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Climate change adaptation and resilience for water management at
Heathrow Airport

School of Water, Energy and Environment
MSc in Water and Wastewater Processes

MSc

Academic Year: 2024 - 2025

Supervisor: Andrea Momblanch

August 2025



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This thesis is submitted in partial fulfilment of the requirements for
the degree of Water and Wastewater Processes

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Academic integrity declaration

I declare that:

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Abstract

Increased duration and intensity of precipitation events are the most cited likely risk for the European aviation sector. Flooding events at airports cause disruptions to operations, increased labour and materials costs, and environmental degradation from stormwater runoff. Building climate resilience into airport infrastructure and operational models for future climate projections is paramount for climate proofing and adapting airports for future needs. A promising growing field of stormwater management practices known as Nature-based solutions align with passive LID, low-impact development objectives while simultaneously providing multiple co-benefits (Social, Ecological, Economic) from their implementation. Through the examination of case studies, modelling studies, and lab based experimental studies I examined the scientific literature critically from the past 10 years. Airports provide a unique set of site characteristics and safety protocols that must be adhered to. The airport that was designed for this literature review case study was Heathrow Airport in the UK. Airside and landside general site NbS were identified with the assistance of aerial satellite imagery and SAR data showing the extent of notable historic flood events. Filter strips utilizing endophyte bonded grasses were the main choice for airside applications for their low maintenance requirements and low potential for bird strike safety concerns at the airport. Rainwater harvesting and green roofs were chosen for building areas depending on Heathrow's decision to reclaim their rainwater harvesting infrastructure which is already in place.

Heathrow Airport Limited: P25523

Keywords:

Nature-based Solutions, NbS, Low-impact development, Flood risk management, airports, SuDS

Acknowledgements

I would like to thank my family and friends for their support during my time here.

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List of Abbreviations

CDA	Chicago Department of Aviation
CDRI	Coalition for Disaster Resilient Infrastructure
FOD	Foreign Object Damage
GSI	Green Stormwater Infrastructure
ICAO	International Civil Aviation Organization
LID	Low Impact Development
NbS	Nature-based Solutions
UNDRR	United Nations Office for Disaster Risk Reduction
WWTP	Waste Water Treatment Plant

1 Introduction and Background

1.1 Climate

Climate change adaptation and resilience for water management is a field of growing interest in the water sector. Climate change hazards pose significant risks to infrastructure, economies, and livelihoods from events or trends such as extreme rainfall, storm surge, flooding, wildfires, drought, sea level rise and extreme storm events (IPCC, 2014; UNDRR, 2025; WMO, 2023). The impacts of climate change are wide in scope ranging across economic, environmental, global public health, and social implications. The most frequent natural disasters to occur annually are hydrological in nature (ICFM, 2022) and in a recent report by Wateraid (2025) it is estimated that 90% of natural disasters are water related. Floods are the most commonly occurring natural climate hazard (Liu et al., 2024) and in a 2020 report released by UNDRR floods made up 44% of all reported disasters from 2000-2019, affecting an estimated 1.6 billion people globally (UNDRR, 2020). It was determined that from 1990-2022 flooding resulted in 218,353 deaths and cost upwards of \$1.3 trillion dollars in economic damages (Liu et al., 2024).

1.2 Cities and Critical Infrastructure

Cities and urban areas are particularly vulnerable to flooding and storm events because of their high population density, centralized public services (police, fire, medical), centralized utilities (water, electricity, sewage) and large land areas covered by impervious surfaces. They have been rapidly evolving in the past three decades and climate proofing cities is a current strategy being used to address and reduce the issues of climate vulnerability and associated risk to city infrastructure (UN Habitat, 2021). Cities contain critical infrastructure such as healthcare facilities, emergency services, communication networks, the energy grid, financial institutions, water and wastewater services, and transportation networks, which need to account for climate change impacts on flooding to ensure service provision. In particular, airports around the world are investing in adaptation strategies to cope with increasing flood frequency and

magnitude (ICAO, 2022). As airports grow or their use case changes in the face of changing environmental or government regulation, flood mitigation strategies and appropriate technologies also evolve over time.

1.3 Airports and Flood Mitigation Strategies

There is a growing body of work that focuses on the climate resilience of airports to prevent and or mitigate flooding. Some literature focuses on the assessment of disaster preparedness and resilience proposing rating systems (Prihartanto et al., 2023), frameworks for assessment including hazard mitigation financial planning (Gale & Persaud-van Der Westhuizen, 2023) and stakeholder collaboration (CDRI, 2023), and adaptation portfolios with generalized operational and infrastructural options (ICAO, 2022).

There are many examples of case studies in the literature assessing historic flood events at airports or highlighting new flood mitigation design projects. Peng et al. (2018) describes the approaches taken two Chinese airports (Qingyang and Changbei) to both mitigate flood events while simultaneously storing rainwater for non-potable on-site utilization. This was accomplished by constructing underground storage tanks and reservoirs. In another case study focused on Chinese airports Ziyin et al. (2020) examined the different types of options available to airports to mitigate flooding while also adhering to a Low Impact Development (LID) strategy. They were able to categorize different zones within the airport (airside, landside, maintenance, depot, etc.) and offered appropriate flood mitigation measures based on the particular zone using airport-specific selection criteria.

Some studies use models to explore the performance of existing flood management infrastructure under future conditions or to test different designs. (Barbi et al., 2023) model alternative runway designs and materials while others model the hydraulic and hydrologic conditions present at the site across different climate scenarios, including flooding (Peng et al., 2020, 2021; Valentine & Apelt, 2011). Haji et al. (2017) focused on modelling storm surge protection alternatives (sea wall, temporary flood barriers, improved on-site

drainage capacity) against a 3ft hypothetical wave that would significantly disrupt operations at Reagan National Airport. These model scenarios were put into departure-arrival simulations to determine the amount of flight delay, cancellations, and time taken until the airport can fully resume operations. Wu et al. (2021) modelled future flood and climate scenarios using the general circulation model at Faleolo International Airport in Samoa. Peng et al. (2020) modelled rainwater drainage performance using SWMM at Beijing Daxing Airport against three proposed Low-Impact Development interventions (one pump, two pump, one pump and storage tanks). They also tested different sizes and locations for a proposed rain barrel, vegetative swale, green roof and storage tank were evaluated for performance (Peng et al., 2020). In a follow-on study, Peng et al. (2023) incorporated functional zoning, usage requirements and special land types in the airport area. In Australia, Valentine & Apelt (2011) explored the factors that affect flooding at the Brisbane Airport such as local and regional catchment data with storm surge and tidal datasets and developed a to perform options appraisal for future development works at the airport.

