*Biodiversity action plan, BAP*
International Standards Organisation	*ISO*
No Net Loss	*No net loss, net gain, loss, gain, NNL*
Biodiversity Offsetting	*Offsetting*
Ecosystem Health	*Ecosystem, ecosystem health*
Geographical Information Systems	*GIS, spatial, geospatial, map*
Fragmentation	*Fragmentation*

The second analysis uses the interview technique to dissect and highlight relevant information from the refined document selection. Two types of documents were reviewed further. Firstly, the documents that contained the highest frequency of keywords were dissected and summarised. The frequencies were ranked from highest to lowest, and the documents that were contained with the first 50% of frequency were analysed. Secondly, Env documentation categorised as a "*Tool*" was reviewed and summarised. The selected documents were analysed based on the function, document structure, key roles, data and technology, and outputs. Brief descriptions of each analysis components can be found in Table 3.3.

TABLE 3.3. THE ANALYSIS COMPONENT AND DESCRIPTION OF THE REFINED DOCUMENT ANALYSIS

Analysis	Description
Function	The purpose of the document
Document structure	The chapters or sections of the documents
Key roles	The roles that perform tasks within the documents
Data required (if applicable)	Any input data for tools and templates
Use of GIS (if applicable)	If GIS was required for any tasks
Outputs	The result of the document

The document review is a cost-effective method that requires a data selection rather than collection (Bowden 2009). However, there are alternative methodologies that could have been used to obtain contextual information regarding Costain. For example, employee interviews could have been prepared and completed to understand the company perspective from its sustainability and innovation leaders. This could have provided insight into the plans and aspirations of the company to reduce biodiversity loss on projects currently and moving forward. The study was not carried in this way for several reasons. Firstly, as the aim of the study was to understand the general management practices across the group, thus using documents made available to every Costain employee, avoiding the bias of personal experience working on projects. Secondly, companies could create biodiversity goals for good public relations (Costain included), an interview regarding sustainability and biodiversity management may not be truthful. There is no guarantee that information provided by any employee or innovator within the company would be unbiased to their personal experience, positive or negative. If the research were specifically looking at opinions and experiences within biodiversity management, then this would be a suitable methodology.

3.5. Method - Model Simulation Baselines

3.5.1. Introduction and Site Area

The simulation baselines are part of the "*Design and Development*" and "*Demonstration*" stages of the Design Science Research Methodology. The demonstration of the model is shown through its use for developing the baselines for the Contract Biodiversity Action Plan (BAP), and for highlighting habitats that are considered of high value based on metrics developed by the Department for the Environment, Food and Rural Affairs (Defra). The following sections discuss the data, software system, and biodiversity calculation framework for developing the GIS applications. A full list of datasets can be seen in Appendix A.

The Chartered Institute of Ecology and Environmental Management (CIEEM) state in their 2013 Guidelines for an Ecological Appraisal that within 1-2km of a site is where notable records of protected species are most relevant. However, if species such as birds and bats are included, then this should be increased. In addition, Beacon Environmental Ltd. (2012) compared literature and compiled impact zones from infrastructure, specifically roads (Figure 3.14.). To identify impacts for a range of protected species, the virtual boundary was set at 5km. When creating the boundary within ArcGIS, the boundary contains all habitat polygons that cross the arbitrary boundary. This was done to avoid a misrepresentation of habitat polygons by modifying their area resulting from the intersection of a virtual boundary.

Stressor	Context	Focal Guild / Species	Impact Zone	Source
road traffic noise	rural	amphibian abundance	recommendation for a 100 m forested Critical Function Zone around wetlands plus a 400 m buffer between the wetland and busy roads (in forested wetlands)	Eigenbrod *et al.* 2008
road traffic noise	urban / suburban	birds - forest-interior species	~ 650 m	Forman and Deblinger 2000
road traffic noise	natural	birds	disturbance distances documented between 30 and 2800 m; 1000 m (on each side of road) recommended	Reijnen *et al.* 1997
roads	natural	birds - forest-interior (Ovenbird)	~ 50 m; disturbance linked to rarely used, unpaved roads	Ortega and Capen 1999
roads and other infrastructure	various	birds	up to 1 km (in forests and open meadows)	Benitez-Lopez *et al.* 2010
roads and other infrastructure	various	mammals	up to 5 km (in forests and open meadows)	Benitez-Lopez *et al.* 2010

FIGURE 3.14. THE STRESSORS AND IMPACT ZONES OF INFRASTRUCTURE ON FOCAL SPECIES AND THEIR LITERATURE SOURCE. SOURCE: BEACON ENVIRONMENTAL LTD 2012

3.5.2. DATA

3.5.2.1. STATUTORY CONSERVATION DESIGNATIONS

The first dataset discussed in this section is the Statutory Nature Conservation Sites that are required as part of the development of the Contract BAP. Conservation designations are protected and regulated areas within the UK. The Joint Nature Conservation Committee (JNCC) website states:

"*The UK supports a wide variety of species and habitats, ranging from cold water coral reefs to saltmarshes and mountain summits. A key policy tool for conserving them all is the designation and management of protected sites - areas of land, inland water and the sea that have special legal protection to conserve important habitats and species*" (JNCC 2016).

The *SHE-T-433 BAP Template* identifies three types of designation that need to be distinguished in this dataset, International, National and Local. The document also recommends that the dataset for these designations is available via the Department for Environment, Food and Rural Affairs (Defra) MAGIC online map application. Natural environment data from across the government is hosted on the MAGIC website. The website has been operational since 2002 and was redeveloped as an interactive map and re-launched in 2013. The map can be accessed using a web browser and hosts a range of open-source data including, Access, Administrative Geographies, Countryside Stewardships, Designations, Habitats and Species, Land Based Schemes, Landscape, Marine, Aerial Photography, Background Mapping, and OS Colour Mapping. Datasets come from sources such as Defra, Historic England, Natural England, Environment Agency, Forestry Commission and Marine Management Organisation.

There are 12 statutory designations hosted on Defra's MAGIC site across 35 layers. Data for England, Scotland and Wales are mapped separately. Data of this type hosted on MAGIC has been applied, for example, to evaluate suitability for wind farms and to evaluate land use impacts of increased biomass production (Lovett *et al.* 2009; Watson and Hudson 2015). In addition, the use of simple spatial overlays, such as statutory designations, is an effective way of communicating complex planning issues (Baker *et al.* 2015). Baker *et al.* (2015) discuss the gap between the use of GIS in research and its application within planning practice. The subsequent growth of housing developing and infrastructure in the UK is subject to restrictions based on designations such as National Parks and Areas of Outstanding Natural Beauty (AONB) being protected landscapes. An overlay of data visualises potential "*sites of conflict*" between the government agenda for infrastructure growth and the environment (Baker *et al.* 2015).

3.5.2.2. SPECIES BASELINE DATA

To inform the species baseline of the *BAP Template*, data for identifying the presence of species was investigated. The National Biodiversity Network (NBN) is the UK's largest collection of biodiversity data. The network is a collaborative partnership for the biodiversity information exchange. The network is overseen by the charity, the NBN Trust. The NBN website states:

"*Wildlife data are recorded by many organisations and people, collected together using a range of systems, verified by experts, curated by a wide range of organisations and then aggregated and shared regionally primarily by Local Environmental Record Centres and nationally via the NBN Atlas which holds almost 223 million wildlife occurrence records*." (NBN 2020).

The NBN has developed a strategy for the collection of the occurrences of around 70,000 species, verified by amateurs and professional experts in their field. Therefore, occurrence data from the NBN was used to inform the species baseline. The data is available from the NBN as 1km, 2km, 10km and 100km grid squares and are available for the whole of the UK, the finest resolution of 1km^2 was used for the baseline to avoid the inclusion of any species outside of the site boundary, however this may restrict the number of species available for mapping. As part of the prototype simulation, the grid squares were downloaded for twelve arbitrary Annex II species (Table A.1), which are part of the Habitats and Species Directive. The number of species selected is arbitrary to the prototype for demonstration purposes. However, more species can be added if the simulation is suitable for implementation within the business. This addition of species would a recommendation which could potentially allow for full UK coverage. The data are presented as a co-occurrence map. The co-occurrence map condenses a subset of species data to create a surface of species distributions. This type of hotspot is not to be confused with the term *biodiversity hotspot* (Myers *et al.* 2010). Many studies identify hotspots by using presence/absence data to generate a species distribution map, these distributions can then be overlaid, and layers can be counted (Baraco and Chiarucci 2011; Hulbert and Jetz 2007).

Rocchini *et al.* (2011) notes that when discussing species data there must be awareness of the difference between collection data and atlas data. The collection data is the original field data and atlas data is the use of field data for mapping. Collection data, such as species occurrences are used to model atlas data such as species distributions (Elith *et al.* 2006). Elith *et al.* (2006) states that understanding geographic distributions of species is imperative for the conservation of species; however, the sparse amount of species occurrence data means that the results can be inadequate. This is a result of the complexity of species distributions. Although reliable maps of the distributions of species is an essential requirement in conservation, there are aspects of uncertainty that surrounds these datasets. "*All the facets of a complex phenomenon are impossible to measure with absolute precision, because the act of measuring itself affects its perception*" (Rocchini *et al* 2011 p212). Uncertainty can begin with the collection data, Rocchini *et al.* (2011) states most Natural History Collections of species occurrence have been collected without a robust sampling scheme with imprecise/uncertain geographic locations. In addition, there may be inaccuracies due to inadequate sample techniques, misidentification of species, and differences in species detectability (Hortal and Lobo 2005). The authors then further discuss the uncertainties with modelling collection data into distributions, calling broad maps of species distributions "*more an art than a science*" (p213) and caution should be taken to avoid considering these maps as "*truth*". Finally, the authors discuss that distribution maps at a fine scale based can give the false impression of a precise estimation of distribution.

The spatial data then had to be reformatted to convert from the NBN OS grid reference system to eastings and northings that ArcGIS recognises. After reformatting, the layers were transformed into a raster layer and reclassified to fit a presence/absence system. This means that if the species was recorded as present within a pixel, that pixel was given a score of 1. If it was recorded as absent, then it was given a score of zero. The raster layers were then added together in the ArcGIS raster calculator to show a hotspot map of the species throughout the UK. This is a methodology that was used by Alessa et al. (2008). An example of the concept is shown in Figure 3.15.

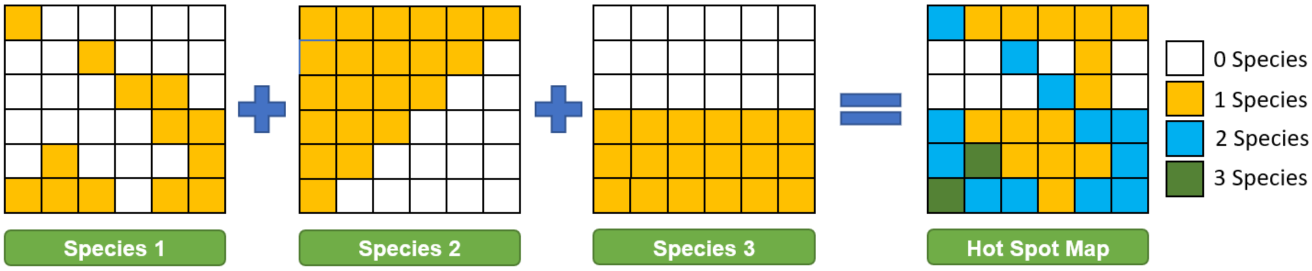


FIGURE 3.15. A CONCEPTUAL DIAGRAM OF HOTSPOT MAPPING USING THREE EXAMPLE SPECIES.

3.5.2.3. LANDCOVER DATA

Different landcover datasets are available for different areas of the UK; however, the data for a habitat and biodiversity baseline requires full UK coverage for consistency between projects. Two full UK landcover datasets are: Corine Landcover (CLC) and Landcover Map (LCM).

Considered to be the most detailed land cover database for the EU, CLC was created by Copernicus, a European monitoring programme to standardise data collection and aid environmental policy development in Europe (Figure 3.16) (Mücher *et al.* 2009). The specifications of CLC were established in 1986 and it is now the main source of spatial land data used by the European Environment Agency (EEA). Data is collected using Earth observation satellites in conjunction with data from sensor networks on the Earth's surface. The data is then processed to create land cover classification of 44 classes (Copernicus 2019). The broad range of data allows for users in a variety of fields to apply the data in spatial and urban planning, forest management, water management, agriculture & food security, nature conservation and restoration, ecosystem accounting, mitigation to climate change. There are four CLC inventories, from 1990, 2000, 2006, and most recently 2012 (CLC2012). CLC data is mostly used as a dataset for land cover change detection.

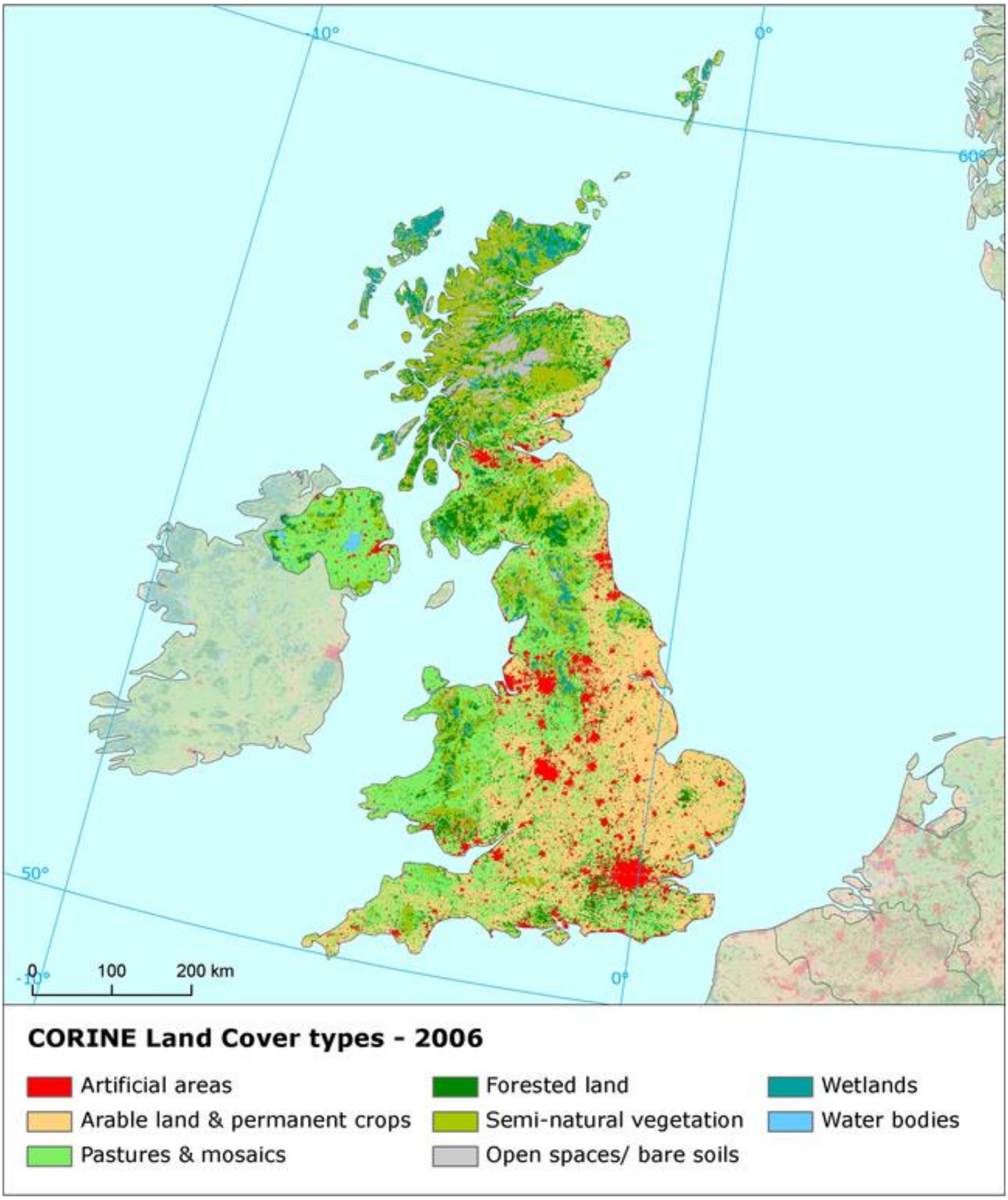


FIGURE 3.16. CORINE LAND COVER MAP WITH LANDCOVER PERCENTAGES ACROSS THE UK. SOURCE: EEA 2012

Created by the Centre for Ecology and Hydrology (CEH), LCM classifies land cover type across the Great Britain and Northern Ireland. The data is derived from satellite images and digital cartography and is based on UKBAP Habitat classes. LCM was originally developed in 1990, known as Landcover Map Great Britain. Further LCM datasets were developed in 2000, 2007, with the most recent being 2015 (LCM2015 released 2017). LCM2015 is available in a raster and vector format (Figure 3.17), the raster Geo Tiff comes at a scale of 25m and 1km pixel sizes, and the vector shapefile has a minimum mappable unit of 0.5ha.

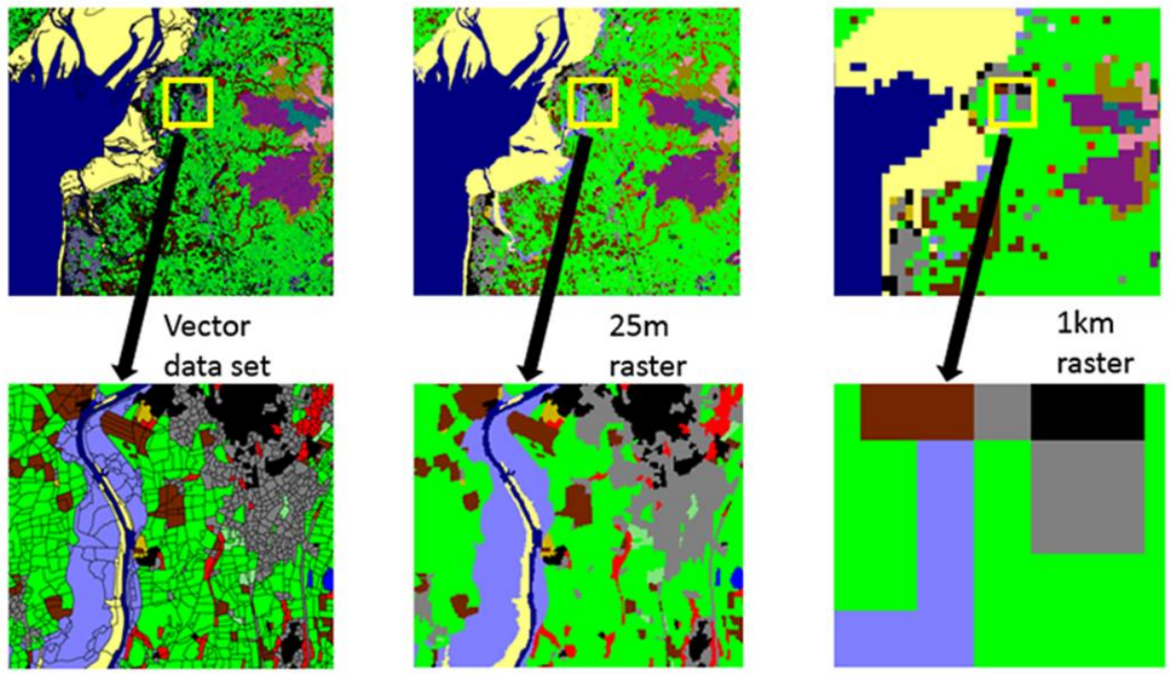


FIGURE 3.17. THE RASTER AND VECTOR DATA FOR LANDCOVER MAP 2015 AT DIFFERENT RESOLUTIONS. SOURCE: CEH 2017)

LCM2015 shows 21 landcover classes in 10 broad aggregate classes in relation to the UKBAP broad habitats. LCM was used as part of the Countryside Survey, a unique study of the UK's natural resources. In addition, the dataset has been used as part of the base data for assessing potential of areas delivering individual ecosystem services by the CEH and Natural England (2014). This includes mapping of services such as climate regulation, pollinations, air quality, wood provision and wildlife species diversity potential (Figure 3.18).

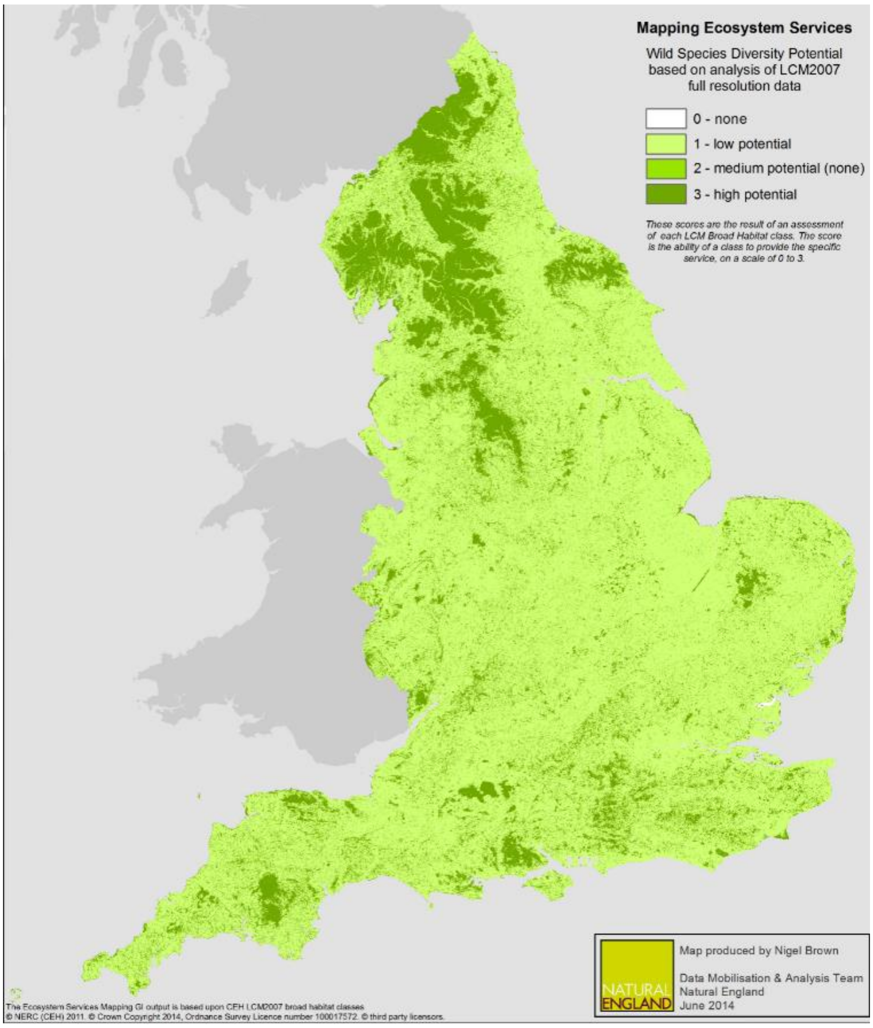


FIGURE 3.18 THE WILDLIFE SPECIES DIVERSITY POTENTIAL ACROSS ENGLAND. SOURCE: NATURAL ENGLAND 2014

Despite the appealing nature of CLC2012 being free to all and any users, at a minimum mapping unit of 25ha, this dataset is too coarse to be suitable for small scale landscape analysis, especially when compared to LCM2015 minimum mapping unit of 0.5ha. CLC has been used more extensively within research than LCM, especially for change detection, however this application of the landcover data is outside of the scope of this research. In addition, CLC’s habitat classes are suitable classifications across the whole of Europe, whereas LCM is more specific to the UK. Moreover, the habitat classes are specifically related to the BAP process within the UK. Therefore, based on the resolution and relevance, the choice in dataset for the simulations is LCM2015. Although simulations are simple with a raster dataset as the pixels are all the same size and shape, the LCM2015 vector data was chosen for this simulation. The vector dataset was chosen as a lot of the analysis involved the adding of further attributes, and calculations within the attribute table, including polygon area.

3.5.3. Software System

The specific GIS software used in this research was. ESRI's ArcGIS. ESRI's ArcMap desktop supports multiple file formats for geospatial files such as shapefiles (.shp) and file geodatabases (.gbd) along with non-ESRI file formats such as JPEG (.jpeg) PDFs (.pdf) and ERDAS Imagine images (.img). ArcMap can run tools that are found within the ESRI toolbox; data such as vectors (.shp) and raster's (e.g. .tiff) can be geo-processed to automate tasks that were previously completed manually. The tools in ArcToolbox are divided into toolboxes that range from analysis and data management to referencing and server tools. Model Builder within ArcMap Desktop was one of the key geoprocessing tools used in this research. GIS layers and maps for Costain projects are shared on ESRI's ArcGIS Enterprise system or ArcGIS Online (AGOL) through the publication of layers from ArcGIS Desktop. ArcGIS Enterprise can run on site premises or in the cloud with applications and web maps being hosted on a secure web server. Other software providers for GIS platforms include MapInfo, Google Earth and QGIS. The other software were not used as ESRI is the industry standard, and due to the combined availability of the software through both the University of Reading, and Costain. More information regarding the server and ModelBuilder can be found in Appendix B.

3.5.4. Biodiversity Unit Calculations

The UK's voluntary biodiversity offsetting scheme, piloted by Defra, is an NNL initiative that quantifies losses and gains. The framework is intended to complement the UK BAP system and should deliver compensation that is additional to any offsets that would have occurred regardless of this initiative. Defra's offsetting metric has been under scrutiny since it was piloted in 2012; the pilot lasted for two years with different companies and local councils. Although this initiative by Defra is currently voluntary, the scheme is discussed in "*A Green Future: Our 25 Year Plan to Improve the Environment*" as a framework that is likely to become the mainstream NNL initiative for the UK and could become mandatory along with a press release from the UK Green Building Council stating that the government are intending to make net gains a requirement on all development projects from Spring 2019 (UKGBC 2019).

Defra's biodiversity calculation scheme uses land quantifications dependent on its "*habitat type band*" (Table 3.4.). The habitat type band is valued at either "*High*", "*Medium*", or "*Low*", with high being priority habitats, medium being semi—natural habitats, and low being areas of intensive agriculture or having low ecological value but some function. The UK government are pushing their net gain agenda by associating a type of offsetting with each habitat type band to ensure that compensation exceeds loss. They are doing this by encouraging local authorities and developers to "*trade up*" areas of lower habitat type bands with the thought in mind that an increase in habitat type band is an automatic increase in compensation, ultimately leading to a gain over its baseline value.

To calculate losses and gains, biodiversity offsetting uses a scheme like the habitat hectares approach, with the area of land multiplied by both predetermined and non-predetermined values. Habitat distinctiveness (Table 3.5) is a predetermined value given to habitats classified to the Phase I level. Condition is calculated based on the result of a ground survey, the Farm Environment Plan (FEP). Rail Central, a freight interchange business, performed biodiversity calculations using the 2012 Defra scheme. The report states:

> "*The condition assessments in this manual involve checking features against a list of criteria for habitat in 'good' condition. If the area under assessment fails to meet one of the criteria, the condition is considered to be 'moderate'. If it fails to meet two or more criteria, the condition is considered to be 'poor*" (Central Rail 208 p4)

Some habitats do not fit into the condition assessment guidance set out in the FEP manual; these are assessed against a generic condition assessment. The losses or gains are then calculated by multiplying the distinctiveness score with condition (Table 3.6), this is the multiplied by the number of hectares of that habitat.

TABLE 3.4.HABITAT BAND TYPES WITH THEIR DISTINCTIVENESS, BROAD HABITAT TYPE COVERED AND TYPE OF OFFSETTING SUMMARISED. SOURCE: DEFRA 2012

Habitat type band	Broad habitat type covered	Type of offsetting
High	Priority habitat as defined by section 41 of the NERC Act	Same and type, and ideally like for like
Medium	Semi natural	Within band type or trade up
Low	E.g., Intensive agricultural – but may still form an important part of the ecological network in an area	Trade up

TABLE 3.5. HABITAT DISTINCTIVENESS AND HABITAT CONDITIONS WITH THE MULTIPLIER SCORE ASSOCIATED WITH EACH SUMMARISED FROM DEFRA 2012

Habitat distinctiveness	Multiplier	Habitat Condition	Multiplier
High	6	Good	3
Medium	4	Moderate	2
Low	2	Poor	1

TABLE 3.6. MATRIX SHOWING HOW CONDITION AND DISTINCTIVENESS ARE COMBINED TO GIVE THE NUMBER OF BIODIVERSITY UNITS PER HECTARE SUMMARISED FROM DEFRA 2012

		Habitat Distinctiveness		
		Low (2)	**Medium (4)**	**High (6)**
Condition	**Good (3)**	6	12	18
	Moderate (2)	4	8	12
	Poor (1)	2	4	6

3.5.5. INDEX

Application 4 condenses metric values into an index that can be viewed on a single map. This was done as an option for Concept Design tenders that may have page limit. Creating an index such as this has its criticisms; for example, there is no real rationalisation of operator functions for combining factors or metrics into one index; this could be multiplying, take a square root, or averaging (Suter 1993). Therefore, Application 4 keeps values independent, providing the user with further knowledge of why a specific habitat is of high value and can be discussed further within the bid, the Contract BAP and scoping within the EIA. The method used to create this index is shown in Figure 3.19. The three metrics are considered input parameters that can be changed or weighed based on the priority of the project and the most recent pre-determined metrics. In this case, Metric I is habitat distinctiveness, Metric II is difficulty of restoration, and Metric III is proximity to disturbance. Habitat condition is not included as part of this index as the specific values are determined based on a site survey. The following section discuss each process within this flow diagram.

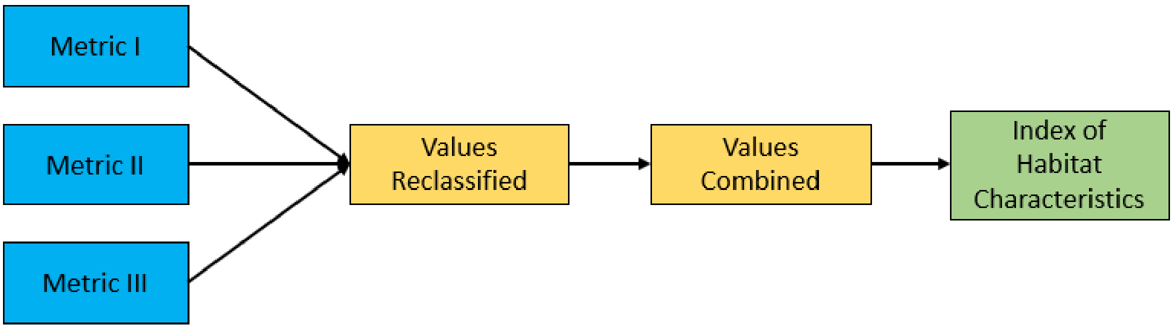


FIGURE 3.19. FLOW DIAGRAM FOR APPLICATION 4

Each metric was reclassified to fit the index; both Metrics I and II are single- and double-digit values, and Metric III is defined by iterations of 1km, however this can be changed based on the size and requirements of the project. The metrics were reclassified, this does not need to take place if each metric is represented by an integer, however, this is not always the case, therefore the metrics have been reclassified as a rank of high to low value. For consistency in rank, the highest numbers represent the highest values or proximity to the site. Metric I was reclassified as a number in the 100s as the first digit. For example, a "*Very High*" score of 8 is reclassified to 400; the value of 400 is arbitrary to the original score, however the score within the index is defined as "*Very High*". The specific reclassified scores can be altered, but it is important to define any index values as part of the application. Metric II was reclassified as a number in the 10s as the second digit. For example, a "*Very High*" score of 10 is reclassified to 40. Similarly, to Metric I, the index score is arbitrary to the original score. This has been summarised in Tables 3.7 and 3.8.

TABLE 3.7. THE SCORES OF "HABITAT DISTINCTIVENESS", THE MULTIPLIER DESCRIPTION AND NEW ASSIGNED SCORES FOR "HABITAT DISTINCTIVENESS". SOURCE DATA: DEFRA 2012

Multiplier Description	Defra Score	Assigned Score
Very High	8	400
High	6	300
Medium	4	200
Low	2	100

TABLE 3.8. THE SCORES OF "DIFFICULTY OF RESTORATION", THE MULTIPLIER DESCRIPTION AND NEW ASSIGNED SCORES FOR "DIFFICULTY OF RESTORATION". SOURCE DATA: DEFRA 2012

Multiplier Description	Defra Score	Assigned Score
Very High	10	40
High	3	30
Medium	1.5	20
Low	1	10

Metric III is the proximity to disturbance, another risk factor could be included as this metric however a location-based factor has been included to provide end-users with a simple degree of distance from the site, without having to use any measuring tools, this has been summarised in Table 3.9. The default proximity for this model is up to 5km from the site with 1km between values; the closer the habitat is to the site, the higher the value is given.

Table 3.9. The scores of "Proximity to site", the multiplier description and new assigned scores for "Habitat Distinctiveness". Source data: DEFRA 2012

Multiplier Description	Geographical Location	Assigned Score
High	Within 1km of the site	5
↓	Between 1km-2km of the site	4
	Between 2km-3km of the site	3
	Between 3km-4km of the site	2
Low	Between 4km-5km of the site	1

After the spatial join, the three metrics values were then combined in the attribute table in ArcMap, allowing for each digit to be independent of the other two digits. A diagram showing the concept of this process can be seen in Figure 3.20. Figure 3.21. shows the concept with each colour representing a different three-digit code.

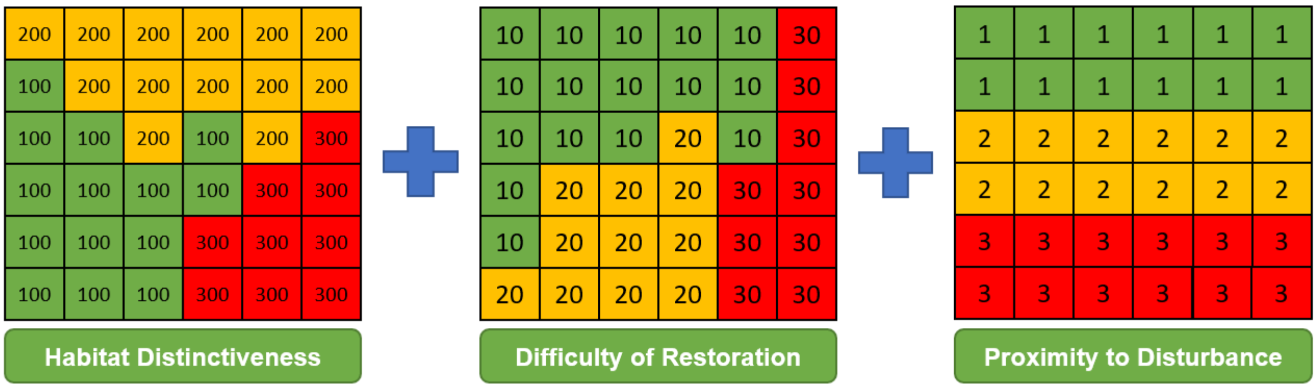


Figure 3.20. The concept of the three factors, Habitat Distinctiveness, Difficulty of Restoration and Proximity to Disturbance and their respective digits being added together.

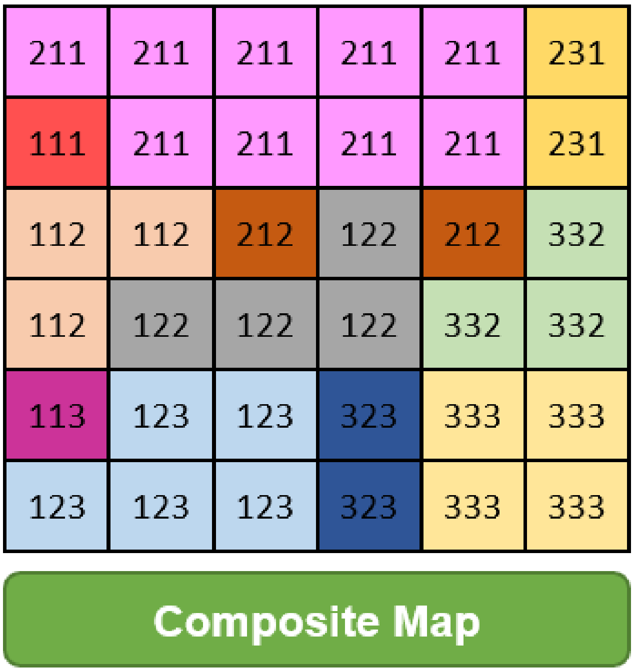


FIGURE 3.21. CONCEPTUAL DIAGRAM OF THE INTEGRATED THREE FACTORS INTO ONE COMPOSITE MAP WITH EACH COLOUR REPRESENTED A DIFFERENT THREE-DIGIT CODE.

The raw numbers from the index were then reclassified to highlight the areas that could be considered of highest risk. The classification was determined using a decision tree that used logical combinations of criteria that identify risk. In this case, the risk is the high value of biodiversity units and being within the first 1km of the site. For example, a very high habitat distinctiveness would increase the biodiversity unit value, therefore any value over and including 400 would be classified as “Very High”. In a similar fashion, any value between 300-400 would be classified as “High”. Any value between 200-300 would be considered “Medium” unless the second two digits were over and including 30, in which they would be classified as “High”. Any value between 100-200 would be classified as “Low” unless the second two digits were over and including 30, in which they would be classified as “High”. In this same instance, the second two digits over and including 20, or a third digit of 5, would be classified as “Medium”. This has been summarised as a decision tree in Figure 3.22.

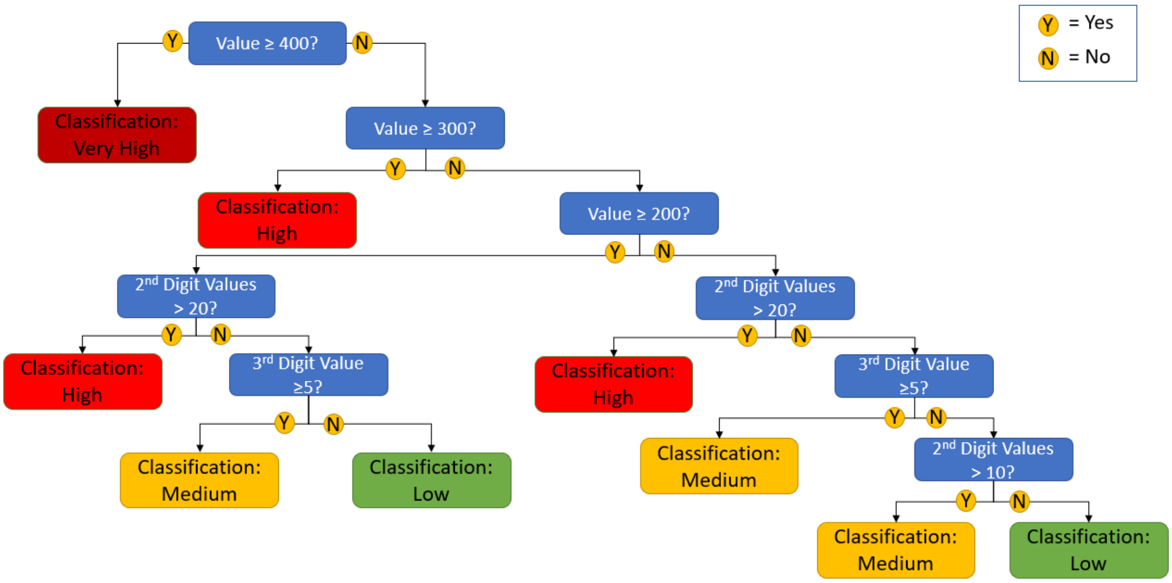


FIGURE 3.22. DECISION TREE TO CLASSIFY THE RAW NUMBERS FROM THE THREE-DIGIT INDEX, WHERE DARK RED = VERY HIGH, RED = HIGH, YELLOW = MEDIUM, GREEN = LOW, AND BLUE = QUESTIONS

3.5.6. MAP VISUALISATION

The output results for the baseline model simulations and simulations for impact values are a mixture of charts and maps. The maps are presented as stand-alone figures rather than screenshots from ArcGIS Enterprise. Although map symbology can be edited on ArcGIS Enterprise, as 1 in 8 men and 1 in 200 women are colour blind (Colour Blind Awareness 2017), a single colour gradient was selected as outputs for this thesis to ensure anyone can identify and distinguished between colours. Map visualisation is discussed further in Chapter 5.

3.5.7. APPLICATIONS

The system specification also describes the requirements of the intended applications, also known as the simulation concept (Liu 2011). The simulation concept includes *"functional and operational capabilities of simulation and considers objectives, assumptions and constraints of the simulation system" (*Liu 2011 p158). The functional and operational capabilities of the simulation is based on the recommendations from the literature review and the Study of the End-user. Five applications were developed to provide baseline values (summarised in Table 3.10). Application 1 is the visualisation of conservation designations, Application 2 shows the species baselines, Application 3 visualises the characteristics of Defra's biodiversity offsetting scheme, introduced above, Application 4 is a condensed index to visualise the offsetting metrics, and Application 5 is a preliminary calculation of biodiversity offsetting units.

