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8th July 2026

RE: An Coimisiún Pleanála PAX07.323761 (www.cooloowfplanning.com)

MKO Agent for Applicant's Response to Observations

Appendix 2 of MKO Response: HES Letter 27th February 2026 (Ref: P1611-1-0001)

I have been asked by Barnaderg Gortbeg GWS to address MKO's "Applicant's Response to Submissions" and specifically Appendix 2 HES's response to the Hydro-G (2025) Report commissioned by the GWS. I was the author of the Barnaderg Gortbeg GWS's November 2025 Observation and Objection to the proposed development. We are writing this communication for An Coimisiún Pleanála's consideration of MKO's Response to Submissions made on the public file for case reference PAX07.323761. My Statement of Expertise and drilling experience in this geographical area are presented in the Hydro-G November 2025 Report on the file. We respectfully request that An Coimisiún Pleanála considers the details in the report previously submitted by Hydro-G and we assert that the information presented for the karst conduit groundwater system are factually correct and in no way misleading. We assert that the proposed development is not justified and that the risks are completely understated by agents for the applicant, as is usual for the EIAR industry associated with 'renewable energy', and justification is heavily reliant on 'mitigation'.

At many locations in HES's letter to MKO, and indeed in the Gavin Doherty Geosolutions Appendix 1 of the 'Response to Submissions, reliance on 'mitigation measures' is put forth as reasoning to support the proposed development. An Coimisiún Pleanála is well aware of the legal precedents in relation to 'mitigation measures'. However, the facts of the matter remain that the applicant has presented no mitigation measure for the potential outcome that the supply of water at Barnaderg Gortbeg GWS and Mid Galway PWS could be interrupted and possibly affected long term. There is no 'Plan B' for the supply of water to residents of this region of north east Galway.

Whilst HES (2026) may critique the work of Hydro-G and allege that the information is incorrect and misleading. Hydro-G for the Barnaderg Gortbeg GWS asserts that the information presented by HES is also incorrect and misleading. For example, the Site Investigation programme completed for this Wind Turbine proposal was far from comprehensive: 26 Trial Pits mean nothing considering the landscape setting; 2 Boreholes are meaningless in the context of the conduit karst setting; whilst the applicant's site investigations do not present information for a conduit karst groundwater flow system – the facts of the environment themselves suggest great volumes of groundwater are available for people and that is the only source of water for homes and farms.

It is interesting to read the misleading statement presented in Appendix 2 (HES, 2026) at the end of 24 pages in which they state that *"best practice mitigation measures which ensure the protection of the receiving environment. Similar mitigation measures have been successfully applied during the construction of countless wind farm developments across the country and were also presented in the EIARs for several recently permitted wind farm developments".* When will accountability be applied? The most high profile Wind Farm case combination of MKO's and HES's assessments is the Meenbog Wind Farm in which the EIAR's conclusion of No Potential for Impact was proven incorrect when the land did slide in November 2020 and there was both water impact and habitat destruction requiring Donegal County Council to secure an order prohibiting further works at Meenbog wind farm (Irish Times, April 2024; Donegal Daily, 12th April, 2024). Photographs of the scale of risk for

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the HES claim of "*Similar mitigation measures have been successfully applied during the construction of countless wind farm developments across the country"* are presented as Plates A & B.

Plate A Proposed Wind farm EIAR author's MKO & HES's previous 'Not Potential for Impact' Meenbog Wind Farm site, which failed in in 2020. (Photo credit Donegal Daily 12th April 2024).

Plate B Proposed Wind farm EIAR author's MKO & HES's previous 'Not Potential for Impact' Meenbog Wind Farm site, which failed in in 2020. (photo credit Donegal Live 4th January 2024).

With specific reference to the scale of watercourse impact shown in Plate A and Plate B, the assessments completed and reported for that Meenbog Wind Farm by the same agents, MKO and HES, are available for review at https://www.pleanala.ie/en-ie/case/300460 and comparison with the information before them now. In 2018 the Board accepted a conclusion by HES (2017) in the Lands, Soils and Geology Chapter that "No significant impacts on the soil and geology of the site of proposed development will occur." and qualifications that "A peat stability assessment undertaken for the site shows that the risk of peat failure is designated trivial and tolerable and that the site has an acceptable margin of safety.". Yet, there was a failure. In the Board's 'Reasons and Considerations' supporting a Grant of Permission for Meenbog Windfarm the opening statement is that "Having regard to: (a) the national targets for renewable energy contribution of 40% gross electricity consumption by 2020….". However, Mr. Justice Holland is reported by the Irish Times (11th April, 2024) as ruling that "the integrity of the planning and environmental law systems "weighs heaviest" in this case of all the factors in play and favour granting the injunction. He did not see that the "undoubted public interest in wind energy" weighs "much at all" in favour of exercising his discretion against making the order. [Hydro-G provides clarification that Mr. Justice Holland has restrained the developers from finishing their "largely complete" 19-turbine project.] Mr Justice Holland said the developers submitted a report of a civil and environmental engineering expert to the EPA estimating that in the November 2020 incident about 86,240m³ of peat slid, of which about 65,740m³ entered a river and ended up on nearby European-protected sites, "causing significant environmental damage". Hydro-G offers that the Meenbog Windfarm slide of 86,240m³ of peat equates to destroying a carbon sequestration asset equivalent to 14.8 million kgs of CO2 emissions. [Source: National Trust for Scotland, 2024, provides that 172 kg of CO2eq is contained in each m3 of peat]. How much carbon will be emitted here?

It is now well reported in the media that the 'renewable energy' and Wind Turbine industry is contrary to Climate Objectives and the Climate Action Plan. Since 2022, Data Centres have consumed all of the energy that the country has gained from 'renewable energy' infrastructure [1, 2]. The United Nations cites Ireland as a "cautionary tale" for the rest of the world[3]. No longer can the judiciary claim that 'renewable energy' projects are necessary because 'the planet is on fire'. The planet is on fire and this crisis is exacerbated by the business of 'renewable energy'. We attach, as Appendix A to this document, recent academic publications for the Inspector's consideration: the current state of affairs regarding the type of economic endeavor that the wind farm proposal is and how is negatively affects the biodiversity, maladaptation, Ireland's important role in carbon sequestration and the degradation of our landscape.

Hydro-G and the Barnaderg Gortbeg GWS stand over every reason for refusal presented to An Coimisiún Pleanála in the Hydro-G (November 2025) Observation and Objection to the development. There is no justification to the nature of the proposed development in this karst conduit landscape where there is no other water source to 1000's of citizens, farms, schools and businesses. Whilst Uisce Eireann may have not asserted an objection, how could they? They may perceive themselves as obliged to obey government dictums. However, An Coimisiún Pleanála is specifically asked to specifically ask Uisce Eireann what their contingency 'Drinking Water Plan' is, and how they would source and supply the Mid Galway PWS's > 5,000 m3/d groundwater sources, in the event of failed 'mitigation measures' for the proposed development. Whilst we are there, might An Coimisiún Pleanála enquire if Uisce Eireann's contingency plan would have surplus potable water to also assist the Barnaderg Gortbeg GWS at that time. An Coimisiún Pleanála is advised that almost 10,000 homes could be negatively impacted and affected. Never mind mitigation, what is the demonstrated contingency plan?

Yours Sincerely

Pamela Bartley

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Dr. Pamela Bartley B.Eng, M.Sc., Ph.D

1 https://www.rte.ie/news/business/2026/0707/1582175-cso-data-centre-energy-figures/

2 https://www.irishtimes.com/business/2026/07/07/data-centres-account-for-almost-one-quarter-of-irish-electricity-usage-in-2025/

3 https://unu.edu/inweh/news/environmental-cost-of-AIs-Enrgy-use-carbon-water-and-land-footprints

Appendix A

Scientific Publications Relevant to the Assessment

(a) Locke *et al.,* (2026) opens with *"Human activities are driving a global decline in biodiversity and are interfering with the natural processes essential for human well-being.* ***Achieving climate and development goals is impossible without keeping nature intact.*** *In this article, we establish the urgent need for a paradigm shift toward a "Nature Positive" (NP) future, where the health and resilience of the Earth system are recognized as the fundamental basis for human prosperity. This requires that humanity acts to halt and reverse the loss of nature by 2030." The same paper closes with "It is time for us to recognize that nature is the foundation of all human affairs. Unless we act swiftly to make the world NP by 2030, our lives are likely to become very difficult in a destabilized Anthropocene.*

- Hydro-G offers that the European Union (2024) Regulation Of The European Parliament And Of The Council on Nature Restoration and amending Regulation (EU) 2022/869 sets out on the path towards attempting to achieve a Nature Positive future.

(b) Damiens *et al.,* (2021) opens with "*Economic development is increasingly impacting biodiversity, leading to a rise in biodiversity offset policies globally that aim to compensate for biodiversity losses. Many developments generating offsets create long-term, irreversible losses of biodiversity and, therefore, require biodiversity gains from offsets to be retained over the long term to have any hope of achieving "no net loss" (NNL) of biodiversity. This raises important ecological and institutional challenges that current offset mechanisms, built for politico-economic systems with short-term policy horizons, do not sufficiently consider. We explore this issue and discuss several responses to the problem ranging from incremental changes for improving on-ground management, through to major governance shifts required to support the long-term social-ecological resilience of offset sites. We argue that without these changes, at best, NNL policies participate in temporarily reducing permanent biodiversity loss. At worst, they participate in a false promise, distracting institutions from the transformative changes needed to reverse biodiversity depletion".*

- Hydro-G offers that it has recently well covered in the Irish media that since 2022 none of the renewable energy MWs have been used to assist citizens in reducing their use of fossil fuels. No Climate Action has been achieved. Instead, Ireland is cited as a 'cautionary tale' by the UN in the context of every single MW of renewable energy been given to new industry, thereby countering Climate Objectives.

(c) Habib *et al.* (2024) in Trinity College, Dublin, research opens with "*Ireland has > 50% of the EU's ocean-raised bogs; however, degradation through land-use activities has transformed them from carbon (C) sinks to sources. Given their significant role in climate mitigation, it is essential to quantify the emissions resulting from land use degradation of these ecosystems".* They developed a mapping system "using Sentinel-2 imagery, random forest machine learning and Google Earth Engine" and their results are fascinating and are summarised as follows: *"The results revealed that agricultural grassland comprised 43% of the land use on raised bogs, followed by, forestry (21%), cutover (11%), cutaway (10%) remnant peatlands (13%), waterbodies and built-up ~ 1% each. The overall accuracy of the map was 89%. The map was used to estimate CO2 emissions for four classes constituting 85% of raised bogs: cutover, cutaway, grassland, and forestry using the IPCC wetlands supplement and literature-based emission factors, we estimated emissions at ~ 1.92 (± 1.58–2.27 Mt CO2-C-yr−1) and ~ 0.68 Mt CO2-C-yr−1 (± 0.44–0.91 Mt CO2-C-yr−1) respectively. This is the first study to spatially quantify land use and related emissions from raised bogs. The results have revealed widespread degradation of these globally rare habitats, making them net emitters of CO2. The map is vital for the conservation of these ecosystems through restoration efforts, and the methodology can also be applied to other regions with similar peatland land use issues".*

- Hydro-G offers that the science is abundantly reported and all points to the importance of restoring peatlands such as the areas around the proposed development. It is not enough anymore to greenwash the business enterprise that accompanies the rush to 'renewable energy' in an Irish context. Construction sites with large machinery that will enable turbines to rotate and change air patterns resulting in 'wake' is something that has previously been presented to An Commissiun in many Observations relating to Wind Farm proposals.

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Nature Positive: halting and reversing biodiversity loss toward restoring Earth system stability

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Abstract

Human activities are driving a global decline in biodiversity and are interfering with the natural processes essential for human well-being. Achieving climate and development goals is impossible without keeping nature intact. In this article, we establish the urgent need for a paradigm shift toward a "Nature Positive" (NP) future, where the health and resilience of the Earth system are recognized as the fundamental basis for human prosperity. This requires that humanity acts to halt and reverse the loss of nature by 2030. The Kunming-Montreal Global Biodiversity Framework (GBF) provides a critical roadmap for this NP goal, and global policy increasingly recognizes that environmental targets can only be effective when integrated with global climate, ocean, and human development agreements. This requires a biodiversity conservation approach that accounts for both biotic and abiotic components of the Earth system. We assess the adequacy of GBF targets for stabilizing the Earth system and highlight key gaps. We employ the Three Global Conditions Framework (3Cs), which categorizes landscapes by human impact levels as a practical method for guiding appropriate NP actions, and we extend its application to the marine realm. We outline specific actions and metrics for patterns and processes across all scales needed to achieve biodiversity conservation in synergy with climate stabilization and securing freshwater systems. Our findings emphasize that preventing the loss of intact biomes, ecosystems, and species assemblages is the most critical strategy while acknowledging the urgency of extinction prevention and the need for restoration. Additionally, we highlight the importance of incorporating

Indigenous and local knowledge systems alongside scientific methods to achieve effective and equitable conservation outcomes. Finally, we discuss the need for economic transformation and the private sector's role in fostering an NP future.

KEYWORDS

biodiversity, climate change, Global Biodiversity Framework, Nature Positive, planetary boundaries, Sustainable Development Goals, Three Conditions Framework, indigenous and traditional knowledge

Key points

- Stabilizing the biophysical components of the Earth system requires a unified "Nature Positive" (NP) approach to global environmental goals and governance through greater integration of global agreements for human development, the climate, biodiversity, and the ocean.
- To achieve the NP goal by 2030, the top priority should be preventing the loss of intact biomes, ecosystems, natural processes, and species assemblages, as they are irreplaceable and cannot be quickly restored. At the same time, urgent efforts to prevent species extinction and restore nature remain essential.
- Three Global Conditions Framework (3Cs) serves as a strategic approach to halt and reverse the loss of both the processes (biotic and abiotic) and patterns (species distribution and assembly) of biodiversity, as these are integral components of the Earth system, and to ensure their sustainable use.
- Incorporating Indigenous or traditional knowledge and practices, which are rooted in responsibility to the living world and inherently include awareness of biotic and abiotic processes, is essential to achieving the NP goal.
- The NP shift requires transforming our economic system to work within the Earth system and equitably support human development.

Introduction

Human exploitation of nature driven by prevailing economic systems of production and consumption is causing a rapid and catastrophic decline in biodiversity (1) while simultaneously disrupting the climate system (2). These actions are actively destabilizing the Earth system upon which human health and development depend (3), and the trajectory of environmental degradation is accelerating, placing life as we know it at grave risk.

Biodiversity loss occurs at three interconnected scales—species, ecosystems, and natural processes—all of which affect Earth system stability. At the species scale, 48% of vertebrate and insect species are in decline, with only 49% remaining stable and 3% increasing (4). Within individual species, genetic diversity is also in decline (5): globally, 6% of species are losing genetic diversity, rising to 24% among island species (6). At the ecosystem scale, 54% of the world's ecoregions are severely degraded, with an additional 25% undergoing further degradation, leaving only a quarter largely intact (7, 8).

Natural processes, which encompass both biotic and abiotic interactions across ecosystem, biome, continental, and planetary scales, are also under threat. Migration, a key biotic process essential for maintaining ecosystem health and structure (9), is increasingly imperiled across terrestrial, freshwater, and marine environments. Alarmingly, 44% of species tracked by the Convention on Migratory Species (CMS) are in serious decline, with 97% of listed migratory fish species facing extinction (10). Similarly, biotic and abiotic interactions, also known as biophysical processes (11), are threatened. For example, running freshwater systems, such as springs, streams, and rivers, are critical biophysical processes that sustain the health of both terrestrial and aquatic ecosystems, yet only 30% of river systems worldwide remain free flowing (Box 1) (12). Excessive nutrient run-off from terrestrial sources has created anoxic "dead zones" in estuaries downstream from the world's most densely inhabited areas (13).

At the biome and continental scales, rainfall processes that involve moisture recycling in rainforests are also at risk, with potentially disastrous consequences for species, the climate, and food security (Box 2). At the planetary scale, ocean warming (14–18), acidification (19, 20), and deoxygenation (17, 21) are altering marine ecosystems. These changes are driving mass coral die-offs due to marine heat waves (22–24), weakening the shells of marine organisms due to acidification (25, 26), and threatening marine foundation species (23).