1.4 Nature-based Solutions (NbS) at Airports

While there are many technologies and approaches to help mitigate the effects of flooding in airports, nature-based solutions (NbS) are being increasingly regarded as a way of reducing net carbon emissions, reducing maintenance requirements and providing additional benefits locally. NbS for water resources management “involve the planned and deliberate use of ecosystem services to improve water quantity and quality and to increase resilience to climate change. They are typically adopted in conjunction with conventional water infrastructure to bring about more sustainable outcomes” (UN Environment-DHI et al., 2018). They can include green-blue infrastructure such as green roofs, rain gardens, swales, buffer strips, retention ponds, detention basins, and constructed wetlands (WWAP/UN-Water, 2018). NbS offer unique opportunities for their application at airports offering enhanced water absorption and storage capacities, increased biodiversity, improved water quality, cooling effects, and potentially lower up-front and ongoing maintenance costs as compared to grey

engineered solutions (UN Environment-DHI et al., 2018). Despite this fact and even with growing interest it is estimated that less than 1% of total investment in water resources management infrastructure is in NbS (WWAP/UN-Water, 2018). Proof of this is the limited examples in literature outlining current NbS approaches and practices at airports regarding inland flooding. ICAO (2025) in a recent study explored NbS in airport operations focusing on enhancing biodiversity through managing wildlife and potential habitat to discourage bird nesting and wildlife cover. This study did not specifically focus on NbS for flood mitigation but instead included it as a co-benefit for certain interventions. Alikhani (2018) reported on the comparison between the Malmi airport area and other green-blue spaces, specifically, 10 public parks in Finland and Germany. The airport was divided into 6 subareas which were then compared to public parks for similarity in terms of site conditions. Recommendations were then made for each subarea based on the site-specific selection criteria. The study focused more on biodiversity and social benefits and less about the flood mitigation potential of NbS.

There are previous pieces of work looking into NbS for flood management in airports which summarize the suitability of NbS under different environmental conditions (climate, soil, slope, etc.). Shi et al. (2015) focused on consolidating green stormwater infrastructure (GSI) best management practices (BMP) used around the world. This work was then used to create two standalone reports in 2017: Green stormwater infrastructure, Vol. 1 Primer and Vol. 2 Guidebook. The first report is intended for airport managers, engineers, and planners focusing on understanding stormwater management and to understand how GSI can comply with regulations and standards (James. Jolley et al., 2017). The second report is tailored toward airport staff and allows evaluation of different GSI strategies and how to select applicable GSI technologies and approaches at airports (J. W. Jolley et al., 2017). AMEC (2014) produced a report for Heathrow Airport titled “Heathrow's North-West Runway Sustainable Drainage Assessment.” This was an engineering assessment of a proposed new runway expansion project which included physical, geologic, hydrological

and hydraulic evaluations of the site and the proposed expansion plan. This is the most recent study of its kind from Heathrow Airport.

2 Aim and Objectives

2.1 Aim

However, given the fast-growing science around NbS, there is a need to update and consolidate the state-of-the-art. The purpose of this report is to outline the vast array of nature-based solutions that are currently being implemented at airports and their use case and present potential implementation options through site specific selection criteria (cost, safety, multi-benefit, etc.) for Heathrow Airport Limited for future drainage infrastructure upgrades or renovations. To realize that aim, this study will:

2.1.1 Objectives

1. Conduct a critical review of climate resilient flood risk management infrastructure from the scientific and grey literature (e.g. government and industry reports) for pluvial, fluvial and groundwater flooding, in consideration of the full range of NbS options;
2. Identify and extract key findings from case studies of flood risk management infrastructure from the aviation sector (and allied sectors), especially passive approaches that adapt or are resilient to climate change;
3. Assess the flood risk management infrastructure options based on potential performance, cost and other criteria in the context of Heathrow airport, incorporating information from previous flood risk assessments.

3 Materials and Methods

3.1 Methodology

The period from 2010-2025 was selected to capture significant advancements in the sector with regards to nature-based solutions being implemented for flood

control at airports. In 2014 the "Heathrow Airport Limited North-West Runway Sustainable Drainage Assessment" was prepared by AMEC Environment & Infrastructure UK Limited and this is the most recent report of its kind outlining current conditions and strategies being implemented by the airport regarding flooding (AMEC, 2014). Google Scholar, Web of Science, and Scopus were used to search for scientific articles. Overton and Google searches were used to identify key contributions in the grey literature (Policy, Resiliency Frameworks, Master Drainage Plans, etc.).

3.2 Airport Methods

An initial search of the Web of Science and Scopus databases was performed using the search string: ("Airport*" OR "Aviation" AND "Flood*" AND NOT "Coast*"). This search yielded 11,749 search results and while some of this information was useful for the background and introduction of the report, the results were too vast to screen with the given search criteria. A final Boolean search string was developed for the formal literature review. This was adapted after initial search results were too broad and included too many irrelevant results. I wanted to focus on inland flooding and not storm surge, sea level rise, tsunamis or other forms of coastal or oceanic induced flooding. These results were mostly eliminated through the final report selection process unless fluvial, pluvial, and or groundwater flooding were also addressed alongside coastal flooding or storm surge. Web of Science and Scopus were the two main databases that were searched on June 15 2025 using the final search string: ((flood*) OR (drainage) AND (airport) OR (aviation) AND (nature based solution) OR (nature-based solution) OR (NbS) OR (green) OR (blue) OR (blue-green) OR (green-blue) OR (sponge) AND NOT (sea) AND NOT (coast*) AND NOT (surge) AND NOT (ocean) AND NOT (tidal)) AND PUBYEAR > 2009 AND PUBYEAR < 2026. The search was restricted to peer reviewed journal articles and conference proceedings published in English between Jan, 1, 2010 until Jan, 1, 2025. The search focused on terms within the article title, abstract and keywords.

A database was created with the .CSV exports from both Web of Science and Scopus databases. This workbook had separate sheets for both the Web of Science and Scopus database search results. This provided the organizational structure for the identification, screening and inclusion phases of the literature review. There were selection criteria columns that were used for each database search result export. The columns were: Relevance, Available/Accessible, Extractable Data. Each of these columns were selected with either the symbol: ✓ representing yes, X representing no, and the question mark (?) representing uncertain and review again. After the creation of the database results Excel spreadsheets, I was then able to begin the identification, screening and exclusion phases for the final identification of studies to be included in the literature review.

The identification process consisted of selecting the final search string and appropriate databases for the study. Web of Science and Scopus were the two main databases that were used for this study. The final search string yielded 97 records across Web of Science and Scopus databases.

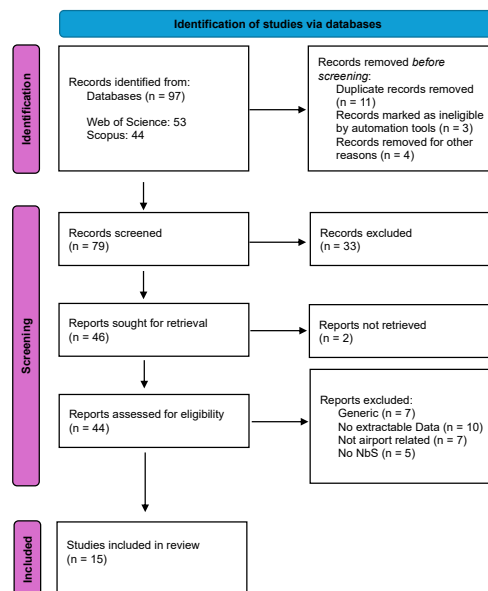


Figure 3-1 Airport Methods for document retrieval from databases

There were 11 duplicate records that were removed. Three records were excluded because of automation tools and 4 records were excluded because of the English language requirement. This left 79 records that would then pass through to the initial screening process. Of the 79 records that were identified after passing the pre-screening process, 33 were excluded for irrelevance. 46 records were then sought for retrieval from the databases, of these 46 records 2 records were excluded for not being accessible. Out of the 44 remaining records 29 records were excluded for various reasons: generic (n = 7), no extractable data (n = 10), non-airport related (n = 7), and no mention of NbS (n = 5). After the final screening and exclusion phase, 15 records were identified for inclusion for the literature review.

3.3 Non-Airport Methods

The journal articles and conference proceedings from the identification and screening process were downloaded and input into Mendeley Reference Manager for organization. This ensured local access to the documents throughout the entirety of the literature review process to help eliminate any issues arising from access becoming unavailable because of licensing purposes, indexing or database/website maintenance.