TABLE 3.10. SUMMARY OF THE DEVELOPED APPLICATIONS FOR THIS CHAPTER

Application	Name	Description
1	Statutory Conservation Designations	Importing of the statutory conservations for England, Scotland, and Wales
2	Species Baseline	The location of previously recorded species within the study area
3	Biodiversity Characteristics	The visualisation on biodiversity metrics from Defra's offsetting scheme
4	Biodiversity Characteristics Index	An index to condense the metrics from Defra's offsetting scheme
5	Baseline for Biodiversity Units	A preliminary calculation of biodiversity units

3.6. METHOD – MODEL SIMULATIONS: IMPACT VALUES

3.6.1. INTRODUCTION

The applications developed in this chapter encompass the calculations of habitat loss and fragmentation across the study sites, acting as a Spatial Decision Support System (SDSS) (see Section 2.3). Applications 1-5 (summarised in Table 3.10.) were developed as baselines for statutory conservation designations, species, and biodiversity values. The calculations of impacts to biodiversity values and fragmentation were built into three applications, with the numbering continuing. Application 6 is the calculation of the change in Biodiversity Units. Application 7 calculates the changes in fragmentation indicators at the patch level, and Application 8 calculates the changes in fragmentation indicators at the class level. Each application and its parameters are discussed in detail in the proceeding section. This has been summarised in Table 3.11.

TABLE 3.11. SUMMARY OF THE DEVELOPED APPLICATIONS FOR THIS CHAPTER

Application	Name	Description
6	Measuring Biodiversity Unit Impacts	Calculating the changes in Biodiversity Units within the study sites
7	Patch Level Fragmentation Impacts	Calculating the changes in fragmentation in individual patches within the study sites
8	Class Level Fragmentation Impacts	Calculating the changes in fragmentation across habitat types within the study sites

3.6.2. PARAMETERS AND UNCERTAINTIES

The parameters and uncertainties for the SDSS are discussed in this section, adapted from the flow chart developed by Geneletti (2003) in Figure 3.23. The uncertainties are considered important as generally, uncertainty factors are missing from impact predictions (Geneletti 2003). The author discusses three uncertainties within this research: the ecosystem map, space-occurrence buffer, and the expert's assessment of ecosystem rarity. The section also includes computing the measured loss on the landscape, the score of the impact, the spatial scale of the applications, and critical thresholds.

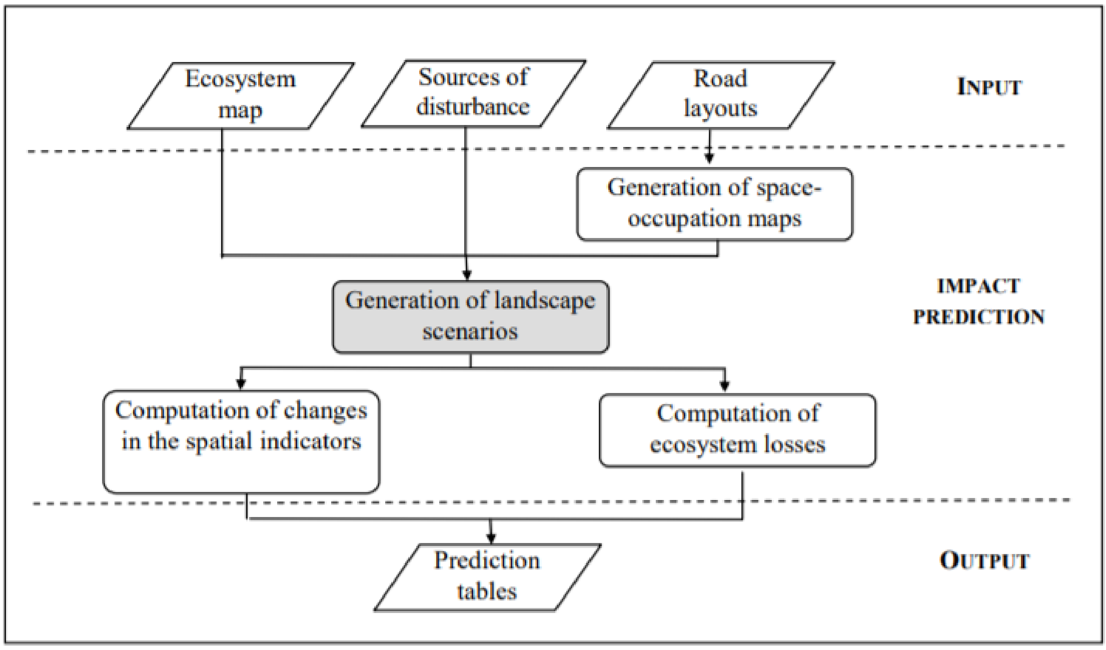


FIGURE 3.23. SCHEMATIC OF IMPACT PREDICTION. SOURCE: GENELETTI 2004

Before decisions regarding any uncertainties or parameters for the SDSS take place, spatial scale needs to be discussed. The quantification of spatial characteristics takes place across three spatial levels: patch, class, and landscape. Patch level represents the base units of the landscape and provides information regarding their spatial context. The class level includes all patches that have the same classification. In the example, Figure 3.24, by Malinverni (2011), the classes are "*Urban*", "*Green*" and "*Other*". Finally, the landscape level incorporates all the patches and classes that make up the whole landscape.

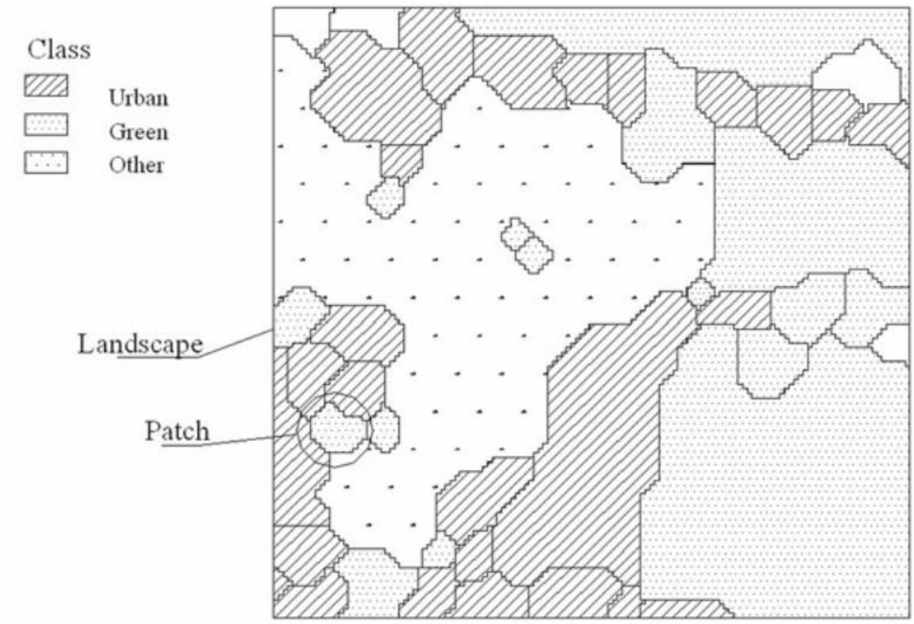


FIGURE 3.24. PATCH, CLASS, AND LANDSCAPE RESOLUTION. SOURCE: MALINVERNI 2011

Geneletti (2004) discussed that impact predictions tend to be done at the landscape level, rather than the patch level. By performing calculations on the patches within a landscape, the risk to individual patches can be highlighted and potentially avoided by the design, justifying analysis at the patch level. This study also includes impacts to species as well as individual habitat patches; larger and more connected ecosystems have increased support for species than habitats that are smaller and more isolated. By calculating changes for at the class level across a landscape, specific species impacts can be assessed by targeting preferred habitat classes. Finally, a landscape-level analysis can provide a broad overview of heterogeneity, the pattern of habitat patches across a landscape. A landscape with a high heterogeneity can facilitate more species, especially species that may have a narrow niche (Verberk *et al.* 2006). However, landscape heterogeneity is not considered as part of the baselines for the Contract Biodiversity Action Plan (BAP), unlike habitats and species. Therefore, landscape heterogeneity was not included as part of the Developed Design.

The first uncertainty described by Geneletti is the ecosystem map, which visualises all ecosystems that are within the boundary of the assessment of impacts. Regarding the ecosystem map, Geneletti (2002) states that "*In particular, it must have a suitable spatial resolution, date and information content. As for spatial resolution, it has to be compatible with the size of the project" (*p69). The ecosystem map provides the patches in which all the impact quantifications and calculations are to take place. Therefore, the quality of the results is dependent on the quality of the baseline database (Geneletti 2002). The author states that landcover maps are commonly used as a surrogate for representing the spatial distribution of ecosystems. With LCM being selected as the landcover dataset for the baseline in the Concept Design. This dataset was selected due to its high resolution and full coverage across the UK. Therefore, this dataset is also recommended for this assessment of impacts *if* a Principal Ecological Appraisal (PEA) has not taken place. For this study, LCM2015 was used (Section 3.5.2.3) Outside of the ecosystem map selection, the uncertainties surrounding the ecosystem map are related to patch boundaries, discussed in the proceeding section.

The first step in establishing the pre-project conditions is to select the site boundary Boundaries have been discussed in the literature extensively, given their potential for bias within landscape simulations (Koen *et al.* 2010). There are two types of boundaries, natural and artificial; natural boundaries are dictated by physical barriers in the real world, for example, a change in land use (i.e., forest to grassland), a change in elevation, a body of water, or a mountain range. Examples of artificial boundaries can still be physical, and include hedges, fences, or political boundaries (i.e., the Great Wall of China); however, examples of non-physical boundaries may include species distribution boundaries and boundaries that measure a certain distance from a line or point. This section discusses bias in three different ways, the spatial placement of a habitat boundary on a map versus on the ground, the size of the boundary, and the inclusion of habitats on the boundary edge.

The spatial placement of patch boundaries is discussed as the primary source of uncertainty of the ecosystem map by Geneletti (2002). As landcover maps, and particularly LCM2015 have crisp boundaries, uncertainty comes from whether the crisp boundary is placed accurately. This uncertainty is based on the resolution of the data, with the assumption that the actual boundary falls within one resolution width of the mapped boundary. This degree of belonging is the transition zone, illustrated in Figure 3.25; the boundary is fuzzy 30m each side of the mapped boundary between patches A and B to account for this uncertainty. To avoid this uncertainty, it would be suggested that a transition zone of 25m would be used on the LCM2015 raster dataset. However, Geneletti (2002) analysed the differences in results between fuzzy and non-fuzzy boundaries and concluded that "*there appears not to be such a "sensitive" situation, in which a few meter shift in a particularly valuable ecosystem could upset* *the overall impact score of some of the alternatives"* (p481). Therefore the boundaries on LCM2015 were kept as crisp boundaries.

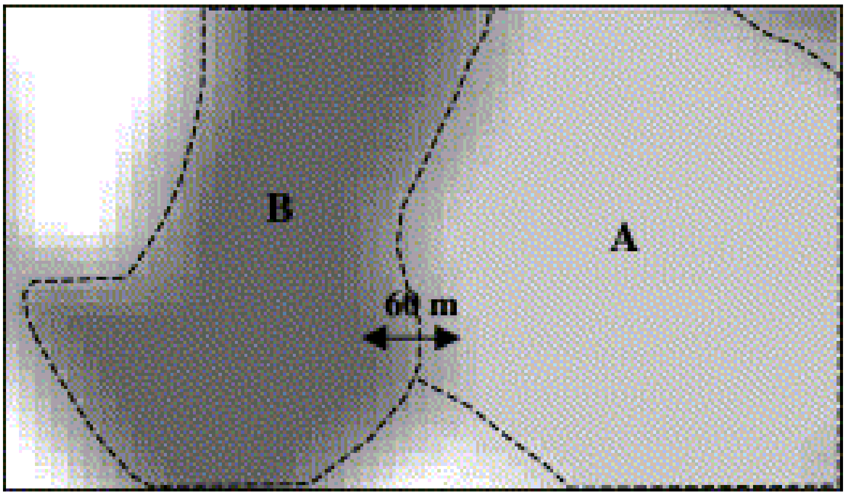


FIGURE 3.25. A CONCEPTUAL EXAMPLE OF A TRANSITION ZONE BETWEEN HABITAT PATCHES A AND B WITHIN A 30M RESOLUTION HABITAT DATASET. SOURCE: GENELETTI 2002

To calculate changes in fragmentation impacts, it is suggested that a virtual boundary be used that is species specific. The concept of spatial scale is important in this thesis as impacts from infrastructure and analysis vary based on scale. For example, different resolutions of data can lead to different conclusions from landscape pattern analysis. The extent is the entire area covered within the landscape boundary and the grain is the individual units that are being measured or observed (McGarigal 1995). This thesis uses the definition of landscape used by McGarigal (1995) of an area of land containing a mosaic of patches or landscape elements to a more specific definition of "an area of land containing a mosaic of habitat patches, within which a particular "focal" or "target" habitat patch often is embedded.

Potential problems could arise from implementing artificial habitat boundaries in landscape simulations as it creates an unknown habitat edge (Koen *et al.* 2010). As this edge is unknown, it could act as a barrier to dispersal when, in real life, the organisms are moving beyond the barrier (Koen *et al.* 2010). The authors also state that there is little instruction on how to approach an issue of bias, such as this in literature. Artificial boundaries have been used in landscape simulations by different authors. For example, a study completed by Tischendorf and Wissel (1997) used a landscape simulation to assess the use of habitat corridors. The authors used an artificial boundary; they used a boundary that was three times the width of the corridor that was being measured. This was done to ensure that all relevant individuals were absorbed into this study. The virtual boundary used in for the baselines was 5km to include the potential impact zones of a range of protected species. However, this study is using a smaller impact zone of 1km. This restricted boundary allows for an example focal species to be targeted. The boundary includes all polygons that intersect with the boundary. This was done to provide accurate calculations of patch areas and distance between patches for habitats located at the boundary edge. It is important to note that the boundary for other focal species, for example, mammals would need to be discussed and ultimately increased (see figure 3.14).

The space-occupation boundary is referred to as the "*Disturbance Indicator*", which is the linear asset design that is added to the landscape (illustrated in Figure 3.26) (Geneletti 2004). Geneletti (2004) states that adding the disturbance indicator simulates the new ecosystem and infrastructure setting, allowing for the creation of landscape scenarios. The study sites for this research are already part of existing infrastructure; therefore, the disturbance indicator is arbitrary to the site design itself. However, to take road widening into account, the disturbance indicator for this study is based on the width of lanes on a road. The width of a road is dependent on the type of road (motorway, A road etc.), type of vehicle that will use the road, the amount of traffic the road will support, the curves of the road, and allowances for other modes of transport (bicycle lanes, footpaths etc.). The average road lane width is 3.65m, which will act as the minimum disturbance indicator for each side of the study site routes. The study will allow for two road widening scenarios:

1) the addition of one lane: 7.3m

2) the addition of two lanes: 14.6m

Having two different scenarios shows not only the repeatability and the adaptability of the simulations for different projects. However, it could also potentially allow for comparison of ecological impacts within different space occupation boundaries.

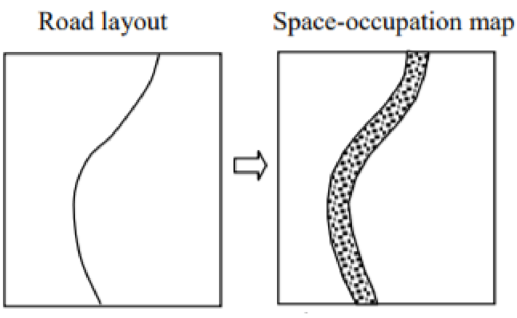


FIGURE 3.26. SPACE-OCCUPATION BOUNDARY EXAMPLE

The critical part of a simulation is the appropriate selection of indicators to calculate fragmentation impacts (Geneletti 2004). The discussion of scale in this research led to the proposal of fragmentation analyses at all two spatial levels, patch, and class. Therefore, this section describes the landscape metrics that are used for each analysis.

For the patch level analysis, two indicators were selected that are suggested by Geneletti (2004) to show al range of fragmentation impacts to individual habitat patches, they are:

1. Core Area (CA)

2. Edge to Edge distance

The core area "*is to represent the area characterised by the absence of edge effects extending from surrounding areas. This indicator simply measures the size of the patch deprived of its outer belt*." (Geneletti 2004 p74). The outer belt is difficult to generalise, but the value of 130m has been commonly used in the core area calculation (Geneletti 2004). The edge-to-edge difference calculates the distance between a patch and its surrounding patches; it is an indicator of patch isolation. This will be known as the Nearest Neighbour (NN) analysis within this study.

Developed to measure spatial patterns of focal habitats, class level metrics have become an important tool in ecological research, allowing for the average calculations of patch shape, size, interpatch distance, and patch connectivity for individual habitat types (O'Neill et al. 1988; Turner 1989; Li & Reynolds 1993; McGarigal 1995; Haines-Young & Chopping 1996; Gustafson 1998; He, DeZonia & Mladenoff 2000; Jaeger 2000). Wang *et al.* (2014) states that "*The spatial patterns of a single class have been shown to be important in studies of species conservation and population dynamics due to their high correlations with various ecological processes*" (p634). A class-level analysis allows for an analysis of either priority habitats or preferred habitats of priority/focal species.

The applications to quantify potential impacts to species takes into account the amount of habitat and how isolated those patches are. Results from a class level analysis can provide insights as to how landscape configuration changes and could potentially guide or inform decisions for restoration post-construction. For example, Zanella (*et al.*) 2012 used landscape metrics to understand the fragmentation of forested areas to inform restoration management plans. The fragmentation analysis showed a large number of small patches throughout the landscape, thus informing a management decision to enlarge these patches to develop core areas (Zanella *et al.* 2012).

This analysis uses two indictors to calculate the change in patch size and isolation across classes:

1. Mean Patch Size (MPS)

2. Patch Density (PD)

MPS has been used within research to quantify landscape structure, quantify habitat loss, and understanding the implications for marine vegetation re-colonisation in the Mediterranean (Almela *et al.* 2008; Bender *et al.* 1998; Li and Archer 1997). Winter *et al.* 2006 state that understanding patch size and its surrounding landscape can influence the focus of habitat management. MPS can be calculated using Equation 1.

$$MPS = \frac{A}{\mathrm{N}}$$

EQUATION 3.1: MEAN PATCH SIZE, WHERE A IS THE TOTAL AREA OF THE SPECIFIC CLASS AND N IS THE NUMBER OF PATCHES IN THAT CLASS. SOURCE: MCGARIGAL AND CUSHMAN 2002

PD is the frequency of patches per unit of the area across a landscape. Patch density is an indicator of patch isolation within a landscape. Patch density has been used within research to present the degree of fragmentation for different habitat types, providing insight into the structure and heterogeneity of the landscape (Plexida *et al.* 2014). PD can be calculated using Equation 2; the formula is multiplied by 10,000 and 100 to give the number of patches per 100 hectares.

$$PD = \frac{N}{S_t}\ (10{,}000)\ (100)$$

EQUATION 3.2. PATCH DENSITY WHERE S_T IS THE TOTAL AREA OF THE SITE AND N IS THE NUMBER OF PATCHES SOURCE: SAURA AND MARTINEZ-MILLÁN 2001

Choosing metrics to describe landscape pattern is no simple task, there are many different metrics that can reflect patterns in the landscape and there is no standard rule for selection of metrics (Li *et al.* 2005). Li *et al.* 2005 states that results of landscape metrics can be interpreted without any explanation of causality, or whether this represents the affected underlying processes. In this case, the causality is physical habitat loss due to expanding road infrastructure, and its effect on the geometric configuration of the landscape based on area and isolation for both patch and class level analysis. Other metrics can be considered for this type of analysis, such as total edge density, or area to perimeter ratio, however, this goes beyond the analysis of geometric configuration and has ecological consequences relating to edge and core preferences. Although these underlying processes are relevant for individual species effects on landscape pattern change, it is suggested that further metrics be included as part of further research expand landscape pattern analysis as part of the EIA.

In summary, this section has discussed the uncertainties and parameters that need to be considered when developing simulations for an SDSS. The simulations will incorporate patch level, and class level, highlighting the patches that are affected, and the potential impact of the infrastructure projects for habitats and species. The ecosystem map for this study will be Landcover Map 2015; however, when implemented onto an infrastructure project, it is recommended to use PEA survey data if this has taken place. As calculations will take place on individual patches, all polygons that intersect with the boundary are included to avoid misleading results. The parameters have been summarised in Table 3.12.

TABLE 3.12. SUMMARY TABLE OF PARAMETERS AND UNCERTAINTIES ADDRESSED

Parameter/Uncertainty	Description
Scale	Patch level analysis
	Class level analysis
Ecosystem Map	Landcover Map 2015
Site Boundary	To include all polygons that intersect with the site boundary
Functional Curve	Habitat distinctiveness values as a functional indicator
Space Occupation Boundary	Scenario A) 7.3m Scenario B) 14.6m
Computation of Ecosystem Loss	Post-project conditions subtracted from the pre-project conditions
Computation of Fragmentation	Patch level: Core area, and Edge to edge difference
	Mean patch size, patch density

3.6.3. MODELLING

All applications use the LCM2015 dataset to calculate biodiversity units once the 7.3m and 13.6m buffers are applied to the planned routes and removed from each of the LCM datasets. However, the original LCM2015 data does not identify roads and their current site occupation boundary. This means that habitat patches that cross the existing routes of the A465 and the A14 are continuous across the route and are not split. To compensate for this, a 7.3m buffer was added to each of the study site routes as part of the calculation. The buffer was then removed from the LCM2015 layer, and the habitat patches were split to ensure each patch is individual (illustrated in Figure 3.27).

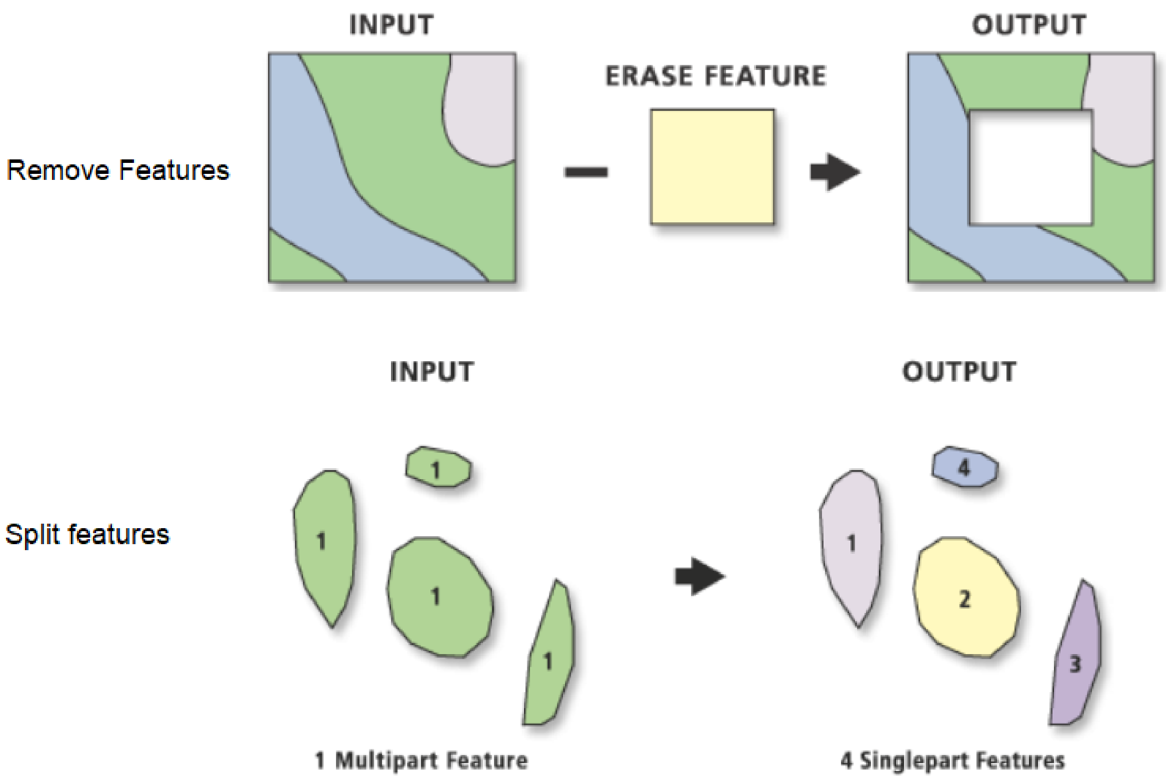


Figure 3.27. Illustrations of the Erase function and Multipart to Single part function. Source: ESRI 2016

Application 6 uses the values that were calculated for Application 5: *The baseline of biodiversity units*. In summary, Application 5 multiplied habitat distinctiveness with the area of each habitat patch derived from the LCM2015 data surrounding the study site routes (illustrated in Figure 3.27A). Application 6 recalculates the biodiversity units once Scenarios A and B are applied; this is the "*Scenario Distance*" parameter in the flow diagram (Figure 3.27B). The buffer is erased from the LCM2015 land cover data, and the area of each polygon is recalculated and multiplied with the distinctiveness metric to provide the Scenario B calculation for Biodiversity Units. This is then subtracted from the baseline calculation to give the impact value. The impact value for Application 6 is the overall loss or gain of biodiversity value across the site (Figure 3.27B). All other applications follow the flow chart structure.

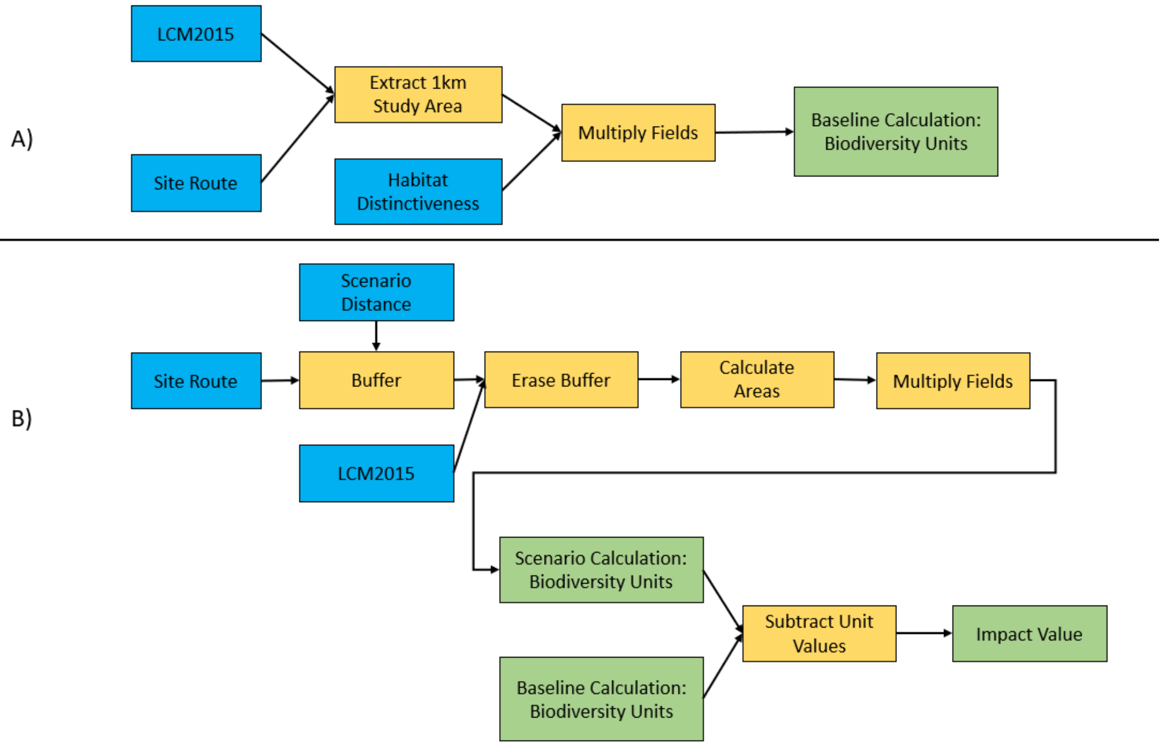


FIGURE 3.28A: CALCULATING THE BASELINE VALUE FOR BIODIVERSITY UNITS, AND THE FLOW DIAGRAM FOR APPLICATION 5
FIGURE 3.28B: CALCULATING THE IMPACT VALUE WHERE BLUE = INPUTS, YELLOW = PROCESSES AND GREEN = OUTPUTS

3.6.4. APPLICATIONS

Each simulation calculates a baseline value, a scenario value, and an impact value, following a similar flow structure (Figure 3.28A and 3.28B). Application 6 calculates the change in biodiversity units by multiplying habitat distinctiveness value with the patch area. Application 7 measures patch level fragmentation indicators by using an outer-belt buffer to calculate CA, and the Nearest Feature Analysis to calculate NN. Finally, Application 8 measures class level fragmentation impacts using Summary Statistics tools to calculate MPS and PD. These have been summarised in Table 3.13.

TABLE 3.13. SUMMARY TABLE OF THE ANALYSES RUN FOR EACH OF THE APPLICATIONS IN THIS CHAPTER

Application	Description	Analysis Run
6	Calculation of Biodiversity Units	Habitat Distinctiveness*Patch Area
7	Measuring Patch Level Fragmentation Impacts	Outer-belt Buffer and Nearest Feature Analysis
8	Measuring Class Level Impacts	Summary Statistics for Mean Patch Size and Patch Density

3.6.5. Visualisation of outputs

The visual outputs for Applications 6-8 are tables, maps, and graphs; the visual outputs use a gradient of a single colour to ensure all users can view these outputs. Application 6 outputs are tables that show the impact value in the change in biodiversity units, this is shown as a quantity of biodiversity units, and as a percentage of the baseline. Application 7 outputs are maps, showing the location of changes in CA and NN. Application 8 outputs are graphs that show the change in the class level metrics, MPS and PD. The visualisation of Application 8 outputs as graphs was done to avoid maps that were visually complex and could lead to misinterpretation of results (Harrie *et al.* 2015).

3.7. Method - End-User Testing

3.7.1. Introduction

Chapters 1 and 2 highlight the need for a business to change their approach and practices to implement an innovation that can improve environmental sustainability. The end-user testing seeks to understand the practicality of implementing GIS applications into the business to inform decision-making, and whether this is viewed as a suitable innovation for improving environmental sustainability. Interviews were chosen as the data collection technique as the research sought to understand the experience and viewpoint of specific individuals within the business rather than general practices. In addition, surveys were not used as part of this study to allow for capturing of thoughts, beliefs, and behaviours rather than numeric or simple information.

This study uses a standardised open-ended interview targeted at environmental managers, ecologists, and environmental advisors within the sponsor company. The participants are asked identical questions that are open-ended, this allows for the participant to provide as much detail as they need with the potential for follow-up questions (Gall *et al.* 2003). This method is the most popular interview technique within research as it allows participants to express their experiences and opinions (Turner 2010). In addition, this technique allows for comparison between participants and can identify inconsistency within the sponsor company around the use of innovation and environmental sustainability. However, this interview technique can make it difficult for the researcher to find similar themes without coded answers from participants, although this could reduce researcher bias particularly in analysis (Gall *et al.* 2003; Turner 2010). The experience-based interview questions were designed to align with the research objectives, in particular:

Objective 3: To understand the barriers, feasibility, and opportunities for the implementation of environmental GIS applications within a general corporate context and within the sponsor company.

Firstly, the interview defines the context of the participant by understanding their relevant industrial experience with GIS, and the visualisation of environmental data. Secondly, their viewpoint and interpretation of the GIS applications for implementation within the business, their limitations and to understand whether they believe innovations such as this are suitable to improve environmental sustainability. The participants were asked questions regarding the responsibility of sustainable development within Costain, and what more can be done.

3.7.2. PARTICIPANT FEEDBACK FOR QUESTION REFINEMENT

Before the study took place, a pilot study was developed on a smaller scale to refine the questions. Two pilot interviews were conducted with employees specifically with a GIS background and knowledge of environmental management within the business. The two participants were shown a demonstration of the applications, and were asked to provide feedback on the following questions:

Q1. What is your experience with GIS?

Q2. Does this visualisation improve your understanding of environmental effects?

Q3. Do you think this technology can be implemented throughout the business?

Q4. What are the barriers to implementation?

Q5. Overall, does this improve environmental sustainability?

Q6. What more could be done?

The results of the pilot indicated that the questions needed more specificity and explanation. In summary, the participant feedback resulted in the following refinements in the interview questions: Q1 only asks about experience with GIS rather than interactions with environmental data and processes on a site. Therefore, an additional question was added to establish the experience of the interviewee with environmental data as well as GIS data. Q2 required more specification with the term "environmental effects" and has therefore been refined as "on-site biodiversity". Q3 could be answered with a "yes" or "no", therefore a follow-up of "how?" was added. Q4 required further definition of barrier to implementation, therefore this question was rephrased using the term "limitation". Q5 was considered too broad of a question, and has therefore been refined to include GIS innovations, the same was said of Q6, therefore more detail in the question was added. Finally, Q4 and Q6 allow the interviewee to look beyond the business to other stakeholders. Therefore, a final question was added to establish the responsibility of sustainable development, which could lead to further research opportunities.

3.7.3. PARTICIPANTS AND QUESTIONS

Participants were chosen based on their role within the business. Within Costain environmental advisors and managers are responsible for managing the works that would be completed by an ecologist. As states in document *SHE-H-470*, the ecologist is responsible for the calculation of biodiversity units, Section 4.2.4. Therefore, employees with the role of environmental manager or advisor were contacted to participate in this interview. The participants were contacted remotely, and interviews took place over Microsoft Teams. Eight individuals were approached and five took part in the interview. Each participant was given a demonstration of the GIS applications, and asked the following questions:

Q1. What is your previous experience with GIS?

Q2. What is your experience of environmental data?

Q3. Does the visualisation of biodiversity values improve your understanding of the on-site biodiversity? If so, how?

Q4. Do you think implementing this technology for all biodiversity management is feasible, and how?

Q5. What do you think are the limitations in an implementation of GIS applications such as this?

Q6. How do innovations such as this GIS implementation improve environmental sustainability?

Q7. Do you believe it is the responsibility of the contractor or client to promote sustainable development?

Q8. Do you think that Costain is doing enough as a business to promote sustainable development? What more could be done?

3.7.4. METHODOLOGY LIMITATIONS

The quality of the research findings is based around the refinement and development of the interview design, with aspects such as ethics, interviewing skills, questions construction, and interview settings (Yeong *et al.* 2018). Some authors state that the experience of the researcher exerts a large influence on the reliability of the data collection rather than the extensive understanding of the research topic (Kim 2010; Turner III 2010). The standardised open-ended interview was used to ensure that the interview does not deviate from the research objectives. In addition, this interview is being carried out as the final research inquiry, therefore extensive knowledge of the research exists with the researcher based on the completion of the literature review and subsequent studies. Finally, the interviews took place via Microsoft Teams due to home-working requirements set out by the sponsor company. This was unavoidable; however, a participant may not feel comfortable with an in-person interview in their own home, office, or public location (Weiss 1994). In addition, a remote interview eliminates travel costs and removes the barrier geographic location without losing the richness of seeing a person during an interview (Tejinder *et al.* 2015; Weiss 1994).

The standardised open-ended interview is not the only technique for performing interviews, alternatives are the informal conversational interview, and the general interview guide approach (Turner III 2010). Gall *et al.* 2003 outlines the informal conversational interview technique as being based "…*entirely on the spontaneous generation of questions in a natural interaction, typically one that occurs as part of ongoing participant observation fieldwork*" (p. 239). The researcher is guided by the participants through the interview process, but this can be seen as unstable and unreliable (McNamara 2008). Thus, this interview is not suitable for this as the research does not involve field observations and is aligned research objectives. The general interview approach is more structured than the previous technique, but the wording of the interview questions varies based on the researcher (Turner III 2010). The research has more control of the interview but flexibility in questions comes from the responses and prompts from the participant. This interview was not chosen due to a potential lack in consistency in the way the questions are asked, with participants not answering the same questions.

3.8. Ethical Considerations

Any research design needs ethical considerations; according to Fouka and Mantzorou (2011): "*Scientific research work, as all human activities, is governed by individual, community and social values. Research ethics involve requirements on daily work, the protection of dignity of subjects and the publication of the information in the research*" (p4). Ethical considerations of research are primarily for the protection of human participants, for example, definition of personal data, consent, transparency, and anonymity. The primary research collection from human participants relates to the end-user testing (Section 3.7). All participants gave consent to participate in data collection, were briefed on the purpose of the data collection, and were kept anonymous through generic numbering. In addition to the primary research, this research uses data from third parties, in this case geospatial data from organisations and agencies. All data used within this research study complies with copy right and licensing laws. All data is used for research purposes not commercial use and is correctly referenced in the main text of this thesis and in the References section at the end of the thesis. Specific ethical considerations with GIS are largely based on crowd-source data collection, how information is commoditised or if it used to monitor the activities of individuals (Radil and Jiao 2016). No information gathered or visualised monitors or displays the activities of any individual employees of Costain.

3.9. CONCLUSION

This methodology chapter discussed the research paradigms, approaches, setting, instrumentation, data collection, and procedures for this research project. The research uses a pragmatic paradigm with a design science approach that identifies the problem, defines the research objectives for a proposed solution, develops and demonstrates an artefact to reach, evaluates the outputs, and communicates key findings and future research. The setting of the research is within the engineering solutions company Costain, who are integrating technological solutions to increase their process efficiency and to provide improved services to clients. The instrumentation in this research is GIS, specifically ESRI ArcGIS and the research uses model building to develop tools and ArcGIS Enterprise as the visualisation platform. The methodology itself is broken down into the four research objectives including an in-depth review of biodiversity management at Costain to develop the scope of the GIS applications, the modelling, validation and verification of GIS tools and processes on two study sites, and the discussion of the applications for business implementation through a value proposition. There are few ethical considerations within this research due to the lack of human participation, however, steps were taken throughout the research process to ensure all data is correctly referenced, used in a research capacity, and was not used to monitor any activities by individual Costain employees.

4. RESULTS

4.1. INTRODUCTION

Chapter 3 established methodological foundations, and research approaches that address the research aims and objectives. The chapter introduced the research inquiries, each of which have their own research paradigm, assumptions, and approaches for data collection and analysis that has influenced the choice of appropriate approach. This chapter presents the findings of the research inquiries, which includes the development of context within the large infrastructure industry and the sponsor company, outputs from simulation models, and findings from implementation within the sponsor company.

The aim of this chapter to present the findings in a cohesive and logical manner, without bias. The chapter is organised into sections based on the individual research inquiries; this has been summarised in Table 4.1, referencing the associated methodology section.

TABLE 4.1. THE SPECIFIC SECTION, RESEARCH INQUIRY, THE TYPE OF RESULT PRESENTED AND THE RELEVANT METHODOLOGY SECTION FOR PROCEDURE AND ASSUMPTIONS

Section	Research Inquiry	Results Type	Methodology Section
4.2.	Study of the End-user	Document Review	3.4
4.3.	Model Simulations – Baseline	Map Visualisations	3.5
4.4.	Model Simulations – Impact Value	Map Visualisations/Charts	3.6
4.5.	End-user Testing	Tables of Interview Key Findings	3.7

4.2. STUDY OF THE END USER

4.2.1. INTRODUCTION

This section presents the results of the Study of the End User. The Study of the End-User biodiversity management practices, using the sponsor company as a case study. This was done by reviewing documentation regarding biodiversity management that is available across the Costain group. The results are presented as charts. The procedure and assumptions were discussed in Section 3.5.

4.2.2. DOCUMENT SELECTION

Thirty documents were retrieved as part of the original search, with five linked documents that were classified as *Env* and *NEnv* then divided into the five categories with an average of 5.40 documents per category. There were four approval documents, eight checklists, nine guides, ten plans and templates and one tool (visualised in Figure 4.1). This section displays the following results: occurrences of each term, the number of documents that contain each keyword, the number of keywords per document, descriptions of high-frequency documents and tools. All raw results can be seen in Appendix C.