Human-caused species extinction, damaged and collapsed ecosystems, and disrupted natural processes are not only factors of an ecological crisis but also an ethical failure with profound consequences for human health. Biodiversity loss is linked to the emergence and spread of infectious diseases in humans, animals, and plants (27). Declines in species diversity can increase the number of zoonotic disease-carrying species (28), while ecosystem disruption, such as forest loss, degradation, and fragmentation (29), elevates the likelihood of pathogen spillover from stressed wildlife to humans directly (30) or to livestock and then on to humans, as happened with Hendra virus (31). Ecological disruptions have already contributed to outbreaks of deadly diseases, including Ebola, Marburg, and mpox (32, 33). Climate change further exacerbates these risks, intensifying 58% of the 375 known infectious diseases (34, 35).

Zoonotic disease spillover to humans is an ecological process and therefore an ecological problem (33). Despite mounting

BOX 1 Hydrological systems are critical to a Nature Positive future

Preserving and restoring freshwater hydrological systems and habitats is crucial for achieving the "Nature Positive" (NP) goal, the Sustainable Development Goals (SDGs), and climate change objectives.

River systems (especially in tropical and boreal environments) are rich in methane, a potent greenhouse gas, and account for a substantial portion of methane emissions. Disturbing river hydrology releases methane into the atmosphere, with 10% of all global freshwater methane emissions resulting from dams (36). Conversely, maintaining and restoring hydrological processes reduces methane emissions (37).

Another example is peatlands, vital carbon and water reservoirs that depend on intact hydrology. Tropical peatlands store more carbon than upland forests (38), while those in the Northern Hemisphere are spatially more extensive (39). Peatlands release carbon when drained, whether through peat mining or infrastructure projects such as roads, dams, and water diversions (40, 41). Protecting intact peatlands and their hydrological functions is crucial for maintaining their carbon storage capacity and preventing them from becoming carbon sources (42, 43). Rewatering degraded peatlands can serve as a climate mitigation strategy, although its benefits are better understood for northern than tropical peatlands (44). High-elevation peatlands in the Andes (páramos or bofedales) are also essential for water supply in Andean nations (45).

Generally, the deleterious effects of dams are well understood. The Columbia River Basin of North America, with over 40 hydroelectric dams, has seen the near collapse of enormous salmon populations, once numbering up to 100 million returns annually. Functional hydrology is also critical to estuary ecosystems. Mangrove conservation and restoration provide effective nature-based solutions to the climate crisis, as mangroves sequester significant amounts of carbon relative to their area and offer critical shoreline protection and food security (46–48). These ecosystems rely on sediment-bearing freshwater inputs, which are threatened by upstream dams. For example, mangroves in Mexico died off following the construction of dams upstream, whereas those in nearby free-flowing rivers thrived (49). Similarly, hydrological alterations in the Mississippi River delta have caused catastrophic mangrove loss (50, 51).

Therefore, hydroelectric dam removal is a powerful NP action. In the United States, the removal of two hydroelectric dams on the Elwha River has led to rapid ecological recovery, benefiting both marine and terrestrial species (52, 53). Likewise, the removal of four dams in the Klamath River system resulted in salmon returning within 2 weeks (54, 55). In an NP world, more dams would be removed, and new dam proposals would need to undergo a "nature veto", proving they would not harm ecological integrity.

BOX 2 Tropical rainforests—vital Nature Positive actions at the biome level

Maintaining and restoring tropical rainforests of the Amazon, Congo Basin, and Southeast Asia regions is critical to "Nature Positive" (NP) actions owing to their roles in carbon sequestration and storage and the enormous number of species they harbor. The first two also play a vital role in rain generation at the continental scale.

Amazonian rainforest generates a significant part of its own rainfall through moisture recycling (56), but estimates suggest this only occurs if the overall forest cover is 75–80% intact (57). The Amazon Basin is already about 17% deforested (58) and under pressure from global warming (59). Its irreversible transition into savannah-like vegetation would greatly affect rainfall patterns and persistence of the remaining forest and the species it supports (60), as well as the global climate (61).

Modeling indicates that losses of 23% forest cover would put these tropical forest biomes at risk of massive disruption, with potential disastrous effects on agriculture outside their basins (62–65). The Amazon provides rain to the La Plata Basin, the most productive agricultural area in South America (66), and as far away as Texas (67). Loss of this rainfall potentially threatens large-scale food security. Forest cover in the Congo Basin (65) also generates spring rains, with 80% of the atmospheric moisture coming from the transpiration of plants (68). This Central African rainforest is also a major source of rainfall to parts of East Africa (63). Moreover, the Congo is much drier than the Amazon and has larger peatlands—drying of Congo peatlands could the release of a vast amount of stored carbon into the atmosphere (69).

These are more than theoretical concerns. The much-degraded southeastern Amazon has already become a carbon source to the atmosphere (70), and at its southern edge, loss of 55% of the forest is causing nearby agricultural losses due to reduced rainfall (64). According to a recent assessment, human-caused changes in 40% of the Amazon rainforest have moved that part of the system to a bifurcation point where it could exist either as rainforest or savannah (71).

evidence that preserving and restoring nature is the most cost-effective and equitable means of preventing zoonotic spillover (72–74), current public health strategies prioritize biomedical interventions over ecological prevention measures (73). Additionally, the degradation of natural systems has serious mental health consequences, contributing to eco-anxiety among the general population (75, 76) and negatively impacting Indigenous communities whose cultural and spiritual well-being is deeply tied to their environments (77). Conversely, access to nature improves physiological, mental, and cognitive health (78). Recognizing these interconnections, over 200 medical journals jointly called on world leaders and health professionals to address climate change and biodiversity loss as a single, indivisible crisis that must be tackled together to preserve human health and avoid catastrophe (79).

The economic implications of environmental degradation are equally severe. The global economy is embedded in the biosphere (80) and fundamentally dependent on a stable Earth system, which, in turn, is sustained by a healthy biosphere (81). Half of global economic activity, including food production, relies directly on nature (82), and the continuing decline of biodiversity threatens financial stability worldwide (83). The most vulnerable communities suffer disproportionately when nature's ability to provide essential services deteriorates (84).

The very conditions that have made modern human civilizations possible are now unraveling. The Holocene Epoch—the stable, warm, interglacial period spanning the past 12,000 years—enabled the rise of sedentary societies and global development. However, since the mid-20th century, human exploitation of the environment has accelerated, ushering in the Anthropocene, an era in which humanity has become the dominant force driving planetary change (85). We are destabilizing critical components of the Earth system, particularly biodiversity and the climate (3, 86, 87). Our ongoing actions have the potential to push the planet into a new self-reinforcing "Hothouse Earth" state (88), rendering the Earth increasingly hostile to human life (88). Our impacts have placed humanity at such risk that the United Nations (UN) Secretary General has called our collective actions "suicidal" (89).

To provide a coherent and hopeful response to the crisis, international environmental, non-governmental, and business organizations issued a call to the 2020 UN General Assembly to establish a "Nature Positive" (NP) global goal for nature (90). This goal was proposed for use by the Convention on Biological

Diversity (CBD) to complement the UN Framework Convention on Climate Change (UNFCCC) Paris Agreement's carbon-neutral "net-zero" target for climate change and the Sustainable Development Goals (SDGs). In April 2021, NP was formally defined as a goal to halt and reverse nature loss by 2030, relative to a 2020 baseline, to ensure full recovery of nature by 2050 (91). The G7 leaders subsequently endorsed NP as a core objective in their 2030 Nature Compact (92).

The Kunming-Montreal Global Biodiversity Framework (GBF) was adopted in December 2022, and it included the NP global goal of halting and reversing biodiversity loss by 2030 on the way to achieving the GBF's vision of restoring a healthy planet and achieving harmony with nature by 2050 (93). However, this, in isolation, is not enough. It is now widely acknowledged that nature conservation and restoration contribute to climate change mitigation and adaptation and that biodiversity and climate objectives must be addressed together (94–96). Notwithstanding the clear connection, international climate and biodiversity treaties have historically operated in isolation (97).

However, parties have now taken steps toward an integrative approach. The 2023 Global Stocktake agreed at the 28th Conference of the Parties (COP28) to the UNFCCC in Dubai (98) recognized the importance of conserving biodiversity in line with the GBF to achieve the Paris Agreement temperature target. Similarly, the GBF's lack of a clear commitment to support climate goals was substantially remedied by the CBD COP16 Cali decision on biodiversity and climate change in 2024 (99). It calls on CBD parties to maximize potential synergies between biodiversity and climate actions, including prioritization of the protection, restoration, and management of ecosystems and species important for the full carbon cycle. Although efforts to agree on a roadmap to halt global deforestation failed at COP30 in Belem (100), there was greater integration of nature at this climate COP than previously. These important developments are a recognition that both treaties operate in the context of the Earth system.

This article is the first to take an interdisciplinary, intercultural, and integrated approach to examining what is needed to achieve the NP goal on land and in freshwater, as well as in the ocean. Specifically, our analysis focuses on:

- Assessing how NP aligns with the SDGs, Paris Agreement, and GBF and discussing how these existing frameworks could contribute to Earth system stabilization.
- Proposing a holistic NP framework and global-scale metrics spanning all aspects of biodiversity (natural processes, ecosystems, and species) using the Three Global Conditions for biodiversity conservation and sustainable use framework and extending it into the marine realm.
- Recommending alignment of GBF, Paris Agreement, and SDG reporting mechanisms.
- Describing an economic transformation that integrates NP principles while ensuring equitable human development.
- Highlighting the importance of the ways of knowing (sometimes called traditional knowledge systems) of Indigenous peoples and local communities to achieving the NP goal.

Nature Positive and Earth system stability: Sustainable Development Goals, Global Biodiversity Framework, and planetary boundaries

Human development and climate goals cannot be met without a healthy, diverse, and resilient natural world. This section explores these interdependencies and clarifies how the NP global goal aligns with key international development and climate instruments, identifies gaps, and provides a foundation for a more integrated approach to achieve an equitable, nature-positive, and carbon-neutral world.

Nature Positive and the Sustainable Development Goals

The SDGs are a set of biophysical, social, and economic normative goals that seek to end poverty, protect the planet, and ensure peace and prosperity for all by 2030 (101). They have been described as universal, interconnected, and inseparable and are of equal importance, balancing the economic, social, and environmental dimensions of sustainable development (102). Thus, economic goals such as promoting inclusive and sustainable economic growth, employment, and decent work for all (SDG 8) and building resilient infrastructure, promoting sustainable industrialization, and fostering innovation (SDG 9) are placed on equal footing with fundamental human survival needs like food security (SDG 2) and access to clean water and sanitation (SDG 6) as well as environmental imperatives such as climate stability and maintaining life on land and in water (SDG 13, 14, and 15).

When social, economic, and environmental goals are expressed as equal and competing, the SDGs are viewed as seeking the "sweet spot" where they overlap and converge (Figure 1, left side). Fundamentally, this is a conceptual failure: the SDGs may be of equal importance politically, but they are not so in reality.

The Earth system existed for billions of years before humans emerged. Human life, and thus all human development goals, are wholly dependent on the Earth system operating in a way that is favorable to humanity. The various SDGs are simply not of equal importance: those that support the Earth system underpin all human activity (SDG 13, 14 and 15), and humans cannot exist without a conducive Earth system that creates food and water (SDG 2 and 6); the economy was invented by and cannot exist without humans—it cannot thrive unless human society has food, water, health, institutions, and skills sufficient enough to support it (103–105).

Therefore, a more accurate framework acknowledges a hierarchical relationship in which the environment forms the foundation for human society, and the economy exists as a subset of society that must serve human interests (106–108), as illustrated in Figure 1, right side. This perspective aligns with early sustainable development principles that recognized biodiversity, ecosystems, and natural processes as an indispensable prerequisite to sustainable development (103). Addressing the SDGs in that light is now more urgent than ever. The NP paradigm embodies this conceptual shift.

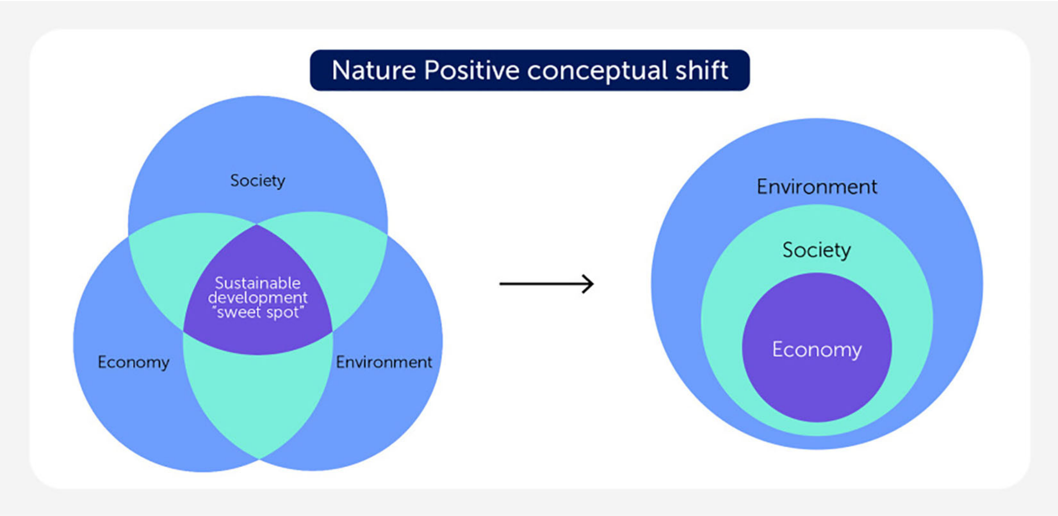

FIGURE 1
"Nature Positive" (NP) involves a conceptual shift from viewing the environment as a competing interest with society and the economy to recognizing it as the context for all human activity. This shift realigns the Sustainable Development Goals (SDGs), moving from the search for the "sweet spot" of overlap between the environment, society, and the economy (left side) to a hierarchical relationship in which the environment is recognized as the context for all aspects of human existence and the economy is understood as a subset of society, existing solely to serve human interests (right side).

Nature Positive and Earth system science

The Earth system comprises the atmosphere, hydrosphere (including the cryosphere), geosphere, and biosphere. The biosphere emerges from interactions among the other three spheres and, in turn, influences them. These feedback mechanisms regulate planetary resilience by buffering stress and shocks (i.e., solar radiative forcing and volcanic eruptions), thereby maintaining equilibrium. The most recent equilibrium state, the Holocene epoch, allowed sedentary civilizations to develop and large human populations to flourish (Figure 2A).

This stable state, however, is now threatened by global human pressures on the Earth system, ushering in the Anthropocene (109). We see more frequent and intensified extreme events (e.g., droughts, floods, heat waves, fires, and disease outbreaks), while we are gradually eroding the biosphere of its life-support capacity, pushing Earth system boundaries toward multiple tipping points (59). Sixteen biophysical and climate tipping points have been identified where self-reinforcing feedback loops threaten to drive irreversible state shifts, ultimately altering the state of the entire planet (Figure 2B) (59). Examples include the transformation of rainforests into savannah-like landscapes due to moisture loss (Box 2), the rapid melting of the Greenland Ice Sheet, and the collapse of tropical coral reef systems.

The Planetary Boundaries Framework emerged from understanding Anthropocene pressures, the risks of crossing tipping points, and the evidence that nature is a precondition for a stable Earth system (110, 111). Nine planetary boundaries that regulate the function and stability of the Earth system have been identified. Humanity's actions have now transgressed seven of them, namely the two core boundaries of biodiversity and climate, together with those for land system change, altered biogeochemical cycles for nitrogen and phosphorus, freshwater change, changes to both blue water (runoff water) and green water (soil moisture), novel entities [human-created chemical compounds, e.g. per- and poly-fluoroalkyl substances (PFAS), persistent organic pollutants (POPs), and microplastics] (3), and, most recently, ocean acidification (112). These crossed boundaries indicate that the Earth is losing resilience and is in a state of internal stress unprecedented in human history (113). In addition, control variables exist but have not yet been quantified for high-seas deoxygenation and ocean heat absorption, which are further exacerbating instability. The Planetary Boundaries Framework is a diagnostic tool providing a dashboard for a safe operating space for humanity on Earth; it does not, however, prescribe solutions or define normative goals (114). NP is the necessary normative goal and pathway derived from Earth systems science that provides a safe landing for humanity within the living biosphere. Combined with carbon emissions reductions, it seeks to return the Earth system to Holocene-like stability by halting the loss of intact nature and transforming nature-negative impacts into nature-positive feedbacks (Figure 2C).