The spreadsheet was divided into different site consideration categories for data extraction from the included database results: Screening (e.g relevance, accessibility), NbS (e.g Type, Cost, Size), Site and Location (e.g region, country, airport name) Hydraulic and Hydrological (e.g runoff coefficient, peak flow reduction, yearly rainfall), Ecological (e.g species richness, wildlife hazard risk, biodiversity index), Physical (e.g slope, soil type, elevation). This spreadsheet was used for all included records from the database results.

4 Results

After compiling the search into the database, I was then able to extract data from the airport related articles and fill in the different site consideration

categories as defined above. Any gaps that I was able to identify I then extracted data from the Scopus non-airport NbS search results and if this was too broad then I searched for additional articles and grey literature focusing on the specific NbS technology with limited data in question.

The number of publications from the date range 2010-2025 is 15 (n = 15). The year 2020 saw the largest number of publications at 5 publications that year (Figure 4-1). In the year 2024 there were two publications (n = 2) and for all other years excluding 2010 (n = 0) the number of publications was 1 (n = 1).

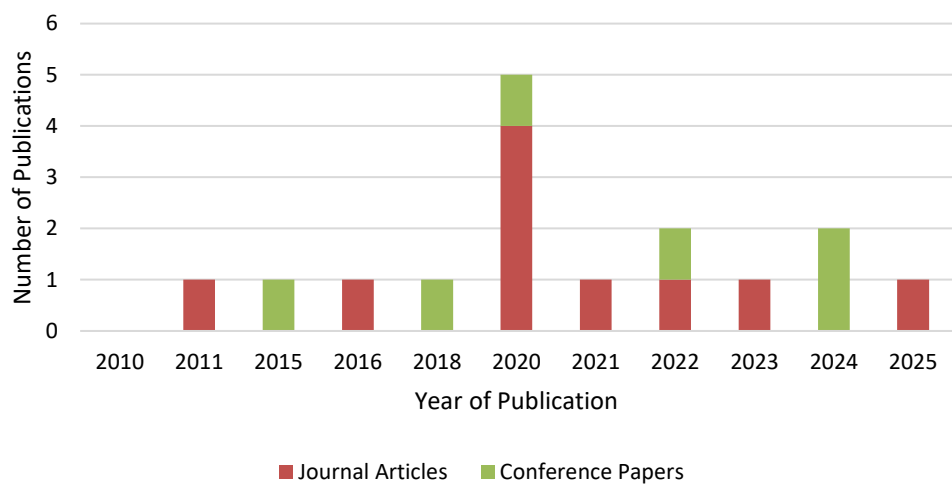


Figure 4-1 Publications by type and year. (Source: Author’s Work)

Out of the 15 publications, 9 were scientific journal articles while the other 6 were conference proceedings (Figure 4-1). Two conference papers were published per conference. All other journal articles were published individually in separate journals.

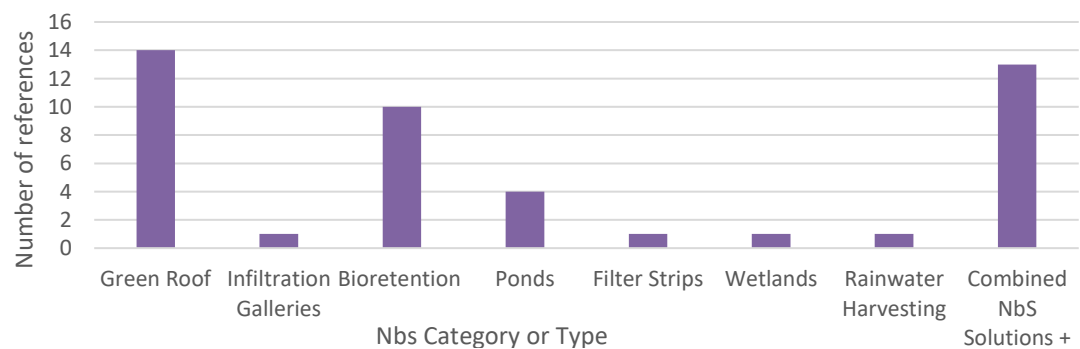


Figure 4-2 Number of Iterations within the literature (Source: Author’s Work)

4.1 Green Roofs

In the literature green roofs were the most reported NbS technology that was implemented at airports. Green roofs were reported in 9 out of the 15 articles and papers that were compiled for this review. Green roofs, also known as

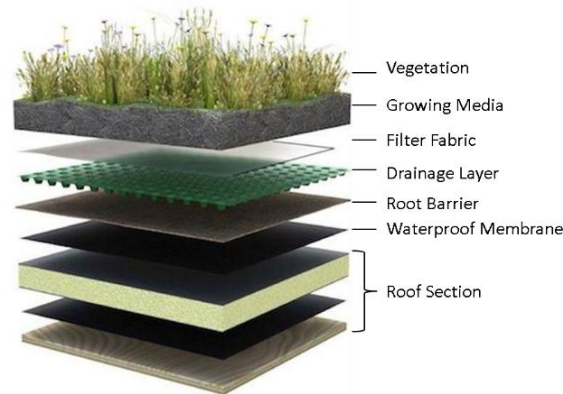


Figure 4-3 Green roof structure (Greener Heights, 2012).

rooftop gardens (Figure 4-3), consist of a layered waterproof membrane, root barrier layer, drainage layer, filter fabric, growing media or engineered soil mixture, and vegetation located on the roof of a building or structure (Gibler, 2015).

Green roofs can be categorized into different levels of complexity and depth. Extensive green roofs require the least soil depth (5-15 cm) and are cheaper to install and maintain. Intensive green roofs have deeper soil depths (>15 cm) that allow plants with deeper root structures to be planted, and less drought tolerant species can be used because of the increased moisture retention properties of the soil depths (Gibler, 2015).

Green roofs are often reported as a new construction element when designing new construction or airport expansion as opposed to retrofitting existing buildings with green roofs (James. Jolley et al., 2017). This is because green roofs often need to be incorporated into the original engineering and architectural design of the buildings because of the increased weight load on the roof and slope requirements. The main requirement for green roofs is a flat roof that can support the weight of the soil and plantings. Green roofs are reported as having a moderate effort requirement in terms of operation and

maintenance with the main requirement being weeding (every 2-4 weeks), pruning and vegetation replacement. Cuttings from green roof plant species during pruning can be used for further plant propagation across the green roof. Fertilizer should be applied each year during the spring for the first 3 to 5 years after installation (J. W. Jolley et al., 2017). Green roofs were reported to cost between £80 and £207 per square meter (Gibler, 2015; J. W. Jolley et al., 2017). The lifespan of a green roof is reported as being 40 years as compared to a traditional membrane roof of 20 years (Gibler, 2015).

One important factor that was outlined by Shi et al. (2015) is that the climate must not be too excessively arid or hot as this make maintaining and preserving the vegetation difficult. Temperature ranges and climates suitable for green roofs vary. For example, Chicago O'Hare Airport is categorized as having a continental climate with average temperature ranges from a low of -4.1°C to a high of 22.2°C in the warmer months (Washburn et al., 2016). Chicago O'Hare Airport has installed green roofs on 16 of its facility buildings covering an area of over $41,800\text{ m}^2$ (J. W. Jolley et al., 2017). The Chicago Department of Aviation (CDA) reports that at the neighbouring Midway Airport they have installed over $1,500\text{ m}^2$ of green roofs. The CDA reports that it is estimated that green roofs at Chicago O'Hare and Midway airports during the summer retain 70-90 percent of the precipitation that falls on them and between 25-40 percent during the winter months (Chicago Department of Aviation, 2025). It is estimated for example that the green roof on the FedEx Main Sort Building (Figure 4-4) at Chicago O'Hare Airport retains approximately $7,570\text{ m}^3$ of storm water annually (Chicago Department of Aviation, 2025).