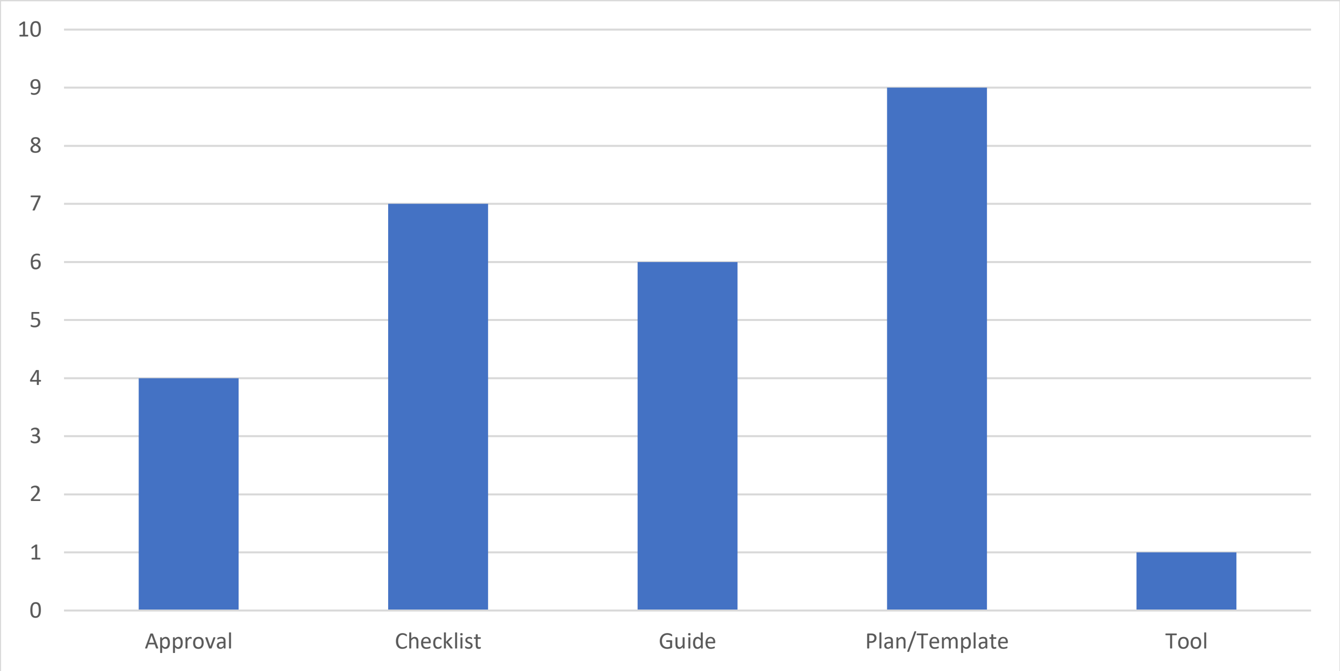


FIGURE 4.1. THE NUMBER OF DOCUMENTS FOR EACH CATEGORY FOR BOTH ENVIRONMENTAL AND NON-ENVIRONMENTAL DOCUMENTS

4.2.3. KEYWORD SEARCH

The keyword search for the environmental documents (visualised in Figure 4.2) found that a total of 241 occurrences of the terms searched. The highest number of mentions was *Biodiversity Action Plan*, mentioned 117 times with a frequency of 0.49. The second-highest number of terms

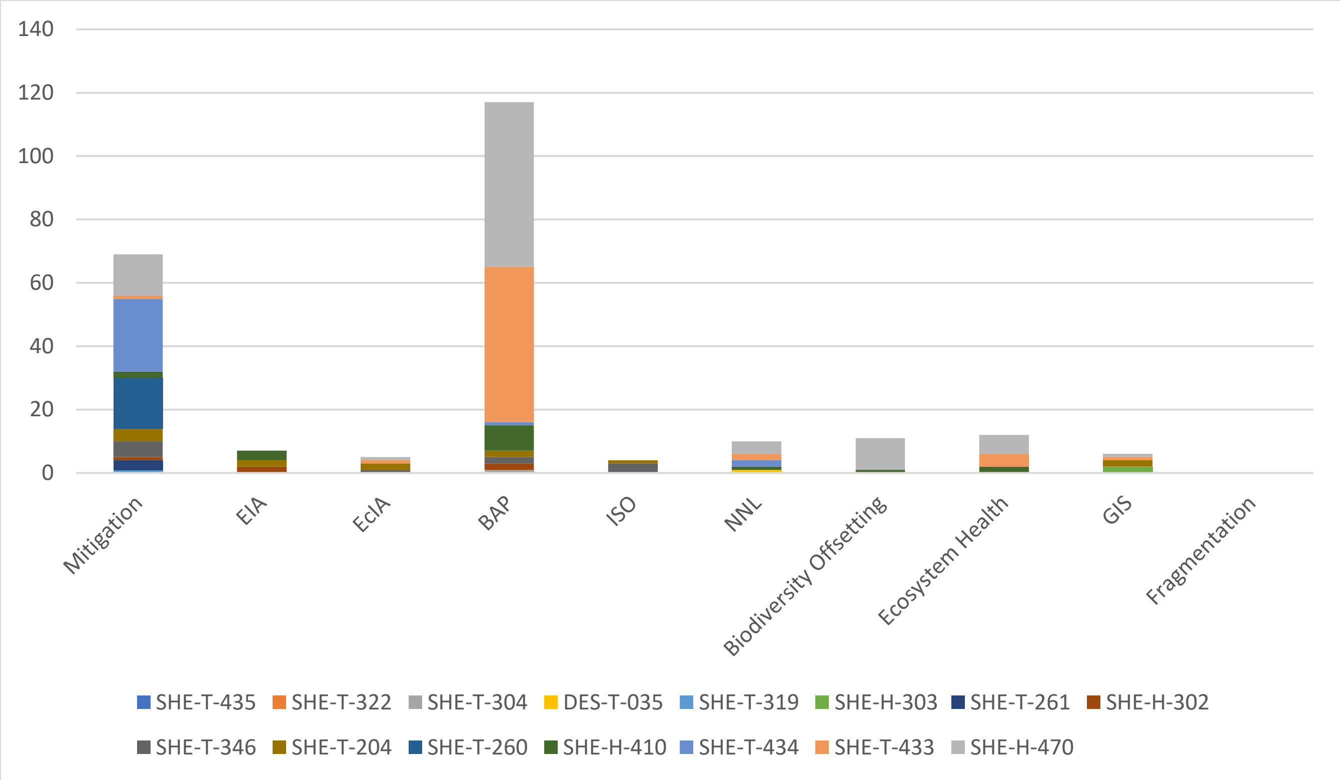


FIGURE 4.2. THE NUMBER OF DOCUMENTS FOR EACH OF THE TERMS IN THE KEYWORD SEARCH FOR EACH ENVIRONMENTAL DOCUMENT SEARCHED

Ten terms were searched in the keyword search, and each term appearing in an average of 4.10 documents (visualised in Figure 4.3). The term that was found in the highest number of documents is *mitigation*, appearing in ten documents. The term found in the second-highest number of documents was *Biodiversity Action Plan*, appearing in eight documents. Fragmentation was not found in any documentation.

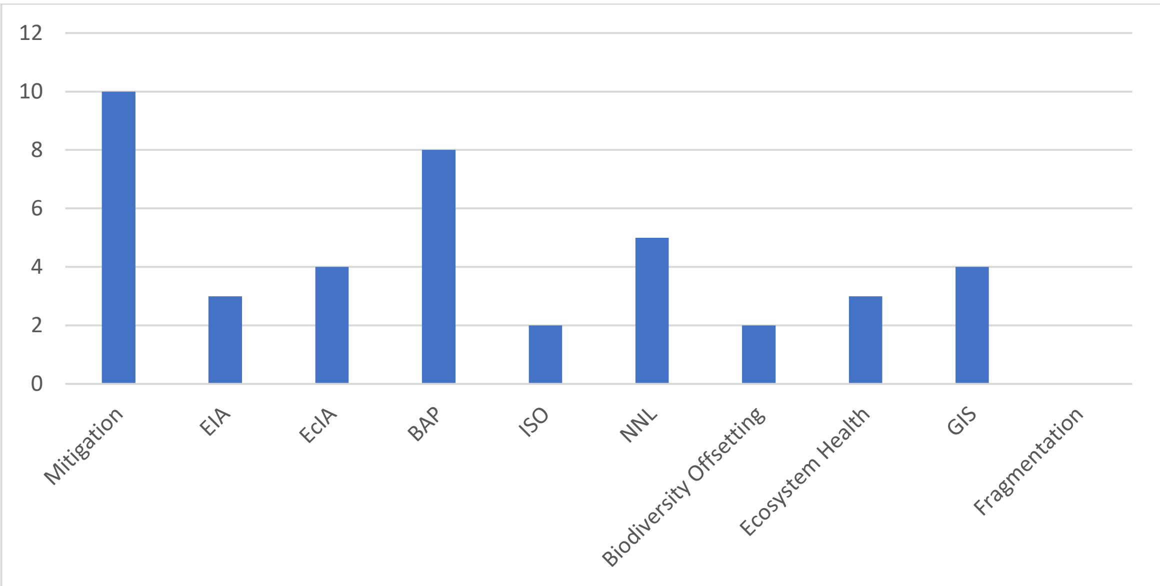


FIGURE 4.3. THE NUMBER OF DOCUMENTS THAT CONTAIN THE KEYWORD FOR ENVIRONMENTAL DOCUMENTATION

Fifteen documents underwent the keyword search, with an average of 16.07 occurrences per document (visualised in Figure 4.4). The document with the highest occurrences of key words was *How to Approach and Manage Biodiversity*, with 87 occurrences (36% of all occurrences), 52 (59.77%) of which being *Biodiversity Action Plan*. The document with the second-highest occurrence rate was *SHE-T-433 BAP Template* with 58 occurrences (24% of all occurrences), 49 (94.23%) being *Biodiversity Action Plan*. Two documents contained none of the searched terms *SHE-T-435 Biodiversity Unit Calculation Template* and *SHE-T-322 Environmental Control Plan*.

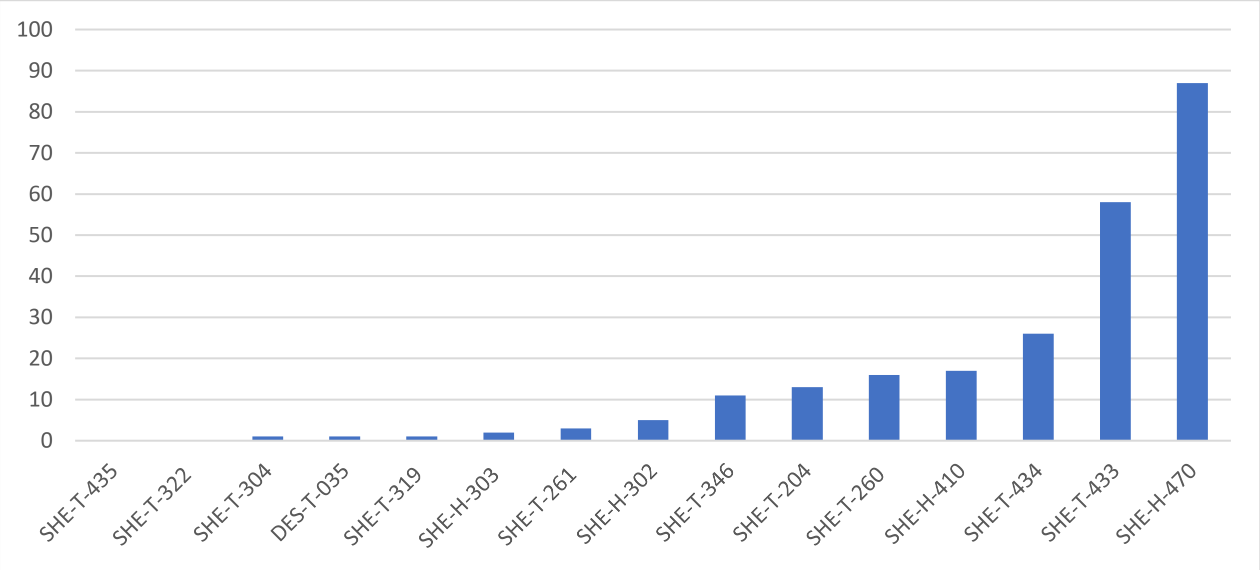


FIGURE 4.4. THE NUMBER OF OCCURRENCES OF KEYWORDS FOR EACH DOCUMENT SEARCHED FOR ENVIRONMENTAL DOCUMENTATION

4.2.4. HIGH-FREQUENCY DOCUMENTS

The two documents that had the majority frequency were *SHE-H-470* and *SHE-T-433 BAP Template*, and the only document that was classified as a tool was, *SHE-T-434*. The following sections discuss these three documents, summarising each on the following information:

1. Function and context

2. Structure

3. Key roles

4. Data required

5. Use of GIS

6. Outputs

How to Approach and Manage Biodiversity is a guide describing the management of biodiversity and the completion of any BAPs that are developed for the contract (known as a contract BAP). The document also contains a summary process flow chart (Figure 4.9) the links to further documentation for managing biodiversity. All linked documents from this process flow chart were analysed as part of the keyword search and can be view in Appendix C. The document is comprised of five sections (summarised in Table 4.2) with definitions of terms, roles, and descriptions of the steps outline in Figure 4.5.

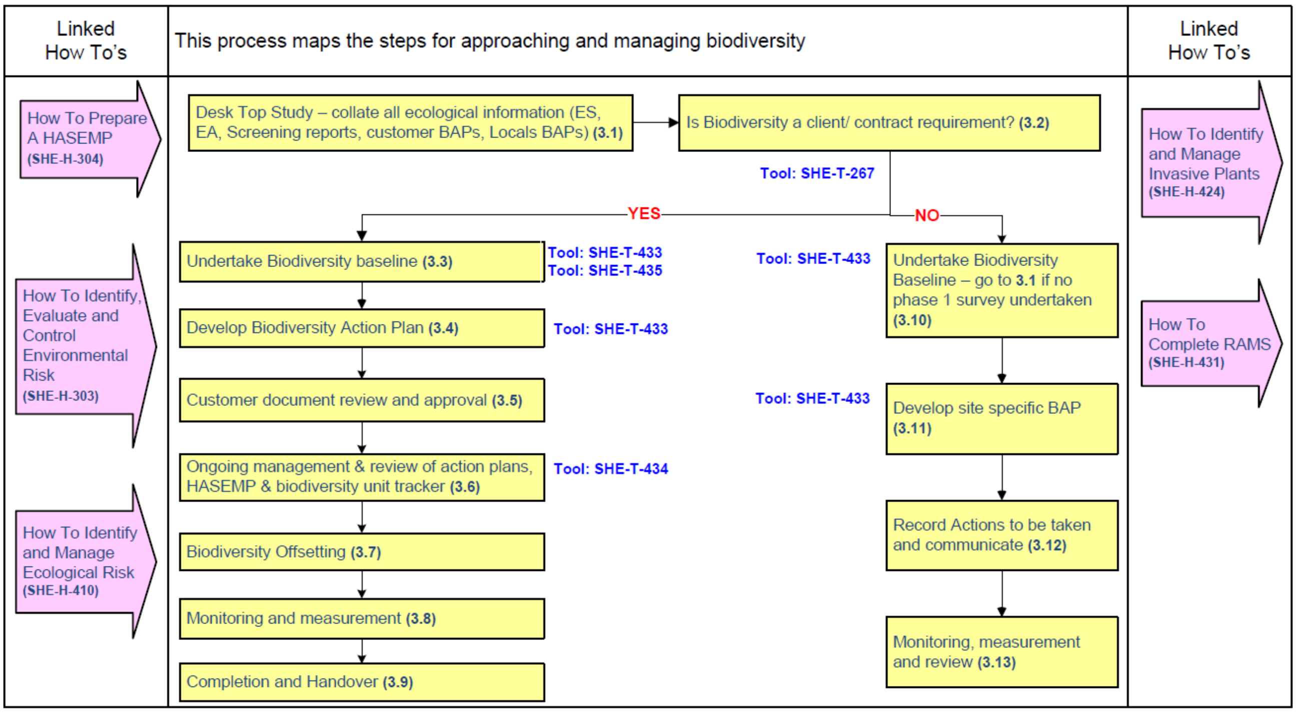


FIGURE 4.5. PROCESS FLOW CHART FOR APPROACHING AND MANAGING BIODIVERSITY

TABLE 4.2. THE SUMMARY TABLE OF THE SECTIONS, DATA, GIS COMPONENT AND OUTPUTS OF SHE-H-470

Section	Title	Data	GIS	Outputs
1	Introduction	Relevant terms, definitions	N	List of relevant terms and definitions
2	Roles	Lists of roles, definitions	N	List and definitions of key roles in the steps
3	The Steps	Contract BAP, Phase I surveys, Defra MAGIC map, biodiversity tool metrics, biodiversity baselines, environmental statement, SHE-T-433, SHE-T-434,	Y	Descriptions of all the steps for managing biodiversity, as outlined on the flow chart
4	Additional Guidance	N/A	N	N/A
5	Tools	Linked documents	N	List of linked documents

Section 1 defines the key terms for approaching and managing biodiversity. The BAP, undertaken by the ecologist, is the programme that addresses any threatened species or habitats within the contract sites and aims to protect and restore these sites. The biodiversity baseline is a collation of information that helps identify species and habitats within the contract boundary. Biodiversity offsetting, discussed in Chapter 2, is the approach to determining compensation for an area that has been lost to development, quantified as biodiversity units by Defra, with the restoration or creation of habitats in another area. The addition measures of mitigation that provide benefits to wildlife are the opportunities for enhancement and can be incorporated as part of the mitigation hierarchy, NNL or biodiversity offsetting. These terms are summarised in Table 4.3.

TABLE 4.3. THE NAME AND DEFINITION OF THE ASPECTS OF BIODIVERSITY MANAGEMENT (SOURCE:)

Term	Definition
Biodiversity Action Plan	A programme that addresses protected species and habitats to protect and restore biological systems (for more detail refer to Section 2.4.3.)
Biodiversity Baseline	Helps identify habitats and species in the contract boundary that may be protected.
Biodiversity Offsetting	Approach for compensating habitats lost to development in one area with the enhancement or creation of habitats in another (for more detail refer to Section 2.6.2.)
Biodiversity Unit	Value calculated using Defra's guideline (for more detail refer to Section 2.6.2.)
Opportunities for Enhancement	Additional measures and mitigation that can provide additional benefits to wildlife because of the development being completed

Section 2 describes the key roles in the steps described in the proceeding section. The Contract Leader (CL) is responsible for employees following the provided documentation. The Contract Health Safety and Environment Advisor (CSHEA) provides support when Risk Assessment and Method Statement are taking place. Finally, the ecologist is required to understand the surveys for the Primary Ecological Appraisal (PEA) (previously known as Phase I), to calculate biodiversity units for NNL as well as the Biodiversity Action Plans (BAP) on contracts. This is summarised in Table 4.4.

TABLE 4.4. THE NAME, ACRONYM AND DEFINITION OF THE ROLES THAT ARE USED IN THE BIODIVERSITY MANAGEMENT DOCUMENTATION WITHIN COSTAIN GROUP PLC. (ADD SOURCES)

Role	Acronym	Definition
Contract Leader	CL	Ensures the "*How to*" documentation is followed
Contract SHE Advisor	CSHEA	Provides support when RMS is being completed
Ecologist	Eco	Required to undertake the PEA, calculate biodiversity units and the BAPs

The next sections of the document as descriptions of tasks that need to be undertaken with the key roles involved, these include a desktop study, contract requirements, biodiversity baseline calculations, developing the Contract BAP, monitoring, and measuring, customer approval and handover. All sections of this document, including function, roles, data, GIS component, and outputs are summarised in Table 4.5.

TABLE 4.5. SUMMARY TABLE OF RESULTS FOR SHE-H-470

Section	Title	Key Roles	Function	Data	GIS	Outputs
3.1	Desktop Study	CSHEA	To understand the site ecology and biodiversity and to produce an appropriate Biodiversity Action Plan (BAP), information regarding the habitats and species present in the area must first be obtained.	Defra MAGIC map, Environmental Statements, Surveys	Y	Collation of pre-existing information for the contract site
3.2	Identity Contract Requirements	CL, CSHEA	The Contract Leader supported by the SHE/Environmental Manager/ Advisor must determine whether Biodiversity Unit calculations or No net loss is a client/ contract requirement.	SHE-T-267	N	A yes or no decision as to whether biodiversity objectives and targets must be recorded in the BAP
3.3	Biodiversity Baseline and Unit Calculations	CL, CSHEA, Eco	The Contract Leader must ensure that a suitability qualified ecologist is engaged. Undertake the biodiversity baseline, biodiversity unit calculations and undertake Phase 1 ecology surveys if necessary.	SHE-T-433, SHE-H-410, SHE-T-435, statutory nature conservations, Environmental Statement, previous Phase I Surveys	N	The developed biodiversity baseline and baseline biodiversity unit calculations
3.4	Developing a Biodiversity Action Plan	Eco	For each habitat and species identified as being important via the biodiversity baseline, related surveys and initial biodiversity unit calculations, conservation objectives and targets are drawn up and set out in the Plan.	SHE-T-433, SHE-T-434	N	BAP
3.5	Customer Document Review and Approval	CSHEA	Biodiversity Action Plan and Units Tracker to be reviewed by SHE advisor.	Contract BAP		Approved Contract BAP that is submitted for customer review
3.6	Ongoing Management	CSHEA	Records of all stages of the mitigation hierarchy should be kept within the Biodiversity Units Tracker. The SHE Manager/Adviser or Environment Manager/Advisor if available is responsible for ensuring this tool is kept up to date and that all evidence is suitably recorded.	SHE-T-434, Contract BAP, evidence of implementation	N	Ongoing management

3.7	Biodiversity Offsetting	Eco	Offsetting requires consultation with the client and numerous parties such as local wildlife trust and local authorities. All plans must be made in agreement with the future landowner and the party responsible for long term management and maintenance.	Evidence that the contract will not achieve the target without offsite opportunities.	N	Sites for biodiversity offsetting
3.8	Monitoring and Measurement	CSHEA	The SHE Manager/Adviser or Environment Manager/Advisor on the completion of any related work, clearance, mitigation, restoration and or offsetting the contract BAP and unit tracker to be reviewed and actions logged.	Contract BAP, unit tracker, physical progress of a project	N	Ongoing measuring and monitoring of biodiversity on the site
3.9	Completion and Handover	CSHEA	On completion of works and associated mitigation, restoration or offsetting works, documentation is to be updated and provided to the customer, including any ongoing long-term management requirements.	Fully updated Contract BAP	N	Updated documents provided to the client
3.10	Undertake Biodiversity Baseline	CSHEA, Eco	If a biodiversity action plan is not a client/contractual requirement: ff a phase 1 Ecology survey has not already been completed an Ecologist is to be engaged to undertaken survey.	SHE-T-433	N	Phase I survey results.
3.11	Develop Site-Specific BAP	CSHEA	If a biodiversity action plan is not a client/contractual requirement: consider the mitigation hierarchy including Avoidance of the loss, Minimisation of the loss when the impact cannot be avoided, Rehabilitation/restoration and offset if there is an opportunity.	SHE-T-433, the mitigation hierarchy, habitats and species on site,	N	Site-specific BAP
3.12	Record Actions to be Taken and Communicate	CSHEA	If a biodiversity action plan is not a client/contractual requirement: once actions and action plan established actions to be taken to be recorded in a Contract BAP.	Contract BAP, knowledge of actions taken	N	A log of recorded actions to be taken
3.13	Monitoring Measuring and Review	CSHEA	If a biodiversity action plan is not a client/contractual requirement: on the completion of any related work, clearance, mitigation, restoration and or offsetting the contract documentation actions should be logged.	Contract BAP, knowledge of actions taken	N	Completed log of completed actions to be reviewed

The *BAP Template* allows an author to fill in relevant information that shows that the contractor has "*conducted a biodiversity baseline and identified those habitats and species that would benefit from particular management or actions.*" (p3) By providing information that is presented in later sections, the contractor can identify aims, targets, and objectives for biodiversity conservation and enhancement. The document is structured in ten sections, six with sub-sections. The first section outlines the objectives of the contract BAP:

- To ensure that habitat and species targets from the UK Biodiversity Action Plan and the local BAP are translated into effective action within the bounds of this contract.
- To identify targets for other habitats and species of local importance within the contract boundary.
- To develop effective local partnerships to ensure that programs for biodiversity conservation are maintained long term.
- To ensure that opportunities for conservation and enhancement of biodiversity are fully considered throughout the contract, and
- To monitor and report on progress in biodiversity conservation.

Table 4.6. summarises the title, data, use of GIS, and outputs of each section. The *BAP Template* does not specify which specific roles were required for tasks within the document, so this information was not included as part of the results.

TABLE 4.6. SUMMARY TABLE OF THE DATA, USE OF GIS AND OUTPUTS FOR EACH SECTION OF SHE-T-433

Sec.	Title	Function	Data	GIS	Outputs
1	Biodiversity – An Introduction	Introduction to the document and biodiversity aspects	Contract name, description, location	Y	Contextual information about biodiversity
2	The BAP Process	A walk-through of the BAP process that is within this document	Local BAPs, Environmental Statements, Ecological Surveys	N	Contextual BAP information
3	Biodiversity Baselines	An introduction to biodiversity baselines and the sources of data	Contract date, Contract area, Environmental Statements, Phase I surveys, Conservation Designations, Local BAPS	Y	Local BAPs, commitments with authorities, designated statutory sites in contract area, spatial data of habitats in area, and species in contract area
4	Habitat Baseline	Table input for habitat baseline information	Habitat type, flagship species, relationship to the site, and potential opportunities for maintaining, restoring or expanding the habitat	N	Table of records for habitats in the contract area
5	Species Baseline	Table input for species baseline information	Common name group, scientific name, relationship to the site, UKBAP species, and potential opportunities for maintaining, restoring, or expanding the habitat.	N	Table of records for species in the contract area
6	Habitat and Species Action Plans	A description of the actions plans that are included in the Contract BAP for species and habitats	List of habitats on-site, list of species on-site, best practice standards, priority parameters	N	List of actions for the habitat action plan, the species action plan, and the procedural action plan
7	Habitat Action Plan	Table input for actions required for recorded habitats	Habitat, Target, Action required, Responsible Party, Target Date, Indicator/Measure	N	A table that is the habitat action plan
8	Species Action Plan	Table input for actions required for recorded species	Species, Target, Action required, Responsible Party, Target Date, Indicator/Measure	N	A table that is the species action plan
9	Procedural Action Plan	The general targets and objectives and associated actions	Target, Action required, Responsible Party, Target Date, Indicator/Measure	N	A table that is the procedural action plan
10	Monitoring, Reviewing and Reporting Progress	Reporting of progress and achievements	Monitoring plan	N	Description of the monitoring plan

4.2.5. TOOLS

The only document categorised as a tool was, *SHE-T-434 Biodiversity Units Tracker*. The tool, in the format of an excel file, allows the user to calculate the biodiversity units before and after the project to determine overall losses and gains. This tracker uses the metrics from Defra's offsetting scheme. The eleven sheets (summarised in Table 4.8) take the user through the process. Sheet 1, the title page states that this tool is Version 4 and released in September 2015. Sheet 2, the user guide, describes the toolkit to the user and states that the toolkit aims to:

- Record actions to avoid, minimise, and restore habitat losses on-site under the 'Mitigation Hierarchy.'
- Track losses and gains of biodiversity units from habitat clearance and replanting
- Calculate biodiversity units generated by offsets
- Illustrate the habitats most affected by clearance
- Produce reports on achieving No Net Loss or Net Positive

The cells are distinguished by being either a data entry point for the user or value that has been automatically updated. The guide then describes each of the sheets moving forward to provide some context of the process for the user. The following sheets allow for the user to input site and project information, the phase I habitat information with distinctiveness band and condition, the on-site calculations of habitats and linear habitats, offsetting, the evidence base for calculating offsets and any notes from the site information. This has been summarised in Table 4.7.

TABLE 4.7. SUMMARY TABLE OF FUNCTION, DATA, GIS, AND OUTPUTS FOR SHEETS ON THE SHE-T-434 BIODIVERSITY UNITS TRACKER

No.	Title	Function	Data	GIS	Outputs
1	BT V5	Title page	Version and date	N	Title page, date, and tool version
2	User Guide	Instructions for the use of the tool	N/A	N	Increased understanding for the user of the tool
3	Project Details	An overview summary of the site/project	Project title, client, start date, project lead, reference number, toolkit lead, toolkit approver, completion date	N	Relevant information and contacts for the project and toolkit
4	Site info	Overview of information about the site	Site name, Local Planning Authority, grid reference, description, description of works, notes, link to the site folder	N	Description and location of the site, with links to any information folders.
5	Habitat Comparison Info	Area to enter Phase I Habitat Type information	Broad/subcategory, Alphanumeric, notes, Defra's metric type, Defra Distinctiveness Band, FEP Condition Assessment	N	List of Phase I habitat types, NVC values, and Defra values
6	On-site Biodiversity Units	The calculations of biodiversity units on-site before and after construction, automatically updating as fields are entered	Phase I habitat types, Distinctiveness, condition, area remaining of habitat	N	Per cent losses or gains from the site
7	Linear Habitats	Calculations of linear habitats that need to be offset, automatically updating as fields are entered	Site name, linear habitat type, condition, length to be lost, offset metres required	N	Amount of linear habitat to be offset
8	Offset Units	Values for offset habitats including multipliers for difficulty to create, spatial risk, and years to maturity	Phase I habitat type, distinctiveness band, target condition, area of habitat biodiversity units, difficulty to create, spatial risk, time to the target condition	N	Units needed to offset
9	Evidence Base	Where all actions of the mitigation hierarchy were undertaken	Site name, hierarchy level, Date, Action, Outcome, Evidence	N	Evidence of adherence to the mitigation hierarchy
10	Summary	Graphs for losses and gains that will update as fields are entered	Number of actions for sites, primary habitat-specific actions, Distinctiveness and condition baselines, hectares of habitat cover before and after, biodiversity units before and after	N	Graphs for each site
11	Notes	Automatically updates with the notes from the site info sheet	Notes from the site	N	Notes

4.3. Model Simulations: Baselines

4.3.1. Introduction

This section presents the results for the baseline model simulations. The simulation baselines are part of the "*Design and Development*" and "*Demonstration*" stages of the Design Science Research Methodology. The demonstration of the model is shown through its use for developing the baselines for the Contract Biodiversity Action Plan (BAP), and for highlighting habitats that are considered of high value based on metrics developed by the Department for the Environment, Food and Rural Affairs (Defra). Five applications were developed to provide baseline values. Application 1 is the visualisation of conservation designations, Application 2 shows the species baselines, Application 3 visualises the characteristics of Defra's No Net Loss scheme, Application 4 is a condensed index to visualise the offsetting metrics, and Application 5 is a preliminary calculation of biodiversity offsetting units. This is summarised in Table 4.8. The results are visualised as map outputs. The procedure and assumptions were discussed in Section 3.6.

Table 4.8. Summary of the developed applications for this chapter

Application	Name	Description
1	Statutory Conservation Designations	Importing of the statutory conservations for England, Scotland, and Wales
2	Species Baseline	The location of previously recorded species within the study area
3	Biodiversity Characteristics	The visualisation on biodiversity metrics from Defra's offsetting scheme
4	Biodiversity Characteristics Index	An index to condense the metrics from Defra's offsetting scheme
5	Baseline for Biodiversity Units	A preliminary calculation of biodiversity units

4.3.2. Application 1: Statutory Conservation Designations

The conservation designations were added to ArcGIS Enterprise as part of a web application that shows the statutory conservation designations for England, Wales, and Scotland. There are no map outputs for this Application as users would be required to used the ArcGIS Enterprise Portal to view some of the data as it is consumed from an online source.

4.3.3. Application 2: Species Baselines

The method for building the co-occurrence map for the baseline of recorded species was successful. Figure 4.6 and Figure 4.7 show the baseline of recorded species (Section 3.5.2.2) within a 5km of Study Site 1: the A465 and Study Site 2: the A14 respectively. However, the data does not cover the entire area of the study sites. Figure 4.6 shows 42 1km grid squares with the total number of species recorded in each grid square ranging between one and four species. Thirty-three of the 42 grid squares contain one recorded species, four grid squares contain two recorded species, four grid squares contain three recorded species, and one grid square contains four recorded species. Figure 4.7 shows 36 1km grid squares with each grid square containing either one or two recorded species, with 31 grid squares containing one recorded species, and five squares containing two recorded species.

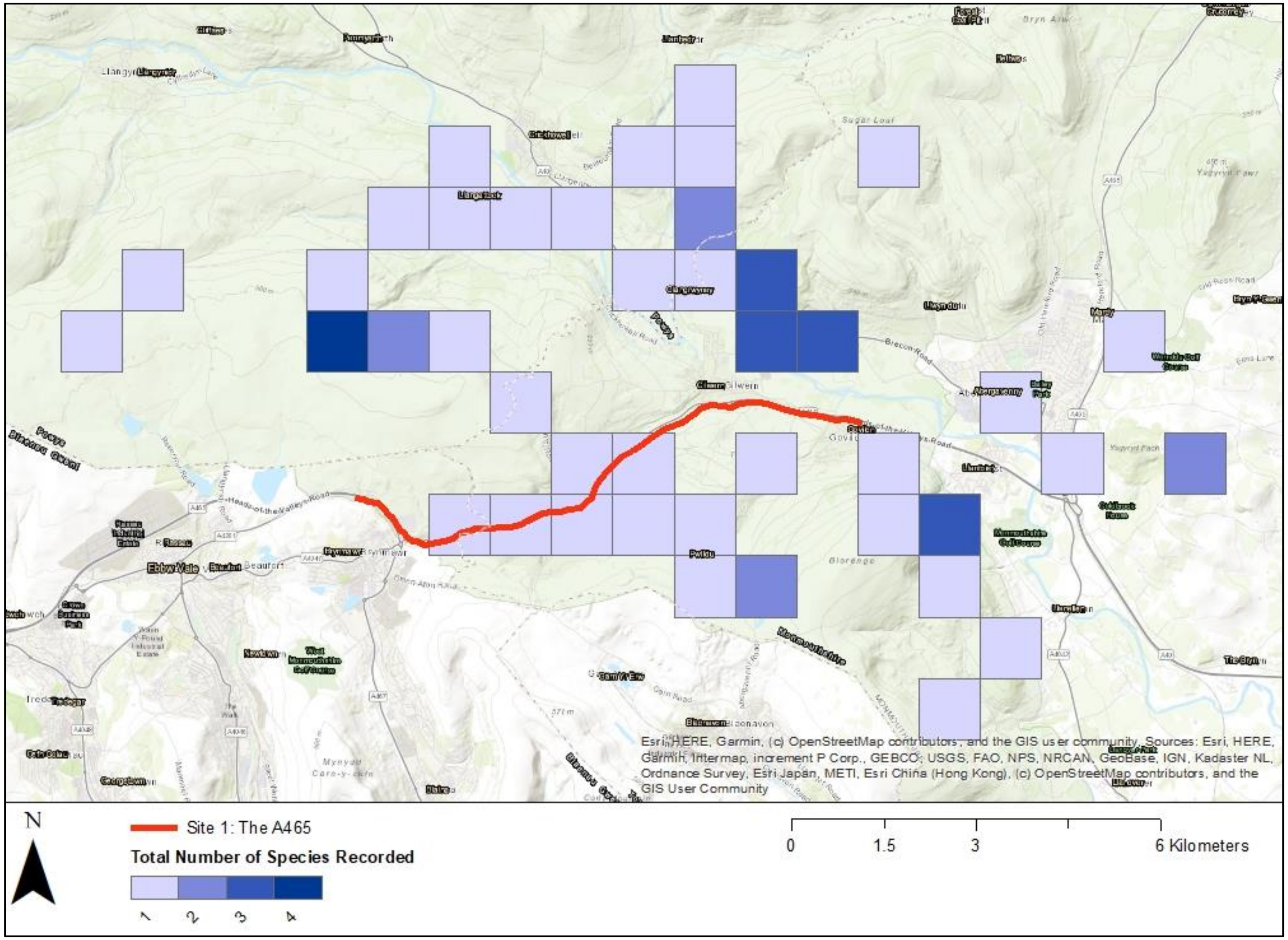


FIGURE 4.6. THE BASELINE CO-OCCURRENCE MAP FOR SPECIES RECORDED IN THE LAST 20 YEARS SURROUNDING STUDY SITE 1: THE A465. SOURCE: NBN 2016

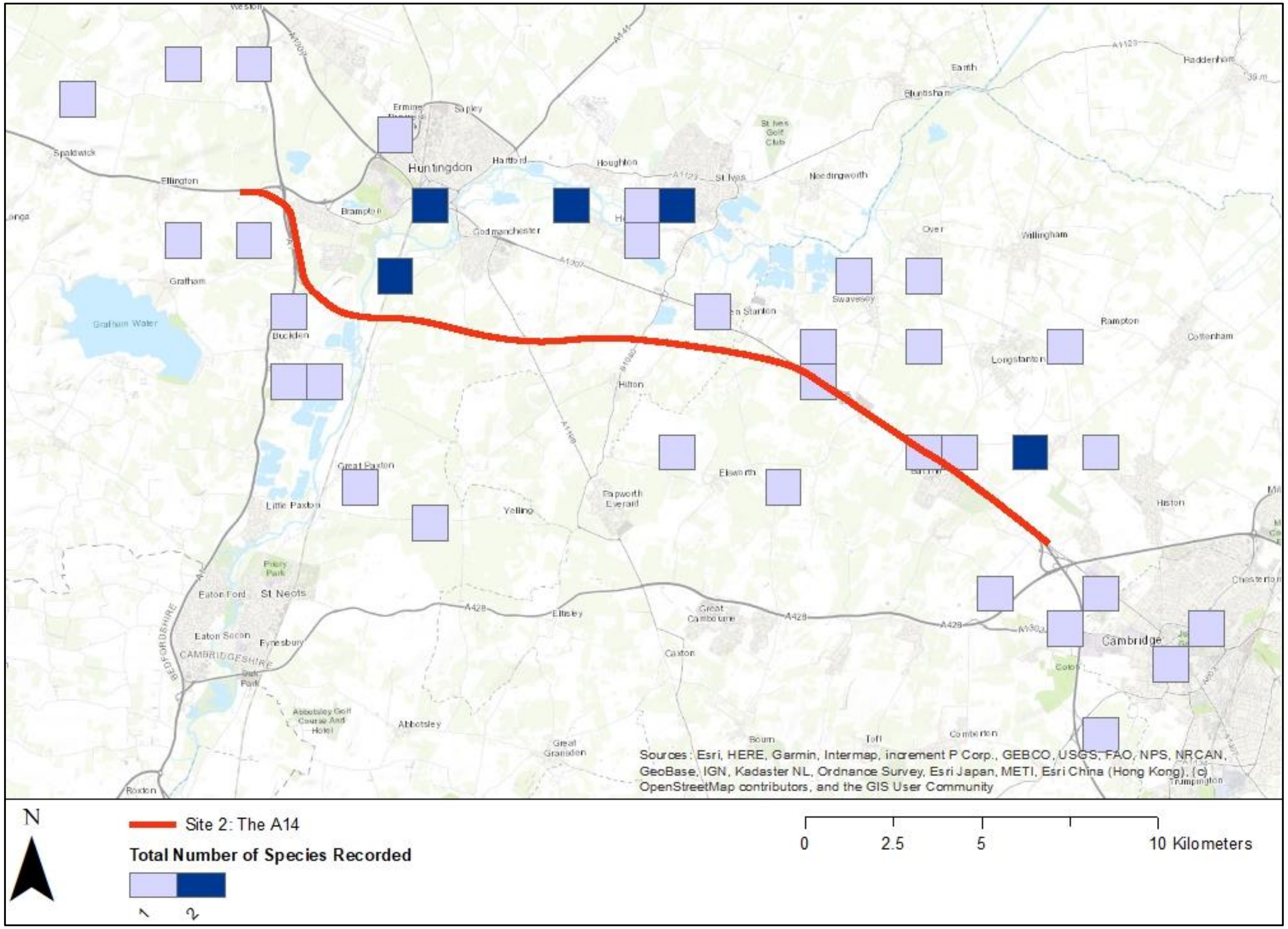


FIGURE 4.7. THE BASELINE CO-OCCURRENCE MAP FOR SPECIES RECORDED FROM 1996-2016 SURROUNDING STUDY SITE 2: THE A14. SOURCE: NBN 2016

4.3.4. Application 3: Baseline for Biodiversity Metrics

The baseline for biodiversity metrics used the method presented by Seo (2005) to join spatial and non-spatial data. This can be completed manually on the ArcMap interface by completing a table join. Figure 4.8 and Figure 4.9 show the value of biodiversity distinctiveness within a 5km buffer of Study Site 1: the A465 and Study Site 2: the A14, respectively. The maps highlight the value through a classification of "Very Low" to "High" with full coverage across both study sites. Figure 4.10 and Figure 4.11 show the values of difficulty of restoration within a 5km buffer of Study Site 1: the A465 and Study Site 2: the A14, respectively. The maps highlight the value through a classification of "Very Low" to "High" with full coverage across both study sites.