Nature Positive and the Global Biodiversity Framework

The GBF is the primary global agreement that relates to nature and is broadly analogous to the Paris Agreement on climate, although it is not binding in its own right. Both agreements were reached under Rio Framework Conventions (CBD and UNFCCC). The GBF consists of an overarching 2050 vision, an actionable 2030 mission, and specific targets to be achieved by 2030. Its mission is to halt and reverse biodiversity loss by 2030 as a pathway to the 2050 vision of humanity living in harmony with nature, ensuring a healthy planet that provides benefits for all. The GBF promotes cohesiveness and

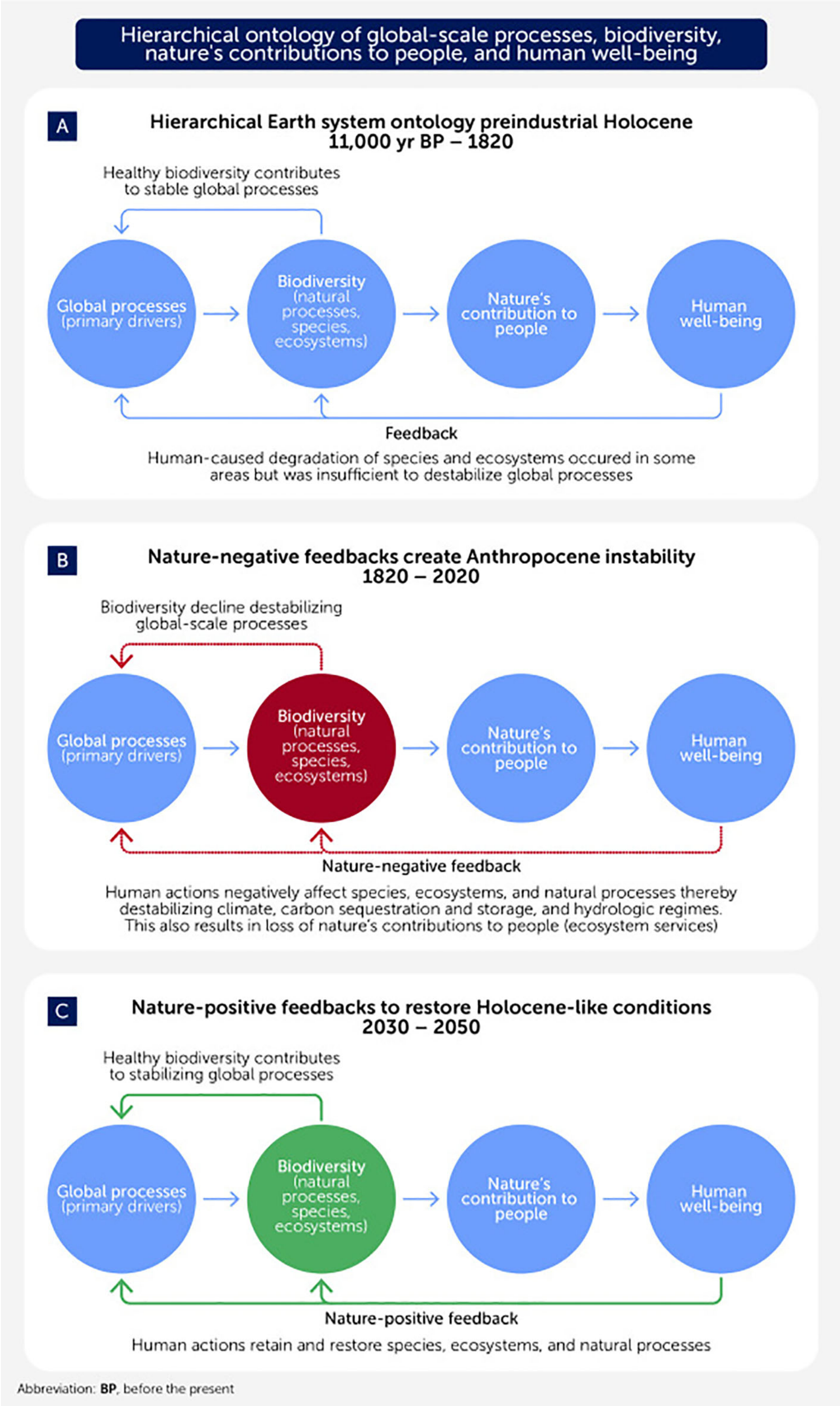

FIGURE 2
Hierarchical ontology of global-scale processes, biodiversity, nature's contributions to people, and human well-being. **(A)** Holocene conditions; **(B)** Anthropocene conditions, during which nature-negative human feedbacks destabilize the Earth system; **(C)** "Nature Positive" actions to halt and reverse biodiversity loss, combined with climate actions to reduce fossil fuel emissions, are needed to restore stable Holocene-like conditions.

complementarity among international agreements (93)[1] and integrates the Rio Declaration on Environment and Development (93),[2] which calls for a global partnership to protect and restore the health of the Earth's ecosystem (115). The GBF also calls for

1 Section B, Global Biodiversity Framework.

2 Section C, Global Biodiversity Framework.

alignment with the SDGs (93) and the One Health approach, which recognizes the link between human, animal, and environmental health (116). To achieve the GBF's 2050 vision, Rio Principle 7, and One Health, we must stabilize the Earth system.

GBF implementation is based on a comprehensive framework that includes monitoring, financial resource mobilization, and an agreement on digital sequence information to support shared benefits from the use of genetic resources. While implementation occurs at the national level through the 196 country parties, the GBF also calls on subnational governments, civil society, business, as well as Indigenous and local communities to participate in a whole-of-society approach.

The GBF's mission of halting and reversing biodiversity loss by 2030 is the NP goal in all but name. Its 2050 goals reinforce this alignment: Goal A calls for the integrity, connectivity, and resilience of all ecosystems to be maintained, enhanced, or restored, thereby substantially increasing the area of natural habitat (93). Goal B calls for biodiversity to be sustainably used and ecosystem functions and services to be maintained and restored. Goals C and D address equitable distribution of benefits, increasing financing, and aligning financial flows with the GBF. While the GBF's goals effectively address many aspects of the 2030 mission, its targets are silent on key elements necessary to meet the GBF's mission, vision, and overarching objective of complementarity with other international agreements. The major shortcoming is a lack of attention to natural processes at all scales. Ameliorating this gap does not require amendment of the GBF, but complementary attention by all actors as discussed below.

Another area requiring focused attention is ocean governance, as there is disagreement over whether the GBF covers areas outside of national jurisdiction, which is almost two-thirds of the global ocean. The Agreement on the Conservation and Sustainable Use of Marine Biological Diversity of Areas beyond National Jurisdiction (BBNJ) under the UN Convention on the Law of the Sea (UNCLOS) is a much-needed complement to the GBF. Its general objective is conservation and sustainable use of marine biodiversity, and it creates a framework for marine protected areas (117). Its specific objectives include building resilience to the adverse effects of climate change and ocean acidification and maintaining and restoring ecosystem integrity, including carbon cycling, in order to underpin the role of the ocean in the climate system. If implemented effectively—through measures such as protecting at least 30% of the ocean and ensuring sustainable fishery management—it could contribute significantly toward the development of an NP world (118). Recognizing this, at the Conference of the Parties (COP16) to the Convention on Biological Diversity (CBD), the Parties decided to "explore opportunities for addressing the ocean-climate-biodiversity nexus in an integrated manner". This integration is urgently required.

Implementing and measuring Nature Positive conservation

In this section, we outline a framework for implementing conservation actions for natural processes, ecosystems, and species, and we present metrics for measuring progress toward the NP global goal.

The scope of the NP global goal was originally described in 2021 as follows:

> *Nature-positive includes a focus on species distribution, abundance, functional traits, genetic diversity, and demographic trends as well as the intactness and integrity of ecosystems and biomes. It also includes the functioning of ecological and global processes such as hydrology, rainfall patterns and migration.... Together these provide a resilient planet able to cope with shocks and stresses without crossing destabilizing tipping points.... Connecting the nature-positive goal to equity and carbon neutrality recognizes the fundamental connection between human development and the health of nature and the deep connection between nature, climate and Earth system stability* (91).

Here, we explore actions and metrics that address the full scope of the 2021 NP global goal. We note a variety of papers published since 2021 that deal with aspects of NP, including an additional proposed metric focused on staying within nature's carrying capacity (119). Useful approaches to measuring biodiversity in terms of patterns and quantification of genes, species, and ecosystems have also been identified (120). However, both biotic and abiotic natural processes must also be addressed to fully conserve biodiversity and contribute to a stable Earth system. We begin with some general principles.

General principles for Nature Positive actions and metrics

To move toward stabilizing the Earth system, the protection of intact nature is our most urgent goal. By "intact" we mean areas free of significant human-induced degradation, which often occur within the territories of local traditional communities and Indigenous peoples (121), and all remnants of primary ecosystems, whether large or small (122–124). Nature restoration is important but secondary to retaining intact nature because any further losses cannot be restored in the critical time we have left. Although tree planting is widely discussed as a climate solution because trees absorb atmospheric carbon dioxide (125), at the global scale, preserving existing intact ecosystems is far more effective for achieving net-zero emissions by 2050 than large-scale afforestation efforts (126–128). This is because most natural systems, when disturbed, lose a substantial portion of their above- and below-ground carbon stores, requiring decades to centuries to recover, which takes us far beyond the 2050 net-zero target (129). Retaining intact nature also maximizes Earth's resilience, which is crucial because climate pressures are already weakening ecosystems' capacity to absorb carbon (130). Remaining intact natural biomes are also vital for retaining rainfall patterns (Box 2), and healthy ecosystems support more species in greater numbers than degraded ones, resist invasive species, reduce pandemic risk (33, 131), and provide greater ecosystem services, such as clean freshwater.

That said, restoration is a primary and urgent strategy in areas of significant ecological degradation, such as New Zealand/

Aotearoa, Western Europe, many Mediterranean-type ecosystems, and in tropical grasslands and dry forests worldwide (132). Reforestation in tropical areas where forest cover has been reduced can rapidly restore some aspects of ecological function (132, 133). Restoration of species composition can improve ecosystem function and help meet carbon-management goals (134); however, this often takes longer than biomass recovery (135). Importantly, reforestation and afforestation are not necessarily synonymous with ecological restoration (136). A singular focus on tree planting for climate mitigation instead of a thoughtful focus on restoring ecosystem composition and protecting native species risks failing both biodiversity and climate goals (137). In two cases, reducing just one human pressure can result in important improvements in species diversity and populations, ecosystem health, and natural processes: (1) discontinuing fishing in ocean areas with minimal human modification (118, 138, 139) and (2) reducing continuous grazing pressure from domestic animals on grasslands that have not yet undergone phase shifts (140).

Establishing baselines is essential for measuring progress (141). The NP global goal is a net improvement in ecological conditions from a 2020 baseline by 2030. The 2020 baseline was set because that is when the last set of conservation targets under the preceding CBD's Aichi Biodviersity Targets expired, and the new GBF was to be negotiated, before the process was delayed by the COVID-19 pandemic. Achieving the NP goal by 2030 does not require every natural process, ecosystem, or species to have improved by 2030. However, it does require that, in aggregate, human actions across the Three Global Conditions Framework (3Cs) have secured the existing intact nature and that substantial ecological restoration actions are underway, so that nature is in better condition in 2030 than it was a decade earlier.

Here, we apply the 3Cs as a practical approach to achieving both the GBF goals and targets and the necessary complementary NP actions that address natural processes.

The Three Global Conditions Framework for implementing the Global Biodiversity Framework and complementary Nature Positive actions

The GBF's targets for actions to protect, restore and sustainably use biodiversity are as follows: reduce loss of intact areas to near zero (T1); restore 30% of degraded areas (T2) and protect and conserve at least 30% of land, freshwater, and ocean in an interconnected way (T3); reduce species extinction risk and curtail unsustainable use (T4, 5, 6, and 9); reduce pollution (T7); address climate impacts on biodiversity (T8); improve sustainable practices for agriculture, aquaculture, wild fisheries, and forestry (T10); and maintain nature's functions and contributions to people or ecosystem services (T11). While the GBF sets global targets that each party will implement in accordance with its own national circumstances (93), it provides no guidance on which of the many required actions apply most effectively in the highly variable conditions that exist among and within countries. For example, while half the world has been transformed by human activity, this transformation is unevenly distributed (142).

Nonetheless, the GBF targets and supplemental NP actions addressing natural processes can be implemented systematically by categorizing the world into three "conditions" of human impact: (1) "Large Wild Areas" with very low human impact (termed Condition 3 or C3, approximately 26% of the terrestrial world), (2) "Shared Lands" ranging from slightly to less than half transformed by human activity (termed C2, approximately 55%), and (3) "Cities and Farms" where land is more than half to entirely transformed (C1, approximately 18%) (Figure 3) (143).

The 3Cs framework has been recommended by multiple expert bodies and institutions, including by: the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) and Intergovernmental Panel on Climate Change (IPCC) as an effective approach to integrating climate and nature actions (95, 144); experts engaged by the CBD as an effective approach to implementing GBF targets in an integrated way (145); African scientists as an effective way to integrate biodiversity targets from local to global levels (146); economists as the most cost-effective means of implementing the 30 × 30 protected and conserved areas under GBF T3 (147); the Dutch Central Bank as an efficient way of reconciling conservation, climate, and food security goals (148); and zoonotic disease experts as an effective way of sorting ecological countermeasures to prevent pandemics (30, 33). It has also been recognized as an approach to support governance that achieves co-benefits alongside social, biodiversity, and climate objectives (149).

For too long, the ocean, freshwater, and land have been treated as separate domains, which has resulted in a fragmented approach to an integrated challenge. For example, no discussion of mangrove conservation is complete without addressing freshwater hydrology and sediment transport (49). Similarly, no effort to remedy oxygen-depleted "dead zones" in marine estuaries is of any value unless it examines harmful terrestrial inputs into freshwater systems (13). Similarly, coral reefs can either be adversely affected by sediments and nutrients from anthropogenic causes or enhanced by background levels of natural nutrients from land (150). Further, the rapid changes in ocean temperature, chemistry, currents, ice cover, foundation species, and fish biomass are cause for alarm. We must therefore pay urgent attention to both reducing stressors and increasing conservation measures across the marine realm. In this article, we seek to remedy the artificial separation of ocean, freshwater, and land by extending the 3Cs approach across all three, allowing for a more holistic and integrated approach.

Human impact on the ocean differs from that on land; the 3Cs approach is not directly transferable except in the case of estuaries immediately adjacent to cities and farms, with C1-level physical impacts (151). However, fisheries-related impacts are analogous to habitat loss on land due to bottom trawling and severely reduced large-bodied fish populations (152–154), which have resulted in ecosystem-level impacts (153, 155, 156). Thus, in the marine context, C1 applies not only to estuaries but also to the 12 nautical mile (22.6 km) territorial waters of most countries, which have been extensively modified by human actions but still retain fragments of semi-intact nature. C2 can be applied to the remainder

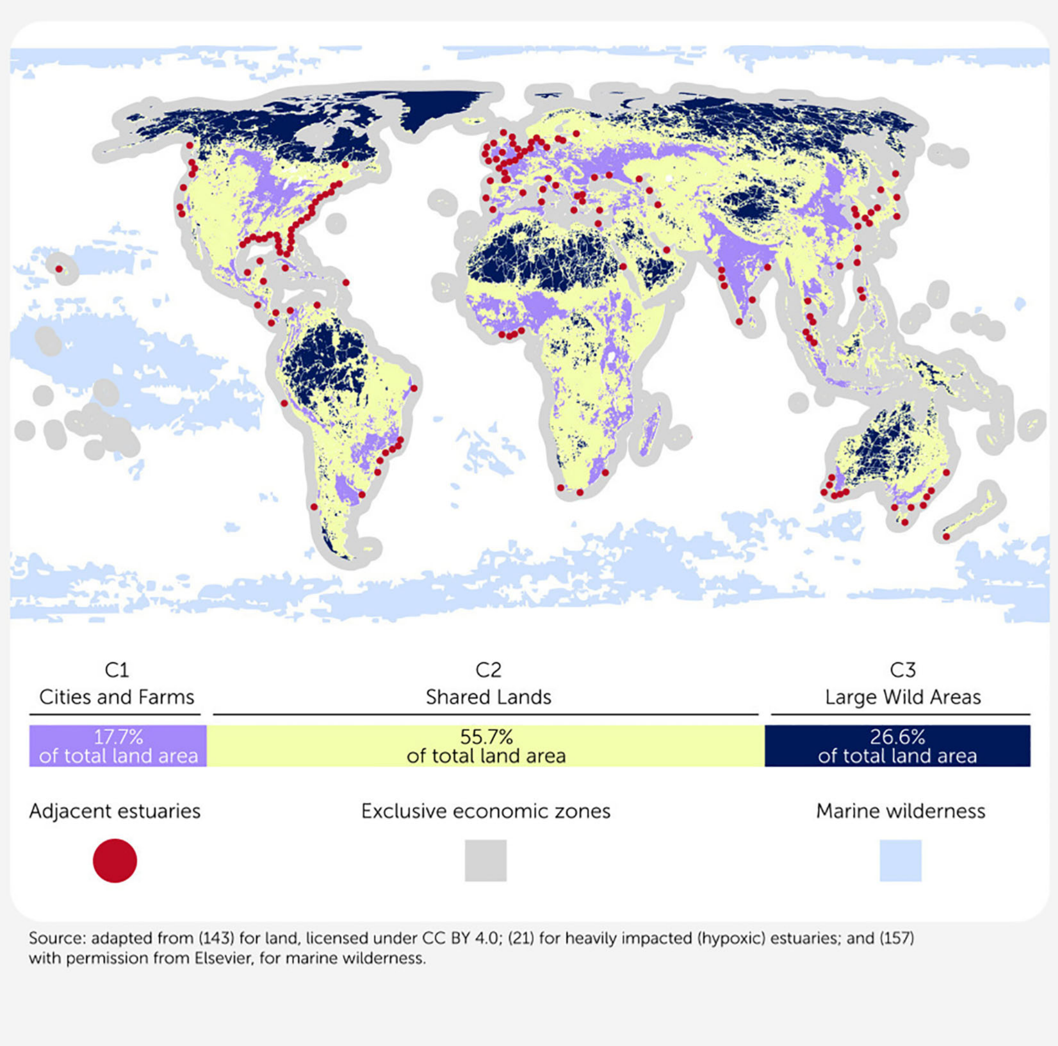

FIGURE 3
The Three Global Conditions Framework (3Cs) for simultaneous conservation and sustainable use strategies applied to land, freshwater, and ocean. Adapted from (143) for land, licensed under CC BY 4.0; (21) for heavily impacted (hypoxic) estuaries; and (157) with permission from Elsevier, for marine wilderness.

of the exclusive economic zones (200 nautical miles) and most of the high seas, where fishing that includes bottom trawling has depleted fish stocks and removed large-bodied fish (152, 155, 158) but where some high-biomass areas with low fishing pressure remain (159). Only the Arctic and Antarctic, which have been protected by large ice sheets, and only the most remote parts of the open ocean (approximately 13%) are “marine wilderness”, a condition analogous to C3 large wild areas on land (157).