Figure 4-4. FedEx Main Sort Building, Chicago O'Hare Airport (Aviation Pros, 2016).

In another study focusing on Beijing Daxing airport (Peng et al., 2021) using SWMM modelled hypothetical LID upgrades for the airport. Green roofs were shown to reduce flooding by 75-80%. J. W. Jolley et al. (2017) reports that green roofs have been shown to retain 25 to 90 percent of precipitation dependent on seasonality.

The other main factor of concern is to ensure the green roof does not create a suitable habitat or attraction for wildlife. The plant species should be chosen so that it does not attract wildlife, mainly birds (Table 1).

Green roofs can pose a FOD (Foreign Object Damage) risk if soil aggregates, plantings, or pieces of the green roof infrastructure become loose and could potentially injure or damage aircraft, airport personnel, or passengers (U.S. Department of Transportation Federal Aviation Administration, 2020). The CDA to comply with regulatory measures and to prevent FOD risk designed the green roofs with wind speed requirements to prevent parts of the green roof from blowing into aircraft movement areas (Chicago Department of Aviation, 2025). Green roofs are usually installed by specialist companies so wildlife and FOD risk should be determining factors brought up in the design phase of the project.

Table 1. Sedum Plant Species at CDA Airports (Chicago Department of Aviation, 2025).

Sedum Species	Common Name	Flower	Height (cm)
album	White Stonecrop	White	5-10
sexangulare	Tasteless Stonecrop	Yellow	5-10
spurium	Dragon's Blood Stonecrop	Pink	10-15
stenopetalum	Wormleaf Stonecrop	Yellow	5-10
ellacombianum	Orange Stonecrop	Yellow	10-15
pulchellum	Widow's Cross	Pink	10-15
oreganum	Oregon Stonecrop	Yellow	5-10
hybridum	Czar's Gold	Yellow	10-15
reflexum	Blue Spruce	Yellow	10-15
acre	Goldmoss Stonecrop	Yellow	5-10

The CDA sought to use native sedum plant species that are unattractive to wildlife, drought tolerant and are common ground cover across that region of the United States (Chicago Department of Aviation, 2025).

4.2 Bioretention

The next most reported NbS type for use at airports was Bioretention. Bioretention technologies are also known as bioretention cells or rain gardens (Figure 4-5). This NbS type was reported as being implemented on the landside of the airport around commercial buildings, roadways, parking areas and around terminals (J. W. Jolley et al., 2017). The main concern regarding bioretention cells and their implementation at airports is the significant wildlife attraction factor. Exclusion devices such as wires and netting have been used to prevent wildlife from using the bioretention systems as habitat (J. W. Jolley et al., 2017). Bioretention systems function as “soil-and-plant-based filtration devices” that remove pollutants through physical, biological, and chemical interactions between the pollutants in the runoff and the plants and the organic media (J. W. Jolley et al., 2017). Bioretention systems can be lined or unlined depending on the soil permeability and the pollutant load concentration regulations and requirements. Ideal soil conditions are reported with a soil permeability of 1.25 cm to 5 cm per hour (Royal Horticultural Society, 2025).

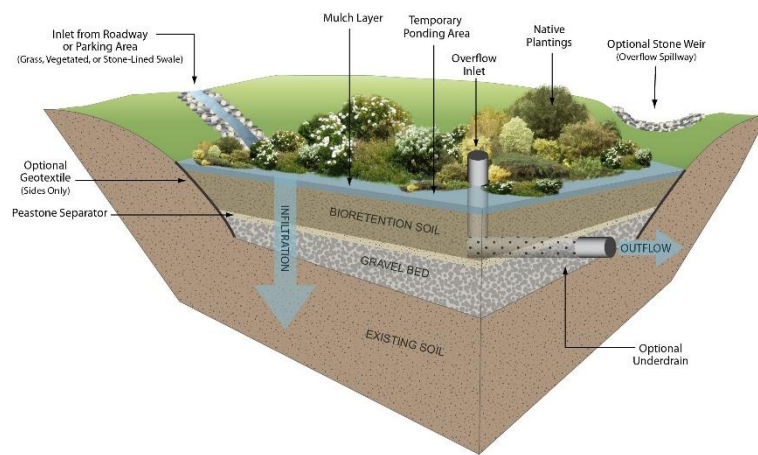


Figure 4-5. Bioretention cell side view cutaway (Geosyntec Consultants, n.d.).

Rain gardens are best suited in areas that have a slope of 10% or less (Royal Horticultural Society, 2025). A berm should be constructed for the rain garden to ensure that water stays within the rain garden. The berm should be 30 cm wide and 10 cm tall (Royal Horticultural Society, 2025). An important factor when selecting the plant species for a rain garden are that the plant species

must be able to remain waterlogged for up to 48 hours at a time. More drought tolerant species can be used at the periphery of the rain garden (Royal Horticultural Society, 2025). For example, at the Fresno Yosemite International Airport the rainfall is insufficient to maintain extensive vegetation so the bioretention system acts as an infiltration gallery or a slow sand filter (J. W. Jolley et al., 2017). Minneapolis–St. Paul International Airport reports that with well-draining soils with a permeability of 1.27 cm per hour flood can retain up to 100% runoff volume through infiltration. Soils with moderate to low permeability show that runoff can be reduced up to 30% through evapotranspiration mechanisms (J. W. Jolley et al., 2017). It is reported that bioretention systems can cost between 83£ and 332£ per m² of area and have a projected lifespan of 20 years. The maintenance requirements are reported as pruning, mulching, planting, weeding, erosion repair, unclogging pipes and drains, trash and debris removal.

4.3 Bioswales

Bioswales were widely reported in the literature as a NbS type for use across airports. Bioswales are a NbS type that is characterized as a stormwater conveyance system that provides remedial infiltration and sedimentation. Bioswales are grassy or vegetated channels that convey and contain stormwater runoff. A bioswale should be designed in areas that receive that least 30 cm of rainfall per year (J. W. Jolley et al., 2017). Bioswales were reported for airside and landside applications across different airport site features (commercial buildings, terminals, roadways, taxiways, parking areas, runways) (J. W. Jolley et al., 2017). Bioswales need to have a moderate slope with well-draining soils to enhance conveyance efficiency and to help mitigate standing or pooling water. A properly maintained and constructed bioswale has a theoretical indefinite lifespan. Costing for bioswales is relatively straightforward as a typical swale has design requirements that are well documented. If engineered soil mixes are used, then the cost can be expected to significantly increase. Seattle-Tacoma International Airport reported that for £480,325 an enhanced bioswale project was completed spanning 21,043 m² (J. W. Jolley et

al., 2017). It was reported that over 33 bioswales were installed at Seattle-Tacoma International Airport in two areas: At the edges of parking lots and along the expressway.



Figure 4-6. Bioswale at San Francisco International Airport Exit Ramp (Leda, 2012).