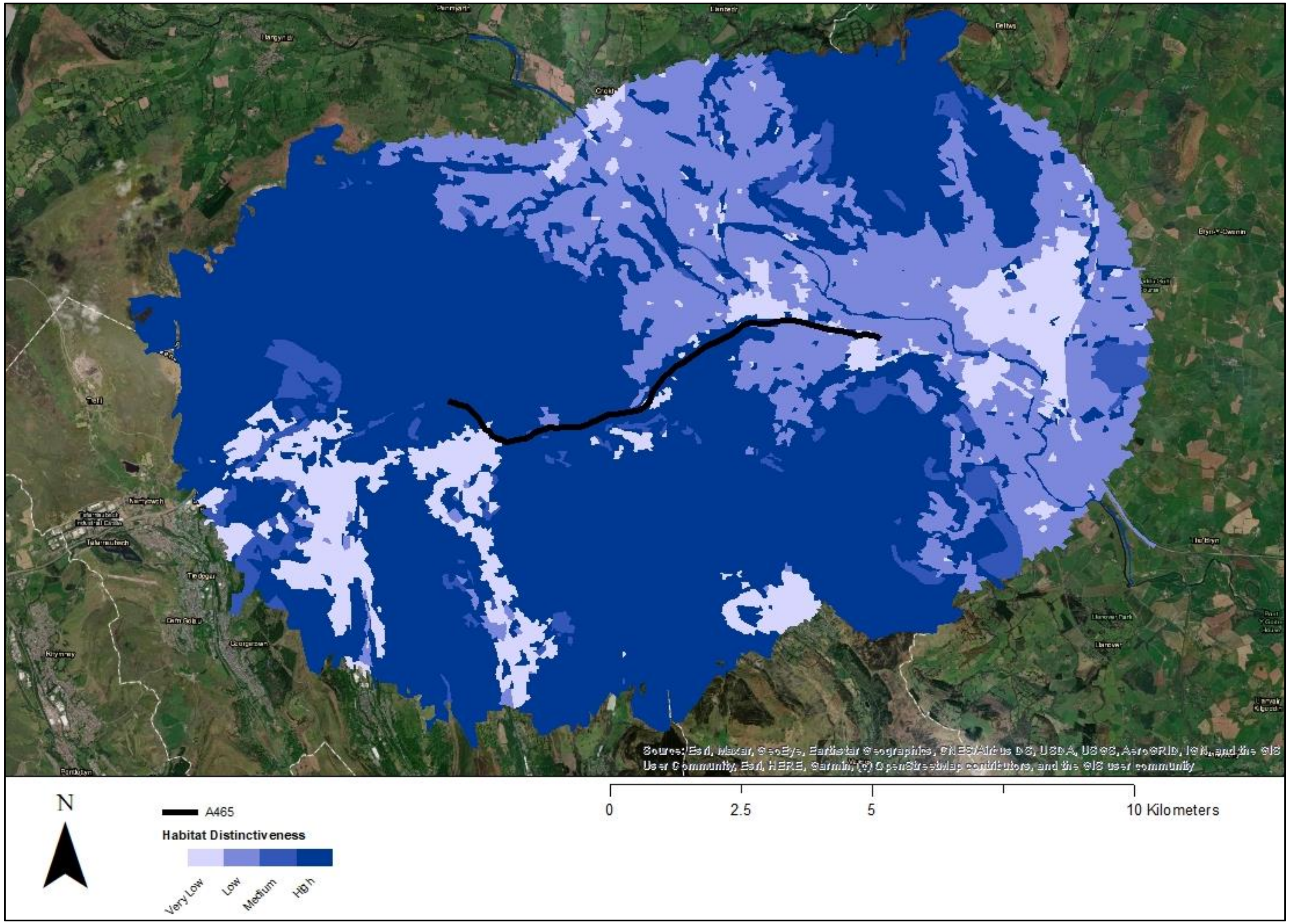


FIGURE 4.8. HABITAT DISTINCTIVENESS WITHIN 5KM BUFFER OF STUDY SITE 1: THE A465. SOURCE: CEH2015

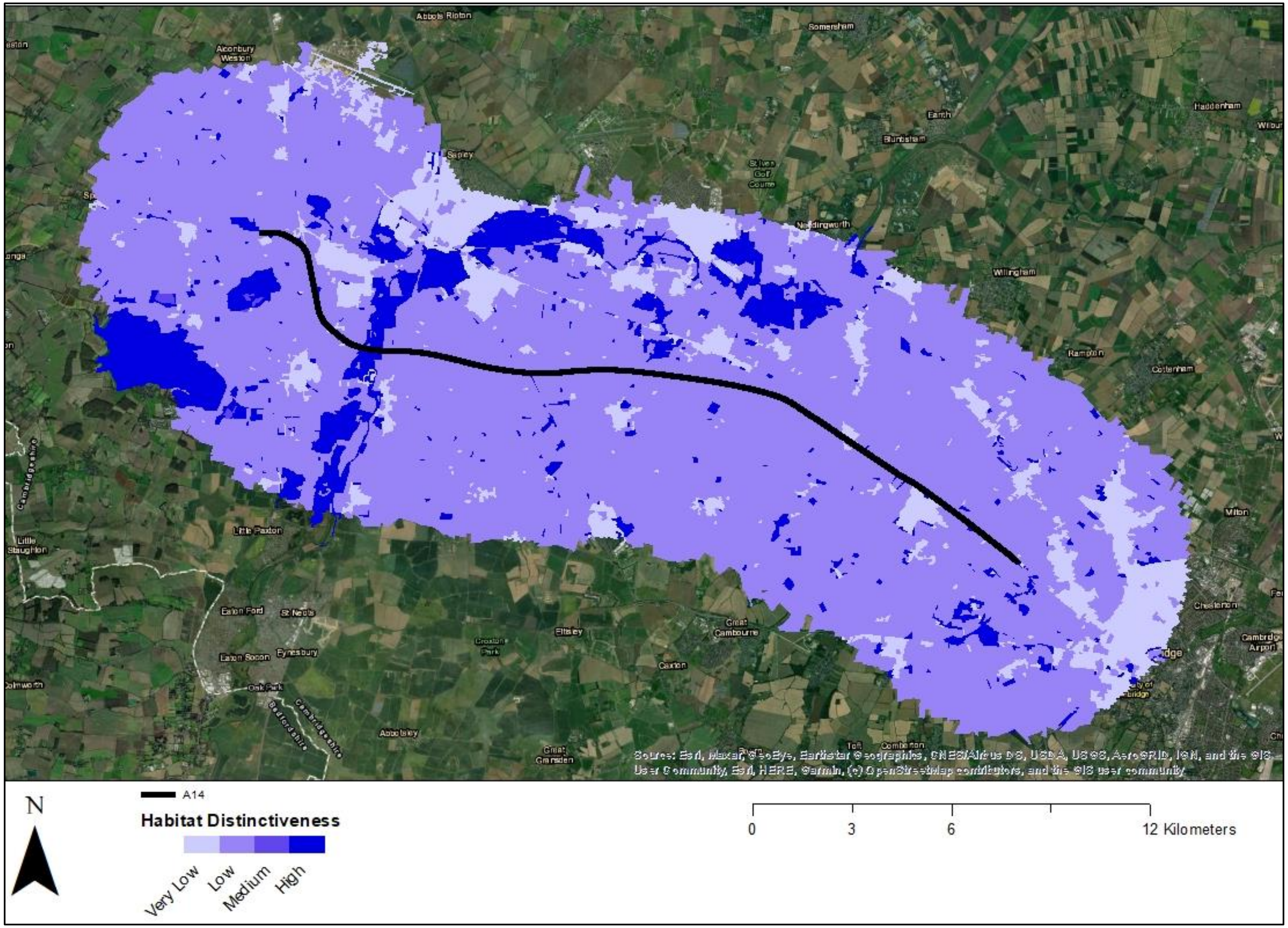


FIGURE 4.9. HABITAT DISTINCTIVENESS WITHIN 5KM BUFFER OF STUDY SITE 2: THE A14. SOURCE: CEH2015

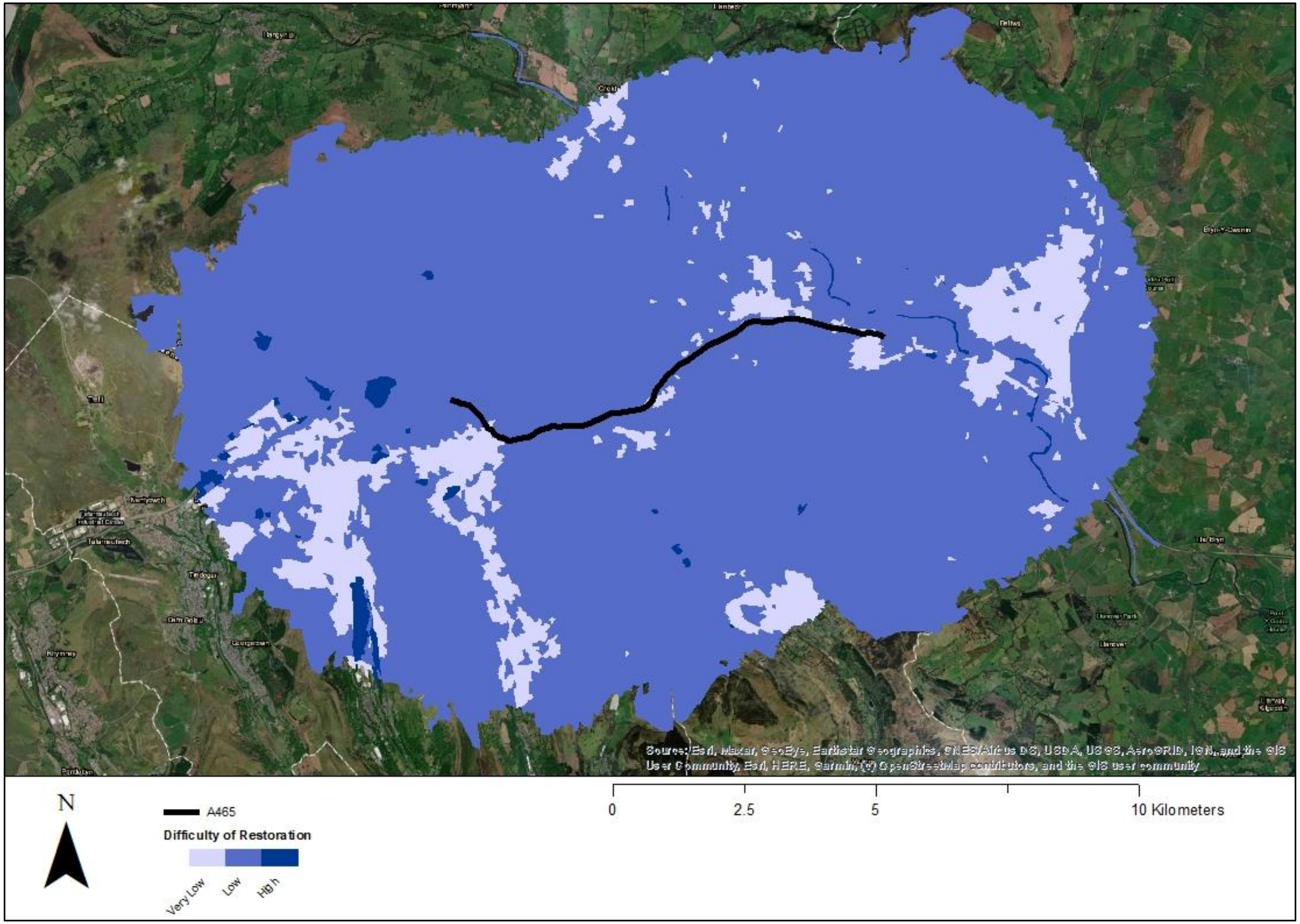


FIGURE 4.10. DIFFICULTY OF RESTORATION WITHIN 5KM BUFFER OF STUDY SITE 1: THE A465. SOURCE: CEH2015

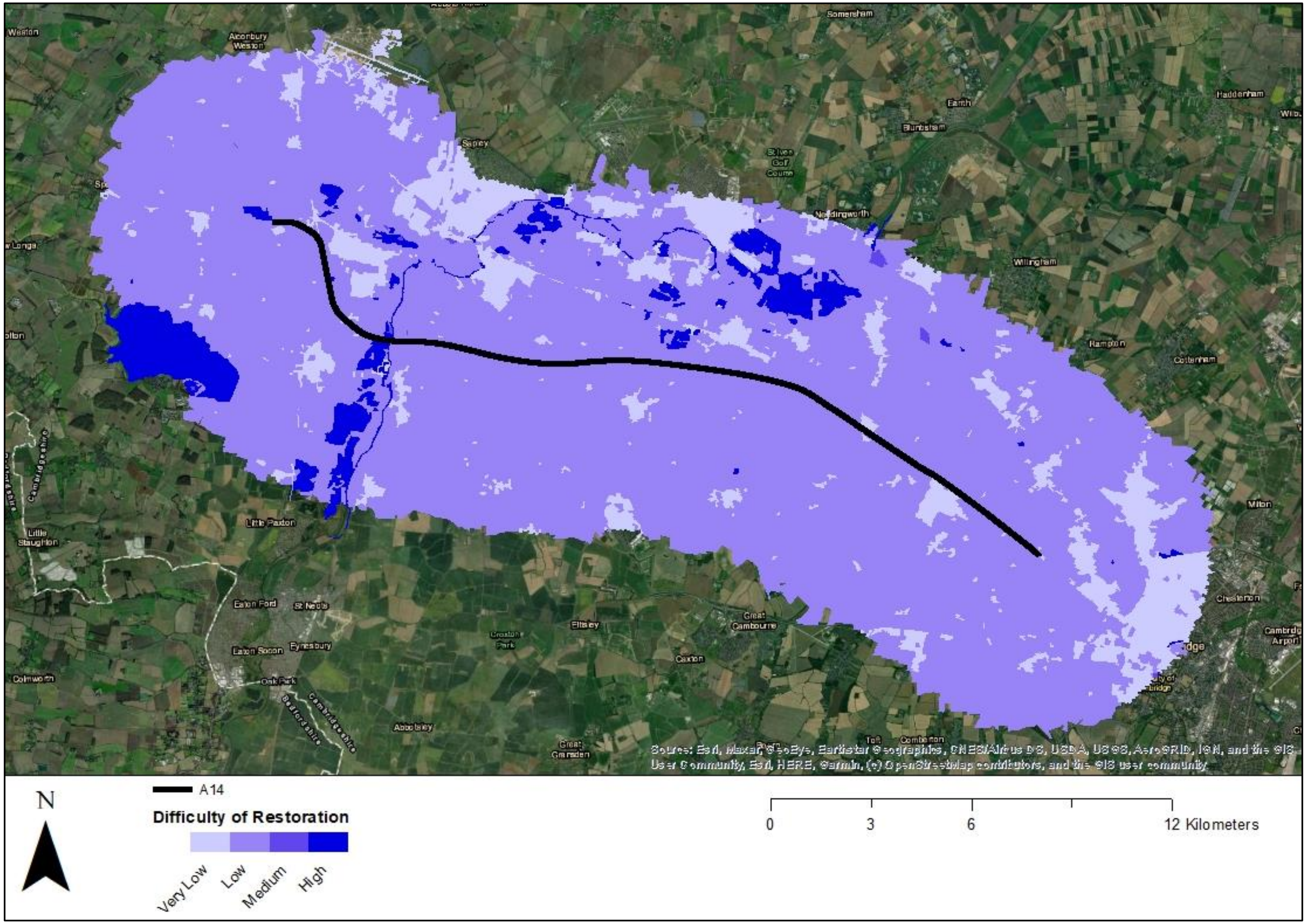


FIGURE 4.11. DIFFICULTY OF RESTORATION WITHIN 5KM BUFFER OF STUDY SITE 2: THE A14. SOURCE: CEH2015

4.3.5. Application 4: Index of Baseline Metrics

The joining of the spatial and non-spatial data for this tool was completed in the previous section, then fields were created for the proximity value and the final three-digit index value. To add the proximity values, each level of proximity was individually selected and assigned an appropriate value (Section 3.5.5.). The index values were reclassified (Figure 3.22) to highlight areas that could be high risk of being of high biodiversity unit value. Figure 4.12 and Figure 4.13 show the baseline metrics within an index within a 5km buffer of Study Site 1: the A465 and Study Site 2: the A14, respectively. The maps highlight the value through a classification of “Very Low” to “High” with full coverage across both study sites.

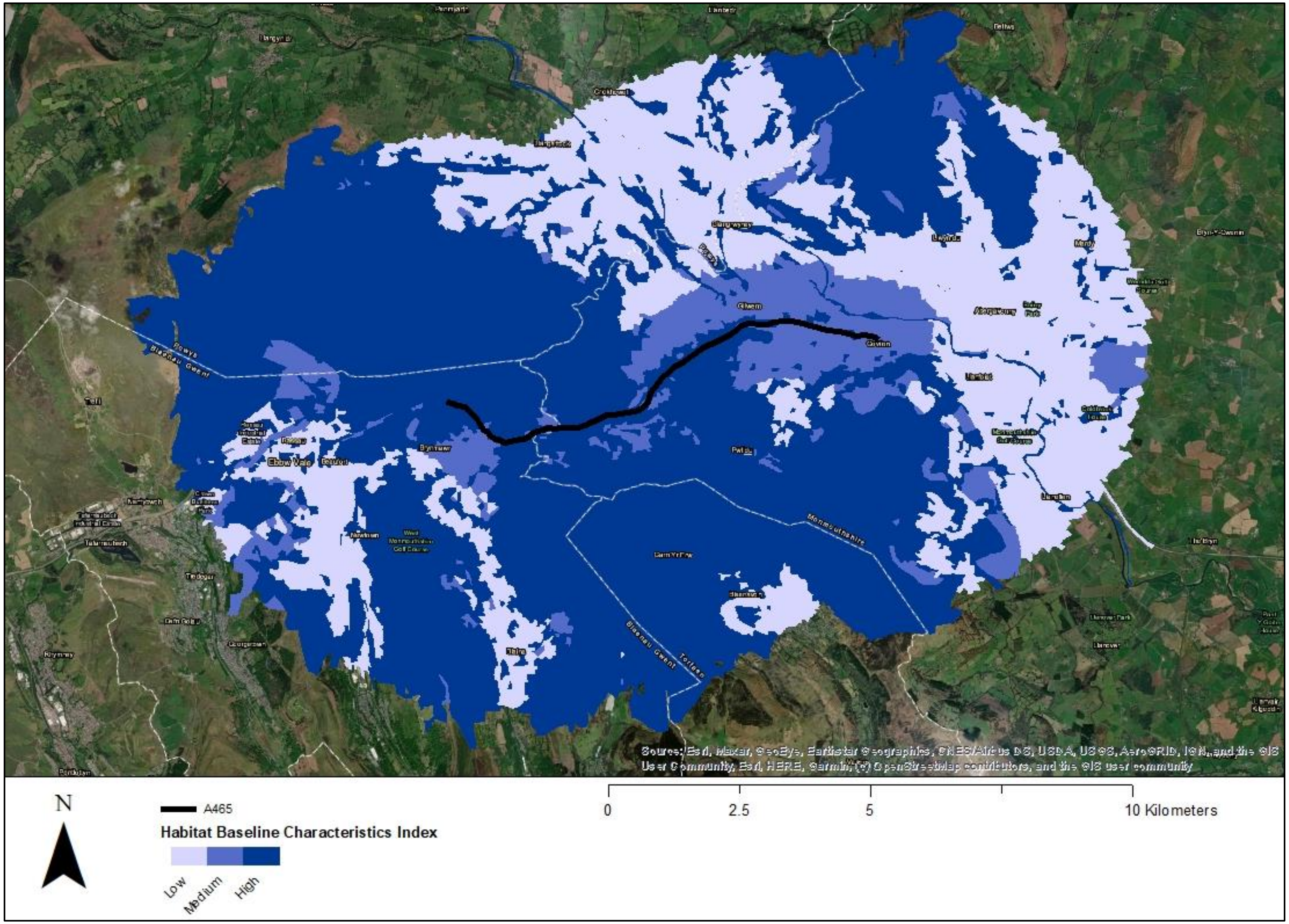


FIGURE 4.12 INDEX OF BASELINE METRICS WITHIN 5KM STUDY SITE 1: THE A465. SOURCE: CEH2015

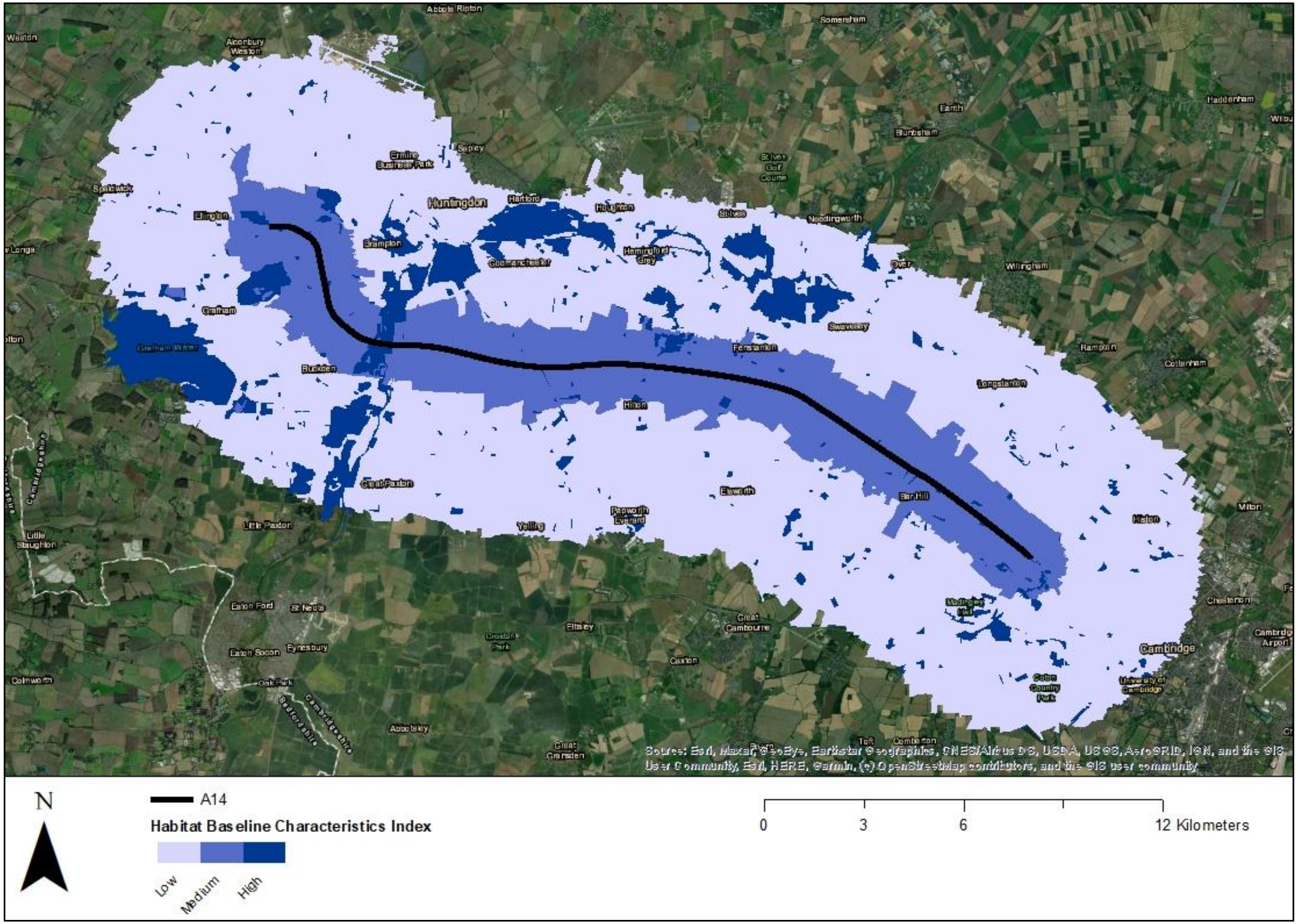


FIGURE 4.13. INDEX OF BASELINE METRICS WITHIN 5KM STUDY SITE 2: THE A14. SOURCE: CEH2015

4.3.6. Application 5: Baseline for Biodiversity Units

The model for calculating biodiversity units can be used in scoping/tending and design phases of development (Section 3.5.4). The baseline for biodiversity units was added as part of Application 3. However, this can also be completed within ArcGIS if the values had not been previously added, or from the original LCM data. Figure 4.14 and Figure 4.15 show the biodiversity unit value of habitats within a 5km buffer of Study Site 1: the A465 and Study Site 2: the A14, respectively. Figure 4.14 shows habitats that have a biodiversity unit value ranging from zero units to 3124 units. The habitats with the lowest value of zero are urban and suburban, and the habitat with the highest value is heather grassland. Figure 4.15 shows habitat that have a biodiversity unit value ranging from zero units to 11385 units. The habitats with the lowest value of zero are urban and suburban, and the habitat with the highest value is freshwater.

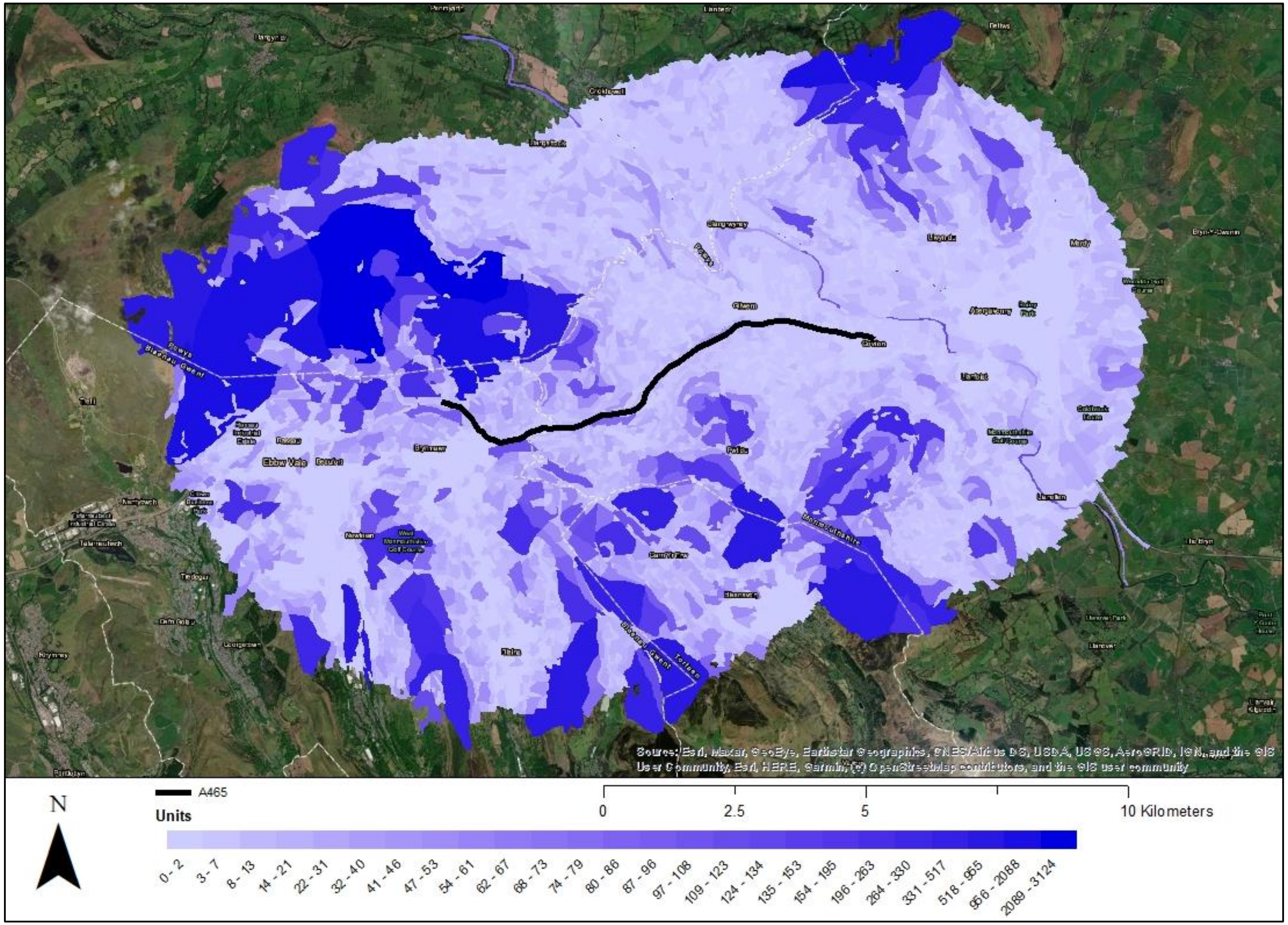


FIGURE 4.14. BIODIVERSITY UNITS BASELINE WITHIN 5KM STUDY SITE 1: THE A465. SOURCE: CEH2015

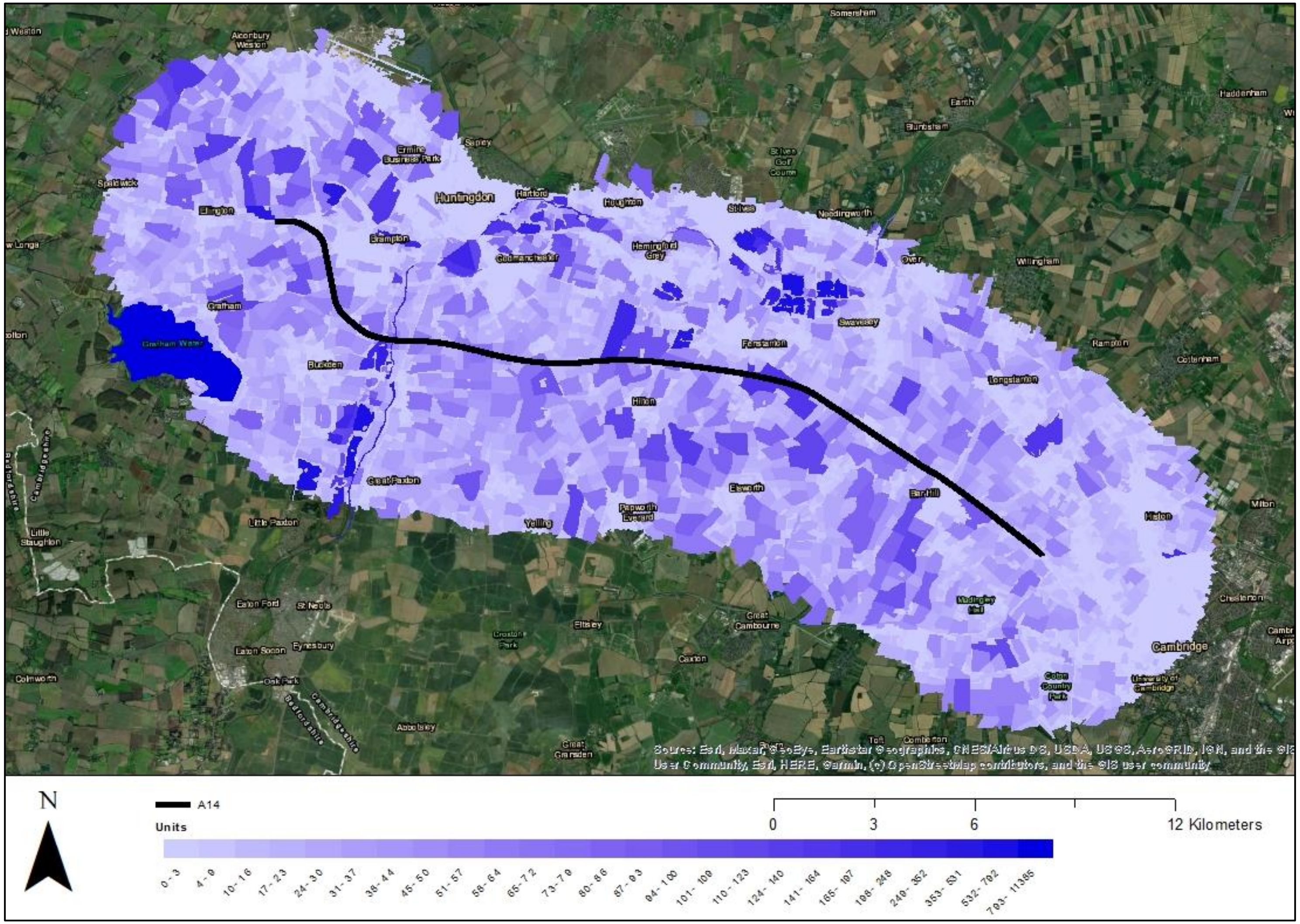


FIGURE 4.15. BIODIVERSITY UNITS BASELINE WITHIN 5KM STUDY SITE 2: THE A14. SOURCE: CEH2015

4.4. Model Simulations: Impact Values

4.4.1. Introduction

This section presents the results from the model simulations showing impact values. Each simulation calculates a baseline value, a scenario value, and an impact value, following a similar flow structure (Figure 3.24). Application 6 calculates the change in biodiversity units by multiplying habitat distinctiveness value with the patch area. Application 7 measures patch level fragmentation indicators by using an outer-belt buffer to calculate Core Area (CA), and the Nearest Feature Analysis to calculate Nearest Neighbour (NN). Finally, Application 8 measures class level fragmentation impacts using Summary Statistics tools to calculate Mean Patch Size (MPS) and Patch Density (PD). This has been summarised in Table 4.9. The results are visualised as map outputs and tables. The procedure and assumptions were discussed in Section 3.7.

Table 4.9. Summary table of the analyses run for each of the applications in this chapter

Application	Description	Analysis Run
6	Calculation of Biodiversity Units	Habitat Distinctiveness*Patch Area
7	Measuring Patch Level Fragmentation Impacts	Outer-belt Buffer and Nearest Feature Analysis
8	Measuring Class Level Impacts	Summary Statistics for Mean Patch Size and Patch Density

4.4.2. Application 6: Impacts to Biodiversity Values

The change in biodiversity unit values is summarised in Table 4.10. Both sites have a reduction of biodiversity unit values for scenarios A and B. Site 1: The A465 had a reduction of 59.88 units or 0.50% for Scenario A, and a reduction of 138.00 units or 1.15% for Scenario B. Site 2: The A14 had a reduction of 69.12 units or 0.46% for Scenario A, and a reduction of 161.01 units or 1.07% for Scenario B.

Table 4.10. Summary table of the change of biodiversity units for Site 1: The A465 and Site 2: The A14 for Scenarios A and B

Site	Scenario	Total units	Units Removed	Impact Value (%)
1	Baseline	11999.84	n/a	n/a
1	A	11939.96	59.88	0.50
1	B	11861.84	138.00	1.15
2	Baseline	14984.22	n/a	n/a
2	A	14915.10	69.12	0.46
2	B	14823.21	161.01	1.07

4.4.3. APPLICATION 7: FRAGMENTATION IMPACTS TO HABITAT PATCHES

4.4.3.1. CORE AREA ON SITE 1: THE A465

The first impact analysed was the change in CA. The results for Site 1: The A465 are summarised in Table 4.11. The total number of patches containing CA remained the same for both scenarios; however, the reduction in the number of patches in the surrounding landscape decreasing by 0.01% for both Scenario A and B. The total amount of CA was not reduced; however, the percent of core area increases for each scenario as the total patch area has decreased. Figure 4.16 shows the "Core Area", which are patches with an out belt of at least 130m (Section 3.6.2), and "Non-Core Area" in the 1km buffer surrounding the study site, with full coverage. The amount of CA for this site did not change with the implementation of Scenarios A and B, therefore Figure 4.16 is the only visualisation for this site.

TABLE 4.11. SUMMARY TABLE OF THE CHANGE IN CORE AREA PATCH COUNTS AND AREA FOR SITE 1: THE A465 FOR SCENARIOS A AND B

		Patch Count			Patch Area		
		Total	**Core Area**	**Percent**	**Total**	**Core Area**	**Percent**
Scenario	Baseline	1497	11	0.73	27658849.62	1122982.73	4.06
	A	1476	11	0.75	27539821.97	1122982.73	4.07
	B	1461	11	0.75	27382859.70	1122982.73	4.10
Impact	A	-21	0	0.01	119027.65	0.00	0.01
	B	-36	0	0.01	275990.62	0.00	0.04

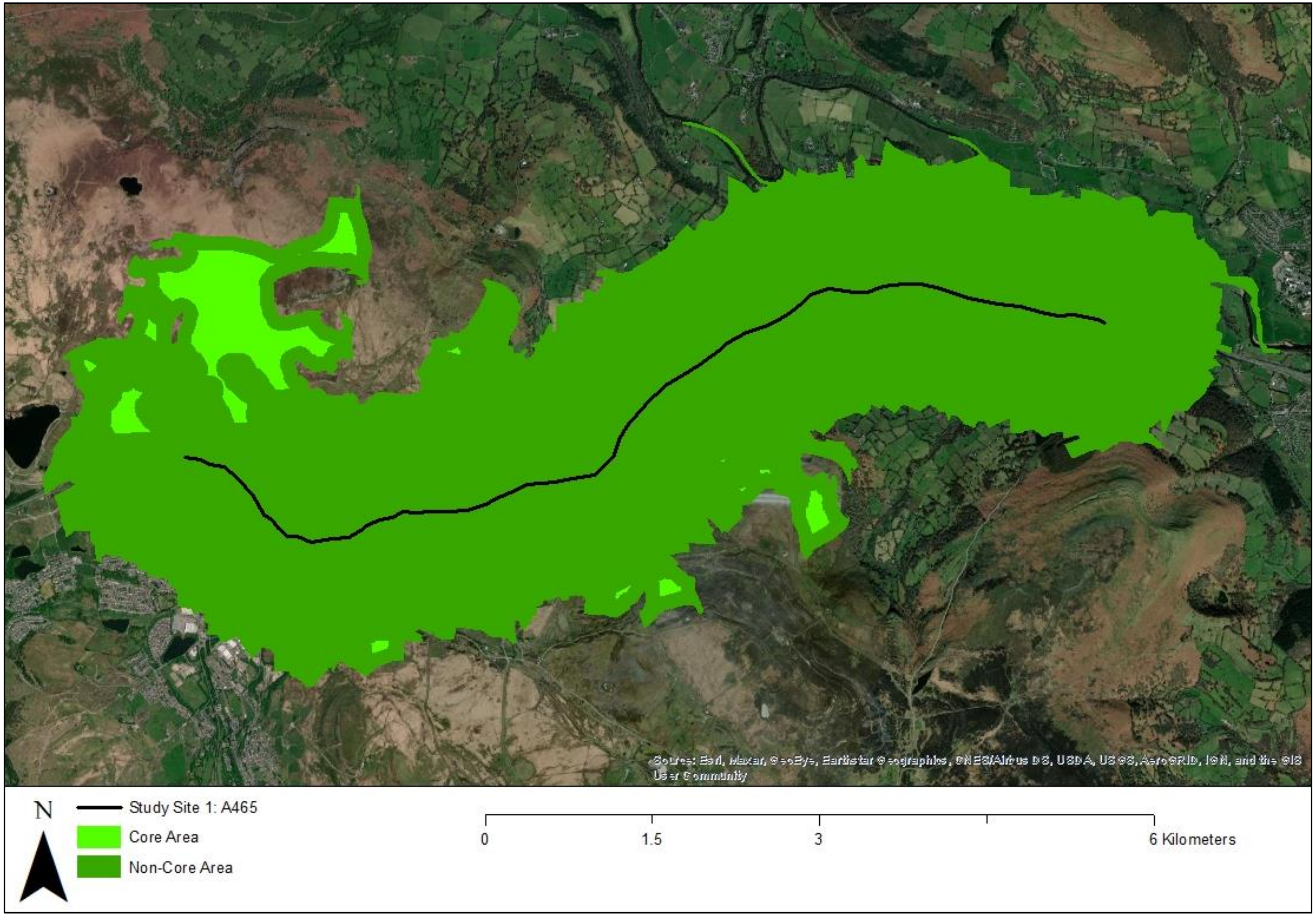


FIGURE 4.16. THE CORE AREAS SURROUNDING SITE 1: THE A465. SOURCE: ROWLAND 2015

4.4.3.2. CORE AREA ON SITE 2: THE A14

The core area results for Site 2, the A14, are summarised in Table 4.12. The total number of patches containing CA was reduced for Scenarios A and B by 0.9% and 1.0% respectively. The total amount of CA was also reduced in both scenarios; however, as the total area of each scenario decreased, the percentage of CA was calculated to be less than 0.00%. In addition to the loss of three CA patches for Scenario A, 20% of remaining CA patches were reduced in size. For Scenario B, in addition to the loss of 5 CA areas, 21.75% of patches were reduced. Figure 4.17 shows "Baseline Core Area" which are patches with an outer belt of at least 130m and "Non-Core Area" across the site before the implementation of Scenarios A and B, within 1km of the site with full coverage. Figure 4.18 and Figure 4.19 show the changes in CA across the site for Scenarios A and B, respectively. The outputs show "Unchanged Core Area" which are unaffected baseline CA patches, "Reduced Core Area" which highlight CA patches that have reduced in size from the baseline, and "Non-Core Area".