The 3Cs framework provides a structured approach for implementing NP actions tailored to the human impacts and resulting ecological and biophysical characteristics of each condition (Figure 3). It is not a prioritization scheme but rather provides coherent points of departure for simultaneous conservation and sustainable-use actions appropriate for each condition, because nature matters everywhere.

Maps of the terrestrial 3Cs for every region and country are found at naturebeyond2020.com. We hope this initial integrative work might stimulate more thorough mapping of the 3Cs in the ocean.

Actions and metrics for natural processes, species, and ecosystems

There are well-known and effective strategies for biodiversity conservation, many of which are found in the GBF. Here, we discuss those actions and metrics necessary to measure progress toward the NP global goal and the GBF’s vision, goals, and targets across the 3Cs. We also identify gaps in the GBF (Table 1).

Large-scale natural processes

Large-scale natural processes relate to the dependence of ecosystems and species upon, and their interactions with, the abiotic component of the Earth system at scales that affect planetary health and functioning. NP actions targeted at species or specific ecosystem types alone are not sufficient to retain overall structure and function. For example, in large intact areas, GBF species and individual ecosystem targets could be met in isolation, but the entire biome could still collapse. This could result in not only the loss

TABLE 1 Global-scale “Nature Positive” (NP) actions and metrics, and their alignment with Global Biodiversity Framework (GBF) goals and targets, applied across the Three Global Conditions Framework (3Cs) using Conservation Imperatives (160), International Union for Conservation of Nature (IUCN) Red List of Threatened Species (161), IUCN STAR Metric (162), IUCN Green Status (163), and Mitigation Hierarchy (123).

	Actions	Metrics	Goals and targets
C1 – Cities and Farms	**Species level**		
	Conservation Imperative sites are secured	All identified *Alliance for Zero* extinction sites/ Conservation Imperative sites are under effective management to secure the target species	Goal B; Target 3, 6
	All species at risk are in the recovery process	Species moves in a positive direction along the Red List continuum: Species Threat Abatement and Restoration (STAR) metric	Goal A; Target 4
	Connectivity is retained or restored	Some structural connectivity is in place in streams and among terrestrial habitat patches	Goal A; Target 12
	Ecosystem level		
	Retain all patches of native vegetation (land and estuaries)	All patches are inventoried and secured 20% of native vegetation is restored with particular attention to pollinator habitats	Goals A, B; Targets 10, 11
	Superabundant species and exotic species are managed	Exotic and superabundant species are controlled to reduce ecosystem harm and disease risk. New exotic species are controlled quickly	Goals A, B; Targets 6, 12
	Agricultural waste and chemicals (nutrients and pesticides) are kept out of freshwater, streams, and wetlands	No nutrients, herbicides, or pesticides are detectable in freshwater systems	Goal A; Target 7
	There is good urban planning to prevent sprawl and keep the best farmland in production	The best farmlands are retained; there is no increase in area under cultivation	No Goal; Target 10
	Provide people with access to nature for mental and physical health	Equitably distributed, convenient access to green and blue spaces is realized	Goal B; Target 12
	Natural processes		
	There is safe travel for migratory birds and marine life and secure migratory stopovers and nesting sites	All migratory stopover and nesting sites are inventoried and secured Safe travel for birds is increased by reducing collision risk (turning off unnecessary lights in buildings) and controlling domesticated cats Fishing nets are managed to avoid interfering with migratory marine species	Goals A, B; No target
	Hydrological processes are retained and improved; restoration of all four dimensions of freshwater connectivity is carried out as much as feasible	Development on floodplains is halted and reversed where feasible No new dams appear and/or dams are removed where appropriate Seasonal sediment transports return to natural patterns	Goals A, B; No target
	To secure carbon sequestration and storage, all mangroves, seagrasses, and wetlands are retained and restored, and patches of native vegetation are retained (see ecosystem-level actions)	Areas of mangroves, seagrasses, and wetlands increased with good hydrological connectivity	No goal; no target
C2 – Shared Landscapes	**Species level**		
	All species at risk are in the recovery process	Species at risk increased to a minimum population size of 500	Goal A; Target 4
	Missing keystone species are reintroduced	Missing keystone species are assessed and the reintroduction process has begun	Goal A; No target
	Harvest levels do not diminish current patterns of abundance or distribution	A species’ status does not fall below its current Red List status or Green Status	Goal B; Target 4 Red List; No target; Green Status
	Ecosystem level		
		Species levels are assessed for Green Status function and secured; harvest levels are consistent with goals	Goals A, B; Target 9 (partial)

(Continued)

TABLE 1 Continued

	Actions	Metrics	Goals and targets
	All native species currently performing ecological functions remain at current levels of abundance or increased if needed		
	Retain all native vegetation (land and estuaries)	No new areas are cultivated All primary ecosystems are retained	Goal A, B; Targets 1, 3, 8
	Industrial resource extraction (mining, logging, oil, and gas) discharges no sediments out of season or pollutants into watercourses	Water quality, sediment load, and timing are adhered to	Goal A; Target 7 (partial)
	Exotic species are eliminated or controlled Superabundant species are reduced	Exotic species are eliminated to reduce ecosystem harm Superabundant species caused by loss of predation are reduced in number to reduce ecosystem harm New exotic species are controlled quickly	Goals A, B; Targets 6, 12
	Further cultivation is prevented	There is no increase in area under cultivation	Goal A; Target 10
	Ecosystem connectivity and core habitats are secured through an ecologically representative and interconnected system of protected and conserved areas covering at least 30% Protected and conserved areas are managed effectively and governed equitably	Key biodiversity areas are identified Protected or conserved areas, as well as functional connectivity, are present for all species Indigenous and local communities are properly engaged At least 30% of land, freshwater, and ocean is effectively protected or conserved to achieve equivalent outcomes to protected areas, with effective management and equitable governance	Goal A, B; Targets 3, 8
	Gaps in ecosystem connectivity are mitigated	Wildlife crossings are built to mitigate infrastructure (trains, roads, and dams), so functional connectivity is restored There is no isolation of minimum viable populations (500 individuals) from their meta population	Goal A, B; Targets 2, 3, 4
	Domestic animal grazing levels are managed appropriately	There are appropriate stocking rates to maintain good range conditions Domestic animals are kept out of streams and wetlands	Goal A; Target 2
	Natural processes level		
	All migratory breeding and wintering sites, migration patterns within the ecosystem, and continental stopovers are secured	All migratory patterns, stopovers, breeding, and wintering sites are inventoried and secured	Goals A, B; No target
	Large-scale hydrological processes are retained and improved There is retention and restoration of all four dimensions of freshwater connectivity	There are no new dams and there are dam removals Seasonal sediment transport is kept at or returned to natural patterns	Goal A, No target (except Target 2 restoration)
	There is efficient carbon sequestration and storage All primary ecosystems are retained and secured	There is no old-growth logging There is no new cultivation	No goal; no target
	There is sustainable resource extraction	Existing disturbance footprint is the primary focus of operations but where new impacts are unavoidable, the Mitigation Hierarchy framework should be followed and overall landscape context improved	Goal A; Target 10
	Water flow is retained with enough energy and volume to drive ecosystem structure	A minimum of 80% natural water flow is retained or restored	Goal A; No target (except Target 2 restoration)
	Sediment flows follow normal seasonal variability	There is no discharge of sediment from roads, railways, or industrial resource-extraction sites outside of natural seasonality	Goal A; No target

(Continued)

TABLE 1 Continued

	Actions	Metrics	Goals and targets
C3 – Large Wild Areas	**Species level**		
	All abundant species are retained and perform ecological functions	Harvesting rates are consistent with abundance All species are managed to Green Status 3 levels	Goal A; No target
	Species at risk are secured	All species at risk are identified with an action plan toward protection and conservation	Goal A; Target 4
	Ecosystem level		
	All species are able to move in existing natural patterns	There is no new fragmenting infrastructure (new dams, roads, and railways)	Goal A, B; Target 1 (accelerated)
	Ecosystems remain intact	There is no new resource extraction industry (logging, mining, oil, and gas)	Goal A, B; Target 1 (accelerated)
	Natural processes level		
	Biome function is secure	There is 80% tropical forest cover Migrations within biomes and across biomes are possible	Goals A, B; No target
	Hydrological processes are maintained in a wild state	No dams or roads are impacting wetlands or peatlands directly or indirectly There are no water diversions All four dimensions of connectivity are intact There are natural patterns of sediment transport and flooding	Goals A, B; No target

of the species and ecosystems that were intended to be conserved but also of hydrological and biome functions critical to humanity (Box 3).

These large-scale Earth system processes are essential to meeting the GBF's vision of a healthy planet and are implied in Goal B. They are also recognized in the "ecosystem approach" (164), which the GBF states should guide its implementation. However, large-scale natural processes are largely absent from the GBF's targets and indicators. They can be broken down into three categories:

- Abiotic hydrological processes: These are major drivers of ecosystem structure and carbon storage, influenced by biotic feedbacks.
- Intact biome functions: These drive global processes, such as rainfall, through the integrity of biotic and abiotic processes.
- Biotic migrations: These occur at the biome and global scales, are essential for maintaining ecological integrity, and have some abiotic effects.

BOX 3 Action at multiple biodiversity scales: example of the harpy eagle and Amazon Basin

All three interacting scales of biodiversity—natural processes, ecosystems, and species—need to be measured and addressed in a nature-positive manner. The harpy eagle (*Harpia harpyja*) in Amazonian forests illustrates this point.

The harpy eagle is a large apex carnivore of the tropical forest that preys on large arboreal mammals and nests on emergent trees. At the species level, we can assess its presence or absence and estimate whether its population is large enough for viability (minimum 500 breeding individuals). However, this alone is insufficient. As a top-down regulator, the eagle's presence and function are vital for maintaining forest health. It must be widely distributed across the forest to regulate herbivore populations and contribute to ecosystem stability (165). Therefore, both presence and ecological function must be measured, along with human-induced mortality rates (166).

Even if the eagle population appears viable based on individual counts, it cannot persist if its forest habitat or prey species are lost. For example, a 50% loss of forest habitat leads to reproductive failure (167). Moreover, the removal of tall canopy trees, essential for nesting, also reduces population viability, even if forest cover remains above 50% (168). But measuring ecosystem extent alone via remote sensing is insufficient; a species-level assessment is needed to determine whether harpy eagles and their prey are actually present.

Further, if we focus only on species and ecosystem assessments, we overlook key dimensions of natural processes. The Amazon rainforest spans multiple ecosystem types, and its hydrological processes are vital for forest survival. Two forest types, *várzea* and *igapó*, are floodplain forests covering 750,000 sq km and rely on seasonal flooding. Changes to hydrology caused by river channeling, damming, and water diversion threaten their structure, composition, and function (169). Heavily used by harpies, these ecosystems depend not only on local fluvial processes but also on hydrological connections upstream, as far as the Andes (Box 1).

Biome function is also critical to consider for harpy eagle survival. Moisture influx from the Atlantic Ocean initiates rainfall in the eastern Amazon, but forest evapotranspiration generates a significant portion of inland precipitation from there all the way to the Andean mountains (56). The forest recycled water is critical for maintaining upland forests, wet peatlands, as well as rivers and floodplains (170), which in turn support the rainforest ecosystem and frugivorous freshwater fish essential for forest regeneration. If more than 20% of the forest cover is lost, the rainforest could transition into a savannah-like state (57), resulting in the extinction of species like the harpy eagle and the collapse of many "tele-connected" ecosystems (171). This would not only devastate biodiversity but also disrupt agriculture, as the Amazon contributes to precipitation patterns across the Western Hemisphere, and would release vast amounts of carbon into the atmosphere (Box 2).

Hydrological processes

The GBF does not address hydrology. This is a major omission because freshwater regimes, unimpeded riverine connectivity, and unpolluted water are of such significance that maintaining or restoring hydrological processes, water quality, and associated floodplain and delta habitats is the most important NP action for a disproportionately wide variety of terrestrial, freshwater, and marine organisms (137, 172, 173).

Healthy running water ecosystems depend on the condition of their terrestrial watersheds (113) and vice versa. Big river systems, such as the Mississippi in the United States or the Brahmaputra, Tsangpo, Yarlung Zangbo, Jamuna, and Ganges system in South Asia, traverse substantially different biomes, making ecosystem-scale metrics inadequate for monitoring continental-scale structure or function. Rivers and streams embody the key elements of ecological connectivity, providing both unimpeded movement of species and flow of natural processes (174–176). Hydrologic connectivity at the ecosystem scale is particularly important to freshwater vertebrates, whose populations have declined by an average of 83% (177). Large-scale connectivity is also critical for a wide range of terrestrial and avian species that interact with river floodplains (178), and it directly influences water quality (179), sediment flows (180), and fish migrations (181).

Intact hydrological regimes are also essential to maintaining the vast carbon storage capacity of peatlands (42) and mangroves (46, 49) and retaining methane (37). However, river systems throughout the world have been significantly modified by dam construction (49, 182). Ostensibly built to supply low-carbon “green energy”, high-head hydroelectric dams are highly nature negative (Box 1).

Freshwater hydrological processes are not limited to water in rivers, lakes, and groundwater (blue water) but also include soil moisture (green water) (183). An essential part of the water cycle, soil moisture transforms into evapotranspiration (vapor flows) in all photosynthesizing terrestrial ecosystems. Green water stocks consist of the soil moisture that feeds all biomass growth. Green water flows are the total flux of vapor, including evaporation and transpiration, as well as interception. Accounting for 60–65% of annual global hydrological flows, they are key to ecosystem functioning and services, supporting food production, biomass on land, and carbon sequestration.

The function of intact forests in green water flows and the climate system is particularly important (121). Stomata (pores in leaves) regulate both water vapor and carbon dioxide (CO_2) exchange between a tree’s intercellular space and the atmosphere (184, 185), affecting both precipitation and carbon sequestration. Forests everywhere have a local cooling effect that is lost whenever they are removed (186). Tropical forests and mid-latitude forests to about 40° North also cool the global climate through evapotranspiration. Climate change also causes variations in green water outside normal seasonal cycles, which in turn leads to major reductions in the land carbon sink. (187).