The airport reported that the capital costs can be moderately expensive >£74,000 to £370,000 with an associated O+M cost of £3,700 to £37,000. The payback return period was stated as being 2-5 years. The staffing requirements associated with bioswale implementation at the airport were reported as <10 hours per month (Walters, 2016). Another example of bioswale implementation at an airport is the 2006-2008 Runway 25L Relocation & Center Transitway Improvement Project at Los Angeles International Airport boasting 4,215 linear meters in length and volume of 11,978 m³ of bioswales (Ecorainwater Solutions, 2023). Beneath these bioswales to help improve infiltration Ecorain ER-502 Double Tanks were installed (Ecorainwater Solutions, 2023). This improvement project implemented these two long bioswales from collaboration between Rainwater Solutions LLC and the engineering firm Tutor-Saliba (Ecorainwater Solutions, 2023). This solution was chosen over more traditional drainage expansion efforts (e.g, wider diameter drainage systems) which would require much more expansive and disruptive excavation work. The shallow installation which is approximately 1 meter in depth, eliminated the need for geogrid substructure which showed significant savings on labor costs (Ecorainwater Solutions, 2023). The estimated cost savings were reported as £2.5 per meter

by eliminating the geogrid substructure. The Ecorain infiltration (Figure 4-7) boxes also could be constructed on-site which reduced transportation costs (Ecorainwater Solutions, 2023).



Figure 4-7. Bioswale installation at Los Angeles International Airport
(Ecorainwater Solutions, 2023).

4.4 Vegetated Filter Strips

Filter strips are a widely reported NbS solution for airports specifically focusing on airside applications adjacent to runways and taxiways (Figure 4-8). Filter strips, or vegetated filter strips are designed to treat stormwater runoff as “overland sheet flow,” (J. W. Jolley et al., 2017). The topography and design requirements of runways and taxiways naturally lends itself to being a desirable area to implement filter strips (Figure 4-9). Filter strips are often implemented along airside roadways and ramps. Filter strips planted with dense vegetation provided additional roughness and friction forces that slow down the runoff while additionally enhancing water quality by reducing pollutant load concentrations by infiltration and evapotranspiration (J. W. Jolley et al., 2017). Vegetated filter strips are often seen used in conjunction with other NbS such as filter strips leading to bioswales.



Figure 4-8 Filter strips at North Carolina Airports (North Carolina Department of Environmental and Natural Resources, 2012).

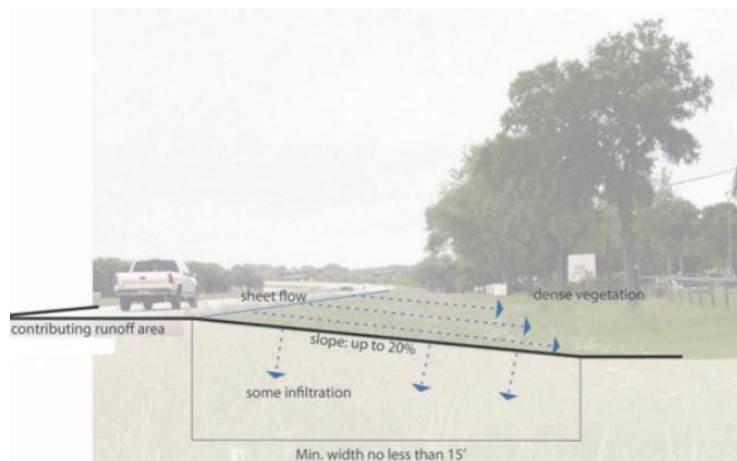


Figure 4-9. Filter strip runoff flows and design aspects (J. W. Jolley et al., 2017).

Vegetated filter strips have varying degrees of runoff volume control. Filter strips designed where the soil has a high permeability can reduce runoff volumes almost entirely (J. W. Jolley et al., 2017). If filter strips are in areas where the soils have a low permeability runoff volume reduction can be achieved up to 50 percent. Vegetated filter strips maintenance requirements are low, and mowing is considered the main maintenance activity. Filter strips are often located within the RSA (Runway Safety Area) and are located at least 76 meters away from the runway centerline. These areas would need to be

mowed anyway so filter strips are considered to have no additional maintenance requirements as opposed to a grassy runway safety area. It is important to not include any grass seed containing millet as this is considered a wildlife attractant (North Carolina Department of Environmental and Natural Resources, 2012).

4.5 Constructed Wetlands

Another NbS that is discussed in the literature are constructed treatment wetlands. These NbS are often used for targeted pollutant reduction as constructed wetlands do little to reduce runoff volume (Higgins & Maclean, 2002; J. W. Jolley et al., 2017). Constructed wetlands can be categorized as surface flow or sub surface flow wetlands. Sub surface flow wetlands (Figure 4-10) are uniquely better suited for use in airports because of the limited interface of surface water to the environment, thus reducing wildlife habitat and attractiveness (Higgins & Maclean, 2002).

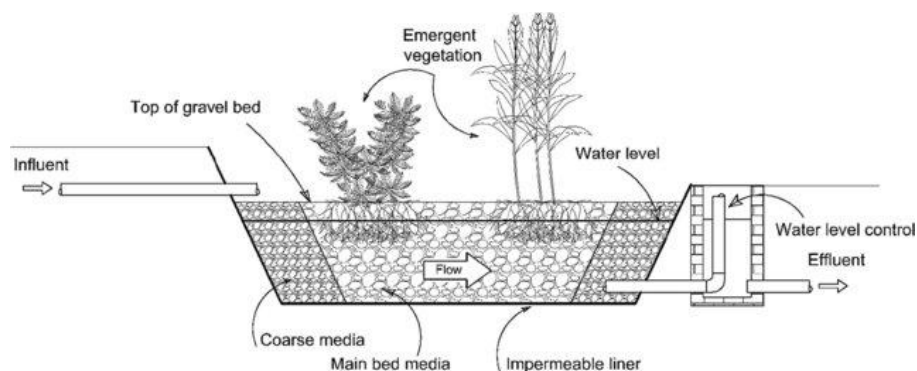


Figure 4-10 Horizontal Flow Subsurface Constructed Wetland (Higgins & Maclean, 2002).

Surface flow wetlands can be used in airport settings but careful consideration must be taken to manage wildlife risk such as netting or dense plantings to discourage open water that could be attractive to wildlife (Higgins & Maclean, 2002). The land requirements for constructed wetlands can be quite large and are an important factor when choosing this NbS option for implementation at an airport. Constructed wetlands are suited to areas with high water tables and wet climates. At the Buffalo Niagara International Airport the de-icing

operations of the 2010-2011 season saw a BOD₅ concentration reduction of 98.3 percent (J. W. Jolley et al., 2017). The system was designed for a 95 percent BOD₅ reduction. At Edmonton International Airport a feasibility study was undertaken using two pilot SSF wetland cells 1.2 m² in area testing “worst case scenario” levels for Ethylene Glycol, NH₃, NO₃, NaCl, and Phenols. This “worst case scenario” feasibility study was tested at the pilot scale and Ethylene Glycol reductions were reported as greater than 99% with and without aeration with residence times ranging from 2 to 4 days (Higgins and Maclean, 2002).