TABLE 4.12. SUMMARY TABLE OF THE CHANGE IN CORE AREA PATCH COUNTS AND AREA FOR SITE 2: THE A14 FOR SCENARIOS A AND B

		Count			**Area**		
		Total	**Core Area**	**Percent**	**Total**	**Core Area**	**Percent**
Scenario	Baseline	1302	198	15.21	71746140.07	6072067.94	8.46
	A	1289	195	15.12	71408616.99	6040989.88	8.46
	B	1277	193	15.11	70963780.68	6000003.06	8.46
Impact	A	13	3	0.9	337523.08	31079.55	0.00
	B	25	5	1.0	782359.39	72052.91	0.00

FIGURE 4.17. THE BASELINE CALCULATION FOR CORE AREA SURROUNDING SITE 2: THE A14. SOURCE: ROWLAND 2015

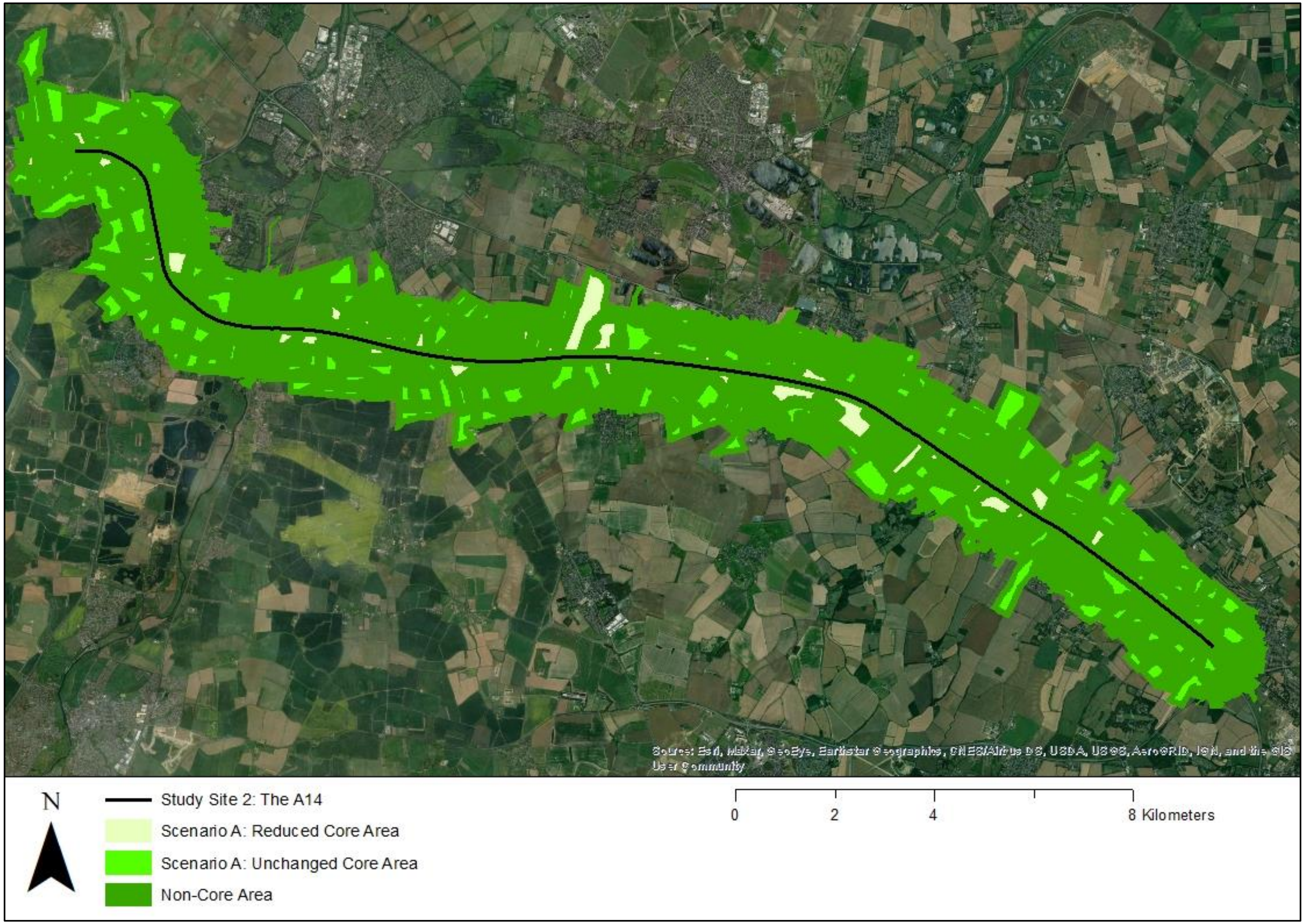


FIGURE 4. 18. SCENARIO A CALCULATION SHOWING UNCHANGED AND REDUCED CORE AREA PATCHES SURROUNDING SITE 2: THE A14. SOURCE: ROWLAND 2015

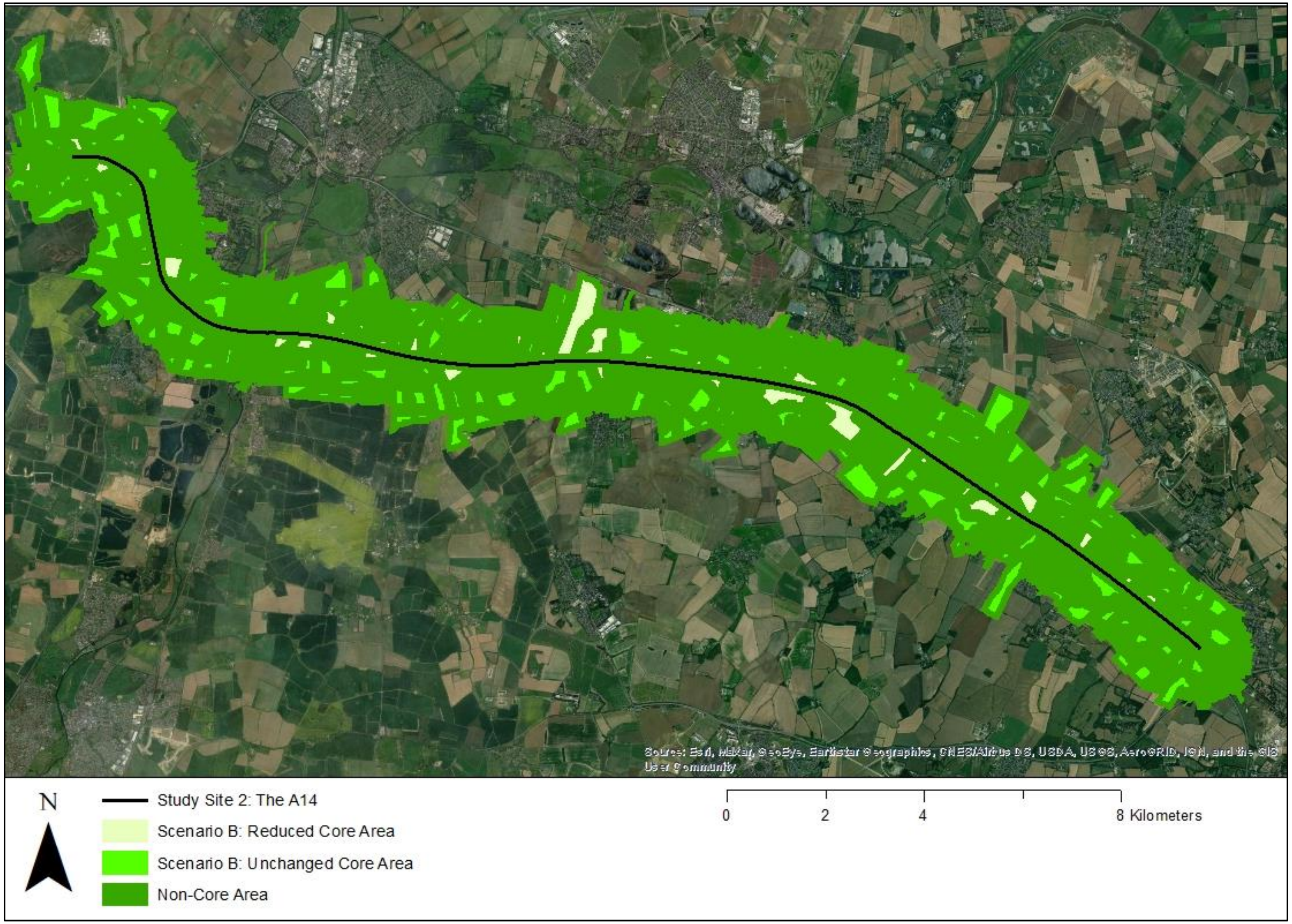


FIGURE 4.19. SCENARIO B CALCULATION SHOWING UNCHANGED AND REDUCED CORE AREA PATCHES SURROUNDING SITE 2: THE A14. SOURCE: ROWLAND 2015

4.4.3.3. Edge to edge different on Site 1: The A465

The second patch level analysis was edge to edge difference. The results for Site 1, the A465 are displayed in Table 4.13. The output is an individual value for the maximum, minimum and average distance between all the patches across the entire study site. The values did not change for either scenario, however the minimum distance between patches increased by 13.11m for both scenarios, and the average distance increased by 1.09m and 1.66m for Scenarios A and B, respectively.

Table 4.13. Summary of the changes of the nearest neighbour tool for Site 1: The A465, showing the minimum, maximum and average distances of all patches across the landscape

		Distance (m)		
		Minimum	**Maximum**	**Average**
Scenario	Baseline	9.30	582.72	89.87
	A	22.41	582.72	90.96
	B	22.41	582.72	91.53
Impact	A	-13.11	0	-1.09
	B	-13.11	0	-1.66

4.4.3.4. Edge to edge different on Site 2: The A14

The results for Site 2: The A14 are displayed in Table 4.14. Similarly, to the previous site, the maximum values did not change for either scenario, however the minimum distance between patches increased by 3.73m and 11.35m for Scenarios A and B respectively. In addition, the average distance between patches increased by 1.65m and 3.34m for Scenarios A and B, respectively.

Table 4.14. Summary of the changes of the nearest neighbour tool for Site 2: The A14, showing the minimum, maximum and average distances of all patches across the landscape

		Distance (m)		
		Minimum	**Maximum**	**Average**
Scenario	Baseline	25.05	719.72	140.91
	A	28.78	719.72	142.56
	B	36.40	719.72	144.25
Impact	A	-3.73	0	-1.65
	B	-11.35	0	-3.34

4.4.4. Application 8: Class level fragmentation impacts

4.4.4.1. Site 1: The A465

The class level impacts analysed across both sites were MPS and PD. The results for the class level impacts for Site 1: The class level results for Site 1: The A465 are summarised in Table 4.15 for Scenario A and Table 4.16 for Scenario B.

There were ten LCM habitat types surrounding this site, each with a change value for MPS and PD for each habitat type and each scenario. For Scenario A, four habitat types had an increase in MPS, two had a decrease in MPS, and four had no change in MPS. The largest change in MPS was for the Arable and Horticulture habitat that increased its MPS by 1126.73m^2. The smallest change in MPS was Coniferous Woodland, that reduced its MPS 16.30m^2. Two habitat types had an increase in PD, four had a decrease in PD, and four had no change in PD. The largest change was for the habitat type Broadleaf woodland with its PD decreasing by 0.46 patches per 100ha. The smallest value of change was seen in two habitat types: Arable and Horticulture with a decrease of 0.07 patches per 100ha, and Improved Grassland with an increase of 0.07 patches per 100ha. For Scenario B, five habitat types had an increase in MPS, one had a decrease in MPS and four had no change in MPS. The largest change to MPS was still Arable and Horticulture, with its MPS increasing by 1551.76m^2. The smallest change to MPS was Improved Grassland with its MPS reducing by 4.61m^2. The habitat with the smallest change was Improved Grassland with a decrease of 29.54m^2. Two habitat types had an increase in PD, four had a decrease in PD, and four had no change in PD. The largest change was for the habitat type Broadleaf woodland with its PD decreasing by 0.69 patches per 100ha. The smallest value of change was seen in Coniferous Woodland with a PD decrease of 0.02 patches per 100ha.The chart outputs are shown in Figures 4.20 to 4.23.

TABLE 4.15 SUMMARY TABLE OF CHANGES IN MEAN PATCH SIZE AND PATCH DENSITY FOR SITE 1: THE A465, SCENARIO A

	Baseline Calculation				**Scenario A**					
	Total Area (m^2)	**MPS (m^2)**	**Total Patches**	**PD (patches per 100ha)**	**Total Area (m^2)**	**MPS (m^2)**	**Total Patches**	**PD (patches per 100ha)**	**MPS Impact (m^2)**	**PD Impact (patches per 100ha)**
Acid Grassland	4763443.10	18534.80	257	9.29	4740964.90	18592.02	255	9.26	-57.22	0.03
Arable and Horticulture	384215.31	16008.97	24	0.87	376985.35	17135.70	22	0.80	-1126.73	0.07
Broadleaf Woodland	3651767.99	11483.55	318	11.50	3584599.18	11791.44	304	11.04	-307.90	0.46
Coniferous Woodland	618759.86	19336.25	32	1.16	618238.25	19319.95	32	1.16	16.30	-0.01
Freshwater	141101.01	35275.25	4	0.14	141101.01	35275.25	4	0.15	0.00	0.00
Heather	203853.26	67951.09	3	0.11	203853.26	67951.09	3	0.11	0.00	0.00
Heather Grassland	8462260.90	42738.69	198	7.16	8458800.07	42938.07	197	7.15	-199.38	0.01
Improved Grassland	6639102.25	15959.38	416	15.04	6627304.45	15931.02	416	15.11	28.36	-0.07
Inland Rock	16824.21	16824.21	1	0.04	16824.21	16824.21	1	0.04	0.00	0.00
Neutral Grassland	6872.78	6872.78	1	0.04	6872.78	6872.78	1	0.04	0.00	0.00

TABLE 4.16. SUMMARY TABLE OF CHANGES IN MEAN PATCH SIZE AND PATCH DENSITY FOR SITE 1: THE A465, SCENARIO B

	Baseline Calculation				**Scenario B**					
	Total Area (m^2)	**MPS (m^2)**	**Total Patches**	**PD (patches per 100ha)**	**Total Area (m^2)**	**MPS (m^2)**	**Total Patches**	**PD (patches per 100ha)**	**MPS Impact (m^2)**	**PD Impact (patches per 100ha)**
Acid Grassland	4763443.10	18534.80	257	9.29	4712128.96	18698.92	252	9.20	-164.13	0.09
Arable and Horticulture	384215.31	16008.97	24	0.87	368775.44	17560.74	21	0.77	-1551.76	0.10
Broadleaf Woodland	3651767.99	11483.55	318	11.50	3497491.77	11815.85	296	10.81	-332.30	0.69
Coniferous Woodland	618759.86	19336.25	32	1.16	617428.46	19917.05	31	1.13	-580.80	0.02
Freshwater	141101.01	35275.25	4	0.14	141101.01	35275.25	4	0.15	0.00	0.00
Heather	203853.26	67951.09	3	0.11	203853.26	67951.09	3	0.11	0.00	0.00
Heather Grassland	8462260.90	42738.69	198	7.16	8453290.12	42910.10	197	7.19	-171.41	-0.04
Improved Grassland	6639102.25	15959.38	416	15.04	6610885.20	15929.84	415	15.16	29.54	-0.12
Inland Rock	16824.21	16824.21	1	0.04	16824.21	16824.21	1	0.04	0.00	0.00
Neutral Grassland	6872.78	6872.78	1	0.04	6872.78	6872.78	1	0.04	0.00	0.00

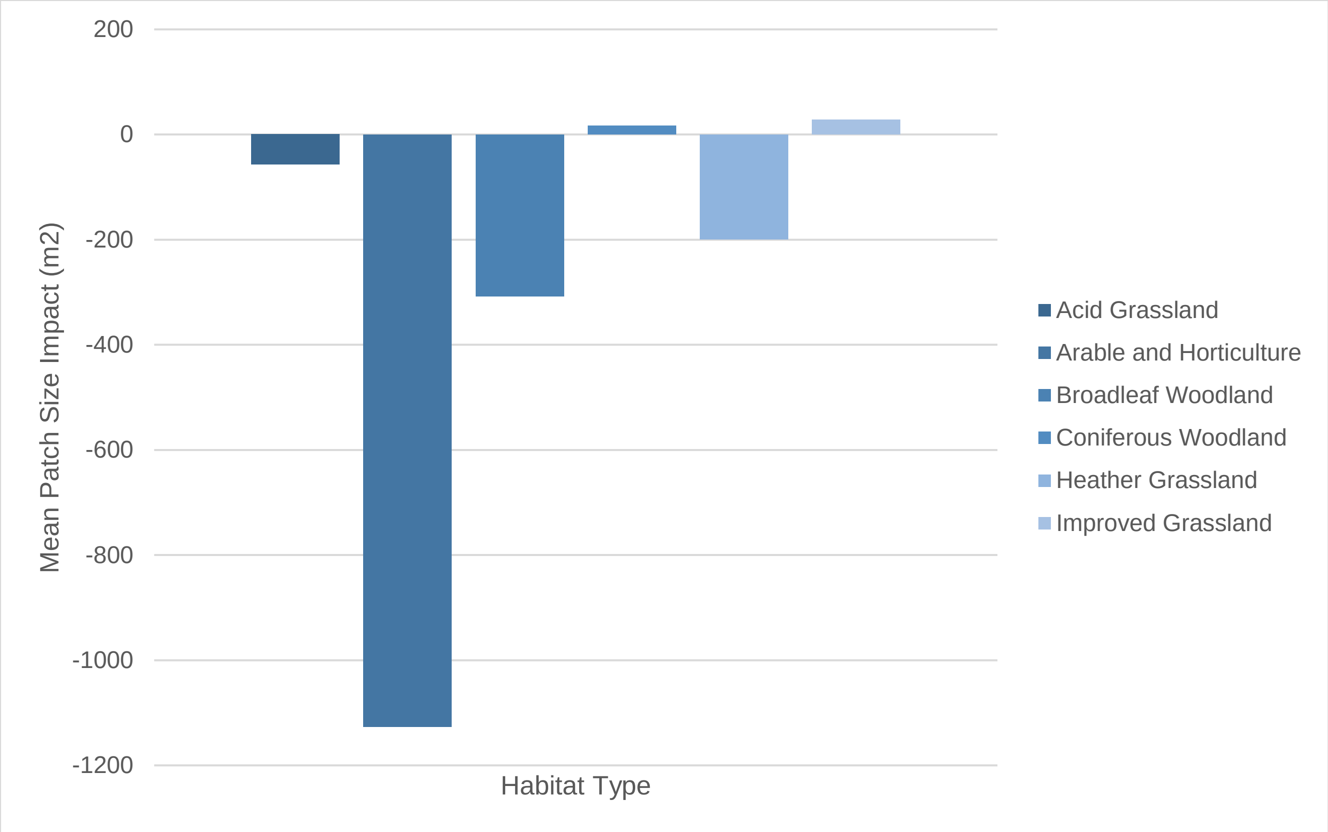


FIGURE 4.20. THE IMPACT VALUE OF MEAN PATCH SIZE ON HABITAT TYPES FOR SITE 1: A465 SCENARIO A

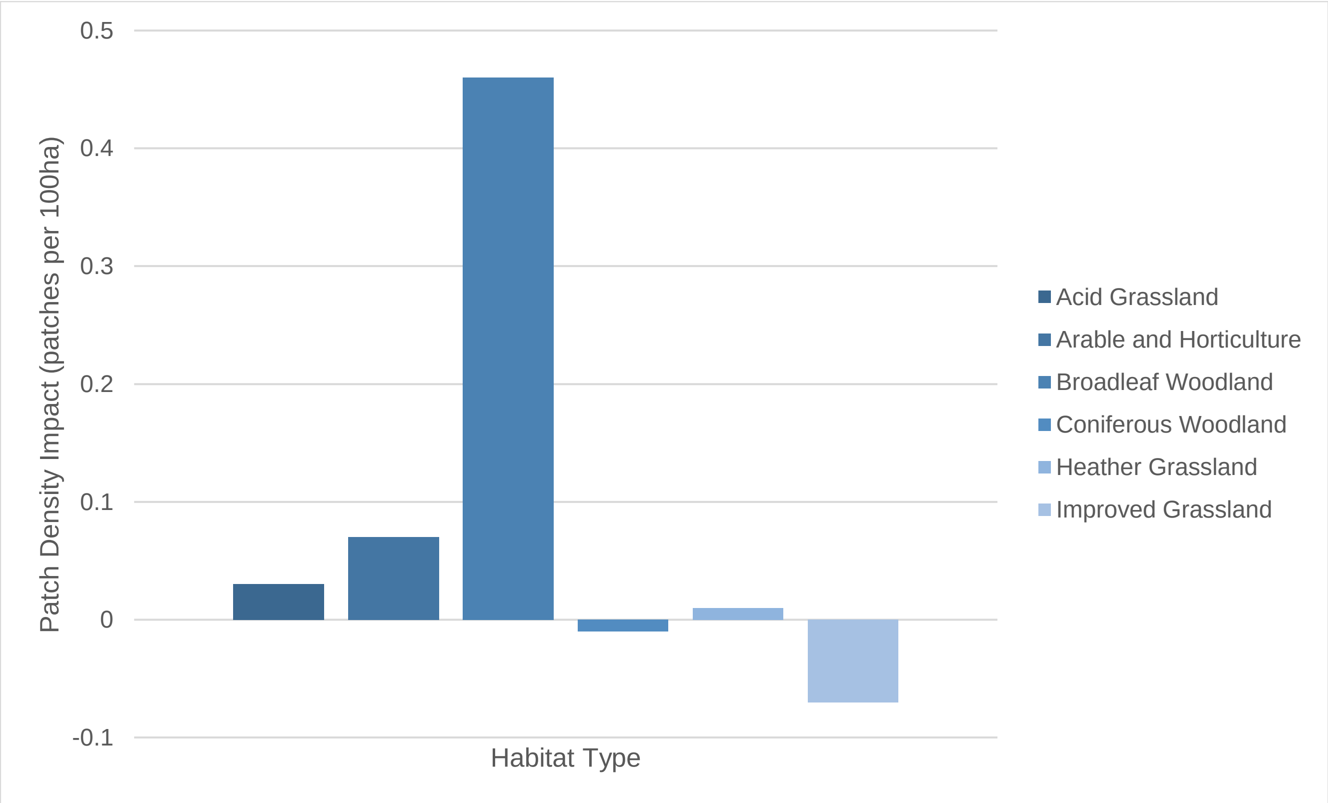


FIGURE 4.21. THE IMPACT VALUE OF PATCH DENSITY ON HABITAT TYPES FOR SITE 1: A465 SCENARIO A

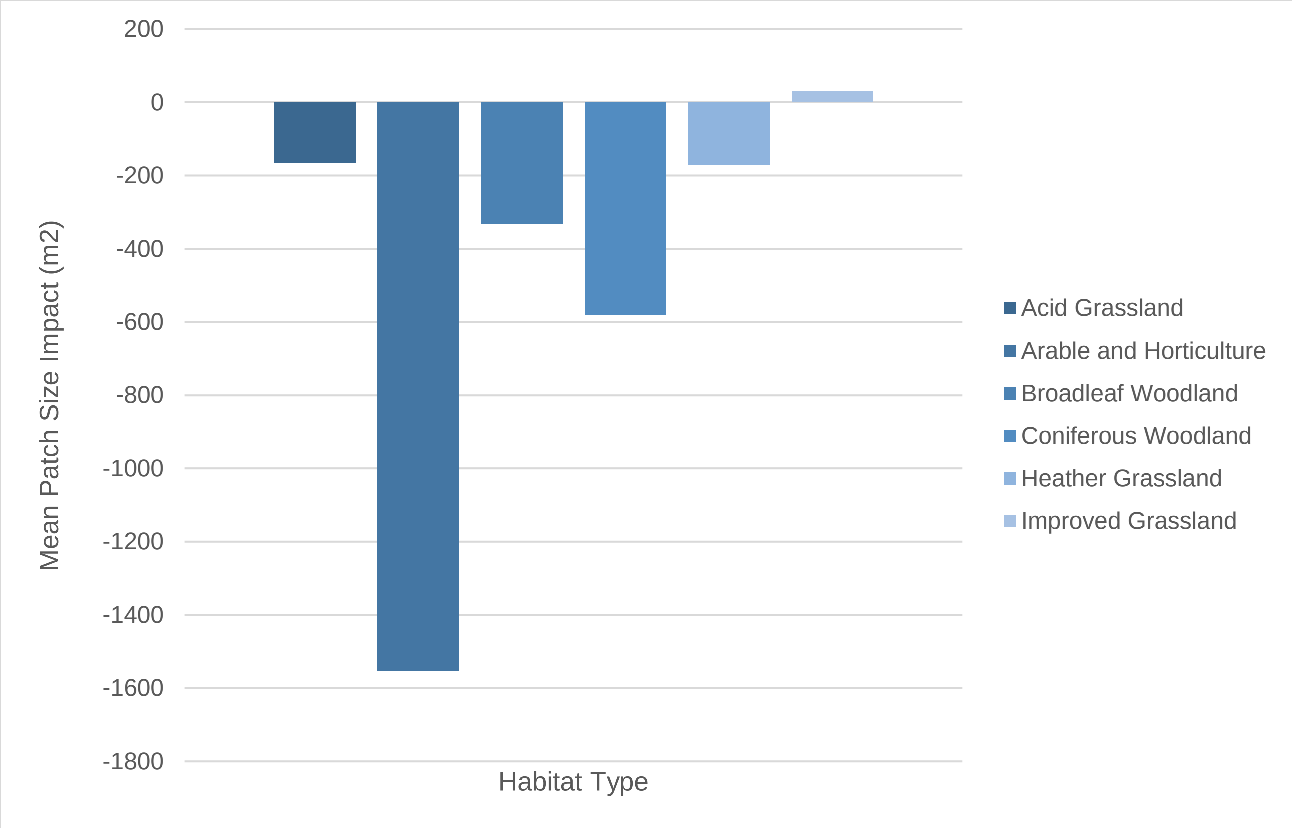


FIGURE 4.22. THE IMPACT VALUE OF MEAN PATCH SIZE ON HABITAT TYPES FOR SITE 1: A465 SCENARIO B

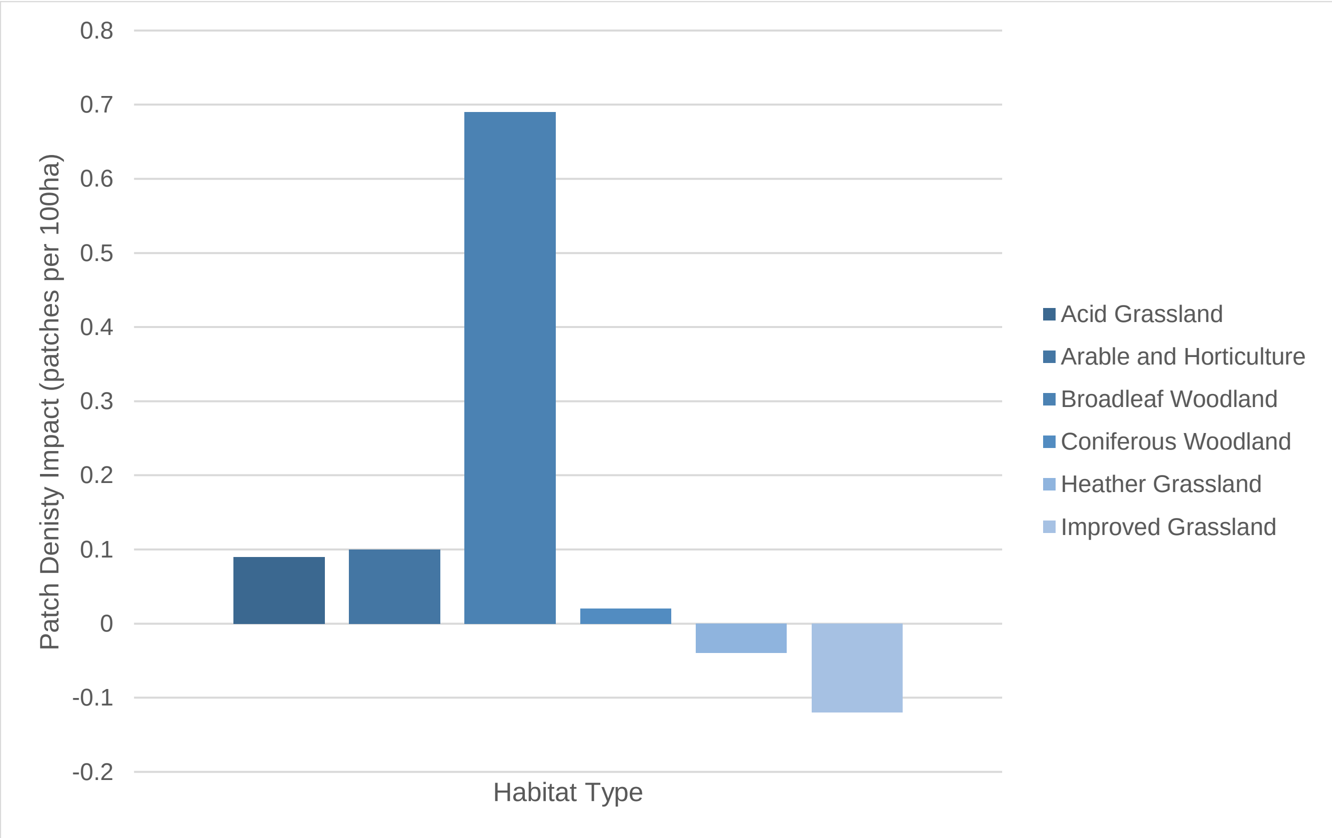


FIGURE 4.23. THE IMPACT VALUE OF PATCH DENSITY ON HABITAT TYPES FOR SITE 1: A465 SCENARIO B

4.4.4.2. SITE 2: THE A14

The class level results for Site 2, the A14, are summarised in Table 4.17 for Scenario A and Table 4.18 for Scenario B. There were LCM habitat types surrounding this site, each with a change value for MPS and PD for each habitat type and each scenario. For Scenario A, two habitat types had an increase in MPS, three had a decrease in MPS, and one had no change in MPS. The largest change in MPS was for the Arable and Horticulture habitat that increased its MPS by 689.19m^2. The smallest change in MPS was Improved Grassland, that reduced its MPS by 85.05m^2. For PD, one habitat type had an increase in PD, two had a decrease in PD, and seven had no change in PD. The two habitat types that saw a decrease in PD were Arable and Horticulture and Broadleaf woodland with both PD values decreasing by 0.06 patches per 100ha. For Scenario B, two habitat types had an increase in MPS, three had a decrease in MPS, and one had no change in MPS. The largest change in MPS was for the Arable and Horticulture habitat that increased its MPS by 1582.28m^2. The smallest change in MPS was Improved Grassland, that reduced its MPS by 84.42m^2, which remained the same from Scenario A. Four habitat types had an increase in PD, no habitat types had a decrease in PD, and two had no change in PD. The largest change was for the habitat type Arable and Horticulture with its PD decreasing by 0.34 patches per 100ha. The smallest value of change was seen in Neutral Grassland with a PD decrease of 0.02 patches per 100ha for Improved Grassland. The chart outputs are shown in Figures 4.24 to 4.27.

TABLE 4.17. SUMMARY TABLE OF CHANGES IN MEAN PATCH SIZE AND PATCH DENSITY FOR SITE 2: THE A14, SCENARIO A

	Baseline Calculation				Scenario A					
	Total Area (m^2)	**MPS (m^2)**	**Total Patches**	**PD (patches per 100ha)**	**Total Area (m^2)**	**MPS (m^2)**	**Total Patches**	**PD (patches per 100ha)**	**MPS Impact (m^2)**	**PD Impact (patches per 100ha)**
Arable and Horticulture	58149364.21	97402.62	597	8.32	57874169.13	98091.81	590	8.26	-689.19	0.06
Broadleaf Woodland	1063708.15	11080.29	96	1.34	1054393.13	11586.74	91	1.27	-506.44	0.06
Fen, Marsh and Swamp	32419.72	16209.86	2	0.03	32419.72	16209.86	2	0.03	0.00	0.00
Freshwater	1800837.27	64315.62	28	0.39	1794922.27	64104.37	28	0.39	211.25	0.00
Improved Grassland	6107188.79	27143.06	225	3.14	6088046.79	27057.99	225	3.15	85.08	-0.01
Neutral Grassland	657888.97	38699.35	17	0.24	656039.22	38590.54	17	0.24	108.81	0.00

TABLE 4.18. SUMMARY TABLE OF CHANGES IN MEAN PATCH SIZE AND PATCH DENSITY FOR SITE 2: THE A14, SCENARIO B

	Baseline Calculation				Scenario B					
	Total Area (m^2)	**MPS (m^2)**	**Total Patches**	**PD (patches per 100ha)**	**Total Area (m^2)**	**MPS (m^2)**	**Total Patches**	**PD (patches per 100ha)**	**MPS Impact (m^2)**	**PD Impact (patches per 100ha)**
Arable and Horticulture	58149364.21	97402.62	597	8.32	57510229.83	98984.91	581	8.66	-1582.28	-0.34
Broadleaf Woodland	1063708.15	11080.29	96	1.34	1042359.85	11581.78	90	1.34	-501.48	0.00
Fen, Marsh and Swamp	32419.72	16209.86	2	0.03	32419.72	16209.86	2	0.03	0.00	0.00
Freshwater	1800837.27	64315.62	28	0.39	1786539.46	63804.98	28	0.42	510.64	-0.03
Improved Grassland	6107188.79	27143.06	225	3.14	6061136.61	27058.65	224	3.34	84.42	-0.20
Neutral Grassland	657888.97	38699.35	17	0.24	653579.18	38445.83	17	0.25	253.52	-0.02

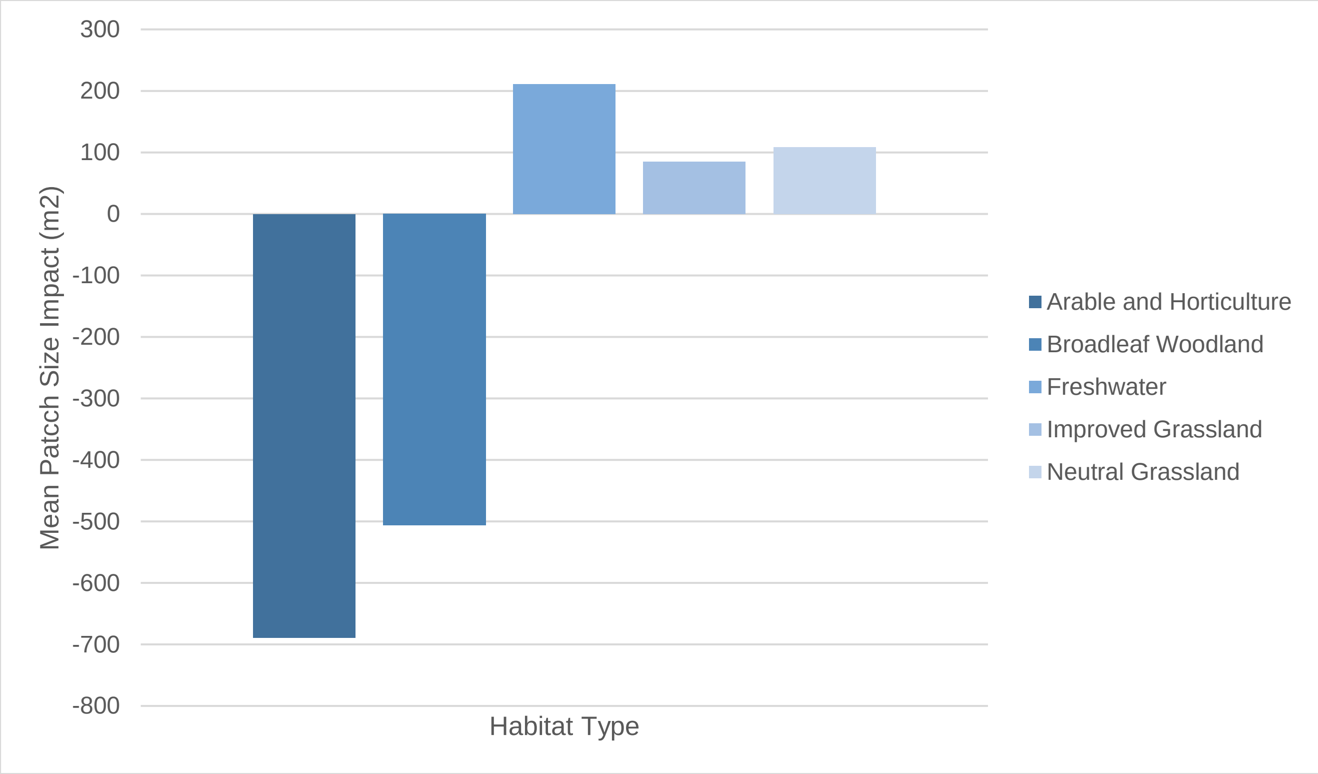


FIGURE 4.24. THE IMPACT VALUE OF MEAN PATCH SIZE ON HABITAT TYPES FOR SITE 2: A14 SCENARIO A

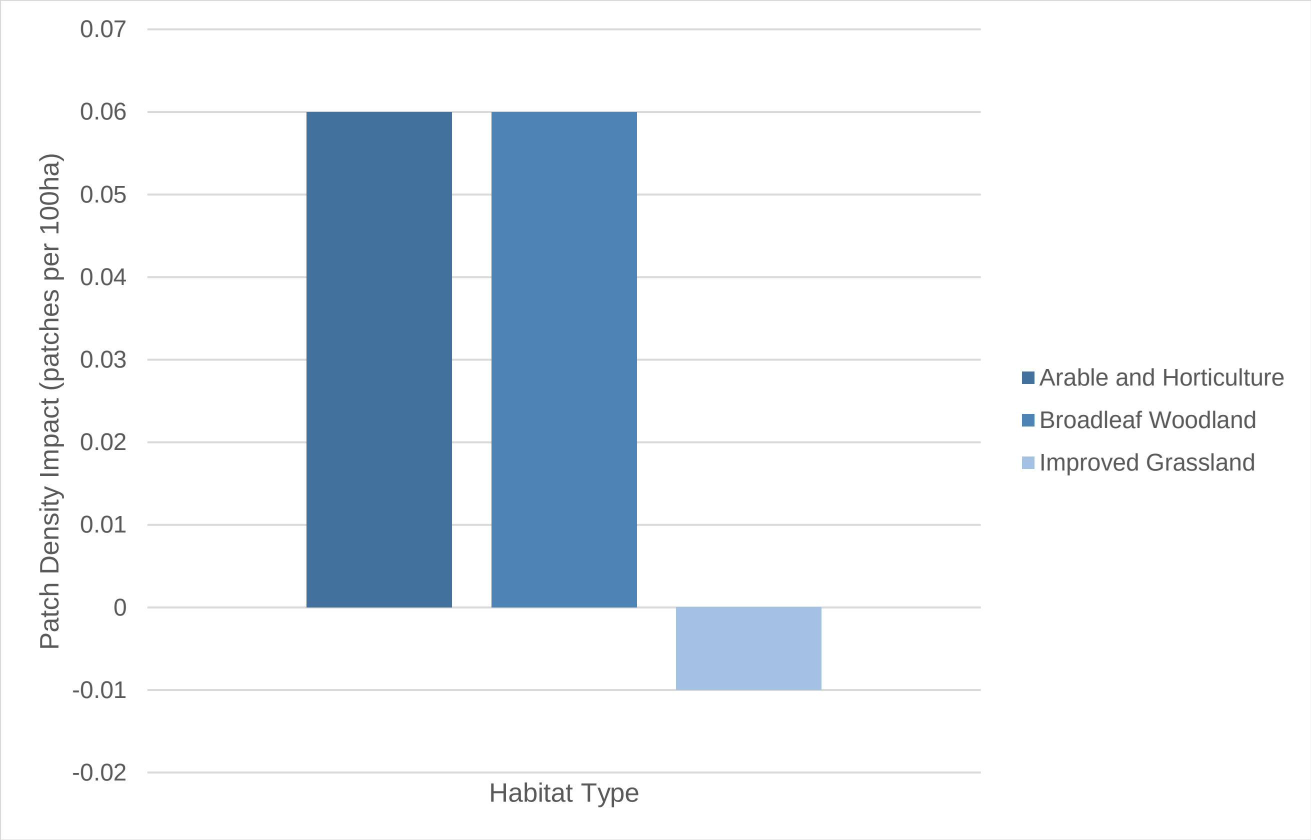


FIGURE 4.25. THE IMPACT VALUE OF PATCH DENSITY ON HABITAT TYPES FOR SITE 2: A14 SCENARIO A

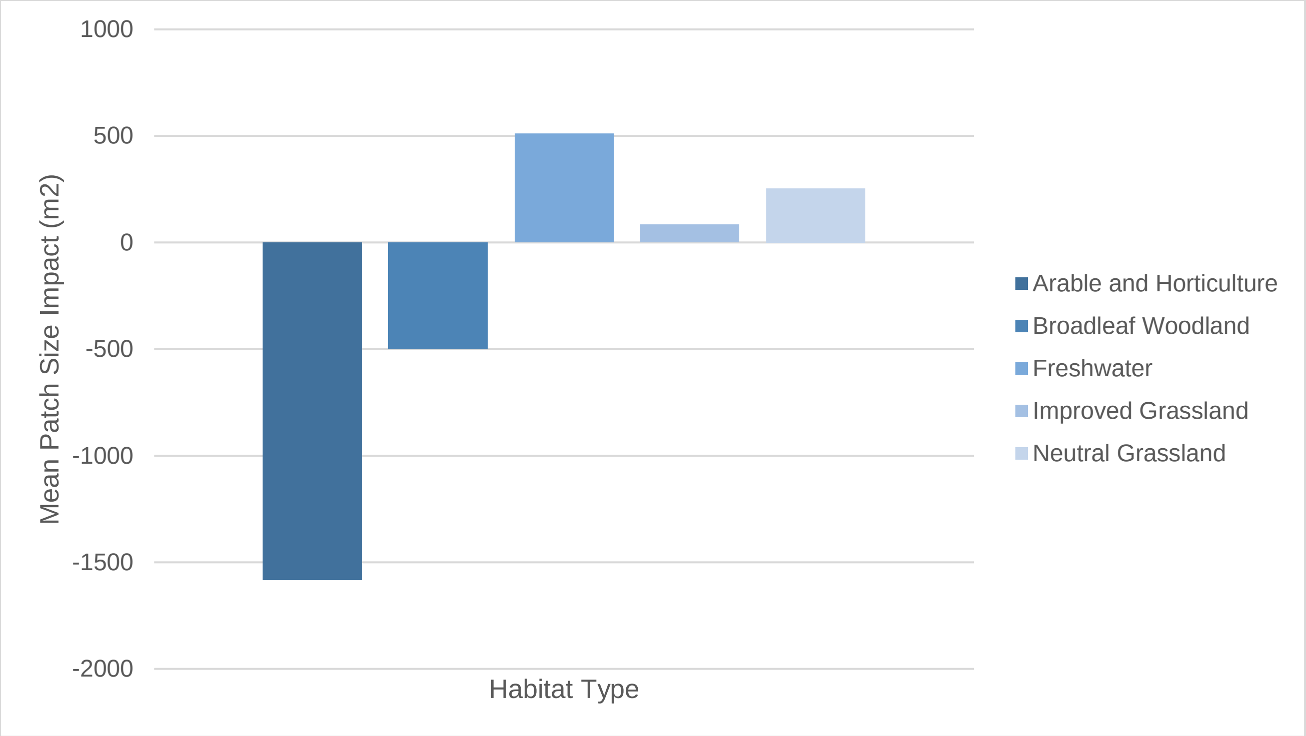


FIGURE 4.26. THE IMPACT VALUE OF MEAN PATCH SIZE ON HABITAT TYPES FOR SITE 2: A14 SCENARIO B

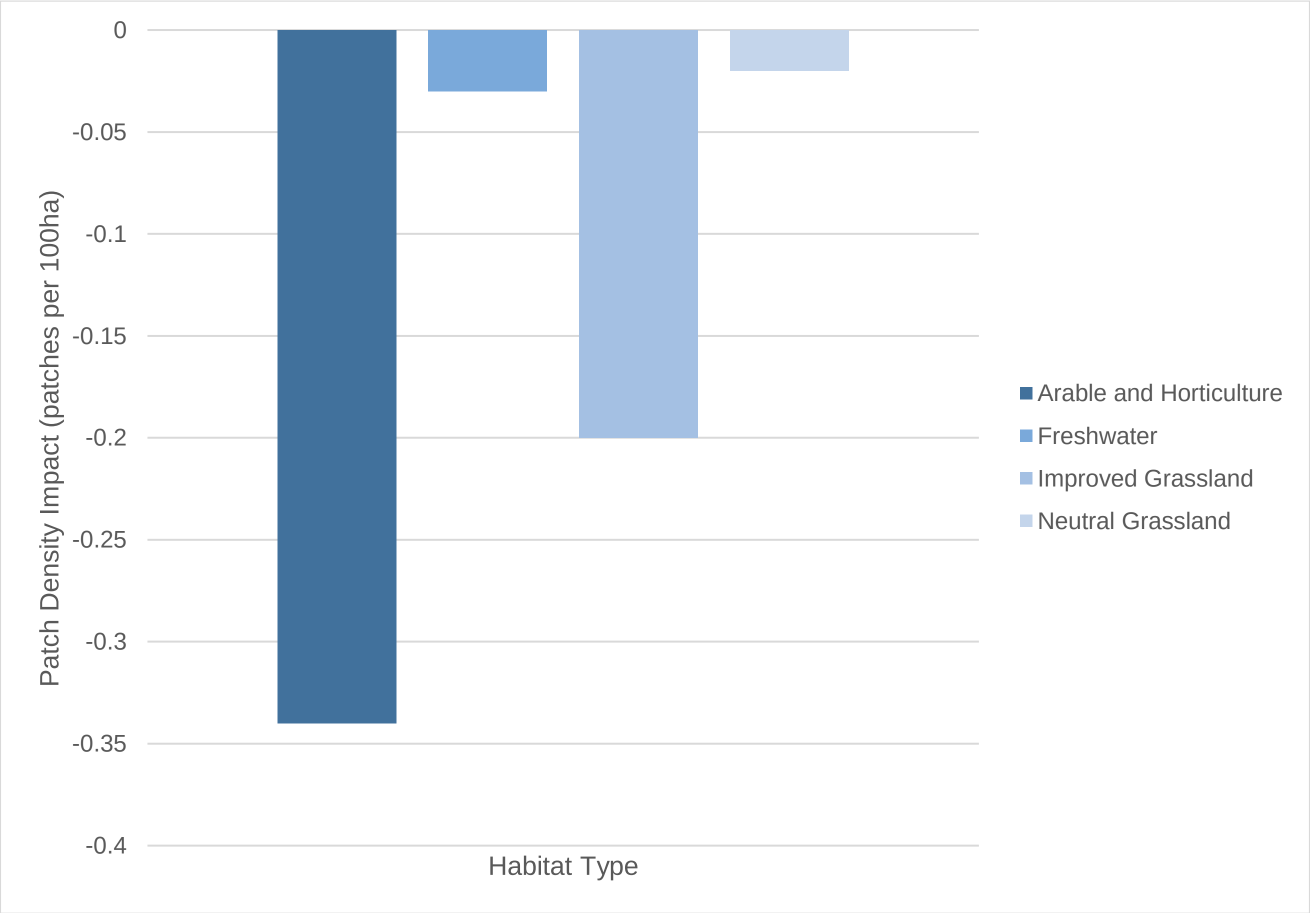


FIGURE 4.27. THE IMPACT VALUE OF PATCH DENSITY ON HABITAT TYPES FOR SITE 2: A14 SCENARIO B

4.5. END-USER TESTING

The end-user testing uses a standardised open-ended interview targeted at environmental managers, ecologists, and environmental advisors within the sponsor company. Five participants were asked eight questions to understand the practicality of implementing GIS applications into the business to inform decision-making, and whether this is viewed as a suitable innovation for improving environmental sustainability. The interview questions can be seen in Table 4.19 and key results summarised in Table 4.20 and Table 4.21, full interview transcripts can be seen in Appendix D.