Water vapor from forests is important to rain generation (188, 189). Extensive forest loss can disrupt precipitation patterns across continents (65, 113), heightening the risk of large-scale food insecurity and financial losses (64), especially in the tropics. Tropical forest losses are caused by forest clearing for commercial and subsistence agriculture, logging, charcoal production, and livestock grazing and by uncontrolled fire (190), dams, mining, overhunting (191), roads, and other linear clearings (67). Elimination of seed dispersers due to habitat loss and overhunting impairs forest regeneration (192) and causes declines in carbon storage (193). Deforestation (responsible for 75% of rainfall reduction) and global warming (25% of the reduction) have combined to reduce precipitation in the Amazon Basin by 16 mm per dry season while in areas with heavy deforestation (>28.5% cleared) the rainfall reduction is three times greater due to the added localized increase in temperature and drying (194).

At the global level, assessments of green water reveal dramatic, detrimental changes to the Earth’s water cycle (113), resulting in critically important structural and functional losses of species, ecosystems, and natural processes.

Hydrological actions and metrics

There are four dimensions of hydrologic connectivity to be addressed and measured for NP (12, 195):

i) Longitudinal connectivity: connectivity between upstream and downstream (river continuum concept) (196)
ii) Lateral connectivity: connectivity between channel, floodplain, and riparian areas (flood pulse concept) (197)
iii) Vertical connectivity: connectivity between groundwater and surface water (function of hyporheic zone) (198)
iv) Temporal connectivity: hydrogeomorphic change through short and long time periods (shifting habitat mosaic concept) (199).

Actions to halt and reverse the loss of connectivity in the world’s rivers align well with the 3Cs:

- C1 (heavily modified landscapes): All four dimensions are likely to be impacted, and restoration is NP.
- C2 (shared landscapes): Retaining existing and repairing impaired longitudinal, lateral, and seasonal connectivity is essential.
- C3 (intact landscapes): Keeping rivers wild and free-flowing is key (200).

An Earth system boundary metric suitable for NP has been developed for natural flows (201), with specific objectives for each of the 3Cs:

- C1: Retain and restore natural flows across landscapes and adjacent marine areas, reduce storm flash flows, and maximize green water retention to mitigate flood risk.
- C2: Aim for a minimum of 80% natural flow retention and restoration.
- C3: Preserve all natural flows in an unimpaired state.

Guidance on maintaining and measuring sediment flows is already available (202). Importantly, while continuing and restoring sediment transport is vital for healthy freshwater and estuarine systems (203, 204), human-induced sediment flux into freshwater systems can be harmful, especially outside normal cyclical seasonal flushes (205, 206).

A global green water planetary boundary metric indicates that no more than 10% of Earth's land area should deviate (in dry or wet direction) from its natural green water variability during the late Holocene (3, 113, 185). Today, 18% of Earth's terrestrial land area exceeds this boundary (3). We discuss this further under the sections *Biome function* and *Biome intactness actions and metrics.*

Biome function

A biome is a large-scale aggregation of related ecosystems (207) characterized by areas of vegetation of the same life form (208), and it is the largest biotic unit after the biosphere. Biome function, tied to intactness, affects continental- to global-scale processes. Despite the absence of biome-specific targets in the GBF, they are needed to achieve both the NP global goal and the GBF's vision.

Biome condition affects rainfall, with widespread effects on carbon storage, ecosystem health, and agricultural productivity, as discussed above and illustrated by Amazon and Congo Basin rainforests (Box 2). Maintaining and restoring forest cover at the biome scale is therefore a priority NP action. Forests are not the only areas where land-use changes affect precipitation. In Western Australia, the clearance of 13 million hectares of dry bush for agriculture using non-native species has directly reduced cloud cover and rainfall relative to areas with native vegetation (209).

The GBF lacks explicit targets or indicators for biome intactness, which should be an explicit conservation objective (210). Indirectly, T1 calls for land-use planning to stop the loss of areas of high biodiversity importance (including ecosystems of high ecological integrity) by 2030. However, action by 2030 is not sufficient. Some tropical forests are on the path toward a tipping point beyond which they may transition into savannah-like vegetation (Box 2). Given recent rates of tropical forest logging, 2030 is too late. Halting tropical forest cover loss and degradation everywhere must be an immediate top priority if these efforts are to protect these biomes, sustain their species and ecosystems, and ensure rainfall throughout the tropics and downwind agricultural regions.

Biome intactness actions and metrics

The best available metric for sustaining rainfall production in tropical forests is to maintain biome-scale forest cover, limiting losses to ≤20% of original primary forest extent (57) and ideally restoring losses to achieve 90% cover to increase resilience to climate change (211). However, some researchers are unwilling to identify any threshold of acceptable forest cover loss (194). For restoration, fast-growing species (including non-natives) aid initial rainforest recovery; the long-term NP goal is to use native slow-growing hardwood species (136, 212). More research is needed to establish a metric for dryland vegetation change.

Migrations

Migration is a specific kind of animal movement where species move between different habitat regions at different times of the year, usually driven by season (213). It has become an urgent conservation problem because not only are migratory populations in decline, but 58% of sites monitored by the CMS are under unsustainable pressure, and 399 endangered migratory species are not even listed for CMS protection (10). In North America, 419 native migratory bird species have experienced a net loss of 2.5 billion individuals since 1970 (214). These losses occur extensively in C1 areas caused by free-ranging domestic cats (mostly unowned) preying on migratory birds (215) and by migratory birds striking illuminated buildings at night (216).

Migration affects species health and diversity (217), ecosystem function and structure (9), and carbon storage in ecosystems (134). Migratory movements range from short seasonal shifts between small habitat patches to transcontinental intergenerational migrations, as seen in monarch butterflies (217). Therefore, conservation strategies focused solely on resident species are insufficient to protect migratory populations (9). Migration is also different from animal movements within a home range to establish a new home range or to find mates in a metapopulation. These all require connectivity but are not migrations (213). Similarly, the need for species to move their range in response to climate change requires connectivity (218), but is not migration *per se* (219), although climate change could lead to migratory range shifts (220).

Migration is not mentioned in the GBF except by implication through ecological and landscape connectivity, which are to be addressed at the country level (GBF T2 and T3) (175). While protecting ecological connectivity across a species' migratory range is essential for migration (10), species movements often transcend national boundaries. The lack of attention to migration is a material deficiency in the GBF because it applies to the CMS as well as to many countries that are not signatories to the CMS.

Migration actions and metrics

For many migrating species, there are well-established approaches to protecting habitats essential for critical life-history events, including wintering and stopover resting habitats, as well as breeding areas (10, 221). These conservation actions require species-specific assessments for NP actions to ensure that habitat patches and their connectivity enable safe breeding, rearing, and travel across a species' full migratory range (222). For sea turtles, for example, a structured conservation framework has been developed to secure their movements across terrestrial, nearshore, and high-seas environments, which could be adapted for other migratory marine animals (223).

Major losses of migratory birds through cat depredation could be substantially reduced by controlling cats in C1 areas (224), and mortality due to building strikes could be greatly reduced by turning off unnecessary lights at night (225). Regarding terrestrial connectivity, metrics to guide conservation efforts are available as outlined by Keeley et al. (226), while conserving hydrologic connectivity is of utmost importance due to its critical role in supporting both freshwater and terrestrial migratory species.

Ecosystem level

The CBD defines ecosystems as a dynamic complex of biotic (plant, animal, and microorganism) communities interacting with their abiotic environment (geophysical, climatic, and chemical processes) (227). Four elements define an ecosystem type: (1) characteristic native species, (2) abiotic environment, (3) key ecological processes and interactions, and (4) spatial distribution (228). While many mechanisms influencing species' vulnerability also apply at the ecosystem level, ecosystems embody natural processes that are not adequately captured through species-by-species conservation efforts (228). This underscores the importance of ecosystem-level actions in biodiversity conservation.

The ecosystem equivalent to species extinction is ecosystem collapse, which occurs when an ecosystem's inherent resilience is overwhelmed, resulting in a phase shift to a different and often novel ecosystem state (229, 230). An ecosystem collapses when one or more key defining variables are functionally impaired, including geomorphological features, species composition, nutrient cycling, disturbance regimes, ecological connectivity, and other biotic and abiotic processes. Vulnerability thresholds have been identified: ecosystems are considered at risk when 30% of their structure is degraded, functionally impaired at 50% degradation, and approaching collapse at 80% degradation (228).

Recently, there has been a discussion of the potential conservation value of novel ecosystems (231). New species assemblages, some of which may be exotic, could create new self-organizing ecosystems that have value for biodiversity conservation or ecosystem function. These emerging systems may warrant conservation attention, but a great deal of research remains to be done on them (232). The primary focus of NP conservation is retaining and restoring the composition and function of native ecosystems.

Some vertebrate species perform processes disproportionately vital to ecosystem function. These species act as ecosystem engineers or keystone species, regulating trophic cascades (e.g., wolves and sea otters), shaping vegetation structure (e.g., elephants and bison), or influencing hydrology and wetland formation (e.g., beavers) (166). Foundational species in nearshore marine environments (e.g., kelp and corals) play critical roles in preserving ecosystem structure (23). Fortunately, small and abundant species that are also vital to ecosystem function benefit from conservation actions that are aimed at suites of larger species through an "umbrella" effect (233), but attention should be paid to their demographic robustness as well (234). Conversely, invasive species can degrade ecosystems by displacing native species and disrupting natural processes.

Ecosystem actions and metrics

NP ecosystem goals will vary according to the 3Cs. C1 areas contain ecosystems that have already collapsed and can be described as crisis ecoregions (235). These landscapes support most of the human population and produce most of the world's food calories, so other important values are at play (143). While ecosystem restoration to full function is impractical under C1 conditions, all remaining fragments of primary ecosystems should be secured, and at least 20% native vegetation cover should be restored to support ecosystem services (236). This includes urban re-greening for multiple ecological and human benefits (237, 238), which is well covered in GBF T12. Agricultural chemicals are most common in C1 areas, which require practices that keep excess runoff out of waterbodies. Safeguarding areas of high agricultural productivity through prevention of urban sprawl serves as an indirect NP practice, preventing further degradation of C2 lands for marginal agriculture and contributing to the SDGs. Combined with improved agricultural practices, dietary adjustments, reduction of food waste, and better global fisheries management, the current cultivated land could feed a global population of up to 10 billion people (239, 240). Such a food systems shift can be done in a just, equitable, and NP manner that halts the loss of intact areas and includes restoration of marginally producing areas to forest cover (241).

NP actions in ecosystems that are less than 50% impaired (C2 areas) should prioritize retaining or restoring overall ecosystem integrity to well above 50%. This requires halting habitat degradation and fragmentation, preserving all remaining intact areas, and retaining and restoring natural abiotic processes, such as fire regimes and hydrology (242). GBF Target 3, which mandates interconnected conservation of at least 30% of land, sea, and freshwater, is particularly well-suited to C2 areas, and such networks will also support climate adaptation efforts (218). Large intact ecosystems (C3 areas) are often aggregated in biomes and should be maintained intact, which requires accelerated action under GBF Target 1.

Across the 3Cs, actions to protect and restore keystone, top-down regulating, and foundational species contribute to NP at the ecosystem level (166, 243). These species also provide positive feedback to the climate system by preventing carbon release and enhancing carbon sequestration (96, 134). Large carnivore and large grazer restoration efforts are best suited to C2 and C3 landscapes. Removals of invasive species can have positive effects across ecosystems (150) and improve green and blue water availability (244). Removing exotic species constitutes an NP action unless they have become part of a novel ecosystem that supports endangered species (245, 246); such exceptions will typically be restricted to C1 areas. Ecosystems also benefit from reducing populations of native generalist species that have become overabundant owing to their adaptability to human-dominated landscapes, the absence of predators, or confined ranges (247), which also aids in zoonotic disease prevention (28).

Species level

Native species are integral to the Earth system, and healthy populations with reliable access to food supplies are less likely to shed pathogens that cause disease in humans (33). The NP goal for species is to increase their distribution, abundance, functionality, and resilience, maintaining genetic diversity and preventing extinctions (91). In contrast, the GBF target for species only focuses on the latter two (T4) (248).

Worldwide, species are in decline due to habitat loss (the primary driver of species loss on land) and overharvesting (the primary driver of loss in the ocean). Other important drivers include industrial production processes, such as deforestation, mining, chemical pollution, cereal crops, and palm oil plantations, the expansion of marginal agriculture, deliberate and inadvertent introduction of invasive species (249), as well as global warming, which alters thermal conditions for species and habitat niches in ecosystems (250).

Species status varies significantly across the 3Cs. At-risk species exist in all three (251), but most are found in C1 areas (143). Moreover, species loss for C1 exceeds detectable presence as many large-bodied species have already been lost from these heavily transformed landscapes (86, 252, 253). In contrast, some largely intact C2 landscapes show remarkably complete faunal assemblages with robust genetic diversity still performing natural processes, such as migration (e.g., Serengeti-Mara). However, while C2 areas often have complete or near-to-complete faunal assemblages, they also suffer from species at risk, extirpations of some populations, declines within populations, and reduced genetic diversity (e.g., large mammals tend to decline first) (86). In addition, their aquatic integrity is often compromised by river damming. C3 areas, being the least disturbed, have few at-risk species, with the primary threat being overexploitation or climate change impacts. However, their sheer size, intactness, and inherent connectivity make them the most resilient of the 3Cs to climate change and least vulnerable to overexploitation (254).

Species actions and metrics

The NP goal to increase the distribution, abundance, function, diversity, and resilience of native species requires halting loss by maintaining intact species assemblages, increasing populations toward ecological functionality, and reducing extinction risk across the 3Cs (Figure 4).

This includes addressing overexploitation of species through enforced regulations or long-standing customary practices, preventing hyper-abundance of species that degrade ecosystems, implementing anti-poaching programs, and promoting active human–wildlife coexistence efforts everywhere.

Maintaining intact species assemblages

Healthy ecosystems that retain the full array of native species interacting with intact natural processes are of the greatest value to the Earth system. They also serve as a barrier against the spillover of potential pandemic-causing pathogens into human populations (131). Despite advances in ecological restoration and species recovery, there is no substitute for preserving original, intact systems. The NP goal of halting nature loss prioritizes the protection of all remaining intact ecosystems and species assemblages wherever they occur—whether in C3 areas, intact parts of C2 landscapes, or in remnant patches within C1 regions. While GBF T4 is silent on maintaining intact species assemblages and abundance, Targets 1 and 3 (spatial conservation) and Target 9 (preventing overexploitation) are aligned with this NP objective.

Restoring functional species populations

Achieving the NP goal of reversing nature loss by 2030 and fully recovering nature by 2050 requires thriving populations. Moreover, NP requires a focus on ecological processes, not just patterns of persistence. The common threshold of an effective population size of at least 500 (Indicator 4 for GBF T4) indicates reduced extinction risk but tells us nothing about whether the species is abundant enough to perform ecological processes at a scale that contributes to Earth system stability (9, 255). Similarly, counting species diversity as a metric of success is insufficient. High diversity of small-bodied species does not compensate for the loss of large vertebrates that perform keystone and regulatory functions such as predation, herbivory, and seed dispersal (243, 255).

The International Union for Conservation of Nature (IUCN) Green Status Framework (163) provides guidance for three NP metrics designed to ensure that species populations are large enough to sustain ecological function across landscapes and maintain resilience:

- Green Status 1 (GS1): The species exists in multiple interconnected populations, each with at least 500 individuals.
- Green Status 2 (GS2): The species is fulfilling its ecological role, with missing species reintroduced where feasible.
- Green Status 3 (GS3): The species exists in a representative set of ecosystems and communities throughout its historical range.

Progressively moving species along this Green Status continuum, from GS1 toward GS3, and maintaining them in a higher status is a contribution to NP (Figure 4). Some C2 systems are close to hosting intact large vertebrate assemblages, often missing only one to three species in the less impacted C2 regions. In such cases, reintroduction is relatively simple and could help move these ecosystems toward GS3 (256). Where species already exist in GS3 status (in many C3 areas), maintaining this state is essential to achieving the NP goal of halting biodiversity loss.

Reducing extinction risk (threatened species)

Preventing extinction is an urgent conservation priority, as the natural background species extinction rate has been greatly exceeded in the Anthropocene (257). Recovery of an extinct species is not yet possible and may never be. Conservation goals should therefore focus on reducing the extinction rate attributable to human activity, which exceeds the natural background rate (258). GBF T4 calls for halting human-induced extinctions of known threatened species and for their recovery and conservation, significantly reducing extinction risk. A key indicator for T4 is the widely used minimum viable population threshold of 500 individuals.