4.6 Rainwater Harvesting and Reuse

Rainwater harvesting and reuse systems were seen implemented worldwide in the literature often for non-potable applications (irrigation, cleaning, toilet flushing). For potable or special use case applications additional treatment such as through an on-site water treatment works may be necessary. Rainwater harvesting and reuse systems are often seen used in conjunction with other NbS systems that may need water for their function such as maintenance of filter strips and rain gardens in times of little precipitation or recent installation of NbS which require time before plantings take hold and establish themselves). Rainwater harvesting and reuse systems main objective is stormwater runoff volume control and storage. Pollutant concentration reduction is minimal (J. W. Jolley et al., 2017). Rainwater storage can be designed with above ground cisterns or sub surface storage tanks depending on the site and intended reuse application. At Zurich airport in the year 2000 the expansion project of Concourse E began. When finally completed the Concourse E rainwater harvesting system connected to two underground tanks which as demand dictates can provide flushing water to 160 toilets and 70 urinals saving 12,000 m³ of potable water annually (ICAO, 2019a). This is equivalent to 1/3 of the total water usage for Concourse E. In France at the Paris Charles Degaulle Airport more than 76,000 m³ of rainwater is collected annually across the airport site generating an annual savings of approximately 130,000 £, offsetting around 5% of the airports annual water usage (ICAO, 2019b). At Rajiv Gandhi International Airport in India a rainwater harvesting

system (roofs, paved areas) was built as part of a great Water Management Project which included recycling wastewater from an on-site WWTP, increased reduction and efficiency in irrigation and sprinkler systems using cloud-based automation technologies, reusing HVAC and air conditioning condensate, and infiltration of rainwater into the aquifer through a specially designed borehole. It was reported that over 35,000 m³ of surface water is reused annually (ICAO, 2019b). The rainwater net recharge was reported as 1.729 million m³ per year with the addition of 3 to 5 meters to the area surrounding the airport thus providing access and water security to the local community.

4.7 General site wide considerations for Heathrow

After conducting the literature review and meeting with members of the Heathrow staff it was decided to provide a site wide map that showed specific zones with possible NbS implementation potential. The two main categories of zones at an airport are: Airside and Landside. Airside is defined as anywhere that aircraft move, park, board passengers, or are serviced while landside areas are essentially everywhere else that does not involve aircraft movement or operations. Landside would include parking areas, ticketing, pick up and drop off areas, taxi services, and shops. The other important zoning factor that was taken into account for NbS options appraisal for Heathrow Airport was the proximity to runways and taxiways. These areas are referred to as the runway safety area and taxiway safety area respectively.

The best viable option for these areas are filter strips. These safety areas are to be maintained and function as a fail safe for airplane excursions. They extend around the perimeter of the runway and taxiways. For the runways there are grassy areas before the runway and after to provide a buffer area for missing the landing zone or for whatever reason over or undershooting the typical landing. It is important to design filter strips to be non-hazardous to aircraft with low maintenance requirements and upfront costs. These safety areas around runways are already of a low slope and should have well-draining soils. Shorter grasses require more maintenance and offer less of a roughness benefit in terms of slowing down overland sheet flow. Shorter grasses and

maintenance regimes and preferred lengths have been studied at airports since the 1980s (Yin et al., 2023). Some bird and wildlife species prefer shorter grasses for better observation of predators and threats while other species prefer longer grasses for greater opportunity for food biodiversity (Yin et al., 2023). An interesting breakthrough in plant biology is in the inoculation of an endophytic fungus within the grass seed (Figure 4-11). The endophytes bond to all parts of the grass structure including the base, stem, and seed head (Yin et al., 2023). The endophytes bond with the different plant sections and cause an alkaloid to be produced that is inhospitable to bird forage (insects and rodents). This causes the relocation of the bird food chain, and this breakthrough could allow grass lengths to be reconsidered. For birds such as Canadian Geese that consume grasses it was shown that they practice “learned avoidance behaviour” for areas surrounding endophyte bonded grassy areas (Yin et al., 2023).

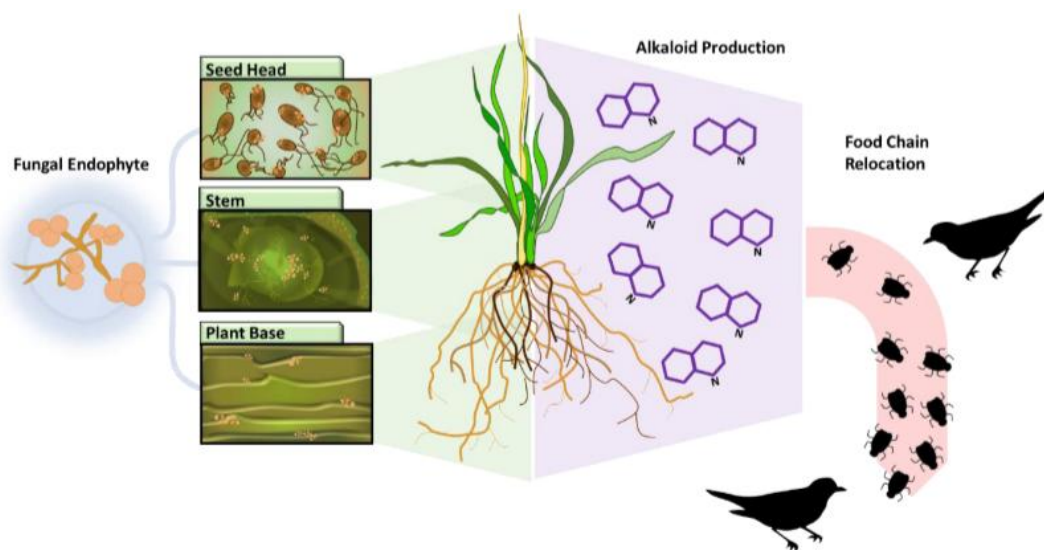


Figure 4-11 Endophyte bonded grasses and food chain relocation. (Yin et al., 2023)

Outside of these safety areas, grasses inoculated with the same endophytic fungus would provide similar levels bird risk mitigation. The grass length could be maintained higher to lower labour and maintenance costs if need be. Grassy areas that are right outside of these safety zones could utilize NbS in the form of bioswales and filter strips using the endophyte fungus inoculated grasses.



Figure 4-12 Heathrow general sitewide NbS suggestions (Map Source: Google Earth, Drawing Source: Author's Work)

As seen above (Figure 4-12) in the areas directly surrounding the runways filter strips are the suggested solution which are marked as orange. Directly outside of that zone moving closer to terminal areas, places where there is already grass can be modified to function like how a filter strip works or bioswales could be installed to move water away from these areas and allow for some filtration and infiltration. These areas are indicated with the colour purple.

Terminal 4 (T4) already has a rainwater harvesting system and conveys the water offsite to a reservoir. Unfortunately, this system is not used because of the pumping, filtration, and flushing requirements. As such the rainwater is not used back onsite and this is a potential resource that Heathrow could be using. An upgrade to this system could help to reduce Heathrow Airports onsite water demand usage. I also suggested rainwater harvesting at and surrounding Terminal 5 (T5). The zone directly to the west was also identified as a potential place for rainwater collection and reuse (stored on or offsite depending on

Terminal 4 rainwater harvesting system upgrade and revitalization). Terminal 5 and the area to the west were identified because of their proximity to the existing reservoir and stormwater outlet tunnel. The areas that I suggest rainwater harvesting are shown in blue.

The final suggestion that I would provide Heathrow Airport is the incorporation of green roofs on terminal and work area buildings. These share some of the same spaces that I have previously suggested rainwater harvesting. I am not suggesting both on the same roofs. The green roofs would be an alternative if Heathrow cannot fix the current rainwater harvesting system in place. These suggested locations are identified in Figure 4-12 in green. Terminal 1 (T1) could serve as a test site for a green roof project as the terminal is currently not used by the public.