TABLE 4.19. SUMMARY OF INTERVIEW QUESTIONS

No.	Questions
1	What is your previous experience with GIS?
2	What is your experience of environmental data?
3	Does the visualisation of biodiversity values improve your understanding of the on-site biodiversity? If so, how?
4	Do you think implementing this technology for all biodiversity management is feasible?
5	What do you think are the limitations in an implementation of GIS applications such as this?
6	Do you think innovations such as this GIS implementation improve environmental sustainability?
7	Do you believe it is the responsibility of the contractor or client to promote sustainable development?
8	Do you think that Costain is doing enough as a business to promote sustainable development? What more could be done?

TABLE 4.20. SUMMARY OF KEY RESULTS FROM QUESTIONS 1-4 OF THE INTERVIEWS

Part.	Q1	Q2	Q3	Q4
1	Multiple university GIS Modules, and industry experience using GIS in environmental role.	Data for environmental statements and technical reports, environmental data collection using GIS	Allows for easy visualisation of biodiversity values and comparisons between the baseline and predicted loss	Potentially feasible but we need sufficient baseline data, if this is not available then we will not be able to see the change.
2	University modules, and used tools developed on other projects. Has only been a viewer.	Plotting of invasive species data, water courses, and used a live web-viewer to view constraints	Makes the concept and changes more understandable and user-friendly	Possible and necessary as we can integrate it with other environmental data.
3	No prior experience of GIS until working with the Costain GIS team. Using interactive maps and looking at site specific layers	Experience is project dependent; some projects have environmental studies and data from the client or JV, others have none.	Allows for consideration of details that hadn’t been looked at previously in regard to environment	Can see this happening, but unsure how well the applications would work on a brownfield site with little biodiversity to begin with,
4	Experience with QGIS to make Phase I survey maps, and working with self-educated GIS technicians	Experience with field survey records, survey maps for Phase I. Using a Google Earth image to annotate Phase I habitats	Helps with understanding the biodiversity of the scheme, which can be lengthy given the size of schemes.	Feasible if commitment comes from a higher level (i.e. government) then the business will have to follow
5	Multiple modules at university, viewer experience with Costain	Constraints data for site selection in modules, open-source data from Natural England, Environment Agency etc.	Makes biodiversity a less abstract concept and helps non-experts understand	Feasible with drive and investment from the business to pay for all projects to have the technology and man-power to implement.

TABLE 4.21 SUMMARY OF KEY RESULTS FROM QUESTIONS 5-8 OF THE INTERVIEWS

Part.	Q5	Q6	Q7	Q8
1	May be used to commoditise nature and remove irreplaceable habitats	Gives people more understanding and visually shows the impact in which a project is having	It is the responsibility of both the client and contractor to promote sustainable development	Costain can do more by only offering sustainable solutions rather than options.
2	GIS is not visually scalable when working in the field collaboratively	This makes the data more understandable to everyday engineers, the visual helps them understand	It is the responsibility of both, the business cannot implement an innovation if the client is not willing to pay for it, or drive the initiative	The business needs to further educate the supply chain
3	Previous comment included in this answer, but also high value data and funding from the client	Potentially significant. Helpful to demonstrate outputs that are easy to understand without needing to know the theory. Helpful for running multiple scenarios and providing options.	It's a two-way street. Contractors should be pushing alternative options to the client, but the client needs to be invested and should be setting expectations. Example of HS2 setting ambitious targets and providing the funds to follow through	Costain are improving but they could do more. For example, challenging the client, be more selective about the project they do, and investing more to ensure we are considering sustainability
4	Communication with design partners as designs and change situations change (e.g., more clearance) which is not relayed back into the biodiversity assessment	Allows for quantification, which can be difficult to do. But in this case, having details about high value biodiversity areas makes the biodiversity assessment easier and more achievable	Both, but the ultimate drive needs to come from the client. However, it is up to the contractor to be innovative to implement client requests	Costain could do more, but so could everyone else. The drive needs to come from the top down and focus should be put onto reducing impacts on schemes.
5	Good baseline data, also drive from the business to implement and realise the benefits	Being able to quantify an impact allows the business to be more transparent, and could be the driver to reducing impacts further	Both. The contractor needs to be able to provide alternative sustainable options, but the clients need to be willing to pay for it.	Costain could do more. They are saying the right things but there is not enough monetary investment or drive to push those alternatives

4.6. CONCLUSION

This chapter presented the findings of the research inquiries. This includes the document review, baseline simulations, impact value simulations, and end-user testing. The format of the results included charts, tables, and map visualisations. The following chapter discusses the findings from this chapter, limitations, recommendations, and opportunities for future research.

5. DISCUSSION AND CONCLUSION

5.1. INTRODUCTION

This research has investigated how GIS applications can be suitably designed to facilitate large infrastructure companies in sustainable development by reducing their impacts to biodiversity. The findings of the research have shown that environmental management and environmental sustainability are improved using the innovation of GIS applications. The research suggests that mitigations in the limitations of geospatial data and visualisation make the use of the GIS applications feasible within the sponsor company and integrate with current environmental procedures for recording baselines and impacts.

This chapter serves to discuss three themes that are relevant to the research objectives: environmental sustainability and management (Objective 1), limitations and critiques within cartographic modelling (Objective 2), and the corporate implementation of GIS applications (Objective 3).

5.2. INTEGRATION OF GIS INTO ENVIRONMENTAL MANAGEMENT

5.2.1. INTRODUCTION

The literature review stated that there was limited literature regarding the implementation of GIS for the implementation of No Net Loss (NNL) initiatives, which are becoming dominant within UK biodiversity policy. There is also no mandate for NNL procedures in the design phases of the stages of construction development. This was incorporated into the research objectives, specifically Objective 1: *To design and build geospatial models that are suitable for improving environmental management on large infrastructure development projects, including relevant context in environmental management and design*. As part of this objective, eight applications were built as a Spatial Decision Support (SDSS) tool for environmental management to ultimately improve environmental sustainability in large infrastructure development. This section discusses the results of the applications, the implications regarding limitations discussed within the literature, limitations of fragmentation metrics, and recommendations and opportunities for future research.

5.2.2. THE ENVIRONMENTAL IMPACT ASSESSMENT (EIA)

The literature review showed that there is a vast amount of integration between GIS and the EIA, with examples from authors going back nearly 20 years. Application 1 visualised the hard borders of statutory conservation designations in England, Wales, and Scotland for the Contract Biodiversity Action Plan (BAP) and the baseline of the EIA on the sponsor company's internal platform. Overlaying different layers over the study site allows for the categorisation of environmental components and attributes and identifying project activities and the network of possible impacts (Erikson 1994), The results of the Study of the End User showed that the imported data from Defra's MAGIC map for Application 1 was only mentioned once, with no further instruction on data availability or instructions for use. GIS is already considered highly relevant, and a versatile platform for efficient data collection, enhanced system requirements and operations (Gontier *et al.* 2010; Yadav and Mishra 2014) for integration with the EIA. Therefore, hosting the data using an internal platform that is available for use across the business could enable more users to use the application. In addition to this, providing a more realistic approach for habitat descriptors and opportunity to analyse their interrelationships, giving more detail to previously vague impacts and a method of evaluation of predicted impacts (Ortolano and Sheppard 2012; Yadav and Mishra 2014).

5.2.3. No Net Loss Values

The existing solution for calculating NNL within the sponsor company was identified as *SHE-T-434 Biodiversity Units Tracker*. The tool, in the format of an Excel file, allows the user to calculate the biodiversity units before and after the project to determine overall losses and gains using the metrics from Defra's 2012 scheme. The version of the toolkit that is available is from September 2015. This could be considered out-dated, considering the UK Government's *25 Year Environment Plan* was published in 2018. There is no GIS component to this tool, thus giving no spatial relevance to the list of habitats. This is in line with the lack of literature that integrates GIS with NNL calculations, no visual representation of surrounding habitats means there is no geographical evidence base for the locating mitigation or offsetting sites (zu Ermgassen *et al.* 2019; Yu *et al.* 2018). The integration of GIS with environmental data allows for the evaluation of changes over time, can be updated and used for multiple projects (Eedy 1995), in the context of the EIA. However, the principle has been successfully applied in this instance to the Defra 2012 scheme through the visualisation of metrics (Applications 3-4) and the biodiversity units (Applications 5-6), which has not previously been done before. Thus, giving the user previously discussed benefit of a GIS integration, including the querying of a specific location, the selecting of a point which allows the user to see the corresponding attributes and any supporting photographs or documents, the suer can also search and query the data and export results and perform data management and configuration (Yadav *et al.* 2014).

5.2.4. Fragmentations Indicators

Application 7 analyses the change in Core Area (CA) and Nearest Neighbour (NN). Both sites had a decrease in CA for both scenarios. As the buffer for CA was 130m and the highest scenario value was 14.6m, the road widening did not affect the actual CA but reduced the size of the patches so they would contain less CA. There was no reduction of CA for the A465, meaning no patches containing CA were removed. For Site 2, the percentage of CA lost in the area across the site for both scenarios is less than 0.00%. However, this can be explained, considering 0.47% of the total area was removed from the site in Scenario A, and 1.09% was removed in Scenario B. However, over 20% of patches on the site had a reduced amount of CA. The impact for reduced CA is an increase in imposed habitat edge. All the reduced CA patches are Arable and Horticulture, which means that the impacts on specialist interior forest species are not relevant.

Changes in NNL imply that patches may not be accessible, potentially disrupting the habitat network of species with a small home range. For example, Baguette *et al*. (2000) state that an increase in patch distance lowers the probability of movement for migrating butterflies and thus reduced mortality of migrant butterflies. With 24 butterflies within the UK that have their own UK Biodiversity Action Plan (UK BAP), the distance between patches could be crucial as part of a Contract BAP that has identified any of those species.

The implications of reduced MPS are the habitat loss within the patches; for example, the largest loss of MPS was on Site 2 Scenario B with a loss 510m^2 of Freshwater habitat. In addition to the general implications of habitat loss to species, the loss of freshwater habitat would have major consequences for amphibian species (Cushman 2006). Cushman (2006) summarised that amphibians have a high vulnerability to death when navigating through hostile terrain, including roads, and are vulnerable to pathogens, environmental pollution, and climate change. With a decrease in habitat size, populations may seek different freshwater patches for reproduction and may affect the viability of the population (Cushman 2008). Four amphibians in the UK are UK BAP priority species (WWT 2020); therefore, measuring the loss of MPS for Freshwater would be a factor to be included on the Contract BAP. The largest increase in MPS was also on Site 2 Scenario B, with the MPS of Arable and Horticulture habitat gaining 1582.28m^2 and losing 16 patches. Lindenmayer (2018) states that conservation has been based around general conclusions that larger and more intact patches are better. However, the author states that there is also high conversation value for smaller patches, particularly within already modified landscapes. For example, smaller patches can promote connectivity between other habitat patches, mainly as arable landscapes are considered permeable to grassland specialists (Lindenmayer 2018; Moseley *et al.* 2008). Also, smaller patches may host smaller prey species that may not support predator populations (Lidenmayer 2018).

Both sites and scenarios also had an increase, decrease and no change in PD across the different habitat types. A decrease in PD means that the frequency of patches is reduced, and an increase in PD means the frequency has increased. The largest decrease in PD was Broadleaf Woodland habitat on Site 1 Scenario B. This means that there are fewer patches of broadleaf woodland have been reduced and make up a smaller proportion of patches within the landscape compared to the baseline. Also, a decrease in PD could affect foraging strategies and dispersal rates (Crespi and Taylor 1990; de Kneght *et al.* 2007). An example of the largest increase in PD was also on Site 1 Scenario B for Improved Grassland habitat. The increase implies there is a higher frequency of patches within the landscape. This is positive for dispersal and foraging efficiency, as previously discussed; however, the scenarios that were placed on the sites were habitat removal; therefore, no new areas of habitats have been created. Therefore, an increase in the frequency of patches could suggest that the placement of the road has caused a division of existing patch into two or smaller patches. This could imply species that have a minimum area required for survival. This suggests the need for further research into the application of dynamics of habitat loss impacts on species that require a minimum area for survival and their thresholds, known as percolation theory.

5.2.5. Limitations

In December 2019 Natural England released The Biodiversity Metric 2.0, which is considered an update on the 2012 scheme. The both the baseline and compensation of units are calculated differently, with the baseline now including the factor of connectivity. The application calculates the removal of units from the site, not the value for compensation as the risk factors of time to target condition, spatial risk and ease of creation/restoration have not been considered. The 2012 biodiversity offsetting metric added multiplies based on the risk factors. For example, for Site 1, Scenario B, 15.43ha of broadleaf woodland were removed from the site, if a high condition score were assumed for the habitat, then the number of units removed would be 277.74 units. With risk factors of 30 years to target condition, medium difficulty of restoration, and a high spatial risk for new habitat creation, then the compensation score is 3499.52 units (Figure 5.1). This is over twelves times the number of units removed, and equivalent to 194.41ha of Broadleaf Woodland.

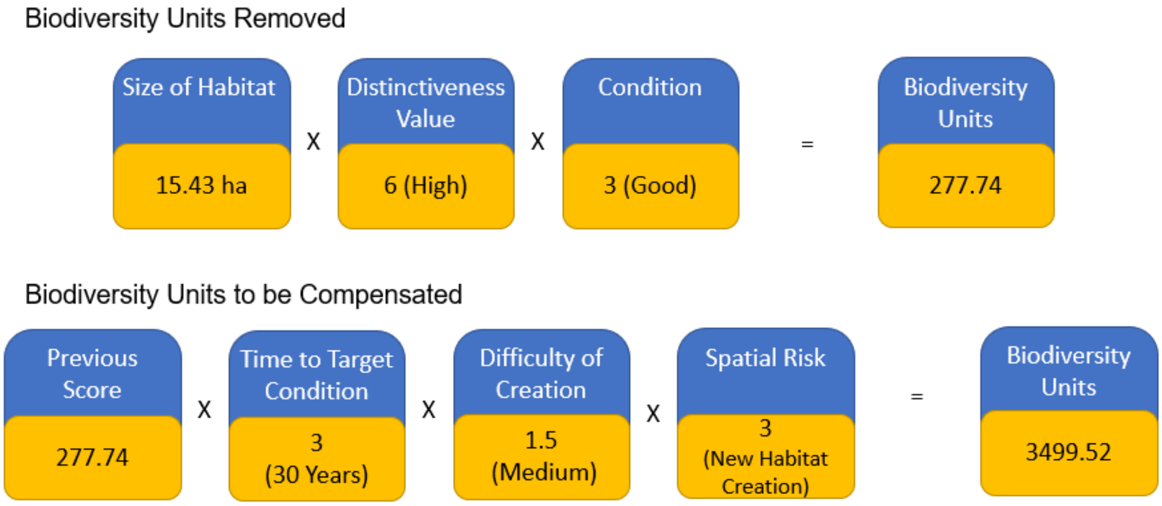


FIGURE 5.1. AN EXAMPLE OF THE BIODIVERSITY UNITS REMOVED WITH THE ASSUMED CONDITION INCLUDED, AND THE COMPENSATION BIODIVERSITY UNIT SCORE BASED ON RISK FACTOR MULTIPLIERS FROM DEFRA'S 2012 OFFSETTING SCHEME

The Biodiversity Metric 2.0 calculates compensation differently to the 2012 scheme. The risk factors for The Biodiversity Metric 2.0 reduce the hectare value of biodiversity units. For the same example, 15.43ha of Broadleaf Woodland removed on Site 1 would have a biodiversity unit value of 319.20, this includes a high connectivity value. This is then multiplied by the 30 years' time to target condition, medium difficulty of creation and new and unconnected habitat risk multipliers to give a value of 63.83 biodiversity units (Figure 5.2). This means that if exactly 15.43ha of Broadleaf Woodland were offset, that offset would be worth 73.40 units, and 67.14ha of Broadleaf Woodland would need to be created to achieve that offset. The Biodiversity Metric 2.0 means contractors can compensate the same removal of habitat with an offset that is smaller than the previous scheme, even with the connectivity value included in the calculation. This further highlights the debate of whether NNL initiatives are suitable for implementation as an environmental management tool. Suter (1993) discusses the use of values that are not a hard measure (e.g., length, volume etc.) and their dependence of subjective opinions. Changing multipliers for metrics is an example of this; with no clear definitions of metric values and a <30% success rate in replacing lost biodiversity (Suding 2011), there is little to suggest whether this change has occurred to improve the likelihood of NNL targets being met due to a decrease in compensation, or whether there is ecological evidence to support these metric values. It is suggested that the new metrics for the calculation of biodiversity units be further reviewed and implemented within future applications as required by policy.

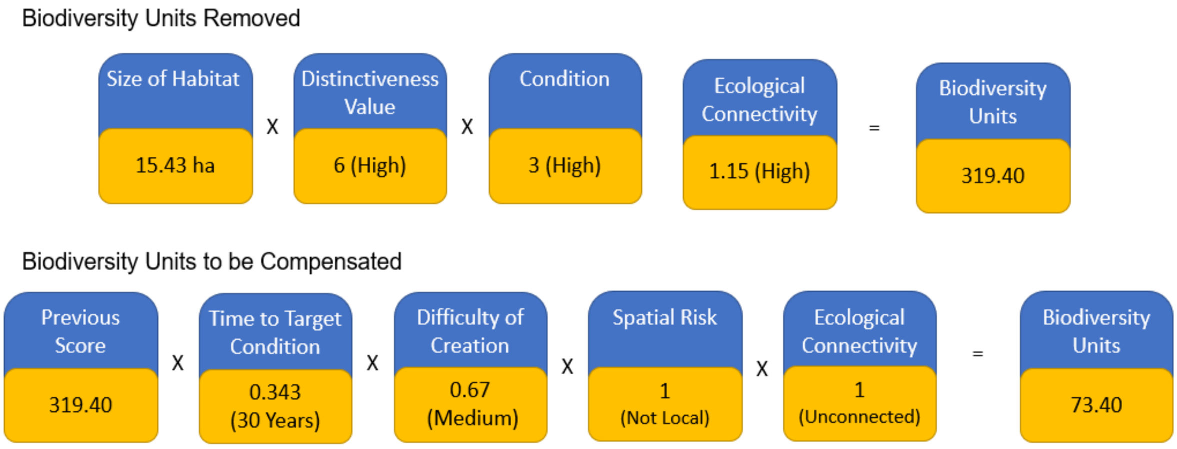


FIGURE 5.2. AN EXAMPLE OF THE BIODIVERSITY UNITS REMOVED WITH THE ASSUMED CONDITION INCLUDED, AND THE EQUIVALENT BIODIVERSITY UNIT SCORE BASED ON RISK FACTOR MULTIPLIERS FROM DEFRA 2.0.

Although the integrated use of landscape metrics is considered useful in landscape mapping and analysis, it is a further limitation to the implementation of GIS in environmental management is the use of landscape metrics. Applying numerous metrics without a clear hypothesis could result in a 'fishing trip', which could confirm a desired outcome by just selecting certain metrics (Gustafson 1998). In addition, the results of landscape metrics can be interpreted without understanding the underlying ecological processes does not address or explain the causality behind these changes (Li *et al.* 2005; Liu and Yang 2005). Liu and Yang (2005) stated that the quantification of changes and that studies should include ancillary data and qualitative methods to fully understand the underlying processes associated with the consequences of landscape changes. In addition, the authors state that quantifying changes at different scales may lead the way to a need for specific measures, and more specific metrics for habitat fragmentation rather than vague indicators.

5.3. ENVIRONMENTAL DATA AND VISUALISATION OF OUTPUTS

5.3.1. INTRODUCTION

The development of GIS applications involves the use of software and data to create visual outputs. The limitations surrounding data and visualisation can impact the accuracy and readability of results. This was incorporated into the research objectives, specifically Objective 2: *To understand the limitations of environmental data, processes, and visualisation that can improve environmental management*. The following sections discuss the limitations around the datasets used for the applications, and the visualisation of the outputs.

5.3.2. ENVIRONMENTAL DATA LIMITATIONS

There has been an increase in the amount of relevant digital environmental data published and being made available by governments, and private companies via remote sensing or environmental monitoring (Kogan *et al.* 2010). Understanding data restrictions and limitations when integrating environmental data into decision-making is key, ensuring that data requirements should be identified early as data availability and accessibility may be influenced if further data collection is needed (Glasson and Therivel 2013; Gontier *et al.* 2010; Johnson and Gillingham 2005). The datasets for Application 1 were provided by Natural England, Natural Resources Wales (NRW), and the Scottish Government, each in their own format. The data from Natural England is hosted by ESRI and can be imported without having to store the layer; as the sponsor company also have a subscription to ArcGIS Online, the data can be consumed as part of that subscription from ESRI. However, the uploading of updated data falls on ESRI, if an update is missed or not provided then the data will become outdated. The data from NRW is consumed as a Web Map Service (WMS). A WMS is a service that is hosted on another server but can be added to ArcGIS Enterprise via a URL. Finally, the data from Scotland is only available as a downloadable shapefile and needs to be published from desktop software onto ArcGIS Enterprise. The lack of consistency and increased heterogeneity in data formats between England, Scotland, and Wales can affect the precision and accuracy of the data (McAfee and Brynjolfsson). Factors affected include storage costs, processing time, and manual checking for updates.

Data for Application 2 was collected from the NBN, this data is based on previous sighting records, with data extracted within a 5km boundary of both study sites. Outside of bias in data collection, the coverage of data is a limitation point for this application. Study Site 1: The A465 has data that covers $42km^2$ across the site of $183.14km^2$, and Study Site 2: The A14 has data that covers $36km^2$ across the site of $364.79km^2$, both in the form of 1km square grids. This means that the percent of coverage of approximately 23% and 10% for sites 1 and 2, respectively. There are many limitations when using species distribution data. The species baselines rely on biological records rather than spatial data that has been refined and updated. Isaac and Pocock (2015) state that the bias in biological records is well documented, but rarely defined and quantified. They list the four major biases as:

1. uneven recording intensity over time

2. uneven spatial coverage

3. uneven sampling effort per visit

4. uneven detectability across space and time

The first bias, uneven recording intensity over time is the most well-known bias within literature (Isaac and Pocock 2015). As records increase, the grids squares that visualise presence and absence are increasingly filled (Telfer *et al.* 2002). This growth in species records over time is not smooth but unbalanced with peaks and valleys (Isaac and Pocock 2015). The bias of uneven spatial coverage is related to the location of the biological records. Many records are submitted within well visited and geographically defined areas (Isaac and Pocock 2015). The bias of sampling effort per visit relates to the effort that has been given to a set of records to accurately reflect present organisms (Isaac and Pocock 2015) This is dependent on the amount of search time. The standard concept of a species accumulation curve means that more species will be recorded the longer the search time (Ugland *et al* 2003). Finally, species detection can be influenced by vegetation structure, Species detection is strongly influenced by the individual recorder, including their experience and skillset in species identification, the tools available to them, and changing methods in ecological surveys (Isaac and Pocock 2015).

Landcover Map 2015 was successfully used as within the models developed and was chosen based on its relative resolution and relevance to UKBAPs. Previous LCM data have been validated, such as LCM2007, the documentation guide for the previous version of the data, LCM 2007, states:

"*Ground reference data were collected to enable the validation of LCM2007 against a set of data designed to match the spatial and thematic resolution of LCM2007. This allowed LCM2007 to be compared against 9127 ground reference polygons producing an average accuracy of 83%*." (CEH 2007 p4).

However, in the guidance for 2015, validation is only referred to in one sentence: "*LCM was never validated at the spectral sub-class level and users were always urged to use caution if using the sub-class data, so this is unlikely to impact many users*" (CEH 2015 p5). Therefore, to use this dataset with confidence, the LCM2015 should be validated. The UK Soil Observatory, a site hosted by the British Geological Society (BGS) has set up a crowd sourcing site to validate LCM2015. The user can contribute ground-truthing data by clicking anywhere on the map, stating whether the habitat is "Correct" or "Incorrect" and then select the suggested "Land Cover Type" with the option of adding a photograph. This is not necessarily a systematic sampling technique and with ground-truthing points needing validation in themselves. As of February 2020, there are ten ground truthing points on the LCM2015 validation map; six of which label the habitat as correct, and four labelling as incorrect. Considering there are 6,737,558 polygon patches in the LCM2015 vector layer, the validation of ten patches is not sufficient.

5.3.3. VISUALISATION OF APPLICATIONS

The generalisation of environmental data for visualisation is a derived dataset that is less complex than the original dataset and does not replicate the full range of ecological processes that are present within a landscape (Bell 2001; Joao 1998). Although this generalisation allows for the analysis of environmental data and improves the display quality of the map (Joao 1998), generalising is not always a suitable approach to data visualisation. The outputs from Applications 1-8 are a mixture of maps and charts, this was done to improve the readability of the results. Map readability is a major issue within cartography and measures should be taken to reduce those factors that could lead to a misinterpretation of results (Harrie *et al.* 2015). The outputs for the applications were completed based around the factors that influence map readability although there are few rules regarding specifications (Alfredsson *et al.* 2014; Spiess *et al.* 2005). Applications 2-7 successfully generalised the environmental data to show presence/absence surrounding the sites, the metric values based on landcover type, the calculation of biodiversity units, and fragmentation impacts at the patch level. Applications 2, 3, 5 and 6 and 7 each showed one factor of environmental management, whether that was a baseline or impact value. This reduced the amount of information shown on a map, thus reducing complexity (Harrie and Stigmar 2010). In addition, a single colour gradient was used to ensure any can identify and distinguished between colours as 8 men and 1 in 200 women are colour blind (Colour Blind Awareness 2017). Application 4 originally attempted to visualise three independent values to avoid creating an index with multiplied metrics and distorting the values associated with each landcover type. If the colour gradient of the map is weighted by the first value of the index, which in this case is Habitat Distinctiveness. This does give each individual 3-digit value its own colour shade, however this increases the number of colours in the gradient and does not accurately visualise higher values of other metrics if the Habitat Distinctiveness is low. Thus, increasing its visual complexity and reducing its readability. However, the three-digits were classified into four categories ranging from "Very High" to "Low" to highlight the areas that may have a high biodiversity unit. Although, this does classification means that the user can not identify which value is considered "High" by looking at Figures 4.12 and 4.13, the user can still see the original three digits through identify tools on an interactive platform.

5.4. Corporate Implementation

5.4.1. Introduction

Implementation and integration of innovations for improved sustainable development is part of the research objective, specifically Objective 3**:** *To understand the barriers, feasibility, and opportunities for the implementation of environmental GIS applications within a general corporate context and within the sponsor company*. The objective involved two studies based around the sponsor company, Costain Group Plc., the first was a document review to assess current procedures and opportunities for implementation, the second was a set of interviews that discussed not only the feasibility of GIS tools but views on sustainable development within the business. This section includes a discussion of the document review results and their implications, and the interview results. This section is concluded with recommendations and opportunities for further research.

5.4.2. Sponsor Company Environmental Practices

The Study of the End-user aimed to understand the procedures for biodiversity management in the sponsor company, what the key roles are, and how GIS applications can be applied to these procedures. This has been successful as the procedures for biodiversity management are described in *SHE-H-470*. The system of linked documents through The Costain Way (TCW) was efficient as was the use of process mapping biodiversity management and guiding the user to the correct documents. TCW was successful in providing a broad view of the biodiversity management practices across the Costain Group. However, there was no specification as to whether these procedures are required for all projects or are just a best practice guide. There is also no indication if project managers are utilising TCW on their projects, and how efficient the procedure is. In addition, there is no guidance as to where biodiversity management procedures should take place in terms of the stages of construction development. The environment is specifically mentioned outside of a sustainability strategy as part of the Design Responsibility Matrix (DRM) in the Technical Design. By this stage, the spatial coordination of the design would have been signed off by the client, with minimal changes to the design permitted going forward. Unless specified, this could indicate that environmental management and the calculation of biodiversity units is completed once the design has been placed spatially and is not part of the consideration for the placement of the design.

Terms relating to GIS were found a total of four times in the entire documentation search. This shows that despite a workstream of digital integration within the company introduced in Chapter 3, Costain is not integrating GIS as standard on their projects or encouraging its use for biodiversity calculations. GIS is referenced in SHE-T-433 "*Biodiversity Action Plan Template*" in which the author is advised to "*insert description and map of area"* (p3). GIS has been discussed in this thesis and extensively within the literature as a multi-functional tool that is capable of big data processing, numerous spatial analyses, and interactive visualisation. However, only requiring a map insert as part of the template document of the most frequently found environmental term in this review, shows that GIS is not being exploited to its full potential, and Costain are not gaining the decision-support benefits. Biodiversity Action Plan was the term that was most common throughout the keyword search, with a frequency of nearly 0.49. However, there is no mandate for the creation of effective Contract BAPs found within the literature review, with emphasis being on the EIA and NNL calculations. The document recommends the use of datasets for local, national, and international conservation designations from Defra's MAGIC online map application. Natural environment data from across the government is hosted on the MAGIC website and allows users to download and collection spatial data. As the keyword search contained the word *Map*, it confirmed that Defra's MAGIC map is not mentioned in any of the other environmental documents.

The only tool that was discussed as part of the document review was, *SHE-T-434 Biodiversity Units Tracker*. The tool contained ten individual sheets that held information about the habitats on-site and their specific characteristics. The specific process is for the calculation of biodiversity offsetting values; however, offsetting is the last action of mitigation hierarchy and should be avoided. However, there is no indication of the level of evidence required, and which body evaluates this evidence. The version of the toolkit that is available on TCW is from September 2015. This could be considered out-dated, considering the UK Government's *25 Year Environment Plan* was published in 2018, and The Biodiversity Metric 2.0 was released in December 2019.

5.4.3. Feasibility of Applications within the Business

Feasibility of the applications within the business was assessed through five interviews with environmental advisors/managers within Costain that had been shown the applications and their capability. All five of the interviewees had some level of experience using GIS, three had completed modules at the university level, one had project experience, and one has used QGIS. Having environmental specialists on projects that are already aware of the capabilities of GIS, at least to the level of viewing environmental constraints is a start to overcoming the problem of embedding GIS technology in organisations, as presented by Hushold and Levinsohn (1995). In addition to this, the awareness of environmental data improves the barrier of data availability and quality (Bregt *et al.* 2001). For example, Participant 5 was aware of open-source environmental constraints data from agencies such as Natural England, Participant 1 was aware the environmental data needed environmental statements, and Participant 4 was aware of using field survey records in GIS. Thus, suggesting if environmental managers are aware of available environmental data, adding biodiversity management data such as biodiversity units would not be an entirely new concept.

All five interviewees thought that implementing the GIS applications was potentially feasible, if there is sufficient data and drive from the business to do so. This highlight both the organisational and technical barriers that were discussed within the literature review. The organisational barriers from Göçmen and Ventura (2010) are around funding and data issues, along with a lack of purpose of mission, as discussed by Ye *et al.*2014. This is also clear from participants 4 and 5 that state that investment and drive from the business is key to improved feasibility, along with further investment from government bodies. An organisational limitation that is not mentioned in literature is communication between design partners and the environmental team; the interviewee stated that if drawing files (.dwg) were not shared or communicated then the applications would not be up-to-date and would eventually be giving inaccurate values. A technical barrier not mentioned within the literature is the scalability of the maps when in the field. This highlights the importance of geographical resolution in map readability (Harrie *et al.* 2015). The interviewee stated that communication with engineers would be affected if the map outputs were on a tablet or mobile device, suggesting paper maps of A1 size would be more suitable in this instance than an interactive online mapping system.

5.4.4. Limitations

There are some limitations with document reviews; documentation may not always be retrievable, the researcher may be biased with an incomplete selection of documentation, and documents that are not created for research purposes may have a lack of detail (Bowden 2009). In this case, the limitations are minor, all documentation relating to biodiversity management within the Costain intranet was retrievable and used within the study, also meaning the dataset was complete. Also, the lack of detail in the documentation in this case in part of the observation that adds to the analysis rather than it being a methodology limitation. Even with the limitations in mind, this the document review methodology has provided the insights that were sought to help answer the research question. In conclusion, as a tool in conjunction with other research methodologies, Bowden (2009) states that "*Given its efficiency and cost-effectiveness in particular, document analysis offers advantages that clearly outweigh the limitations*." (p32)

5.5. Conclusion

5.5.1. Research Summary

The overall project aim of this Engineering Doctorate, was to critically evaluate how GIS applications can be suitably designed to facilitate large infrastructure companies in sustainable development by reducing their impacts to biodiversity. The research involved in answering these questions are reflected in the following objectives:

Objective 1: To design and build geospatial models that are suitable for improving environmental management on large infrastructure development projects, including relevant context in environmental management and design.

Objective 2: To understand the limitations of environmental data, processes, and visualisation that can improve environmental management.

Objective 3: To understand the barriers, feasibility, and opportunities for the implementation of environmental GIS applications within a general corporate context and within the sponsor company.

The objectives in this thesis used mixed methods; however, the overall research follows a pragmatic approach for performing research in information systems, based on the Design Science Research Method (DSRM). Following the DSRM structure, GIS simulations were developed.

The Study of the End-user identified the specific process within the sponsor company that could benefit from geospatial integration through a review of group-wide environmental management documentation. It was concluded that simulations should focus on the Concept Design and the Developed Design, both of which are stages in construction development for which the contractor is responsible. The simulations were also designed to provide ecological information for the Contract Biodiversity Action Plan (BAP), a group-wide planning procedure within the sponsor company. The simulations for the Concept Design (Applications 1-5) were baselines for habitats, species and biodiversity units that also aligned with the requirements of a Contract BAP.

The models were built and applied to two sites: the A465 and the A14. The simulations for the Developed Design (Applications 6-8) focused on calculating and visualising changes based on the design. The models used parameters developed in research by Geneletti (2002-2004) and were selected and discussed based on the context of the two study sites, the A465 and the A14. Two scenarios were used to represent the change in design: Scenario A represented a road widening of 7.3m, and Scenario B represented a road widening of 14.6m. The models calculated a baseline value and a scenario calculation. The scenario calculation was subtracted from the baseline to generate the impact value. The implications of the impact values were discussed based on the site.

Finally, employees at the sponsor company were interviewed to investigate whether they thought the GIS applications were feasible for implementation within the business. Five environmental managers or advisors were subject to a standardised open-ended ended interview that established their experience with GIS, the feasibility of implementing the GIS applications, and the limitations they saw moving forward. In addition, their views on sustainable development were investigated, including and what more they believed the business could do, and who needs to be the driving force behind that progression. The interviews established that it is feasible to implement the GIS applications, however, there needs to be more support from the business and for reliable baseline data. All the interviewee agreed that both the contractor and client need to be invested in sustainable development, but the client is the ultimate driving force rather than the contractor. Finally, the interviewees suggested that the business could be doing more to promote sustainable development by educating the supply chain in sustainable practice, putting pressure on the client to invest in sustainable development, being more selective when tendering for projects, and only providing delivery options that promote sustainable development.

5.5.2. Conclusions and Recommendations

The results and discussion of the research within this thesis has led to a number of conclusions and recommendations. Firstly, the document review has provided insights relevant to the research problem; through understanding the current methods of biodiversity management, the research can move forward confidently knowing the applications have contextual relevance. In addition to this, the document review has also highlighted some shortcomings and limitations in the practice of biodiversity management. The document review and subsequent discussion have developed into the following recommendations for the end-user:

1. The documents on The Costain Way should specify the placement of documents within the stages of construction development.

2. The sponsor company should mandate the use of GIS in visualising all aspects of the biodiversity management process.

3. Data from Defra's MAGIC map should be used as part of the Concept Design in both tendering and non-tendering stages.

4. The *Biodiversity Units Calculator* should include the visualisation of habitats using GIS, including characters for the calculation of biodiversity units.