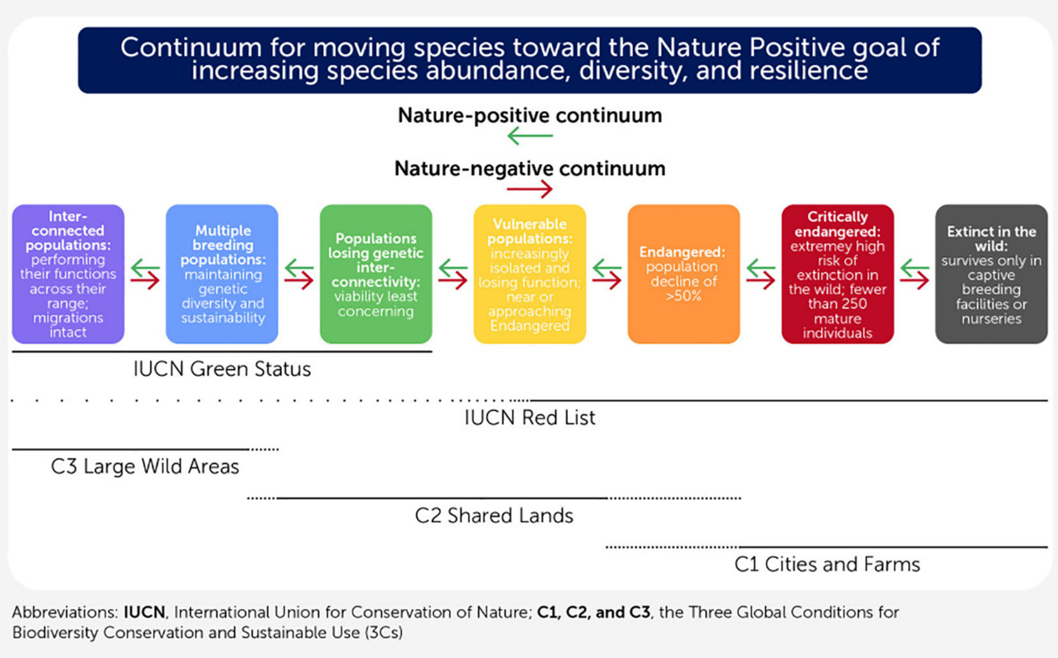

FIGURE 4
Continuum for moving species toward the "Nature Positive" (NP) goal of increasing distribution, abundance, function, diversity, and resilience of species and avoiding extinction. The present trend is either nature negative (i.e., moving species toward the right side of the continuum) or neutral (i.e., static on the continuum). Species on the far left-hand side are already contributing to NP, and their distribution, abundance, and function should be retained to halt biodiversity loss. Actions to reverse species loss and increase their distribution, abundance, function, diversity, and resilience will progressively move species toward the left. At the bottom, the likely location in the Three Global Conditions Framework (3Cs) of species relative to their status along this continuum is indicated. Controlling species exploitation levels is essential across all 3Cs.

The IUCN Red List remains the most comprehensive assessment tool for identifying and categorizing threatened species along a continuum from least concern to global extinction (161). NP-aligned actions for threatened species aim to progressively improve their status along this continuum. Moving each species up one category or more, in a ratchet-like manner, contributes to NP (Figure 4). A "Reverse the Red" campaign actively promotes this approach, emphasizing targeted conservation actions to improve a species' status (259).

A tool for measuring the progress of species toward nature positivity along the extinction risk continuum is the IUCN's Species Threat Abatement and Restoration (STAR) metric (162). Unlike the IUCN Green Status, which focuses on the functional distribution across a species' range, STAR emphasizes reducing extinction risk at specific sites and highlights opportunities for interventions to reduce extinction risk where they are greatest. The STAR system is particularly useful in C1 areas and in the more fragmented parts of C2. For an actor seeking to contribute to NP at the species level, STAR provides a multi-step assessment process that leads to an appropriate threat reduction strategy. The IUCN has published guidance on using the STAR metric to contribute to NP outcomes (260).

Protecting areas to avoid imminent extinction of rare, narrow-range, endemic, and threatened species is an important action under GBF T3, particularly in C1 areas. The Conservation Imperatives approach provides a guide for identifying such priority sites across all 3Cs (160).

Genetic diversity

Genetic diversity is essential for maintaining healthy populations of any size. It is inherently supported by many of the above actions. However, care must be taken to ensure that large populations of recovered species are genetically robust enough to retain resilience, which may require reintroducing genetic diversity (261).

Enabling social and economic conditions for a Nature Positive shift

We now move from conservation actions and metrics to enabling social and economic conditions necessary to achieve the NP global goal. We begin with diverse cultural perspectives, governance, and equity between the Global North and Global South.

Engaging diverse cultural perspectives in Nature Positive

Arising from contemporary empirical science, the NP approach incorporates a holistic understanding of life and a responsibility to act for the health of the planet. It positions human development as being embedded in nature rather than as a competing interest with it (Figure 1) and emphasizes the importance of considering the flow of natural processes over time at varying scales. But not all cultures are driven by empirical science.

Humans interacted with nature throughout the Holocene (262). Many ethnocultural traditions from South Asia, China, Africa, and Indigenous peoples worldwide converge in viewing humans as embedded ecological participants with relational responsibilities to live in balance and harmony with a dynamic natural world, rather than as having rights to exploit static natural resources (263–265). The NP approach is aligned with those cultural perspectives that provide a basis for a shared vision for humanity to live well while respecting nature's biological patterns and natural processes, as discussed further in *Nature Positive Society*, a companion paper to this article (266). Engagement on an equal footing with other cultures' relational and intrinsic values (267) will increase support for NP goals.

Other knowledge systems could also give rise to NP conservation approaches and metrics complementary to those we have outlined. For example, Indigenous and local communities often possess deep knowledge of the sustainability of their ecological contexts based on long-term observation and interactions. This can be embraced alongside empirical science through mutual respectful engagement in "ethical space", where the goal is reconciliation of knowledge systems to achieve NP (268).

Nature Positive governance reform

Meeting biodiversity, climate, and social goals contemporaneously will require greater integration of governance to carefully identify co-benefits, trade-offs, and co-detriments (149, 269) and is urgently necessary to avoid tipping points (270). Yet we lack strong global governance for sustainability. The CBD and UNFCCC/Paris Agreement are structured to place primary responsibility for implementation on state parties, although an International Court of Justice (271) advisory opinion has created the possibility for Global South countries that suffer adverse effects of climate change to sue for damages where a Global North country's failure to meet its commitments has led to direct harm.

In many countries, nature is usually the purview of an environment department rather than fully integrated into high-level decision-making processes, which is necessary if we are to meet global goals (92). Through systemic national-level integration, Costa Rica successfully halted and reversed biodiversity loss from 1990 levels (272). It is common in federal systems for provinces to control land use and, in some countries, for municipalities to govern large areas. Integration of national and sub-national governance, policies, and actions is essential and will be the focus of a global Nature Positive Summit in Japan (273).

Indigenous peoples' territories often have significant biodiversity, but frequently they have been marginalized from governance of those areas, contrary to the UN Declaration of the Rights of Indigenous Peoples (274). Power imbalances and lack of capacity can be addressed effectively and equitably (269) in a bio-cultural approach (275) that moves beyond consultation or financial compensation into design, governance, and financial participation (276). NP governance innovations that embed nature in all aspects of decision-making have emerged from Indigenous peoples themselves—e.g., the Buffalo Treaty among First Nations and Tribes of North America (277) and Māori people initiating personhood for rivers in New Zealand/Aotearoa (278).

Nature Positive shift and finance

Funding is required to implement conservation measures. Informed by the Paulson Report (279), GBF T19's funding target to implement national biodiversity strategies and action plans is at least US$200 billion from all sources. This includes overseas development assistance (ODA) from rich nations of at least US $20 billion annually by 2025 and US$30 billion annually by 2030, which we discuss next in the context of equitable sharing of responsibilities between the Global North and Global South.

Equitable sharing of responsibilities between the Global North and South

In the developed North, advanced economies must conserve remaining intact nature, restore degraded natural systems, and decarbonize at their own expense. This transition requires strong political will, which could be driven by self-interest: continued environmental degradation will destabilize economies (80), threaten capital stocks (83), and intensify political instability through increased climate-related displacement and refugee crises (280).

In the Global South, similar actions are required. While degradation of nature occurs in both wealthy and poorer nations, the consumptive footprints of the Global North and newly industrialized nations are major drivers of biodiversity loss in developing regions. Similarly, climate change—primarily caused by emissions from wealthy industrialized countries and, more recently, by rapidly developing economies (281) —disproportionately affects poorer nations (282). Financial transfers from developed to developing nations are therefore equitable (283–286).

Both the CBD and UNFCCC have agreed on financial commitments. GBF Target 19 calls for overseas development assistance from rich nations of at least US$20 billion annually by 2025 and US$30 billion annually by 2030. A multilateral mechanism for the fair and equitable sharing of benefits from the use of digital sequence information on genetic resources, including a global fund, has also been agreed (99). The UNFCCC has an agreed US$300 billion annual resource mobilization goal from North to South by 2035. It also operationalized a Loss and Damage Fund, with US$730 million in initial pledges (287). Fulfilling these commitments is critical for achieving shared environmental goals equitably.

Many Global South countries struggle with national debt burdens, which restrict the financial resources available to them for both human development and NP implementation. Debt for nature swaps (DNS) started as an international public finance incentive to protect nature, involving debt forgiveness in exchange for conservation commitments (288). More recently, DNS have involved a reduction in the cost of borrowing for a developing country in return for NP actions (289, 290). Concessional finance from multilateral development banks (MDBs) or guarantees from rich countries improve the investment grade of developing countries' debt, which reduces interest rates. Such debt cost reduction projects have been implemented in several countries with NP conservation outcomes (291, 292).

Nature Positive transformation of the dominant economic system

The NP shift also requires a transformation of the dominant economic system, which is recognized in the GBF. We discuss how this can be enabled by valuing nature in public accounting standards, and through ODA, MDBs, innovations in financial markets, and changes in business operations. We begin with valuing nature.

Valuing nature

T14 calls for changes in national accounting and fully integrating the values of biodiversity. Many people attach non-economic value to nature (293, 294), but the world's dominant economic system does not. There are critiques of attaching financial value to nature because it undervalues or ignores values reflective of human–nature relationships (267) and could result in privatization of public goods (295) or economic imperialism (296). However, achieving the NP shift will require alignment of the dominant financial system, which is currently driving the loss of biodiversity (80, 297). We focus first on public sector mechanisms to attach economic value to nature in national accounts.

Public sector finance and Nature Positive

The global financial system treats "natural assets" as free for the taking with the only cost being the expense of extraction or harvesting (80). The result is private enterprise capturing the value at the expense of the common biosphere (298). Private enrichment with externalized costs is counted as a positive number in standard national accounts and Gross Domestic Product (GDP) (299). Thus, nature-negative actions are counted as positive economic outputs in government finances. For the world to become NP, governments must address this systemic problem through standards, regulations, and the creation of market mechanisms (80).

The externalized cost of economic activity can be viewed as depreciating the "natural capital" that underpins the economy and human well-being, but without accounting for that loss of value to society (80) (Figure 1). Valuing natural capital and ecosystem services is an effective way to correct this by measuring and counting the value to society alongside the extracted value realized by an individual or corporation (80, 300). Natural capital (also known as tangible natural assets or stocks of nature) produces flows of ecosystem services that can be measured through a "shadow" price. In 2012, the UN System of Environmental-Economic Accounting (SEEA) created a statistical Central Framework (CF) that enables countries to measure their natural capital and understand the contributions of nature to national prosperity and the importance of protecting it. Building on the CF, the UN also developed SEEA Ecosystem Accounting (SEEA EA), which provides a more in-depth view of the health of natural capital in each jurisdiction (301, 302). So far, over 90 countries compile accounts using SEEA CF, while over 50 countries also use the more detailed SEEA EA. However, these statistical frameworks are satellite standards to the System of National Accounts (SNA) and therefore have limited influence on how GDP is calculated by countries. To make an NP change, governments must meaningfully integrate SEEA EA into their system of national accounts and use this information to inform public sector decision-making.

Another avenue for integrating the value of natural capital into mainstream financial markets is to address barriers that limit the value of nature from being accounted for in public sector accounting standards. Currently, intact nature is left out of international accounting frameworks, and its economic value is not counted until it is exploited, purchased, or sold. Even formal area-based conservation actions by the state are viewed as an expense rather than an investment, and the resulting conservation areas are not viewed as assets in public accounting. However, in January 2026, the International Public Sector Accounting Standards Board (IPSASB) released IPSAS 51, Tangible Natural Resources Held for Conservation, which will allow governments to count conservation areas as tangible natural assets (303, 304). Getting countries to adopt this new accounting standard will be an important NP action (305).

Private sector investment in conservation

T19 seeks to increase private investment as part of the US$200 billion for conservation measures, but it provides no pathways for it. In market terms, nature is worth more dead than alive. New markets for the "social value" of nature are needed (80), whether through regulatory support or capital market evolution.

Nature markets began with "no net loss" biodiversity harm mitigation laws, such as the United States Clean Water Act (306) and the United Kingdom's biodiversity net gain requirement under the Environment Act 2021 (307). Since these markets are inherently about mitigating loss, they can lead to further degradation of an intact area "offset" through restoration of a degraded area. This can help the world move toward less loss on the road to nature positivity (91, 308), but more than an offsets market is required to engage private investment to halt and reverse nature loss.

The European Union is evaluating a voluntary nature credits system (309). It builds on earlier private and government efforts to create biodiversity credits to sell to the private sector (310). Biodiversity credits require additionality, which means some improvement in the conditions of the underlying nature asset. Additionality is good for reversing loss through restoration (310). The International Advisory Panel on Biodiversity Credits (IAPBC) also includes improved governance and protection as an additionality. This may include Indigenous stewardship agreements or legal designations that did not previously exist (310). Biodiversity credits are of interest to buyers motivated by charitable or social license considerations but not to investors who seek a financial return on investment.

Unlocking large amounts of private capital for intact nature will require financial innovations (311) that provide a return on investment or reduce risk to capital. Governments can stimulate the creation of market mechanisms through concessional finance. This approach underpins the innovative Tropical Forest Forever Facility (TFFF), intended to attract private investment to halt the loss of tropical forests. Led by Brazil, TFFF was launched at UNFCCC COP30 in Belem. Its goal is to raise an initial US$25 billion from MDBs, ODA, and philanthropies to invest and also improve the investment grade of US$100 billion of debt to be sold to private investors. The resulting US$125 billion fund would then be invested to generate returns above the cost of borrowing, which is expected to net US$4 billion a year. This would be paid to governments of tropical forest countries to halt deforestation, with a specific percentage of the funds earmarked for Indigenous and local communities (312). In the month it was launched, there were over US$6 billion in pledges toward the initial US$25 billion (313).

Heightened awareness of nature risk and interest in investing to reduce it (314) could create a market for halting the loss of nature. Large investors are "universal owners" of climate and nature risks because they are widely invested in the global economy (315). Thus, ensuring the stability of the Earth system represented by natural capital is in their business interest, and they could invest in it. There is an existing natural capital protocol for business (316, 317) that is consistent with SEEA (318, 319). Initiatives to "put nature on the balance sheet" have identified the limitations in accounting standards and frameworks that prevent the inclusion of non-purchased natural assets in financial statements and provided a road map for addressing the problem (319).

The International Organization for Standardization (ISO) released the world's first international biodiversity standard in October 2025. ISO 17298 "Biodiversity — Considering biodiversity in the strategy and operations of organizations — Requirements and guidelines" provides companies, investors, and public institutions with a globally agreed rulebook for how to measure, manage, and report their relationship with natural capital (320). For the private sector, this defines how biodiversity risk enters credit rating, audit trails, and shareholder expectations.

Meanwhile, natural asset companies create an asset class for nature, enabling direct investment in protected natural capital (321). Similarly, insurance arrangements focused on avoiding loss of natural capital, in which part of the premiums received are invested in nature to reduce the likelihood of loss of ecosystem services vital to a particular economic sector, could be created. To stimulate the market and create a level investment environment, governments could regulate financial institutions and businesses to hold some percentage of their assets as natural capital (this could also create a market for biodiversity credits).

Local and Indigenous communities should be involved in the design, returns, and governance of nature and climate investments that affect their areas to ensure both equitable outcomes and security of title. Including traditional knowledge systems will also likely enhance the performance of the underlying nature asset (269).

Private sector operations and subsidies

The NP shift requires economic transformation beyond government finances and private markets. Economic factors and consumption patterns are major drivers of both biodiversity loss and climate change and must be fundamentally transformed if we are to achieve the NP global goal (322). Here, we focus on realigning business operations.