5 Discussion

NbS in airports are being reported more and more often in the scientific literature. This comes with growing pressures in the industry and stricter environmental regulations. There are also financial and certification incentives that are currently seen in the aviation industry for example, the Airport Carbon Accreditation program. NbS have been shown to be effective for flood mitigation at airports globally. The US, Europe and China saw the most reporting regarding NbS at airports and this knowledge base is growing. There has been considerable research in NbS at airports and many airports are taking a greener approach to airport design and operational strategies moving forward.

After performing the literature review, I was able to discover that there have been notable advancements NbS in the scientific literature. Many airports around the world are implementing NbS as part of their flood mitigation approach. In comparison to the Heathrow Northwest Runway Sustainable Drainage Assessment there are some similarities and some differences with the proposed solutions (AMEC, 2014). It is important to understand that this was a Sustainable Drainage Assessment that did not specifically address NbS but some examples of NbS were included. This was also a feasibility study that

focused on brand new construction of a planned expansion and was not a retrofitting study. Our two approaches were different but our results overlap in some areas. The main similarity that both designs share are the inclusion of rainwater harvesting and reuse. AMEC (2014) concluded that a combination of rainwater harvesting and reuse and sub-surface storage were the best solutions to address flooding issues. A wetland was proposed as a water quality treatment solution. This expansion plan and the proposed project never got built due to various reasons. It would be interesting to see if this proposed sustainable drainage assessment in 2025 would reflect the same findings from the 2014 assessment. AMEC (2014) rejected the use of filter strips, green roofs, and bioswales because of their potential to attract wildlife. There has been more research since the 2014 report was published and I found more evidence that these technologies if implemented correctly can be appropriate at airports.

My findings also indicate that my search criteria was different than from the drainage assessment that was conducted for Heathrow in 2014. My findings were focused only on flood mitigation and did not focus on resource recovery such as glycol from de-icing operations. My research was less focused on water quality issues and was more concerned with issues surrounding water quantity, specifically flooding. Droughts and lack of water were not addressed specifically but with the use of rainwater harvesting and reuse systems water quantity issues could be co-addressed.

The most reported potential drawback of NbS for use in an airport context are their inclusion of vegetation (e.g. Bioswales, Retention Cells). This can potentially pose a risk to an airport area in that it can be attractive to wildlife, notably birds, and can provide shelter to rodents and insects which birds consume. It was reported that specific species of plants should be used that are unattractive to wildlife and this will depend on the geography and climate of the airport. It was often recommended that if using NbS at an airport a professional biologist should be consulted to provide an ecological assessment

of the proposed NbS project. Balancing the potential benefits versus the risks associated with NbS at airports make their implementation very site specific. While economic, environment and social benefits can be greater with the inclusion of NbS airports critically need to address safety and operational concerns first and foremost. One of the most promising advancements in NbS technology was the research conducted by Yin et al. (2023) with the endophyte bonded grasses and their ability to make grassy areas not hospitable for wildlife and their prey.

The second most reported drawback of NbS at airports is also specifically related to wildlife habitat. The use of open water like in the case of balancing ponds poses risks associated with nesting birds and wildlife habitat. The use of underground storage tanks is often a solution that airports use to prevent open water risks. An approach that is currently used at Heathrow Airport is the use of “bird balls” that are located in a reservoir on site. These bird balls cover the surface of the water and act as a deterrent against bird nesting. They cover the entirety of the waters surface and float up and down with the rising and falling water levels. This is a creative approach to modify a potentially dangerous NbS approach and use non-traditional technology to make it acceptable for use.

It is through creative adaptation measures such as these that allow certain NbS to fit into the special context of an airport. As more research is conducted in the field of NbS and NbS applications at airports there are bound to be more creative adaptive measures that allow the benefits that can come with using NbS to be highlighted and valued (Social, Economic, Environmental) while also addressing very real safety concerns (bird strike, habitat creation). Creative adaptive measures like these will likely help to tip the scales in favour of greater NbS adoption at airports in the future.

6 Conclusion

Building climate resilience into airport operations and infrastructure is a growing trend in the sector. Many airports have implemented sustainable measures to reduce their greenhouse gas emissions, lower energy needs, efficient use of resources, investing in renewables, and lowering their environmental impact. As airports respond to the short and long-term challenges posed by climate change ensuring future resilience is a growing priority for airport planners, operators, investors, and the local communities in which they serve. Flood mitigation and prevention strategies through the use of NbS can provide airports with resilient infrastructure that can serve future generations. NbS for stormwater management often times have lower capital costs and associated lower operations and maintenance costs. NbS can also be well suited for airports because they are often less disruptive than traditional engineered grey solutions (e.g expanding existing drainage network or increasing diameter of drainage pipe network) which could significantly alter operations and could result in loss of revenue from disrupted operations.

Currently at Heathrow Airport filter strips with endophyte bonded grass species were suggested for areas directly adjacent to the runway areas. Further away from the runways bioswales and or filter strips were suggested as potential areas for NbS implementation. Upgrading the rainwater harvesting system in the Terminal 4 area was suggested as a lot of the necessary infrastructure is already there for this system to work. If this option is abandoned green roofs could serve as a viable alternative for this area. Rainwater harvesting was also suggested at and around Terminal 5 because of its proximity to the stormwater outlet tunnel and the receiving water body for storage purposes. Green roofs were also suggested in the Terminal 5 area if investment or reclamation of the current rainwater harvesting system is decided against. The area to the Northeast of the Terminal 5 area was also suggested to utilize green roof technology. If Heathrow Airport does go ahead with the Northwest runway expansion, then NbS can be built into this master plan from the start and would not require retrofits or existing upgrades like at the current site.

References

- Alikhani, S. (2018). *The concept and practice of green-blue infrastructure in new urban area of Malmi airport*. Lahti University of Applied Sciences.
- AMEC. (2014). *Heathrow's North-West Runway: Sustainable Drainage Assessment*. https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/300223/airports-commission-appraisal-framework.pdf
- Aviation Pros. (2016, April 18). *Chicago Airports' Green Buildings Highlighted for Earth Week*. Photograph. <https://www.aviationpros.com/airport-business/airport-infrastructure-operations/press-release/12196389/chicago-department-of-aviation-chicago-airports-green-buildings-highlighted-for-earth-week>
- Barbi, P. S. R., Tavassoti, P., & Tighe, S. (2023). Enhanced Pavement Design and Analysis Framework to Improve the Resiliency of Flexible Airfield Pavements. *Transportation Research Record*, 2677(8), 118–136. <https://doi.org/10.1177/03611981231155909>
- CDRI. (2023). *Five Steps towards Resilience of Airports: Global Study on Disaster Resilience of Airports*. <https://www.marketsandmarkets.com/PressReleases/future-of-airport-in->
- Chicago Department of Aviation. (2025). *O'Hare and Midway International Airports: Vegetated Roofs*. <https://www.flychicago.com/community/environment/vegetatedroofs/pages/default.aspx#collapseFour>
- Ecorainwater Solutions. (2023). *Los Angeles International Airport Runway 25L Bioswale*. <https://eco-rainwatersolutions.com/lax-international-airport-ecorain-system/>
- Gale, J., & Persaud-van Der Westhuizen, D. (2023). The future of airport infrastructure resilience. *Journal of Airport Management*, 18(1).
- Geosyntec Consultants. (n.d.). *Bioretention Areas & Rain Gardens*. Massachusetts Clean Water Toolkit. Retrieved August 27, 2025, from <https://megamanual.geosyntec.com/npsmanual/bioretentionareasandraingarden.s.aspx>
- Greener Heights. (2012, April 22). *Greener Heights*. <https://greenerheights.wordpress.com/page/2/>
- Gibler, M. R. (2015). *Comprehensive benefits of green roofs* [Masters Thesis, Missouri University of Science and Technology]. https://scholarsmine.mst.edu/masters_theseshttps://scholarsmine.mst.edu/masters_theses/7396
- Haji, M., Alawaji, N., Aldakhil, D., & Diriye, M. (2017). Design and analysis of a storm surge protection system for Reagan National Airport. *2017 Systems and Information Engineering Design Symposium (SIEDS)*, 62–66. <https://doi.org/10.1109/SIEDS.2017.7937754>