5. Biodiversity units should be calculated during the spatial coordination of the design.

6. Changes in species fragmentation should be calculated during the spatial coordination of the design.

The development of the GIS applications to improve environment management, and ultimately environmental sustainability has resulted in the following conclusions and recommendations:

1. Commonly used geospatial modelling techniques within environmental research are suitable for industrial application, providing the limitations of environmental data are understood, along with visualisations that allow for map readability

2. The integration of technology is not a barrier integrating environmental data to the concept design, however, sufficient data and drive to implementation by business are considered key barriers

3. Fragmentation indicators, particularly building from Geneletti's existing research can be applied solely within a GIS environment, using available land cover data, to show changes in landscape pattern at the patch and class level.

4. Based on the use of GIS within the context of infrastructure development, applications are applicable to projects outside of the highways sector, e.g., rail, water, and energy sectors.

Investigations into feasibility through standardised open-ended interviews with environmental employees within the sponsor company resulted in the following preliminary conclusions:

1. As environmental employees have a basic conceptual knowledge of GIS and have used the technology to visualise environmental constraints, the integration of Application 1 should be feasible.

2. Limitations in integrating GIS applications for improved environmental management vary between data quality, appetite from the business, and suitability based on site.

3. Applications and innovations to improve the use of environmental data are considered useful tools in improving sustainable development.

5.5.3. FUTURE RESEARCH

Based on the results, discussion and conclusions of this thesis, a number of opportunities for future research have been identified.

1. As this study focused on one organisation, the implementation and feasibility results may not be transferrable to other organisation and further along the supply chain. In addition, it was discussed that the client needs to be the driving force behind improving sustainable development. Therefore, further research as to the current practices of other large infrastructure sub-contractors, along with clients across different sectors is recommended.

2. The calculations of biodiversity were completed using the Defra 2012 scheme. It was previously mentioned that The Biodiversity Metric 2.0 was released in December 2019 with the added metric of connectivity, and a structural change in the calculation of land for compensation. Therefore, it is suggested that further research to investigate the implications of this change in scheme would be valuable, in addition to updating applications to be implemented within business.

3. As there is no standard rule for the implementation of landscape metrics, and which are most suitable for representing the landscape, information regarding landscape change could be lost through the absence of a particular metric. Therefore, further research into the most suitable metrics for analysing land-use change due to large infrastructure development would be valuable.

4. Limitations and barriers to implementation were discussed in the interviews that had previously not been established within the literature review. Geographical resolution in map outputs could affect effective communication on site due to smaller mobile screens. It is

suggested that further research into visualisation of environmental data on mobile devices and its impact on implementation of innovations for environmental management are investigated.

5. Finally, this thesis looks at aspects of biodiversity, and the presence of particular habitats and species. However, there are further methodologies for quantifying the value of land that are not currently required by policy or have developed initiatives for industry. Therefore, it is suggested that the calculation and visualisation of ecosystem services and natural capital be investigated in the context of large infrastructure planning and sustainable development.

5.5.4. Final Thesis Remarks

The research has met its aims and objects (Chapters 2-5) and confirmed that GIS is a suitable and feasible innovation for improved environmental sustainability. Understanding how new infrastructure impacts the environment is crucial in the development of tools to limit those impacts. The integration of GIS in sustainable development allows contractors to visualise and analyse environmental data to improve decision making in design. Improving design decisions in the Concept Design, when costs are lowest, brings benefits to both the contractor and the environment through the avoidance of habitats and species on the site. Furthermore, GIS integration allows for the adherence to biodiversity policies, and company environmental planning procedure whilst providing a further opportunity to integrate fragmentation into the Contract BAP and EIA. The research, although applied within the context of the sponsor company, has broader implications for GIS in infrastructure design. Through adding standardisations and requirements within infrastructure design that incorporate biodiversity and require GIS, contractors have an opportunity to reduce their impacts. This reduction could allow contractors to reach their sustainability goals and contribute to a reduction of impacts that could aid global biodiversity goals.

REFERENCES

Adams, W.M., Aveling, R., Brockington, D., Dickson, B., Elliott, J., Hutton, J., Roe, D., Vira, B. and Wolmer, W., 2004. Biodiversity conservation and the eradication of poverty. *science*, *306*(5699), pp.1146-1149.

Aydin, N.Y., Kentel, E. and Duzgun, H.S., 2013. GIS-based site selection methodology for hybrid renewable energy systems: A case study from western Turkey. *Energy conversion and management*, *70*, pp.90-106.

AEngD (2016). *AEngD :: About the EngD*. [online] Aengd.org.uk. Available at: http://www.aengd.org.uk/programmes/ [Accessed 6 Jan. 2016].

Al-Reshaid, K., Kartam, N., Tewari, N. and Al-Bader, H., 2005. A project control process in pre-construction phases: Focus on effective methodology. *Engineering, Construction and Architectural Management*, *12*(4), pp.351-372.

Alberti, M. and Waddell, P., 2000. An integrated urban development and ecological simulation model. *Integrated Assessment*, *1*(3), pp.215-227.

Alhaddi, H., 2015. Triple bottom line and sustainability: A literature review. *Business and Management Studies*, *1*(2), pp.6-10.

Almela, E.D., Marba, N., Alvarez, E., Santiago, R., Martínez, R. and Duarte, C.M., 2008. Patch dynamics of the Mediterranean seagrass Posidonia oceanica: Implications for recolonisation process. *Aquatic Botany*, *89*(4), pp.397-403.

Almenar, J.B., Bolowich, A., Elliot, T., Geneletti, D., Sonnemann, G. and Rugani, B., 2019. Assessing habitat loss, fragmentation and ecological connectivity in Luxembourg to support spatial planning. *Landscape and Urban Planning*, *189*, pp.335-351.

Amirebrahimi, S, Rajabifard, A, Mendis, P and Ngo, T 2015 A Data Model for Integrating GIS and BIM for Assessment and 3D Visualisation of Flood Damage to Building. CEUR Workshop Proceedings, 1323(March), pp.78-89.

Anderson, C., Narus, J.A. and van Rossum, W., Customer Value Propositions in Business Markets–[Електронний ресурс]–Режим доступу: http://www. academia. edu/10395145. *Customer_Value_Propositions_in_ Business_Markets*.

Andreasen, J., O’Neill, R., Noss, R. and Slosser, N. 2001. Considerations for the development of a terrestrial index of ecological integrity. *Ecological Indicators*, 1(1), pp.21-35.

Aultman-Hall, L., Hall, F.L. and Baetz, B.B., 1997. Analysis of bicycle commuter routes using geographic information systems: implications for bicycle planning. *Transportation research record*, *1578*(1), pp.102-110.

Azevedo, S.G. and Barros, M., 2017. The application of the triple bottom line approach to sustainability assessment: The case study of the UK automotive supply chain. *Journal of Industrial Engineering and Management (JIEM)*, *10*(2), pp.286-322.

Azhar, S. and Brown, J., 2009. BIM for sustainability analyses. *International Journal of Construction Education and Research*, *5*(4), pp.276-292.

Baker, T.R., Battersby, S., Bednarz, S.W., Bodzin, A.M., Kolvoord, B., Moore, S., Sinton, D. and Uttal, D., 2015. A research agenda for geospatial technologies and learning. *Journal of Geography*, *114*(3), pp.118-130.

Baltsavias, E., Mason, S. and Stallmann, D., 1995. Use of DTMs/DSMs and orthoimages to support building extraction. In *Automatic extraction of man-made objects from aerial and space images* (pp. 199-210). Birkhäuser Basel.

Bank, A D 2015 Rail Infrastructure in Africa Financing Policy Options. African Development Bank, Transport, Urban Development & ICT Department.

Beacon Environmental Ltd 2012. [ebook] Available at: https://cvc.ca/wp-content/uploads/2013/08/Ecological-Buffer-Guideline-Review.pdf [Accessed 1 Mar. 2018].

Bell, S., 2001. Landscape pattern, perception and visualisation in the visual management of forests. *Landscape and Urban planning*, *54*(1-4), pp.201-211.

Bender, D.J., Contreras, T.A. and Fahrig, L., 1998. Habitat loss and population decline: a meta-analysis of the patch size effect. *Ecology*, *79*(2), pp.517-533.

Bogaert, J., 2003. Lack of agreement on fragmentation metrics blurs correspondence between fragmentation experiments and predicted effects. *Conservation Ecology*, *7*(1).

Bowen, G.A., 2009. Document analysis as a qualitative research method. *Qualitative research journal*, *9*(2), p.27.

Boyes, G.A., Ellul, C. and Irwin, D., 2017, October. Exploring BIM for operational integrated asset management-a preliminary study utilising real-world infrastructure data. In *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences* (Vol. 4, No. 4W5, pp. 49-56).

Brown, M.M., 1996. An empirical assessment of the hurdles to geographic information system success in local government. *State & local government review*, pp.193-204.

Bull, J.W., Brauneder, K., Darbi, M., Van Teeffelen, A.J., Quétier, F., Brooks, S.E., Dunnett, S. and Strange, N., 2018. Data transparency regarding the implementation of European 'no net loss' biodiversity policies. *Biological Conservation*, *218*, pp.64-72.

CEH 2012. *Corine Landcover UK*. https://www.eea.europa.eu/data-and-maps/figures/land-cover-2006-and-changes/united-kingdom. Accessed 9 April 2018.

CEH, 2017. *Land Cover Map 2015 Dataset Documentation*. https://www.ceh.ac.uk/sites/default/files/LCM2015_Dataset_Documentation.pdf. Accessed 15 September 2020.

Chaudhry, O.Z., Mackaness, W.A. and Regnauld, N., 2009. A functional perspective on map generalisation. *Computers, environment and urban systems*, *33*(5), pp.349-362.

Connolly, D., MacLaughlin, S. and Leahy, M., 2010. Development of a computer program to locate potential sites for pumped hydroelectric energy storage. *Energy*, *35*(1), pp.375-381.

Costanza, R., 1992. Toward an operational definition of ecosystem health. *Ecosystem health: New goals for environmental m anagement*, pp.239-256.

CIEEM, 2016. *Guidelines for Ecological Impact Assessment in the UK and Ireland*.

Copernicus 2019. *CORINE Land Cover — Copernicus Land Monitoring Service*. [online] Available at: <https://land.copernicus.eu/pan-european/corine-land-cover> [Accessed 9 January 2020].

Cooper, I., 2008. Sustainable Urban Development and the Professions in the UK. *Sustainable Urban Development Volume 4: Changing Professional Practice*, p.99.

Coralie, C., Guillaume, O. and Claude, N., 2015. Tracking the origins and development of biodiversity offsetting in academic research and its implications for conservation: a review. *Biological Conservation*, *192*, pp.492-503.

Corry, R.C. and Nassauer, J.I., 2005. Limitations of using landscape pattern indices to evaluate the ecological consequences of alternative plans and designs. *Landscape and Urban Planning*, *72*(4), pp.265-280.

Costain,Smart thinking, improving lives Sustainability Report 2017. (2017). https://www.costain.com/media/598488/2017-costain-sustainability-report.pdf. Accessed 1 Aug. 2017.

Costain, 2011. *Photograph Of The A465*. [image] Available at: <https://www.costain.com/news/news-releases/costain-awarded-a465-heads-of-the-valleys-contract/> [Accessed 16 December 2018].

Costain 2015. *Our history | Costain*. [online] Costain.com. Available at: https://www.costain.com/about-us/our-history/ [Accessed 18 Mar. 2019].

Costain, 2019. *Photograph Of The A14*. [image] https://www.costain.com/news/news-releases/a14-huntingdon-bypass-opens-to-the-public/. Accessed 26 October 2020.

Costain, 2020. *Environmental Policy*. https://www.costain.com/media/598890/environmental-policy.pdf. Accessed 13 June 2020.

Coutinho-Rodrigues, J., Simão, A. and Antunes, C.H., 2011. A GIS-based multicriteria spatial decision support system for planning urban infrastructures. *Decision support systems*, *51*(3), pp.720-726.

Countryside Survey, 2007. *Land Cover Map 2007 Dataset Documentation.* http://lcm2007_land_cover_map_of_great_britain.pdf. Accessed 11 April 2019.

Cowan, C., 2019. *Costs Of LCM2015/LCM2019*. [email].

Crespi, B.J. and Taylor, P.D., 1990. Dispersal rates under variable patch density. *The American Naturalist*, *135*(1), pp.48-62.

Cunningham, R.B., Lindenmayer, D.B., Crane, M., Michael, D., MacGREGOR, C., Montague-Drake, R., and Fischer, J., 2008. The combined effects of remnant vegetation and tree planting on farmland birds. *Conservation Biology*, *22*(3), pp.742-752.

Curnow, J., 2019. Environmental economics in UK environmental policy: Defra's 25 Year Environment Plan. *Journal of Environmental Economics and Policy*, *8*(4), pp.353-358.

Curran, M., S. Hellweg, and J. Beck. 2014. Is there any empirical support for biodiversity offset policy? Ecological Applications 24:617–632.

Cushman, S.A., 2006. Effects of habitat loss and fragmentation on amphibians: a review and prospectus. *Biological conservation*, *128*(2), pp.231-240.

Daneshgar, F., Sadabadi, K.F. and Haghani, A., 2018. A conflation methodology for two GIS roadway networks and its application in performance measurements. *Transportation Research Record*, *2672*(45), pp.284-293.

Darbi, M. and Tausch, C., 2010. Loss-gain calculations in german impact mitigation regulation. *Occasional paper contributed to BBOP. Consulted on-line at http://www. forest-trends. org/publication_details. php*.

de Knegt, H.J., Hengeveld, G.M., Van Langevelde, F., De Boer, W.F. and Kirkman, K.P., 2007. Patch density determines movement patterns and foraging efficiency of large herbivores. *Behavioral Ecology*, *18*(6), pp.1065-1072.

De Luca, M., Dell'Acqua, G. and Lamberti, R., 2012. High-speed rail track design using GIS and multi-criteria analysis. *Procedia-Social and Behavioral Sciences*, *54*, pp.608-617.

Defra, 2011. Biodiversity 2020: A strategy for England's wildlife and ecosystem services.

Defra, 2012. Biodiversity Offsetting Pilots: Technical Paper: the metric for the biodiversity offsetting pilot in England.

Defra, 2018. "A Green Future: Our 25 Year Plan to Improve the Environment" https://www.gov.uk/government/publications/25-year-environment-plan

Densham, P.J., 1991. Spatial decision support systems. *Geographical information systems. Vol. 1: principles*, pp.403-412.

Department for Transport, 2013. *London-West Midlands Environmental Statement*. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/259487/NTS_for_web_ES_3.0.0.pdf. Accessed 23 October 2020.

Drayson, K., Wood, G. and Thompson, S., 2017. An evaluation of ecological impact assessment procedural effectiveness over time. *Environmental Science & Policy*, *70*, pp.54-66.

Du Puy, D.J. and Moat, J.F., 1998. Vegetation mapping and classification in Madagascar (using GIS): implications and recommendations for the conservation of biodiversity. *Chorology, taxonomy and ecology of the floras of Africa and Madagascar*, pp.97-117.

Eadie, R., Browne, M., Odeyinka, H., McKeown, C. and McNiff, S., 2013. BIM implementation throughout the UK construction project lifecycle: An analysis. *Automation in construction*, *36*, pp.145-151.

Ebright-McKeehan, K., Systematics, C. and Murtha, T., 2009. A GIS Data-Driven Process for Identifying Rail Infrastructure Improvements.

Eedy, W., 1995. The use of GIS in environmental assessment. *Impact Assessment*, *13*(2), pp.199-206.

Elbeltagi, E and Dawood, M. 2011. Integrated visualized time control system for repetitive construction projects. Automation in Construction, 20(7), 940-953.

Elder, M., Bengtsson, M. and Akenji, L., 2016. An optimistic analysis of the means of implementation for sustainable development goals: Thinking about goals as means. *Sustainability*, *8*(9), p.962.

Elith, J., H. Graham*, C., P. Anderson, R., Dudík, M., Ferrier, S., Guisan, A., J. Hijmans, R., Huettmann, F., R. Leathwick, J., Lehmann, A. and Li, J., 2006. Novel methods improve prediction of species' distributions from occurrence data. *Ecography*, *29*(2), pp.129-151.

Elkington, J. 1997. *Cannibals with Forks: The Triple Bottom Line of 21st Century Business*. USA: New Society Publishers.

Erickson, P.A., 1994. *A practical guide to environmental impact assessment*. Academic Press Inc..

Eriksson, P E and Pesämaa, O. 2007. Modelling procurement effects on cooperation. Construction Management and Economics, 25(8), 893-901.

Esnard, A., 2007. Institutional and organizational barriers to effective use of GIS by community-based organizations. *URISA-WASHINGTON DC-*, *19*(2), p.13.

ESRI, 2019. *Components Of Arcgis Server—Documentation | Arcgis Enterprise*. https://enterprise.arcgis.com/en/server/10.5/get-started/windows/components-of-arcgis-for-server.htm . Accessed 14 November 2019.

ESRI, 2020a. *Arcgis Pro Pricing | Buy Now*. [online] Available at: <https://www.esri.com/en-us/arcgis/products/arcgis-pro/buy> [Accessed 26 October 2020].

ESRI, 2020b. *Arcgis Spatial Analyst Pricing | Add License To Arcgis Pro Or Arcgis Enterprise*. [online] Available at: <https://www.esri.com/en-us/arcgis/products/arcgis-spatial-analyst/buy> [Accessed 19 August 2020].

Fischer, J. and Lindenmayer, D.B., 2007. Landscape modification and habitat fragmentation: a synthesis. *Global ecology and biogeography*, *16*(3), pp.265-280.

Foody, G.M., 2002. Status of land cover classification accuracy assessment. *Remote sensing of environment*, *80*(1), pp.185-201.

Fosu, R, Suprabhas, K, Rathore, Z and Cory, C. 2015. Integration of Building Information Modeling (BIM) and Geographic Information Systems (GIS) - A literature review and future needs. In: Proceedings of the 32nd CIB W78 Conference, 27th-29th October, Eindhoven, The Netherlands, 196-204.

Fouka, G. and Mantzorou, M., 2011. What are the major ethical issues in conducting research? Is there a conflict between the research ethics and the nature of nursing?. *Health Science Journal*, *5*(1).

Friends of the Earth, 2018. Biodiversity offsetting and net gain: licence to trash nature. [online] Available at: <http://biodiversity-offsetting-and-net-gain-licence-trash-nature> [Accessed 1 February 2019].

Garrido-Baserba, M., Corominas, L., Cortés, U., Rosso, D. and Poch, M., 2020. The fourth-revolution in the water sector encounters the digital revolution. *Environmental science & technology*, *54*(8), pp.4698-4705.

Gaston, K.J., Jackson, S.F., Cantu-Salazar, L. and Cruz-Piñón, G., 2008. The ecological performance of protected areas. *Annual review of ecology, evolution, and systematics*, *39*, pp.93-113.

Geneletti, D., 2002. *Ecological evaluation for environmental impact assessment* (pp. 48-49). Koninklijk Nederlands Aardrijkskundig Genootschap.

Geneletti, D., 2003. Biodiversity impact assessment of roads: an approach based on ecosystem rarity. *Environmental impact assessment review*, *23*(3), pp.343-365.

Geneletti, D., 2004. A GIS-based decision support system to identify nature conservation priorities in an alpine valley. *Land Use Policy*, *21*(2), pp.149-160.

Geneletti, D., 2005. Multicriteria analysis to compare the impact of alternative road corridors: a case study in northern Italy. *Impact Assessment and Project Appraisal*, *23*(2), pp.135-146.

Geoghegan, J., Wainger, L.A. and Bockstael, N.E., 1997. Spatial landscape indices in a hedonic framework: an ecological economics analysis using GIS. *Ecological economics*, *23*(3), pp.251-264.

Gharehbaghi, K. and Scott-Young, C., 2018, March. GIS as a vital tool for Environmental Impact Assessment and Mitigation. In *IOP Conference Series: Earth and Environmental Science* (Vol. 127, No. 1, p. 012009). IOP Publishing.

Gibbons, P., Evans, M.C., Maron, M., Gordon, A., Le Roux, D., von Hase, A., Lindenmayer, D.B. and Possingham, H.P., 2016. A loss-gain calculator for biodiversity offsets and the circumstances in which no net loss is feasible. *Conservation Letters*, *9*(4), pp.252-259.

Gibbons, P. and Lindenmayer, D.B., 2007. Offsets for land clearing: no net loss or the tail wagging the dog?. *Ecological Management & Restoration*, *8*(1), pp.26-31.

Glasson, J. and Therivel, R., 2013. *Introduction to environmental impact assessment*. Routledge.

Göçmen, Z.A. and Ventura, S.J., 2010. Barriers to GIS use in planning. *Journal of the American Planning Association*, *76*(2), pp.172-183.

Gontier, M., Mörtberg, U. and Balfors, B., 2010. Comparing GIS-based habitat models for applications in EIA and SEA. *Environmental Impact Assessment Review*, *30*(1), pp.8-18.

Goodland, R., 1995. The concept of environmental sustainability. *Annual review of ecology and systematics*, *26*(1), pp.1-24.

Guler, H, Akad, M and Ergun, M. 2004. Railway Asset Management System in Turkey: A GIS Application. Working Paper, FIG Working Week, May 22-27, Athens, Greece, 1-11.

Gustafson, E.J., 1998. Quantifying landscape spatial pattern: what is the state of the art?. *Ecosystems*, *1*(2), pp.143-156.

Hanford, J.K., Crowther, M.S. and Hochuli, D.F., 2017. Effectiveness of vegetation-based biodiversity offset metrics as surrogates for ants. *Conservation biology*, *31*(1), pp.161-171.

Hargis, C.D., Bissonette, J.A. and David, J.L., 1998. The behavior of landscape metrics commonly used in the study of habitat fragmentation. *Landscape ecology*, *13*(3), pp.167-186.

Harrie, L. and Stigmar, H., 2010. An evaluation of measures for quantifying map information. *ISPRS Journal of Photogrammetry and Remote Sensing*, *65*(3), pp.266-274.

Harrie, L., Stigmar, H. and Djordjevic, M., 2015. Analytical estimation of map readability. *ISPRS International Journal of Geo-Information*, *4*(2), pp.418-446.

Herold, M., Couclelis, H. and Clarke, K.C., 2005. The role of spatial metrics in the analysis and modeling of urban land use change. *Computers, environment and urban systems*, *29*(4), pp.369-399.

Hevner, A.R., March, S.T., Park, J. and Ram, S., 2004. Design science in information systems research. *MIS quarterly*, pp.75-105.

Hevner, A. and Chatterjee, S., 2010. Design science research in information systems. In *Design research in information systems* (pp. 9-22). Springer, Boston, MA.

HM Treasury, 2018. Budget 2018. Policy Paper. https://www.gov.uk/government/publications/budget-2018-documents/budget-2018. Accessed 23 October 2019.

HM Treasury, 2020. 2020 Budget. Policy Paper. https://www.gov.uk/government/publications/budget-2020-documents/budget-2020. Accessed 14 June 2020.

Holl, A., 2004. Manufacturing location and impacts of road transport infrastructure: empirical evidence from Spain. *Regional Science and Urban Economics*, *34*(3), pp.341-363.

Hortal, J. and Lobo, J.M., 2005. An ED-based protocol for optimal sampling of biodiversity. *Biodiversity & Conservation*, *14*(12), pp.2913-2947.

Howes, M. Politics and the Environment: Risk and the Role of Government and Industry; Allen & Unwin: Sydney, Australia, 2005.

Howes, M., Wortley, L., Potts, R., Dedekorkut-Howes, A., Serrao-Neumann, S., Davidson, J., Smith, T. and Nunn, P., 2017. Environmental sustainability: a case of policy implementation failure?. *Sustainability*, *9*(2), p.165.

Hughes, W.P., 2003. A comparison of two editions of the RIBA Plan of Work. *Engineering, Construction and Architectural Management*.

IUCN. 1980. United Nations Environment Programme (UNEP); World Wide Fund for Nature (WWF). World Conservation Strategy; IUCN/UNEP/WWF: Gland, Switzerland

Irizarry, J., Karan, E.P. and Jalaei, F., 2013. Integrating BIM and GIS to improve the visual monitoring of construction supply chain management. *Automation in construction*, *31*, pp.241-254.

Irizarry, J, Karan, E P and Jalaei, F .2013. Integrating BIM and GIS to improve the visual monitoring of construction supply chain management. Automation in Construction, 31, 241-254.

Irizarry, J and Karan, E P. 2012. Optimizing location of tower cranes on construction sites through GIS and BIM integration. Journal of Information Technology in Construction, 17, 361-366.

Isaac, N.J. and Pocock, M.J., 2015. Bias and information in biological records. *Biological Journal of the Linnean Society*, *115*(3), pp.522-531.

Isikdag, U, Underwood, J and Aouad, G. 2008. An investigation into the applicability of building information models in geospatial environment in support of site selection and fire response management processes. Advanced Engineering Informatics, 22(4), 504-519.

Jaeger, J.A., 2017. Improving EIA for roads at the landscape-scale: 1-5

Janke, J.R., 2010. Multicriteria GIS modelling of wind and solar farms in Colorado. *Renewable Energy*, *35*(10), pp.2228-2234.

JNCC. 2016. *UK BAP Priority Habitats* | JNCC - Adviser To Government On Nature Conservation. https://jncc.gov.uk/our-work/uk-bap-priority-habitats/. Accessed 12 November 2017.

Joao, E., 1998. *Causes and consequences of map generalization*. CRC Press.

Johnson, C.J. and Gillingham, M.P., 2005. An evaluation of mapped species distribution models used for conservation planning. *Environmental Conservation*, pp.117-128.

Jones, V., Gardner, M. and Ellor, B., 2014. Concentrations of trace substances in sewage sludge from 28 wastewater treatment works in the UK. *Chemosphere*, *111*, pp.478-484.

Jones, H.P. and Schmitz, O.J., 2009. Rapid recovery of damaged ecosystems. *PloS one*, *4*(5), p.e5653.

Kang, M.W., Jha, M.K. and Buddharaju, R., 2014. Rail transit route optimization model for rail infrastructure planning and design: Case study of Saint Andrews, Scotland. *Journal of Transportation Engineering*, *140*(1), pp.1-11.

Karr J.R. 1996. Ecological integrity and ecological health are not the same P. Schulze (Ed.), Engineering Within Ecological Constraints, National Academy of Science, Washington, DC, USA

Kaundinya, D.P., Balachandra, P., Ravindranath, N.H. and Ashok, V., 2013. A GIS (geographical information system)-based spatial data mining approach for optimal location and capacity planning of distributed biomass power generation facilities: A case study of Tumkur district, India. *Energy*, *52*, pp.77-88.

Kenley, R., Harfield, T. and Behnam, A., 2016. BIM interoperability limitations: Australian and Malaysian rail projects. In *MATEC Web of Conferences* (Vol. 66, p. 00102). EDP Sciences.

Kim, M., Miller-Hooks, E. and Nair, R., 2011. A geographic information system-based real-time decision support framework for routing vehicles carrying hazardous materials. *Journal of Intelligent Transportation Systems*, *15*(1), pp.28-41.

Koen, E.L., Garroway, C.J., Wilson, P.J. and Bowman, J., 2010. The effect of map boundary on estimates of landscape resistance to animal movement. *PloS one*, *5*(7), p.e11785.

Kogan, F., Powell, A. and Fedorov, O. eds., 2011. *Use of satellite and in-situ data to improve sustainability*. Springer.

Kolbe, T H, König, G and Nagel, C. 2011. Advances in 3D Geo-Information Sciences. Berlin: Springer-Verlag, 310.

Kouziokas, G.N. and Perakis, K., 2017. Decision support system based on artificial intelligence, GIS and remote sensing for sustainable public and judicial management. *European Journal of Sustainable Development*, *6*(3), pp.397-404.

Kucuksari, S., Khaleghi, A.M., Hamidi, M., Zhang, Y., Szidarovszky, F., Bayraksan, G. and Son, Y.J., 2014. An Integrated GIS, optimization and simulation framework for optimal PV size and location in campus area environments. *Applied Energy*, *113*, pp.1601-1613.

Kurwi, S., Demian, P. and Hassan, T.M., 2017, September. Integrating BIM and GIS in railway projects: A critical review. In *Proceedings of the 33rd Annual ARCOM Conference, Cambridge, UK* (pp. 4-6).

Lélé, S.M., 1991. Sustainable development: a critical review. *World development*, *19*(6), pp.607-621.

Li, B.L. and Archer, S., 1997. Weighted mean patch size: a robust index for quantifying landscape structure. *Ecological Modelling*, *102*(2-3), pp.353-361.

Li, X., He, H.S., Bu, R., Wen, Q., Chang, Y., Hu, Y. and Li, Y., 2005. The adequacy of different landscape metrics for various landscape patterns. *Pattern recognition*, *38*(12), pp.2626-2638.

Li, Y., Gong, H., Zhu, L. and Li, X., 2017. Measuring spatiotemporal features of land subsidence, groundwater drawdown, and compressible layer thickness in Beijing Plain, China. *Water*, *9*(1), p.64.Lindenmayer, D., 2019. Small patches make critical contributions to biodiversity conservation. *Proceedings of the National Academy of Sciences*, *116*(3), pp.717-719.

Lin, T., Lin, J.Y., Cui, S.H. and Cameron, S., 2009. Using a network framework to quantitatively select ecological indicators. *Ecological Indicators*, *9*(6), pp.1114-1120.

Liu, T. and Yang, X., 2015. Monitoring land changes in an urban area using satellite imagery, GIS and landscape metrics. *Applied Geography*, *56*, pp.42-54.

Liu, R. and Issa, R.R.A., 2012. 3D visualization of sub-surface pipelines in connection with the building utilities: Integrating GIS and BIM for facility management. In *Computing in Civil Engineering (2012)* (pp. 341-348). Lombera, J.T.S.J. and Rojo, J.C., 2010. Industrial building design stage based on a system approach to their environmental sustainability. *Construction and Building Materials*, *24*(4), pp.438-447.

Lovett, A., Sünnenberg, G. and Dockerty, T., 2014. The availability of land for perennial energy crops in Great Britain. *Gcb Bioenergy*, *6*(2), pp.99-107.

MacDonald, C. and Norman, W., 2007. Rescuing the baby from the triple-bottom-line bathwater: a reply to Pava. *Business Ethics Quarterly*, pp.111-114.

Mackenzie, N. and Knipe, S., 2006. Research dilemmas: Paradigms, methods and methodology. *Issues in educational research*, *16*(2), pp.193-205.

Mahavir, D., 2000. High (spatial) resolution vs. low resolution images: a planner's view point. International archives of photogrammetry and Remote Sensing, 33(7).

Malinverni, E.S., 2011. Change detection applying landscape metrics on high remote sensing images. *Photogrammetric Engineering & Remote Sensing*, *77*(10), pp.1045-1056.

McAfee, A., Brynjolfsson, E., Davenport, T.H., Patil, D.J. and Barton, D., 2012. Big data: the management revolution. *Harvard business review*, *90*(10), pp.60-68.

McCarthy, M.A., Parris, K.M., Van Der Ree, R., McDonnell, M.J., Burgman, M.A., Williams, N.S., McLean, N., Harper, M.J., Meyer, R., Hahs, A. and Coates, T., 2004. The habitat hectares approach to vegetation assessment: an evaluation and suggestions for improvement. *Ecological Management & Restoration*, *5*(1), pp.24-27.

McCollin, D., 1993. Avian distribution patterns in a fragmented wooded landscape (North Humberside, UK): the role of between-patch and within-patch structure. *Global Ecology and Biogeography Letters*, pp.48-62.

McGarigal, K. and Cushman, S.A., 2002. Comparative evaluation of experimental approaches to the study of habitat fragmentation effects. *Ecological applications*, *12*(2), pp.335-345.

McGarigal, K. and Marks, B.J., 1995. FRAGSTATS: spatial analysis program for quantifying landscape structure. *USDA Forest Service General Technical Report PNW-GTR-351*.

McGarigal, K., Tagil, S. and Cushman, S.A., 2009. Surface metrics: an alternative to patch metrics for the quantification of landscape structure. *Landscape ecology*, *24*(3), pp.433-450.

Medrano, M., Brouwer, J., Carreras-Sospedra, M., Rodriguez, M.A., Dabdub, D. and Samuelsen, G., 2008. A methodology for developing distributed generation scenarios in urban areas using geographical information systems. *International journal of energy technology and policy*, *6*(4), pp.413-434.

Merriam, S.B., 1988. *Case study research in education: A qualitative approach*. Jossey-Bass.

Mertens, D.M., 2005. Quality criteria in qualitative research. *Pattons version*.

Michelmore, F., 1994. Keeping elephants on the map: Case studies of the application of GIS for conservation. In *Mapping the diversity of nature* (pp. 107-125). Springer, Dordrecht.

Mignard, C. and Nicolle, C., 2014. Merging BIM and GIS using ontologies application to urban facility management in ACTIVe3D. *Computers in Industry*, *65*(9), pp.1276-1290.

Morelli, J., 2011. Environmental sustainability: A definition for environmental professionals. *Journal of environmental sustainability*, *1*(1), p.2.

Moreno-Mateos, D., Maris, V., Béchet, A. and Curran, M., 2015. The true loss caused by biodiversity offsets. *Biological Conservation*, *192*, pp.552-559.

Mücher, C.A., Hennekens, S.M., Bunce, R.G., Schaminée, J.H. and Schaepman, M.E., 2009. Modelling the spatial distribution of Natura 2000 habitats across Europe. *Landscape and urban planning*, *92*(2), pp.148-159.

NBN, 2020. *Who We Are*. The National Biodiversity Trust. https://nbn.org.uk/about-us/who-we-are/> Accessed 10 August 2020.

Nielsen, S. and Möller, B., 2013. GIS based analysis of future district heating potential in Denmark. *Energy*, *57*, pp.458-468.

Nivala, A.M., Sarjakoski, L.T. and Sarjakoski, T., 2007. Usability methods' familiarity among map application developers. *International journal of human-computer studies*, *65*(9), pp.784-795.

Noardo, F., Biljecki, F., Agugiaro, G., Arroyo Ohori, K., Ellul, C., Harrie, L., Stoter, J., 2019. GeoBIM benchmark 2019: intermediate results. In Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci., XLII-4/W15, 47–52.

Oldewurtel, F., Parisio, A., Jones, C.N., Gyalistras, D., Gwerder, M., Stauch, V., Lehmann, B. and Morari, M., 2012. Use of model predictive control and weather forecasts for energy efficient building climate control. *Energy and Buildings*, *45*, pp.15-27.

Omitaomu, O.A., Blevins, B.R., Jochem, W.C., Mays, G.T., Belles, R., Hadley, S.W., Harrison, T.J., Bhaduri, B.L., Neish, B.S. and Rose, A.N., 2012. Adapting a GIS-based multicriteria decision analysis approach for evaluating new power generating sites. *Applied Energy*, *96*, pp.292-301.

Opoku, D.G.J., Ayarkwa, J. and Agyekum, K., 2019. Barriers to environmental sustainability of construction projects. *Smart and Sustainable Built Environment*.

Orland, B., Budthimedhee, K. and Uusitalo, J., 2001. Considering virtual worlds as representations of landscape realities and as tools for landscape planning. *Landscape and urban planning*, *54*(1-4), pp.139-148.

Ortolano, L. and Shepherd, A., 1995. Environmental impact assessment: challenges and opportunities. *Impact assessment*, *13*(1), pp.3-30.

Painter-Morland, M., 2006. Triple bottom-line reporting as social grammar: integrating corporate social responsibility and corporate codes of conduct. *Business ethics: a European review*, *15*(4), pp.352-364.

Pandey, A. and Shahbodaghlou, F., 2016. Measuring Contribution of BIM (Building Information Modeling) to the Construction Sustainability Goals. *Journal of Civil Engineering and Architecture*, *10*(17265), pp.1934-7359.

Palve, S.N., 2013. Application of gis in infrastructure project management. *International Journal of Structural and Civil Engineering Research*, *2*(4), pp.110-122.

Parker, D.C., Evans, T. and Meretsky, V., 2001. *Measuring emergent properties of agent-based landcover/landuse models using spatial metrics* (No. 261). Society for Computational Economics.

Parkes, D., Newell, G. and Cheal, D., 2003. Assessing the quality of native vegetation: the 'habitat hectares' approach. *Ecological Management & Restoration*, *4*, pp.S29-S38.

Pfeffers, K., Tuunanen, T., Rothenberger, M.A. and Chatterjee, S., 2007. A design science research methodology for information systems research. *Journal of management information systems*, *24*(3), pp.45-77.

Penghua, Q., Songjun, X., Genzong, X., Benan, T., Hua, B. and Longshi, Y., 2007. Analysis of the ecological vulnerability of the western Hainan Island based on its landscape pattern and ecosystem sensitivity. *Acta Ecologica Sinica*, *27*(4), pp.1257-1264.

Pimm, S.L., Russell, G.J., Gittleman, J.L. and Brooks, T.M., 1995. The future of biodiversity. *Science*, *269*(5222), pp.347-350.

Pollalis, S.N., Georgoulias, A., Ramos, S.J. and Schodek, D. eds., 2013. *Infrastructure sustainability and design*. Routledge.

Pons, J.M.S. and Pérez, M.R., 2003. Geographic information systems and intelligent transport systems: technologies used to form new communication networks. *Networks and Communication Studies*, *17*(1-2), pp.53-70.

Raar, J., 2002. Environmental initiatives: towards triple-bottom line reporting. *Corporate communications: An international journal*.

Radil, S.M. and Jiao, J., 2016. Public participatory GIS and the geography of inclusion. *The Professional Geographer*, *68*(2), pp.202-210.

Rainey, H.J., Pollard, E.H., Dutson, G., Ekstrom, J.M., Livingstone, S.R., Temple, H.J. and Pilgrim, J.D., 2015. A review of corporate goals of No Net Loss and Net Positive Impact on biodiversity. *Oryx*, *49*(2), pp.232-238.

Ramachandra, T.V.; Shruthi, B.V. Spatial mapping of renewable energy potential. Renew. Sustain. Energy Rev. 2007, 11, pp. 1460–1480.

Reid, C.T., 2011. The privatisation of biodiversity? Possible new approaches to nature conservation law in the UK. *Journal of Environmental Law*, *23*(2), pp.203-231.

Resch, B., Sagl, G., Törnros, T., Bachmaier, A., Eggers, J.B., Herkel, S., Narmsara, S. and Gündra, H., 2014. GIS-based planning and modeling for renewable energy: Challenges and future research avenues. *ISPRS International Journal of Geo-Information*, *3*(2), pp.662-692.

Reza, M.I.H. and Abdullah, S.A., 2011. Regional Index of Ecological Integrity: A need for sustainable management of natural resources. *Ecological indicators*, *11*(2), pp.220-229.

RIBA. (2013). *RIBA Plan of Work 2013*. Retrieved from http://www.ribaplanofwork.com

RIBA, 2019. *RIBA Sustainable Outcomes*. RIBA. https://www.architecture.com/-/media/GatherContent/Test-resources-page/Additional-Documents/RIBASustainableOutcomesGuide2019pdf.pdf. Accessed 13 February 2020.

Riitters, K.H., O'neill, R.V., Hunsaker, C.T., Wickham, J.D., Yankee, D.H., Timmins, S.P., Jones, K.B. and Jackson, B.L., 1995. A factor analysis of landscape pattern and structure metrics. *Landscape ecology*, *10*(1), pp.23-39.

Rocchini, D., Hortal, J., Lengyel, S., Lobo, J.M., Jimenez-Valverde, A., Ricotta, C., Bacaro, G. and Chiarucci, A., 2011. Accounting for uncertainty when mapping species distributions: the need for maps of ignorance. *Progress in Physical Geography*, *35*(2), pp.211-226.

Robins, F., 2006. The challenge of TBL: a responsibility to whom?. *Business and society review*, *111*(1), pp.1-14.

Robinson, J., 2004. Squaring the circle? Some thoughts on the idea of sustainable development. *Ecological economics*, *48*(4), pp.369-384.

Rowland, C.S.; Morton, R.D.; Carrasco, L.; McShane, G.; O'Neil, A.W.; Wood, C.M. 2017. Land Cover Map 2015 (vector, GB). NERC Environmental Information Data Centre.

Şahin, Ş. and Kurum, E., 2002. Erosion risk analysis by GIS in environmental impact assessments: a case study—Seyhan Köprü Dam construction. *Journal of Environmental Management*, *66*(3), pp.239-247.

Salem, B.B., 2003. Application of GIS to biodiversity monitoring. *Journal of arid environments*, *54*(1), pp.91-114.

Salt, D., Lindenmayer, D. and Hobbs, R., 2004. *Trees and biodiversity: a guide for Australian farm forestry*. Rural Industries Research and Development Corporation.

Saura, S. and Martinez-Millan, J., 2001. Sensitivity of landscape pattern metrics to map spatial extent. *Photogrammetric engineering and remote sensing*, *67*(9), pp.1027-1036.

Schumaker, N.H., 1996. Using landscape indices to predict habitat connectivity. *Ecology*, *77*(4), pp.1210-1225.

Seiler, A., 2003. Effects of infrastructure on nature. In *COST* (Vol. 341, pp. 31-50).