Business interests have been involved in NP efforts since its inception, including in co-authoring the foundational NP paper (91) and successfully supporting the inclusion of targets in the GBF that encourage businesses to make an NP shift (317). The aims are as follows:

- All sectors should align their activities with the GBF (T14).
- Corporations should reduce their impact on nature and report their dependencies on nature (T15).
- Governments should eliminate US$500 billion in nature-negative subsidies to business by 2030 (T18).
- Corporate and financial sectors should participate in GBF financing (T19, discussed above).

T14 and 15 have attracted significant interest from both operating companies and the financial sector (323), and there was substantial private sector participation at the Global Nature Positive Summit hosted by Australia and the state of New South Wales (324). In 2025, the World Economic Forum reported growing consensus around business alignment with the NP goal (325).

To transform operations, businesses will need to embed NP approaches across all business decisions (317). Alignment methods include both internal decision-making tools (such as the Natural Capital Protocol) and disclosure-related tools. The Task Force on Nature-related Financial Disclosures has developed voluntary guidance (adopted by hundreds of companies and financial institutions) to help businesses integrate nature into decision-making and shift financial flows away from nature-negative outcomes and toward nature-positive outcomes. (326). The Nature Positive Initiative is developing voluntary corporate NP metrics for businesses to make meaningful and reportable contributions to the global NP goal (327). Science Based Targets for Nature is developing a drivers-oriented framework to help companies align their activities with NP (328).

Measures like these will be mandatory in the European Union, which has passed rules scheduled to come into force in 2027 that will require companies to report on "sustainability matters" (environmental, social and human rights, and governance factors), including their supply chains and actions to prevent or mitigate adverse impacts (329).

Many of the world's largest mining companies have collectively endorsed NP, asserting that "nature positive must be both an objective to be achieved, as well as an embedded approach to doing business" (330). Industry-specific NP approaches have now been proposed for the mining sector (331), the agricultural sector

(239), and wind farming (332). The Nature Positive Universities Initiative involves 500 private and public higher education institutions across the world committed to promoting nature on their campuses, in their supply chains, and within their cities and communities (333). There is also a well-developed mitigation hierarchy available for businesses to reduce inevitable impacts as part of the transition to NP (334). Rigorous attention to achieving assured NP outcomes will be required to avoid "greenwashing" (335, 336).

T18 materially understates the flow of public subsidies to private activities that must be changed: there is an annual net US$7 trillion in nature-negative financial flows, US$5 trillion of which are private (337). This requires public policy shifts in incentives (279), which will be more likely to happen with business support.

An NP world will only be achieved if there is a transformed, enabling economic environment. This requires alignment of financial incentives, business operations, innovation to make intact nature investable, public and private investments in conservation, and integration of government actions across the treaties.

Integration through co-reporting progress toward Nature Positive, climate goals, and the Sustainable Development Goals

We have demonstrated that achieving the SDGs and global climate goals is intrinsically linked to the NP goal. An explicit overarching objective for all three should be the integrated pursuit of an equitable, nature-positive, and carbon-neutral world (91).

Now that there is recognition of the nature–climate nexus from the parties to the CBD and UNFCCC and also the International High Court, national governments should align their reporting of Nationally Determined Contributions (NDCs) under the Paris Agreement and National Biodiversity Strategic Action Plans (NBSAPs) under the GBF. At CBD COP16, an initial step toward this integration was made by "urging … parties to consider integrating into their NBSAPS … approaches … to climate change adaptation and mitigation" (99).

NBSAPS could immediately include carbon sequestration and storage indicators under GBF Targets 1–3 and 11. Similarly, the SDGs should explicitly acknowledge the GBF in SDG 14 and 15, as they currently recognize the Paris Agreement in SDG 13. Integrating NBSAPs and NDCs could be facilitated through the existing architecture under provision 4.19 of the Paris Agreement, which calls for long-term low-emission development strategies (338). Joint reporting across the Paris Agreement and CBD/GBF could also serve to track progress on SDGs 13, 14, and 15, while incorporating shifts in production and consumption patterns and the transformation of subsidies, aligning with SDG 12.

Both the GBF and Paris Agreement emphasize equitable outcomes, which are also a focus of SDGs 1–7, 16, and 17. Joint reporting on equity across these global agreements would mark a major advance as it would foster integrated thinking, improve efficient deployment of financial resources, address underlying drivers in a coordinated manner, and achieve positive outcomes for both people and the Earth system. All of this joint reporting across the GBF, UNFCCC/Paris Agreement, and the SDGs should start immediately. As a further step, the integration of planetary boundaries and equitable objectives has been proposed through the concept of safe and just Earth system boundaries (104), for which Rockström et al. (201) provided Earth system boundary metrics. They should be widened to include the species, ecosystems, and natural processes discussed above. These global metrics could then be used by governments to assess progress toward living within all nine planetary boundaries.

Conclusion

The Earth system is rapidly unraveling. Protecting intact nature and restoring damaged ecosystems must be prioritized in global policy to the same extent as climate action under the Paris Agreement and the SDGs for human development. Realizing the GBF's NP mission, goals, and targets, with heightened attention to natural processes and feedbacks, would be an essential stabilizing action. However, actions under the GBF alone are insufficient. We are at or near the critical threshold of 1.5°C of climate warming (339–341), beyond which the Earth system could cross tipping points (59).

Concerted, aligned, and monitored efforts across the CBD, UNFCCC, SDGs, and all of society are needed to create an NP future that is equitable and carbon neutral. To achieve this requires conservation action and an enabling social and economic environment that includes money to pay for it, reorientation of financial flows, a shift in production and consumption practices away from nature-negative activities toward positive outcomes, new financial mechanisms, and stronger coordinated governance that is equitable and people positive.

It is a grim irony that just as the need for integrated action at all scales has become both apparent and urgent, the UN system and multilateralism in general are under enormous pressure (309). Time has shown, however, that what is urgent eventually becomes apparent to even the most reluctant. There remain many actors who are both deeply concerned about the state of the world and highly committed to improving it, including a broadly based Nature Positive Initiative (342).

Achieving the NP goal of halting and reversing nature loss, with a net improvement by 2030 from a 2020 baseline, is essential for the well-being of humanity and the rest of life. It is the only pathway to ensuring that the 21st century progresses toward peace, prosperity, stability, better health, and natural beauty, rather than descending into a future marked by large-scale human displacement, violent conflict, fires, floods, disease, food and freshwater shortages, inhospitable climates, and ecosystem collapse.

It is time for us to recognize that nature is the foundation of all human affairs. Unless we act swiftly to make the world NP by 2030, our lives are likely to become very difficult in a destabilized Anthropocene.

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Author contributions

HL: Writing – original draft, Conceptualization, Writing – review & editing, Visualization.

JR: Writing – original draft, Conceptualization, Writing – review & editing.

RP: Writing – original draft, Writing – review & editing.

DL: Writing – original draft, Writing – review & editing.

LL: Writing – original draft, Writing – review & editing.

CP: Writing – original draft, Writing – review & editing.

FW: Writing – original draft, Writing – review & editing.

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LZ: Writing – review & editing, Writing – original draft, Visualization.

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Data availability statement

The original contributions presented in the study are included in the article/supplementary material. Further inquiries can be directed to the corresponding author.

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Perspective

Governing for "no net loss" of biodiversity over the long term: challenges and pathways forward

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SUMMARY

Economic development is increasingly impacting biodiversity, leading to a rise in biodiversity offset policies globally that aim to compensate for biodiversity losses. Many developments generating offsets create long-term, irreversible losses of biodiversity and, therefore, require biodiversity gains from offsets to be retained over the long term to have any hope of achieving "no net loss" (NNL) of biodiversity. This raises important ecological and institutional challenges that current offset mechanisms, built for politico-economic systems with short-term policy horizons, do not sufficiently consider. We explore this issue and discuss several responses to the problem ranging from incremental changes for improving on-ground management, through to major governance shifts required to support the long-term social-ecological resilience of offset sites. We argue that without these changes, at best, NNL policies participate in temporarily reducing permanent biodiversity loss. At worst, they participate in a false promise, distracting institutions from the transformative changes needed to reverse biodiversity depletion.

INTRODUCTION

With the increasing environmental impacts of economic development, biodiversity offset policies are spreading globally, aiming to compensate for the biodiversity losses induced by these activities, notably in the infrastructure, urban development, and extractive sectors.[1] Biodiversity offsetting (henceforth referred to as "offsetting") is defined here as a set of institutional rules and practices that enable the production and retention of "biodiversity gains" across time and space to compensate for the loss of biodiversity from authorized damage, with the aim of reaching "no net loss" (NNL) of biodiversity (Box 1, and references therein). Although regulations, policies, and voluntary practices can define offsetting in different ways,[2,3] here we focus on regulatory offsets and follow the terminology commonly used in the academic literature and best practice offset guidelines (Box 1). Offsetting usually corresponds to the last step of the mitigation hierarchy (Box 1) where the first step is to avoid impacts, followed by minimizing and remediating impacts. Finally, offsetting mitigates the remaining residual impacts on biodiversity.

Both biodiversity offset schemes and the NNL objective are already operationalized in multiple jurisdictions around the world.[1,22] This uptake of offsetting schemes has been driven by the search for reformist solutions to conflicts over limits to development occurring across scales, including infrastructure and extractive activities.[3] Offsetting theoretically enables the operationalization of the "polluter-pays" principle (Box 1). This conceptualization takes the current politico-economic system as a given, often proposing solutions based on technocratic approaches that empower the state, markets, and experts.[3]

Despite this global uptake, offsetting and NNL have remained controversial within the field of conservation.[3] For example, the ecological feasibility of recruiting biodiversity gains through ecological restoration and/or by averted losses (Box 1) has been questioned, due to the limits, uncertainties, and inherent time lags associated with both restoration and the accrual of averted losses.[7,11,23,24] In addition, the current institutional capacity to deliver and maintain gains has been questioned due to limited evidence on offset effectiveness.[4,25]

Best practice guidelines for biodiversity offsetting specify that offset gains need to be maintained until the authorized impacts on biodiversity cease, and preferably in perpetuity.[12,15] Thus, the retention of biodiversity gains over the long term is a critical aspect of offsetting as developments generating offsets often create long-term and irreversible loss of biodiversity. The capacity to retain gains over the long term is therefore a fundamental requirement for offset schemes to deliver on the promise of NNL. Yet, this temporal commitment inevitably stumbles due to the fact that Western institutions are structurally blind to long-term concerns,[26,27] being constructed to consider time frames of no more than few decades, and often much shorter periods based on policy cycles.

In this perspective, we investigate key challenges associated with ensuring the recruitment and retention of offset biodiversity gains over long periods of time. Using an interdisciplinary lens that draws from both natural and critical social sciences, we examine these challenges by (1) presenting key relevant concepts underpinning biodiversity offsetting, (2) clarifying the time frames involved in recruiting and retaining offset gains, (3) presenting some of the key approaches currently promoted and/or implemented to recruit and retain biodiversity gains "over the long term," and (4) critically reviewing these approaches and proposing pathways to move forward.

Box 1. Glossary of key concepts used in the offset and social sciences literatures

Additionality: all recruited gains should not have occurred in the absence of the offset project and are fully additional to the expected scenario without the offset.[4]
Anthropocene: a proposed new geological epoch induced by the impacts of human activities on the Earth system since the industrial revolution of the late eighteenth century and accelerating since the 1950s; characterized by changes in major features of the system's structure and functioning, including the climate system, the water and nitrogen cycles, and biosphere degradation.[5,6] These changes are and will cause major shocks to the social-ecological systems that have thrived in the previous epoch, the Holocene.
Averted-loss or avoided-loss offsets: offsets aiming to prevent future biodiversity loss via actions, such as the protection of existing biodiversity that mitigate threatening processes that would otherwise cause the depletion or loss of biodiversity.[7]
Biocultural diversity: "the diversity of life in all of its manifestations—biological, cultural, and linguistic—that are interrelated (and likely coevolved) within a complex socio-ecological adaptive system."[8]
Biodiversity: "the variability among living organisms from all sources, including, inter alia, terrestrial, marine, and other aquatic ecosystems, and the ecological complexes of which they are part: this includes diversity within species, between species, and of ecosystems."[9]
Biodiversity surrogate: a representation of biodiversity. Surrogate metrics are often promoted to measure and account for biodiversity losses, recruited gains, and their equivalence.[4,10]
Equivalence: when the measured losses and gains in biodiversity surrogates are the same in nature and magnitude.[11]
Like-for-like or better rule: the recruited gains benefit either the same biodiversity surrogate as impacted by the development, or benefit another surrogate considered of a higher value (e.g., more threatened) than the impacted one.[4,12]
Mitigation hierarchy: the mitigation hierarchy is a series of four steps to be followed during the life cycle of a project impacting biodiversity: avoid, minimize, remediate, and offset residual impacts. It is to be deployed when the options of renouncing to the project or selecting alternatives have been disregarded.[2,12,13]
No net loss (NNL) or net gain: objective of the mitigation hierarchy and its offsetting step. The frame of reference against which NNL is to be evaluated (i.e., the counterfactual) should be specified to avoid unreasonable expectations in the actual achievements of the NNL objective.[2,14]
Offset project: set of offset measures that ensure that residual impacts, if any, are compensated by equivalent gains. Gains are usually accrued after the permit has been granted, unless gains are accrued in anticipation of future losses via "banking."[15]
Polluter-pays principle: principle founded in welfare economics, proposing to internalize negative externalities induced by damaging activities into the market, via monetary compensations (taxes) set at the level of the lost values. The expression "polluter-restores," not commonly used, better reflects the transposition of the principle to biodiversity offsetting, where preferred compensations take the shape of restoration-related activities rather than monetary compensations.[16]
Regulatory offsets: offsets that are deployed for projects with significant impacts on biodiversity-related matters, as part of permit conditions under conservation-related regulations; for examples, see Sundseth and Wegefelt,[17] the Australian Government,[18] and the US EPA.[19]
Resilience: "the capacity to persist in the face of change, to continue to develop with ever changing environments."[20]
Voluntary offsets: offsets that are not prescribed by law and deployed on a case-by-case basis, following a voluntary initiative of a party impacting biodiversity.[21]

KEY CONCEPTS OF OFFSETTING

Best practice suggests that offsets should follow the "like-for-like or better" rule and meet the "additionality" requirement (Box 1). In practice, offsetting uses biodiversity surrogates to measure losses and gains because the full set of components and processes that make up "biodiversity" cannot never be practically measured (Box 1). Different biodiversity surrogates (and their metrics) capture different aspects of biodiversity, ranging from utilitarian valuations to more ecocentric ones that attempt to capture ecological function or the maintenance of individual species.[28] In practice, surrogates used in regulatory offsets are often based on the components of biodiversity protected under conservation-related legislation, and are reflected in simple metrics, such as acres of suitable habitat for threatened species (e.g., US Endangered Species Act and French compensatory practices[29]) or habitat hectares of native vegetation (Planning and Environment Act 1970 in VIC, Australia).[30] The choice of surrogate has strong implications for the implementation of offset schemes; for example, the more ecologically complex a surrogate is, the more difficult it is to find an equivalent (like-for-like) biodiversity offset.[28]

In the offset literature, two phases are commonly differentiated for reaching an NNL, measured through the relevant biodiversity surrogate. In the first phase, gains are recruited through initial on-ground management actions and, in best practice standards, the legal and physical protection of offset sites. Depending on the contextual conservation challenges (e.g., background trends, surrogates being offset, and legal obligations), gains are progressively accrued over time via three different strategies which we label A–C: approach A—the establishment of an ecosystem or ecological community in a location where it did not exist previously, an approach commonly used in wetland mitigation;[31,32] approach B—the ecological restoration of degraded sites to their former ecological composition and function;[11] or approach C—averted (or avoided) loss, the removal of