- Higgins, J., & Maclean, M. (2002). The Use of a Very Large Constructed Sub-Surface Flow Wetland to Treat Glycol-Contaminated Stormwater from Aircraft De-Icing Operations. In *Water Qual. Res. J. Canada* (Vol. 37, Issue 4). <http://iwaponline.com/wqrj/article-pdf/37/4/785/228993/wqrjc0370785.pdf>
- ICAO. (2022). *Climate Change: Climate Risk Assessment, Adaptation and Resilience - Menu of Adaptation Options*.
- ICAO. (2025). *Skyward Action Realizing Aviation's Sustainable Future 2025 ICAO Environmental Report*.
- ICFM. (2022). *A Compilation of 2020-2021 Global Flood Events and International Experience in Flood Management*.
- IPCC. (2014). *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Intergovernmental Panel on Climate Change.
- Jolley, J. W., Tuccillo, M. E., Young, M. L., Barrett, M., & Lantin, A. (2017). *Green Stormwater Infrastructure - Volume 2: Guidebook*. Transportation Research Board. <https://doi.org/10.17226/24816>
- Jolley, James., Tucillo, M. Ellen., Young, M. L. ., Barrett, M. E. ., & Lantin, Anna. (2017). *Green stormwater infrastructure. Volume 1, Primer*. Transportation Research Board, the National Academies of Sciences, Engineering, Medicine.
- Leda, M. (2012). The Trees and Plants of San Francisco International Airport. Deep Root Blog. <https://www.deeprooot.com/blog/blog-entries/the-trees-and-plants-of-san-francisco-international-airport/>
- Liu, Q., Du, M., Wang, Y., Deng, J., Yan, W., Qin, C., Liu, M., & Liu, J. (2024). Global, regional and national trends and impacts of natural flood1990–2022. *Bulletin of the World Health Organization*, 102(6), 410–420. <https://doi.org/10.2471/BLT.23.290243>
- North Carolina Department of Environmental and Natural Resources. (2012). DWQ BMP Manual Toolbox for Airports Version 4.3. In *NCDENR Stormwater BMP Manual*.
- Peng, J., Ouyang, J., & Yu, L. (2021). The model of low impact development of a sponge airport: A case study of Beijing daxing international airport. *Journal of Water and Climate Change*, 12(1), 116–126. <https://doi.org/10.2166/wcc.2020.195>
- Peng, J., Yu, L., Cui, Y., & Yuan, X. (2020). Application of SWMM 5.1 in flood simulation of sponge airport facilities. *Water Science and Technology*, 81(6), 1264–1272. <https://doi.org/10.2166/wst.2020.221>
- Peng, J., Zhang, X. M., & Zhang, Y. H. (2018). Study on combining flood control with rainwater utilization of airports in China. *IOP Conference Series: Earth and Environmental Science*, 191(1). <https://doi.org/10.1088/1755-1315/191/1/012133>

- Peng, J., Zhao, H., Luo, Z., Ouyang, J., & Yu, L. (2023). A new approach for sensitivity analysis of the StormWater Management Model applied in an airport. *Water Science and Technology*, 88(9), 2453–2464. <https://doi.org/10.2166/wst.2023.335>
- Prihartanto, E., Rohman, M. A., & Wiguna, I. P. A. (2023). Assessment of airport conditions in resilience efforts: A review. *E3S Web of Conferences*, 429. <https://doi.org/10.1051/e3sconf/202342903001>
- Royal Horticultural Society. (2025). *Rain Gardens*. <https://www.rhs.org.uk/garden-features/rain-gardens>
- Shi, X., Beutel, M., Long, T., Andrew Hellenthal, & Bristoll-Groll, C. (2015). *Green Stormwater Infrastructure Strategies for Airports: Challenges and Opportunities*.
- UN Environment-DHI, UN Environment, & IUCN. (2018). *Nature-Based Solutions for Water Management: A Primer*.
- UN Habitat. (2021). *Climate Proofing Toolkit: For basic urban infrastructure, with a focus on water and sanitation*. www.unhabitat.org
- UNDRR. (2020). *Human cost of disasters: An overview of the last 20 years (2000-2019)*.
- UNDRR. (2025). *Global Assessment Report on Disaster Risk Reduction 2025: Resilience Pays: Financing and Investing for our Future*.
- U.S. Department of Transportation Federal Aviation Administration. (2020). *Advisory Circular Subject: Hazardous Wildlife Attractants on or near Airports*.
- Valentine, E. M. ., & Apelt, C. J. . (2011). *Proceedings of the 34th IAHR World Congress, 33rd Hydrology and Water Resources Symposium, 10th Conference on Hydraulics in Water Engineering : balance and uncertainty - water in a changing world, 26 June - 1 July 2011, Brisbane Australia*. Engineers Australia.
- Walters, M. (2016, August 15). *Install bioswales (non-wildlife attracting) to encourage groundwater infiltration of stormwater runoff*. Sustainable Aviation Guidance Alliance. <http://www.airportsustainability.org/practice/265>
- Washburn, B. E., Swearingin, R. M., Pullins, C. K., & Rice, M. E. (2016). Composition and Diversity of Avian Communities Using a New Urban Habitat: Green Roofs. *Environmental Management*, 57(6), 1230–1239. <https://doi.org/10.1007/s00267-016-0687-1>
- Wateraid. (2025). *Water and climate: Rising risks for urban populations*.
- WMO. (2023). *The Global Climate 2011-2020: A decade of accelerating climate change*. World Meteorological Organization.
- Wu, L., Taniguchi, K., & Tajima, Y. (2021). Impact of climate change on flood hazard at airports on pacific islands: A case study of faleolo international airport, samoa. *Journal of Disaster Research*, 16(3), 351–362. <https://doi.org/10.20965/jdr.2021.p0351>

- WWAP/UN-Water. (2018). *The United Nations World Water Development Report 2018: Nature-Based Solutions for Water*. United Nations Educational, Scientific and Cultural Organization.
- Yin, T., Tibbetts, D., Knudsen, P., Faris, C., & Johnson, M. E. (2023). *Implementing Airside Bioswales for Stormwater Management at the Airport*.
- Ziyin, Q., Jie, O., & Xingang, H. (2020). Research on the Design of Comprehensive Storm Flood Prevention and Treatment Project of Sponge Airport. *IOP Conference Series: Earth and Environmental Science*, 568(1).
<https://doi.org/10.1088/1755-1315/568/1/012024>

Appendices A

Ethical approval letter



9 June 2025

Dear Mr Coco ,

Reference: CURES/25585/2025

Project ID: 29153

Title: Climate Change Adaptation and resilience for water management at Heathrow Airport

Thank you for your application to the Cranfield University Research Ethics System (CURES).

We are pleased to inform you your CURES application, reference CURES/25585/2025 has been reviewed. You may now proceed with the research activities you have sought approval for.

If you have any queries, please contact CURES Support.

We wish you every success with your project.

Regards,

CURES Team