Seiler, A. and Eriksson, I.M., 1995, September. New approaches for ecological consideration in Swedish road planning. In *Proceedings of the international conference on" Habitat fragmentation, infrastructure and the role of ecological engineering" Maastricht & DenHague* (pp. 253-264).

Seto, K.C. and Fragkias, M., 2005. Quantifying spatiotemporal patterns of urban land-use change in four cities of China with time series landscape metrics. *Landscape ecology*, *20*(7), pp.871-888.

Sharif, H.O., Al-Zahrani, M. and Hassan, A.E., 2017. Physically, fully-distributed hydrologic simulations driven by GPM satellite rainfall over an urbanizing arid catchment in Saudi Arabia. *Water*, *9*(3), p.163.

Sheppard, S.R., 2001. Guidance for crystal ball gazers: developing a code of ethics for landscape visualization. *Landscape and urban planning*, *54*(1-4), pp.183-199.

Silvestre, B.S. and Ţîrcă, D.M., 2019. Innovations for sustainable development: Moving toward a sustainable future. *Journal of Cleaner Production*, *208*, pp.325-332.

Sinclair, D., 2019. *Guide to Using the RIBA Plan of Work 2013*. Routledge.

Skidmore, A. ed., 2017. *Environmental modelling with GIS and remote sensing*. CRC Press.

Soetanto, R., Zanni, M.A. and Ruikar, K., 2014. Defining the sustainable building design process: methods for BIM execution planning in the UK. *International Journal of Energy Sector Management*.

Sridhar, K. and Jones, G., 2013. The three fundamental criticisms of the Triple Bottom Line approach: An empirical study to link sustainability reports in companies based in the Asia-Pacific region and TBL shortcomings. *Asian Journal of Business Ethics*, *2*(1), pp.91-111.

Suding, K.N., 2011. Toward an era of restoration in ecology: successes, failures, and opportunities ahead. *Annual review of ecology, evolution, and systematics*, *42*.

Suter, G.W., 1993. A critique of ecosystem health concepts and indexes. *Environmental Toxicology and Chemistry: An International Journal*, *12*(9), pp.1533-1539.

Tekeli, A.E., 2017. Exploring Jeddah floods by tropical rainfall measuring mission analysis. *Water*, *9*(8), p.612.

Telfer, M.G., Preston, C.D. and Rothery, P., 2002. A general method for measuring relative change in range size from biological atlas data. *Biological conservation*, *107*(1), pp.99-109.

The Guardian, 2012. Biodiversity offsetting will unleash a new spirit of destruction on the land. https://www.theguardian.com/environment/georgemonbiot/2012/dec/07/biodiversity-offsetting-unleash-wildlife-destruction#:~:text=Biodiversity%20offsetting%20will%20unleash%20a%20new%20spirit%20of%20destruction%20on%20the%20land,-A%20place%20of&text=The%20idea%20is%20called%20biodiversity,to%20create%20new%20habitats%20elsewhere. Accessed 13 April 2018.

Toman, M.A., 1992. The difficulty in defining sustainability. *Resources*, *106*(Winter), pp.3-6.

Tischendorf, L. and Wissel, C., 1997. Corridors as conduits for small animals: attainable distances depending on movement pattern, boundary reaction and corridor width. *Oikos*, pp.603-611.

Tomislav, K., 2018. The concept of sustainable development: From its beginning to the contemporary issues. *Zagreb International Review of Economics & Business*, *21*(1), pp.67-94.

Trombulak, S.C. and Frissell, C.A., 2000. Review of ecological effects of roads on terrestrial and aquatic communities. *Conservation biology*, *14*(1), pp.18-30.

Tsai, C.Y. and Chang, A.S., 2012. Framework for developing construction sustainability items: the example of highway design. *Journal of Cleaner Production*, *20*(1), pp.127-136.

TWT, 2020. What's The Damage? Why HS2 Will Cost Nature Too Much. The Wildlife Trust. https://www.wildlifetrusts.org/sites/default/files/2020-01/What%27s%20the%20damage%20-%20Summary%20Report%20FINAL%20digital%202.pdf. Accessed 1st September 2020

Ugland, K.I., Gray, J.S. and Ellingsen, K.E., 2003. The species–accumulation curve and estimation of species richness. *Journal of Animal Ecology*, *72*(5), pp.888-897.

UK Government, 2013. *Construction 2025*. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/210099/bis-13-955-construction-2025-industrial-strategy.pdf. Accessed 9 March 2020.

UN. 2015. Sustainable Development Goals; United Nations: New York, NY, USA.

Van Hoesen, J.; Letendre, S. Evaluating potential renewable energy resources in Poultney, Vermont: A GIS-based approach to supporting rural community energy planning. Renew. Energy 2010, 35, pp.2114–2122.

Ventura, S.J., 1995. The use of geographic information systems in local government. *Public Administration Review*, pp.461-467.

Verberk, W.C.E.P., Van Duinen, G.A., Brock, A.M.T., Leuven, R.S.E.W., Siepel, H., Verdonschot, P.F.M., Van der Velde, G. and Esselink, H., 2006. Importance of landscape heterogeneity for the conservation of aquatic macroinvertebrate diversity in bog landscapes. *Journal for Nature Conservation*, *14*(2), pp.78-90.

Vitolo, C., Elkhatib, Y., Reusser, D., Macleod, C.J. and Buytaert, W., 2015. Web technologies for environmental Big Data. *Environmental Modelling & Software*, *63*, pp.185-198.

Vos, R.O., 2007. Defining sustainability: a conceptual orientation. *Journal of Chemical Technology & Biotechnology: International Research in Process, Environmental & Clean Technology*, *82*(4), pp.334-339.

Wach, E. and Ward, R., 2013. Learning about qualitative document analysis.

Wang, R., Chen, J. and Wang, X., 2017. Comparison of IMERG Level-3 and TMPA 3B42V7 in estimating typhoon-related heavy rain. *Water*, *9*(4), p.276.Wang, Q K, Li, P, Xiao, Y P, and Liu, Z G (2014) Integration of GIS and BIM In Metro Construction. Applied Mechanics and Materials, 608-609, 698-702.

Wang, X. and Xie, H., 2018. A review on applications of remote sensing and geographic information systems (GIS) in water resources and flood risk management. *Water*, *10*(5), p.608.

Watson, J.J. and Hudson, M.D., 2015. Regional Scale wind farm and solar farm suitability assessment using GIS-assisted multi-criteria evaluation. *Landscape and Urban Planning*, *138*, pp.20-31.

Wei, X. 1996. Using GIS Technology For Railway Design And Management. International Archives of the Pho

Wiens, J.J., 2007. Species delimitation: new approaches for discovering diversity. *Systematic Biology*, *56*(6), pp.875-878.

Xu, L., 2005, June. A decision support model based on GIS for vehicle routing. In *Proceedings of ICSSSM'05. 2005 International Conference on Services Systems and Services Management, 2005.* (Vol. 2, pp. 1126-1129). IEEE.

Yadav, S.K. and Mishra, G.C., 2014. GIS in EIA for Environment Management. *International Journal of Applied Engineering Research*, *9*(3), pp.335-340.

Ye, H., Brown, M. and Harding, J., 2014. GIS for all: exploring the barriers and opportunities for underexploited GIS applications. *OSGeo Journal*, *13*(1), pp.19-28.

Yu, S., Cui, B. and Gibbons, P., 2018. A method for identifying suitable biodiversity offset sites and its application to reclamation of coastal wetlands in China. *Biological Conservation*, *227*, pp.284-291.

Zambelli, P., Lora, C., Spinelli, R., Tattoni, C., Vitti, A., Zatelli, P. and Ciolli, M., 2012. A GIS decision support system for regional forest management to assess biomass availability for renewable energy production. *Environmental Modelling & Software*, *38*, pp.203-213.

Zanella, L., Borém, R.A.T., Souza, C.G., Alves, H.M.R. and Borém, F.M., 2012. Atlantic forest fragmentation analysis and landscape restoration management scenarios. *Natureza & Conservação*, *10*(1), pp.57-63.

zu Ermgassen, S.O., Baker, J., Griffiths, R.A., Strange, N., Struebig, M.J. and Bull, J.W., 2019. The ecological outcomes of biodiversity offsets under “no net loss” policies: A global review. *Conservation Letters*, *12*(6), p.e12664.

APPENDIX A

GEOSPATIAL DATASETS

TABLE A.1. LAYER NAME, DATA PROVIDER, DATA FORMAT AND PUBLICATION DATE FOR ALL GEOSPATIAL DATASETS USED

Layer Name	Data Provider	Data Format	Publication Date
Areas of Outstanding Natural Beauty (England)	Natural England	ESRI Living Atlas	April 2019
Limestone Pavement Orders (England)	Natural England	ESRI Living Atlas	April 2019
Local Nature Reserves (England)	Natural England	ESRI Living Atlas	February 2020
National Nature Reserves (England)	Natural England	ESRI Living Atlas	February 2020
National Nature Reserves (Scotland)	Scottish Government	Shapefile	December 2019
National Nature Reserves (Wales)	Natural Resources Wales	Rest URL for WMS and WFS	March 2018
National Parks (England)	Natural England	ESRI Living Atlas	April 2019
National Parks (Scotland)	Scottish Government	Shapefile	
National Parks (Wales)	Natural Resources Wales	URL for WMS and WFS	Unknown
RAMSAR Sites (England)	Natural England	ESRI Living Atlas	July 2019
RAMSAR Sites (Scotland)	Scottish Government	Shapefile	December 2019
RAMSAR Sites (Wales)	Natural Resources Wales	URL for WMS and WFS	January 2016
Proposed RAMSAR Sites (England)	Natural England	ESRI Living Atlas	April 2019
Sites of Special Scientific Interest (England)	Natural England	ESRI Living Atlas	November 2019

Sites of Special Scientific Interest Impact Risk Zones (England)	Natural England	ESRI Living Atlas	February 2020
Sites of Special Scientific Interest (Scotland)	Scottish Government	Shapefile	December 2019
Sites of Special Scientific Interest (Wales)	Natural Resources Wales	URL for WMS and WFS	October 2019
Special Areas of Conservation (England)	Natural England	ESRI Living Atlas	July 2019
Special Areas of Conservation (Scotland)	Scottish Government	Shapefile	December 2019
Special Areas of Conservation (Wales)	Natural Resources Wales	URL for WMS and WFS	March 2019
Possible Special Areas of Conservation (England)	Natural England	ESRI Living Atlas	May 2019
Special Protection Areas (England)	Natural England	ESRI Living Atlas	July 2019
Special Protection Areas (Scotland)	Scottish Government	Shapefile	December 2019
Special Protection Areas (Wales)	Welsh Government	URL for WMS and WFS	October 2014
Biosphere Reserves (England)	Natural England	ESRI Living Atlas	April 2019
Biosphere Reserves (Scotland)	Scottish Government	Shapefile	September 2019
Biosphere Reserves (Wales)	Welsh Government	URL for WMS and WFS	July 2014
Wild Bird General License Exclusion Zone (England)	Natural England	ESRI Living Atlas	April 2019
Wild Bird General License Restriction Zone (England)	Natural England	ESRI Living Atlas	May 2019
Barbastelle's bat (*Barbastella barbastellus)*	National Biodiversity Network	.CSV	Ongoing publication, accessed December 2015

Bechsteins bat (*Myostis bechsteinii)*	National Biodiversity Network	.CSV	Ongoing publication, accessed December 2015
Dormouse (*Muscardinus avellanarious)*	National Biodiversity Network	.CSV	Ongoing publication, accessed December 2015
Great crested newt (*Triturus cristatus)*	National Biodiversity Network	.CSV	Ongoing publication, accessed December 2015
Greater horseshoe bat (*Rhinolophus ferrumequinum)*	National Biodiversity Network	.CSV	Ongoing publication, accessed December 2015
Lesser horseshoe bat (*Rhinolophus hipposideros)*	National Biodiversity Network	.CSV	Ongoing publication, accessed December 2015
Natterjack toad (*Epidalea calamita)*	National Biodiversity Network	.CSV	Ongoing publication, accessed December 2015
Noctule (*Nyctalus noctule)*	National Biodiversity Network	.CSV	Ongoing publication, accessed December 2015
Otter (*Lutra lutra)*	National Biodiversity Network	.CSV	Ongoing publication, accessed December 2015
Sand lizard (*Lacerta agilis)*	National Biodiversity Network	.CSV	Ongoing publication, accessed December 2015

Smooth snake (*Coronella austriaca)*	National Biodiversity Network	.CSV	Ongoing publication, accessed December 2015
Wild cat (*Felis silvestris silvestris)*	National Biodiversity Network	.CSV	Ongoing publication, accessed December 2015
Landcover Map 2015	Centre for Ecology and Hydrology	Shp.	April 2017

APPENDIX B

ARCGIS SYSTEMS: SERVER AND MODEL BUILDER

System specifications describe the behaviour and features of a system or software application. This section describes and introduces the components of the ESRI ArcGIS software used in both Chapters 5 and 6. This includes the processing tools available, the format for model building, and the preferred method of visualisation.

The tools in ArcToolbox are divided into toolboxes that range from analysis and data anagement to referencing and server tools. These toolboxes are then refined further into toolsets that house tools with a similar functionality. For example, Figure 3.5. shows ArcToolbox and the toolsets that are shown within "*Analysis Tools*" and the subsequent tools that are within the "*Proximity*" toolset, and the buffer tool has been selected. The buffer tool is a simple geoprocessing tool that creates a polygon around inputted features to a specified distance. There are four ways to use the geoprocessing tool in ArcToolbox: the first selecting the tool from the toolbox and completing the dialogue box. This is a manual process that allows the developer to select the input features, where the output will be saved and any parameters, in this case the length of the buffer. The other methods of using geoprocessing tools are through models, scripts, and command lines. This research focuses on the use of models for automating workflow.

Model Builder within ArcMap Desktop is the means in which the geoprocessing tools are going to be used in this research. Model Builder has a "*input – process – output*" functionality that allows the user to drag and drop datasets and tools from the ArcToolbox into the new model window. Input data can be inter-changed along with tool parameters to fit the purpose of the model. An example model using the buffer tool can be seen below in Figure B.1.

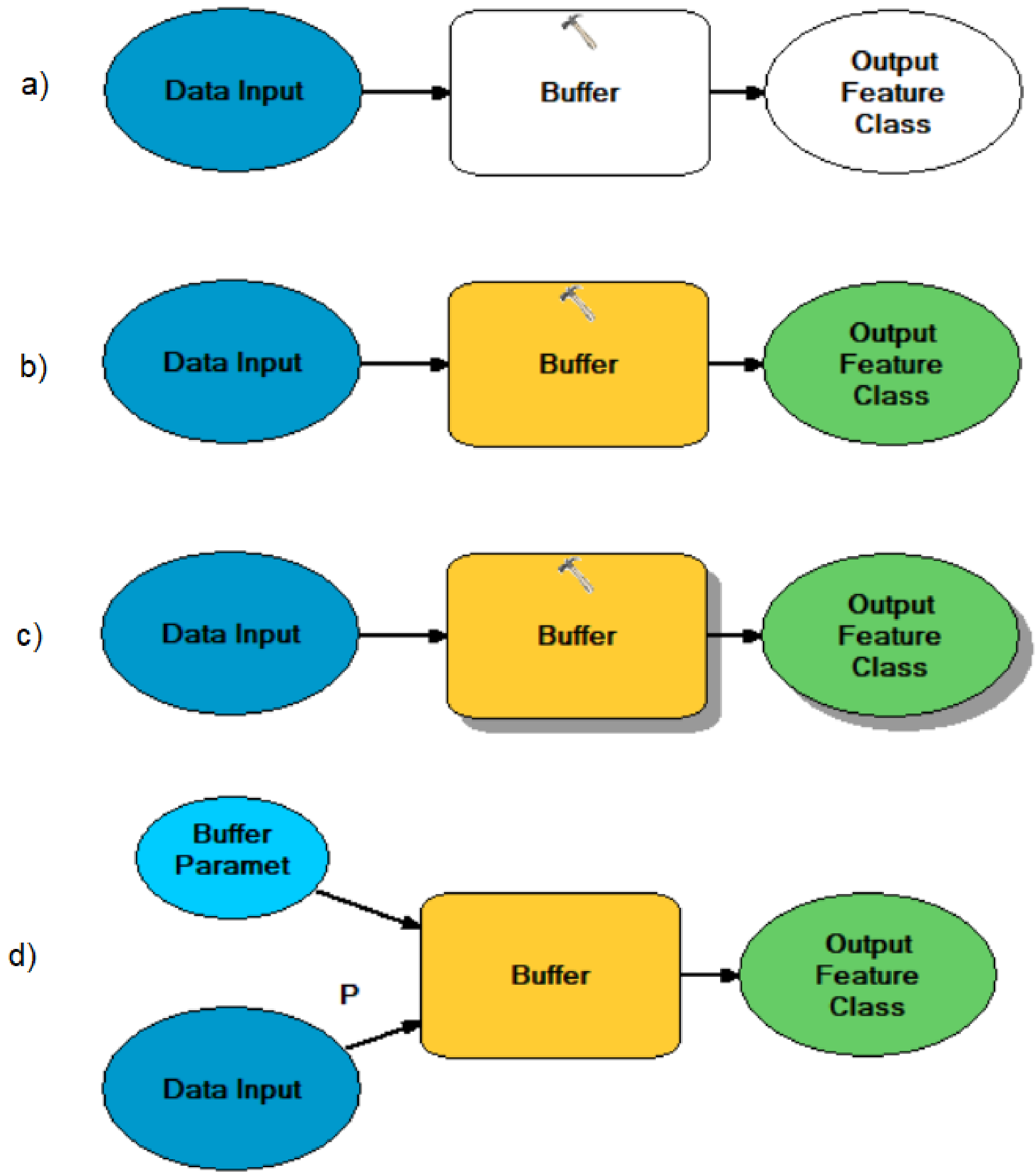


FIGURE B.1. AN EXAMPLE BUFFER MODEL BUILT WITH ARCGIS MODEL BUILDER: A) INPUT, TOOL, AND OUTPUT WITH NO PARAMETERS, B) INPUT, TOOL, AND OUTPUT WITH DEFINED PARAMETERS, C) INPUT, TOOL, AND OUTPUT THAT HAS BEEN SUCCESSFULLY RUN AND D) INPUT, TOOL, AND OUTPUT THAT SHOWS THE MODEL PARAMETERS

Figure 3.5. is an example of a simple model using the buffer tool mentioned in the previous section, a) is the model before any parameters are entered by the model developer, for example a buffer would need to be defined by a linear unit such as 100 metres. Once the parameters of the tool have been defined, the model will look like b), which is fully coloured and ready to be run, running the model shows c) which indicates a successful run with the option of adding any results to the ArcMap display. As seen in d), when an input value is selected as a model parameter it will show a "*P*", and when a tool parameter is selected as a

model parameter is it added as part of the tool this allows the end user to define the parameters for their own needs.

GIS layers and maps on Costain projects are shared on ESRI's ArcGIS Enterprise system or ArcGIS Online (AGOL) through the publication of layers from ArcGIS Desktop. ArcGIS Enterprise can run on site premises or in the cloud with applications and web maps being hosted on a secure web server (Figure B.2.). Data created in geodatabases are stored on a data server which allows for unlimited connections to GIS servers, so the data can be used on web, mobile and desktop devices. Access to published layers can be restricted to specific users, groups of users, or can be able available to view publicly. All Enterprise users need a username and password to access restricted data and maps, providing a secure environment for safe data sharing. The Enterprise system has two types of users: Level 1 users can view data while Level 2 users have publishing and editing capabilities. Costain can have unlimited Level 1 users for the Enterprise system; as of July 2019, the number of Level 1 users has increased to over 1000 Level 1 users. This number is continuing to rise as Costain's geospatial capability spreads throughout the company.

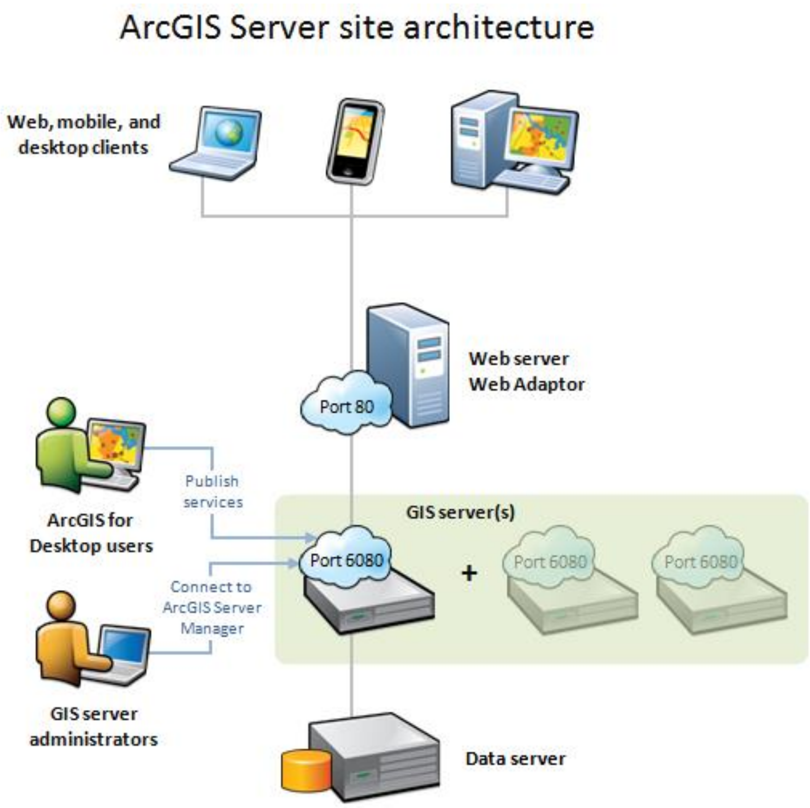


FIGURE B.2. THE ARCGIS SERVER ARCHITECTURE SOURCE: ESRI 2019

Applications created on these two platforms are web maps or applications viewed from a web browser. This application allows the creator of the map to develop interactive and intuitive maps without writing a code and can be shared as a HTML link (ESRI 2018). The interactive nature of the web application allows the user to zoom in and out, and to see meta-data of the layer. The web app builder has a feature in which the app creator can add "*widgets*" to the web application, the widget acts as a function that allows the user to manipulate and interact with the map. There are a variety of default widgets available, Chapter 5 discusses the appropriate widgets to select for an environmental planning web application. Outputs from model building in this research will be published to the Enterprise system, in addition to feature layers, the models themselves can be published and presented to the user as a custom widget within an application. The custom widget was used in the research as a means of creating as a user-friendly way to use the developed solutions for use by Level 1 users that may have limited experience using GIS.

APPENDIX C

COSTAIN DEPARTMENT CLASSIFICATION CODES

TABLE C.1. ALL DEPARTMENTS FOR THE COSTAIN WAY DOCUMENTATION CLASSIFICATION CODES AS OF JANUARY 2020.

Code	Name
WWG	Work Winning
CPM	Contract Management
CON	Consultancy
TEC	Technology Delivery
AOM	Asset Optimisation
CBS	Behavioural Management
CMG	Commissioning
CPR	Commercial Management
CPR	Supply Chain & Procurement
CPR	Subcontract Management
CSS	Security Solutions
CWR	Collaborative Working
DES	Design Management
EGD	Engineering Design
INF	Information Management
INK	Innovation
PAP	Planning Management
PCT	Project Controls
PGM	Programme Management
PSM	Process Safety
QUA	Quality Control
RAO	Risk & Opportunity Management
SHE	SHE Procedures & Guidance
SUR	Land Surveying
TWS	Temporary Works
CU	Upstream
AOR	Corporate Accounts & Reporting
BAA	Business Assurance
BAA	Internal Audit
ITS	Information Technology

CDV	Corporate Development
COM	Corporate Communications
CPR	Insurance
CPR	Supply Chain Management
CSR	Corporate Responsibility
FAP	Property, Facilities & Administration
FIN	Treasury
HRS	Human Resources
LEG	Legal

Initial Biodiversity Document Search

Table C.2. The documents from the initial search of "Biodiversity" on The Costain Way

Document Reference	Name
SHE-T-437	Risk Based Monitoring Check Sheet
SHE-T-377	Health, Safety and Environmental Management Plan
BAA-T-017	Controls Audit
SHE-T-326	SHE Readiness Review
EDG-G-001	Engineering Design Gate 1 – Approval to Submit Tender
SHE-T-100	Group SHE Management System Structure
SHE-T-258	Leadership SHE Engagement
WWG-T-018	Joint Venture Strategy
CSR-T-002	Legacy Case Study Template
SHE-H-410	How to Identify Ecological Risk
SHE-T-203	Costain Network Rail Construction Phase Plan
EGD-G-002	Engineering Gate 2 – Approval to Proceed Through Contract Mobilisaiton
EGD-G-005	Engineering Design Gate 5- Approval to Proceed to Engineering Design
SHE-T-204	Costain Network Rail Environmental Management Plan
SHE-T-346	London Underground Environmental Management Plan
EDG-G-004	Engineering Design Gate 4 – Approval to Proceed to FEED
SHE-H-619	How to Conduct Safety, Health and Environmental Advisory Visits and Leadership in SHE Engagement Tours
TEC-T-023	Technology Optimisation Plan
EGD-H-208	How to Conduct Design Assessments
EGD-M-036	No title
EGD-H-107	How to Prepare a Design Health, Safety and Environmental Management Plan
SHE-H-438	How to Procure Materials in a Responsible Manner
SHE-H-302	How to Design for the Environment
SHE-H-470	How to Approach and Manage Biodiversity
SHE-T-433	Costain BAP Template
CPR-T-053	Sub-Contract Target Budget
AOM-T-005	Asset Optimisation Green Reviews
SHE-T-434	Biodiversity Units Tracker
SHE-T-435	Biodiversity Unit Calculation Template
SHE-T-304	Corporate Environmental Aspects Register
DES-T-035	Design for Environment Checklist

INITIAL GIS DOCUMENT SEARCH

TABLE C.3. THE FULL LIST OF DOCUMENTS SHOWN ON THE INITIAL SEARCH OF "GIS" ON THE COSTAIN WAY

Document Reference	Name
TEC-T-025	Smart Delivery Platform Minimum Requirements
CPM-T-037	Do it Right Guide
TEC-T-022	Technology Champions Community Steering Group Terms of Reference
TEC-T-027	Smart Delivery Platform Forms Catalog
SHE-T-204	Costain Network Rail Environmental Management Plan
DES-T-025	BIM Roles
TEC-T-028	Smart Delivery Platform Discipline Benefits
DES-T-011	Design BIM Capability Questionnaire
DES-T-024F	GIS
TEC-T-023	Technology Optimisation Plan
TEC-T-021	Technology Champion Description
DES-H-0141	How to Prepare a BIM Execution Plan
DES-T-030	Software Matrix
DES-T-207	BIM Process
DES-T-024K	Environment
DES-T-024H	Augmented Reality
DES-T-024A	Laser Scan
PAP-T-022	Subcontract Procurement Programme

DOCUMENTS IN THE FLOW DIAGRAM

TABLE C.4. THE DOCUMENT TITLE, FOCUS, KEY ROLES, CONSTRUCTION STAGE AND DESCRIPTION OF LINKED DOCUMENTS FROM "HOW TO APPROACH AND MANAGE BIODIVERSITY"

Document	Title	Focus	Key Roles	Construction Stage	Description
EDG-H-107	Design HASEMP	NEnv	CM, LDSE, LPE, LDE, TA	2-4	Identifies the arrangements that have been put into place for the management of process safety, occupational safety, and environmental hazards during the design phase of the contract
SHE-H-619	SHE Advisory Visits and Leadership SHE Engagement Tours	NEnv	DIR, CL, CSHEA	5	Defines how and when to undertake SHE advisory visits, which are to provide written advice and support to a project.
SHE-H-410	Identifying and Managing Ecological Risk	Env	CL, BM, CSHEA, FLS	2-5	This document addresses ecological issues that may occur where construction activities are located in, near to, or affect ecologically valuable or sensitive species that need to be managed prior to and/or after the construction period The document also includes information on common protected species which may have been identified as a result of a survey or mitigation requirements. This is based on a case-by-case basis
SHE-H-438	Procuring Materials Responsibly	NEnv	DM, CM. QS, CL, BM, CSHEA	2-5	Provides details of sustainable materials and materials which are not.

SHE-H-302	Designing for the Environment	Env	DM, DE, CSHEA, DSHED	2-4	Guidance on how to minimise environmental risks and maximise the environmental opportunities during the design phase
SHE-H-470	Approaching and Managing Biodiversity	Env	CL, BM, CSHEA, FLS, Eco		Guidance for managing biodiversity and the development and completion of an appropriate contract BAP

APPENDIX D

RAW DATA FROM END-USER INTERVIEWS

D.1. PARTICIPANT 1

Q1. What is your previous experience with GIS?

My GIS experience began at university whereby I took several GIS modules. This included carrying out site-suitability analyses for mariculture locations. I then used GIS in my previous role as a Marine Environmental Consultant, mapping MPAs, fisheries and fishing activity, marine licensing for use in Environmental Statements.

Q2. What is your experience of environmental data?

I have a wide range of experience with environmental data, from making maps in my previous role for Environmental Statements and Technical Reports, as well as data collection the Collector App in the field.

Q3. Does the visualisation of biodiversity values improve your understanding of the on-site biodiversity? If so, how?

Definitely. It allows me to quickly see the quantification of biodiversity units associated with the site. I can easily visualise baseline biodiversity values compared to predicted values from the landscape design, allowing me to get an idea of the impact of the project on the natural environment.

Q4. Do you think implementing this technology for all biodiversity management is feasible and how?

Potentially, however it depends on if we have sufficient baseline data. If the contract does not have baseline data, we cannot see how that baseline has changed in terms of biodiversity units.

Q5. What do you think are the limitations in an implementation of GIS applications such as this?

Decision-makers may use this for the wrong reasons. They may choose to remove ancient woodland because they can offset those units elsewhere. When really, in my opinion, that habitat can never be replaced. Similarly, they can choose to offset far from the original site, where people who originally benefited from the natural environment live too far to benefit.

Q6. Do you think innovations such as this GIS implementation improve environmental sustainability?

Yes, definitely. It gives people with little understanding about the natural environment a mechanism in which to monitor it. It allows decision-makers to visually understand the impact in which the project is having and think about their actions.

Q7. Do you believe it is the responsibility of the contractor or client to promote sustainable development?

Both. It is the responsibility of everyone to promote sustainable development.

Q8. Do you think that Costain is doing enough as a business to promote sustainable development? What more could be done?

No. I think Costain need to push sustainable development as their niche. Rather than offering sustainable designs as options, they should be the only option. However obviously there are many other considerations to this, such as cost.

D.2. Participant 2

Q1. What is your previous experience with GIS?

I did it University and kind of not a lot since I've really since then, just used. We've had tools developed by the design age. We can just go in and basically look at GIS. They plotted environmental data on it and it's just been literally as a Reference I've not done much work with it, sort of calculate anything, it's just been a reference.

Q2. What is your experience of environmental data?

So, plotting the position of invasive species protected species, water courses, that sort of thing. When you when you have like a PDF constraints but in the past we've had design agencies have generated that is a live GIS Web-viewer basically so you can just go in and look at it.

Q3. Does the visualisation of biodiversity values improve your understanding of the on-site biodiversity? If so, how?

Yes, I understand it a lot better. It is much more user-friendly because you can see it. You can change it. You can delete something and then it will calculate what the differences are, so it is much more user friendly.

Q4. Do you think implementing this technology for all biodiversity management is feasible and how?

Yes, and I think it is also necessary because there are other things you can do with it. You can use in construction for the environmental stuff, because that's where we've got operations where we might have great crested newts were working around or Badger sets that we're working nearby.

Q5. What do you think are the limitations in an implementation of GIS applications such as this?

It is the fact that it is nature being viewed on computer screens and tablets. In an office not too much of a problem because you can put it on big screens. You can put it on laptop screens, but when you're out in the field and you only have a tablet or smartphone it is difficult to see the area, you're working in. You are quite zoomed in and sometimes it is a lot easier, or you need to see the bigger picture with something so having it on a big A1 drawing, everyone can talk around it a lot easier. Or you can take the big drawing onto the site and sit in a cabin with the guys at work inside and talk them through something. This scale just doesn't work with GIS on a tablet or smartphone as you keep needing to zoom in and out and back in again.

Q6. How do innovations such as this GIS implementation improve environmental sustainability?

The format is more understandable to the everyday engineer. I have heard this area in environment being called the dark arts or black magic because everything blends in together and can be confusing. Having the GIS tool makes data easily accessible to engineers, showing that work is happening here, and which areas are high risk for biodiversity.

Q7. Do you believe it is the responsibility of the contractor or client to promote sustainable development?

It is the responsibility of both. But it does have problems. One of the jobs I've worked on the client, to be honest, wasn't really too fussed about environmental legislation and sustainable development or what they wanted was a new road. And as long as they got there, they weren't too fussed. To the point where they were, not in direct words, instructing us to skirt around the law. So with those it's very difficult. As a contractor we can promote it all we want. By the end of the day, it's going to cost us a fortune. If the clients are uninterested then we're not going to get paid for it or pay for some of it. It's not going to happen, so I think you do need both. You need a willingness from the client to commit some funds.

Q8. Do you think that Costain is doing enough as a business to promote sustainable development? What more could be done?

I think one thing we particularly struggle with is we have lots of initiatives that we plan to do. We roll a lot of things out from, particularly that sort of London things at the Euro 3B engines that came out of London, which is a good idea. But we sort of throw it out right now. This is a company standard across the entire country. Great thing to do. But we didn't do much to educate the supply chain.

D.3. PARTICIPANT 3

Q1. What is your previous experience with GIS?

Previous to Costain GIS team I didn't have any experience at all with GIS, didn't know what it was and didn't know how to use it or it's capabilities. Then I think over the last 3 years I've started to learn a lot more, and I think initially it was around data processing in particular sites, having an interactive map for the site project, and being able to put on different layers when you're doing the design. Then I've seen it gradually grow into analysis tools to help us make decisions.

Q2. What is your experience of environmental data?

It depends on the project, definitely a mixed bag. There will be some projects where we get an environmental study from a JV partner or client with quite a bit of information, and then some projects you don't get anything at all. So it really depends on the client and the stage of the project.

Q3. Does the visualisation of biodiversity values improve your understanding of the on-site biodiversity? If so, how?

Yes, definitely. Without this I would not have considered the detail that goes into reporting biodiversity.

Q4. Do you think implementing this technology for all biodiversity management is feasible and how?

I can't really see why not. I thnk maybe when you're working in more brownfield developments in built up areas the biodiversity mapping may not work as well. Just from what I've seen so far it may not be applicable as there isn't much biodiversity value there to start with.

Q5. What do you think are the limitations in an implementation of GIS applications such as this?

So the previous comment I just mentioned, but I think having high value data and if we don't have that from the client then we need to figure out how to get it. Also if the client doesn't have funding for implementation then that can be a challenge.

Q6. How do innovations such as this GIS implementation improve environmental sustainability?

I think it is potentially significant. It's a really helpful tool to demonstrate geographically to the client and the project team. It's really easy to understand, especially as there is a fair amount of theory behind. You don't have to know that theory to understand the outputs, anyone with *any discipline can appreciate and understand. Particularly when you start looking at the options and run multiple scenarios to give you a real opportunity to know those options and do something with it. It's just how do we get the client to give us that extra bit of investment?*

Q7. Do you believe it is the responsibility of the contractor or client to promote sustainable development?

It's definitely a two-way street. I think there's a responsibility on the contract to challenge and push the client where there is an opportunity to use an alternative material or product. We should be identifying that and giving those options. But I think the client should also be setting expectations from the state and being more ambitious than they are. I think HS2 has been very good at that, I think because of the nature of the scheme and it being quite controversial. They've been very ambitious with their environmental and carbon targets and also putting their money where their mouth is.

Q8. Do you think that Costain is doing enough as a business to promote sustainable development? What more could be done?

I don't think we are doing enough. I think we are slowly getting there. I thnk we have made a lot of promises and I feel like we're not fully delivering on them yet. I've noticed over the past year that things are starting to speed up a bit and there's a lot more momentum behind it. So maybe it is beginning to change but I do think there's more that we can do. I thnk we could challenge clients more. I think we could be more selective about the projects that we do, and investing more to make sure we are considering sustainability.

D.4. Participant 4

Q1. What is your previous experience with GIS?

I've worked with QGIS producing Phase I Habitat maps, bat survey diagrams as well. These were mostly set up by non-GIS specialists, rather people that have done a training course or two on QGIS or educated themselves.

Q2. What is your experience of environmental data?

Environmental data was things like field survey records, survey maps for Phase I Habitat surveys. We used to take out a Google Earth image to help with the landscape and then annotate it with Phase I habitat codes and then bring that back to the office and digitise it on QGIS.

Q3. Does the visualisation of biodiversity values improve your understanding of the on-site biodiversity? If so, how?

I think yes. For the schemes we have done it's not just limited to being biodiversity based, but schemes can be quite lengthy, and it can take some time to get your head around a scheme given the general size of them. It's the same for biodiversity, knowing where those hotspots and less diverse areas are, it definitely helps.

Q4. Do you think implementing this technology for all biodiversity management is feasible and how?

I think it is definitely feasible, but the questions is more related to how committed the business is to do it at the end of the day. I think that will come if there is a commitment from a higher level, like the government commitment with the environmental bill towards reducing biodiversity loss and moving towards a biodiversity gain. If there is a strong commitment then the business will follow and the applications will definitely be feasible.

Q5. What do you think are the limitations in an implementation of GIS applications such as this?

The limitations come from the schemes, situations change, and designs aren't always as conclusive, and things are different when we get on the ground. One particular scheme we found that the design runs outside of the client boundary, and that more clearance has taken place than originally thought, including hedgerows. To be able to capture this in the GIS tool we need stronger lines of communication with our design partners to ensuring we are logging those changes.

Q6. How do innovations such as this GIS implementation improve environmental sustainability?

It means we can quantify it, and it's hard to have the ability to and it not just being numbers on a spreadsheet. If you can see and identify hotspots you get that spatial distribution to it and it makes the biodiversity assessment much easier as you have those details right there.

Q7. Do you believe it is the responsibility of the contractor or client to promote sustainable development?

I think it's both. At the end of the day it needs to be client driven although the contractor needs to be as innovative and imaginative as possible in finding ways to implement the requests of the client, but it's got to come from the client really.

Q8. Do you think that Costain is doing enough as a business to promote sustainable development? What more could be done?

I think they're probably not doing enough because no one is. I think more focus needs to be put on reducing impacts on schemes. It needs to be from the top down, so it's not just Costain. The incentivisation needs to be there for the actions to follow

D.5. Participant 5

Q1. What is your previous experience with GIS?

Multiple modules and projects with GIS at University in undergrad and in my Masters. I use it to look at data on our project and I also work a bit with the GIS team within Costain

Q2. What is your experience of environmental data?

I used environmental data in my modules I constraints data looking at site selections and also looking at some of the open source data that we have for our project so things from the Environment Agency, Natural England, Canal and River Trust etc.

Q3. Does the visualisation of biodiversity values improve your understanding of the on-site biodiversity? If so, how?

I think it does. I think it makes biodiversity a less abstract concept when you can see it and it's not just numbers on a spreadsheet. I know people have had difficulty understanding it before and how it's calculated and so being able to see it and see the numbers behind it is very useful when you're talking to people that don't necessarily understand the theory behind the calculations

Q4. Do you think implementing this technology for all biodiversity management is feasible and how?

I think it's potentially feasible, but I think that that needs to be more drive from the business to implement this. Not only drive but funding as well. I think that we have the technology and the capability in house to support this but a lot of people associate GIS with high cost typically on individual projects and so I feel there needs to be some funding from the business to make this more feasible to pay as the both the technology and the people to do it

Q5. What do you think are the limitations in an implementation of GIS applications such as this?

I think limitations are around data, you need to have good data in any project really, but we've dealt with out-of-date environmental data, missing data that can really affect the baseline and without that accurate baseline overall the calculations are not going to be particularly accurate. I also think like with my last comment that there needs to be drive from the business to implement this properly because the advantages are there, but it just needs some more investment from the business to realise those benefits fully

Q6. How do innovations such as this GIS implementation improve environmental sustainability?

I think these innovations do help us with environmental sustainability, I think that being able to quantify an impact on a site is a very strong capability and I think it not only helps environmental sustainability, but it also helps us be transparent in what we're doing to try and combat sustainability in general. Also, if we understand the impacts that we are having and we are being transparent I believe it would drive us more to reduce those impacts

Q7. Do you believe it is the responsibility of the contractor or client to promote sustainable development?

I do believe this is both I don't think you'll have alternative sustainable options without the contractor, or contract to investment in those kinds of initiatives but ultimately the need needs to come from the client, and the funding needs to come from the client to be able to implement these. Without these innovations from contractors will just go to waste if the clients aren't willing to pay for them

Q8. Do you think that Costain is doing enough as a business to promote sustainable development? What more could be done?

I don't think I Costain is doing enough as a business. I think that we are trying, and we are saying the right things but I don't think there is enough investment, particularly money, when it comes to pushing those sustainable alternatives or pushing capabilities like the biodiversity mapping to our clients to get them onto projects. I think we could be doing a lot better job of pushing that kind of agenda and potentially only pushing that agenda