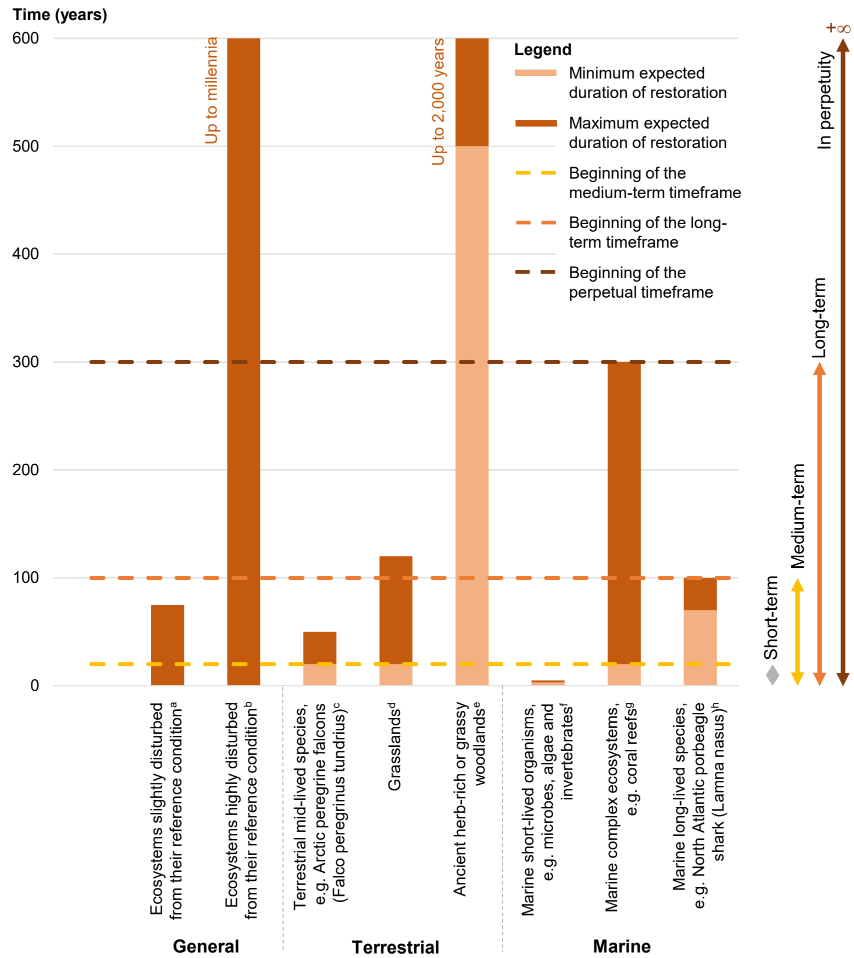

Figure 1. Examples of restoration and recovery time frames for ecosystems and species populations

The indicated time frames are the ones we propose based on the restoration literature (see Tables S1 and S4 for references). Ecosystem restoration and species population recovery and survival depend on the starting system state, reference condition, multiple social-ecological factors that are interconnected, and the influence of stochastic environmental events, including human-induced climate change (see Table S4 for the references). [a]Potential full recovery within a human lifetime, with a global average life expectancy of 75 years; recovery depending upon availability of propagules and appropriate landscape-scale ecological processes. [b]Reach millennia; probably not restorable but will likely form novel ecosystems. [c]Dependent upon, for example, population density, habitat quality, and climate. [d]Dependent upon, for example, nutrient loading, soil structure, and availability of propagules. [e]Dependent on soil chemistry, mycology, and availability of propagules. Restoration a possibility for plant assemblages but questionable for rarer invertebrates and vertebrates. [f]Dependent on amelioration of environmental stressors and availability of biological resources. [g]Dependent on appropriate marine biological conditions and protection from environmental stressors; for example, habitat destruction and coral bleaching. [h]Dependent on the implementation and enforcement of sustainable fishing practices, protection of habitat, and appropriate marine biological conditions.

threatening processes thereby avoiding declines in condition (e.g., averting weed invasion) or complete loss (e.g., avoiding land clearing).[7] Approach B may involve ecological management and/or the (re-)establishment of traditional land-use practices.[33,34] Despite limitations, approaches B and C remain the most common, and some offset policies combine them.[7,35]

The second phase starts once sufficient gains have been recruited. The objective of this phase is to retain accrued biodiversity gains until the impacts of the authorized project cease.[12,15] When moving to the retention phase, it is usually assumed that sufficient gains have accrued as measured by the biodiversity surrogate, and that the associated ecological components have become resilient and self-sustaining, with no (or minimal) human intervention, beside the continuation of traditional land-use practices when relevant.

Target-based offsets have been recently conceptualized as a way to better align project-level offsets with jurisdictional biodiversity targets.[36] This approach involves setting retention targets for given biodiversity features and specifying trajectories—"net gain," NNL, or "managed net loss"—based on the states of biodiversity features relative to their targets. The offset actions (comprising of approaches B and/or C) are then calculated such that, with development and offsetting continuing, retention targets will (theoretically) never be breached due to the amount of protection and/or improvement from offsets.[36] However, once calculated, offsets within this target-based approach still apply the same practices as current offset policies, and thus still face the same challenges regarding the recruitment and retention of biodiversity gains over long periods of time.

In both the gray and academic offset literature, the terms "long term" and "in perpetuity" are commonly used in reference to the duration of the retainment phase, but often without being precisely defined. It is thus critical to clarify the range of time frames implicitly assumed by these terms when applied to offsetting activities; a task to which we now turn.

DEFINING THE TIME FRAMES OF BIODIVERSITY OFFSETTING

Here, we propose definitions for short-, medium- and long-term time frames, based on ecological considerations (Figure 1). Our proposed definitions are based on restoration time frames obtained from a diverse set of biodiversity surrogates described in the restoration literature: short term (<20 years), medium term (20–100 years), and long term (100–300 years); we take in perpetuity to mean more than 300 years or "forever more" (for references, see Figure 1 and Table S1).

Using these restoration time frames (Figure 1), phase 1 (the recruitment phase) can range from a few decades through to beyond a century when recruiting equivalent gains for complex ecosystems and long-lived species. Conservation legislation remains biased toward long-lived vertebrates (especially mammals and birds),[37,38] as well as complex ecosystems and other biodiversity features that are in good condition, rare, and/or threatened.[39,40] Consequently, surrogates generated for like-for-like offsets based on these biodiversity features are likely to require medium- to long-term time frames if recruited through approach B (restoration), and even longer under approach A (establishment of ecosystems). As demonstrated by the restoration literature, there is large variability in the time frames needed for restoration of ecosystems and species (Figure 1, and references therein). These range from slow-growing, high conservation value ecological communities (e.g., old-growth forests and species-rich grasslands), to biodiversity surrogates that can be restored or established over shorter time scales, such as dynamic ecosystems comprising fast-recovering species that can adapt to multiple habitats or thrive in modified habitats (Figure 1). Best practice offset guidelines also encourage the use of complex surrogates that require medium- to long-term recruitment time frames due to the complexity of, for instance, "species composition, habitat structure, and ecosystem function and people's use and cultural values associated with biodiversity."[41] Regarding averted-loss offsets (approach C—the removal of threatening processes), if properly designed,[7] this strategy could potentially accrue gains slowly or rapidly, depending on the likelihood of occurrence of the averted threat and its potential impact.[42,43] However, little research has been done to estimate time frames for accruing gains due to averted-loss; therefore, we have relied solely on the restoration literature to define expected time frames.

These recruitment time frames bring ecological challenges. The recruitment of biodiversity gains for offsets involves working with a range of interconnected biophysical processes and functions, including nuanced species interactions that are variously subject to natural disturbance regimes overlaid with anthropogenic impacts, such as human-induced climate change and landscape transformation.[44–46] In combination with limited ecological restoration and re-establishment knowledge,[47,48] this results in significant uncertainties regarding both what biodiversity has been lost, and therefore what needs to be recruited, and whether recruitment attempts can deliver appropriate and equivalent biodiversity gains that can then be retained.[11,49] These uncertainties imply that biodiversity gains from offsets will often be unlikely to fully compensate for biodiversity losses from development.[11,49,50]

While the time frame of the recruitment phase (phase 1) depends on the biodiversity surrogate being offset and the actions being undertaken, the retention phase (phase 2) is bound by the duration of the impacts on biodiversity that generated the offset. In practice, many authorized impacts that trigger offsets are effectively permanent because of the type, duration, and magnitude of the disturbances they induce on biodiversity. The fact that only significant biodiversity impacts require a permit (and therefore offsets) to be legally authorized[9,17,18,19] means that most impacts requiring offsets are thus by definition "significant" impacts and likely to result in long-term or permanent losses. For these cases, phase 2 (the retention of biodiversity gains) then needs to cover time frames in the order of centuries to meet any practical definition of in perpetuity. This also explains the stated preference for the perpetual protection of offset gains in leading policies and offset standards.[12,51] There have been institutional innovations in Australia and the US in attempting to strengthen the long-term protection of offset gains,[32,52,53] and concerns have been expressed over the long-term protection of offset sites in Europe.[54,55]

LONG-TERM GOVERNANCE IN GUIDELINES AND POLICIES

Here, we briefly review the time horizons specified in leading offset policies and best practice literature, and the range of recommended institutional arrangements mentioned in these sources to recruit and retain biodiversity gains, for the long term or in perpetuity.

Duration of offset obligations

Best practice guidelines and leading offset policies, from the US, Australia, and within Europe, vary in the time frames used for the recruitment and retention phases of biodiversity gains (Table 1). They tend to associate the recruitment phase (phase 1) with a time span of 5–30 years, and the retention phase (phase 2) with a time span of 20–50 years, which is often framed as long term (Table 1). These time frames align with policy cycles and life cycles of major development projects (Figure 2), but only correspond to short- to medium-term ecological time frames (Figure 1). Therefore, they do not match the long-term ecological time frames required to recruit or retain gains for long-lived and complex biological features that trigger biodiversity offsets (Figure 1). Based on our review, there is currently little to no engagement with time horizons expanding beyond 50–100 years within existing offset policies or within the best practice literature. The exception is the reference to the in perpetuity concept in Common law, mainly in the US and Australia, although the efficacy of the mechanisms deployed to achieve this are not well understood and have limitations.[56,57]

In the next subparts, we expand on the existing and proposed mechanisms that the best practice literature has promoted to improve the recruitment and retainment of gains beyond a few decades. These mechanisms are also listed in Table 2, columns 1 and 2.

Legally securing the gains

Three legal instruments have been proposed to protect the biodiversity gains on offset sites from incompatible land uses over time (Table 2, "legally securing the gains"). Without these legal instruments, the offset measures to recruit and retain gains are solely bound to the permit conditions of the development project and associated contractual obligations, and thus, are at risk of lapsing once the project's contract ends. The proposed legal mechanisms rely mainly on offsetting experiences from the US and Australia (Table 2, "legally securing the gains") and include: (1) the transfer of land ownership rights to the state, to transform an offset site into a publicly accessible conservation reserve, preferably associated with a land stewardship agreement that supports appropriate management practices; (2) the transfer of land to a conservation organization associated with deed restrictions; and (3) the use of conservation easements (US) or covenants (Australia) that protect biodiversity gains on private property, and facilitate any management and/or activity

Table 1. Summary of the specifications of temporal duration for offset recruitment and retention phases from leading offset policies and guides

Duration of the recruitment phase	Duration of "long-term" and/or the retention phase	Duration of perpetual retention
United States: wetland mitigation rules under the Clean Water Act		
Until the performance standards have been met and monitoring requirements have been fulfilled	the period following the recruitment phase; in practice, 10- to 50-year time frame; alterations to compensatory mitigation projects permitted on public land in case of incompatible uses, if provision of alternative compensatory mitigation	forever (easements in some states); legal discussions regarding the perpetual nature of easements
Australia (federal): EPBC Act offset policy		
Case-by-case approach	for at least the full duration of the impact; impact on federal offset sites permitted if provision of a new offset package	N/A
Australia (Victoria): private land offsets		
10 years	beyond 10 years	forever (covenants applied in perpetuity, yet subject to mineral exploration and mining exemptions)
Australia (New South Wales): on-title biodiversity stewardship agreement		
20 years (can be extended)	beyond 20 years	forever (deeds applied in perpetuity)
France: first- and third-party offsets		
Case-by-case approach; for infrastructure projects, the duration of the concession contractually determines the maximum duration of the offset obligations (25–30 years); third-party offsets: agri-environmental schemes usually renewed every 5 years, with longer contracts being discussed	legally, as long as the impacts remain; in practice for infrastructure projects, bound by contractual offset obligations, unless the site is granted some form of public conservation protection, or benefits from an environmental real obligation on private land (99 years maximum)	perpetual contractual engagements prohibited by law
France: first four pilot supply offsets (compensatory natural sites)		
30 years (active management)	no contractual obligations for active restoration, yet various solutions proposed to pursue the ecological objectives of the sites beyond 30 years	N/A
Germany: compensation pools		
25–30 years (active management, under the responsibility of those who caused the damage)	the period following the active management phase	ideally should permanently protect sites and measures
UK DEFRA leading Pilot Offset projects (Essex and CSWAPO)		
N/A	20–25 years (long-term management)	no definition (Essex) or "a minimum of 30 years" (CSWAPO)
The European REMEDE Toolkit		
N/A	N/A	50–75 years
The World Bank's biodiversity offsets user guide		
Case-by-case basis, with the proponent supporting the up-front investment costs of the offset site	at least the operating life of the original project and ideally longer, with the proponent responsible for the first few years of the recurrent offset costs only	forever (funded via public conservation funding, philanthropy, or other non-additional funding)

In many jurisdictions, diverse types of offsets and offset mechanisms may be deployed within an offset scheme. Here, we only report the cases where offset schemes or some of their mechanisms specify or imply specific temporal durations for offset recruitment and retention. Many schemes tend to conflate the long-term with the retention phase, with limited specification of what long-term means. See Table S2 for references.

restrictions in perpetuity, meaning legally (in Common law) and literally forever.[56,57] Yet, perpetual protection may not be always perpetual in practice. There may be significant resourcing shortfalls, arrangements may be subject to exemptions, and management and monitoring may be non-existent in practice, and non-compliance can go undetected[53,57,58] (Table 1). The feasibility of

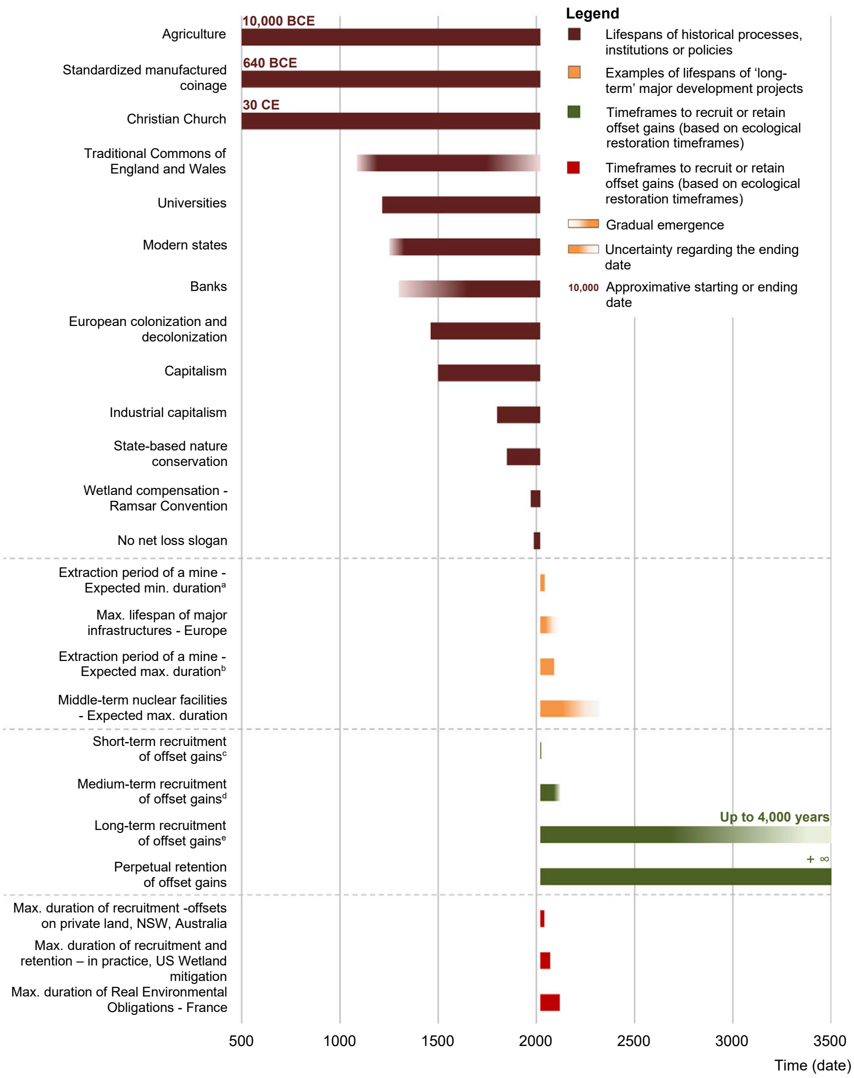

Figure 2. A comparison of time frames to recruit and retain gains with historical lifespans of Western institutions, and the expected lifespans of development activities and offset policies

See Table S5 for the numerical details and references. [a]Minimum duration of the expected extraction period of a metallurgical coal mine, corresponding to the shortest expected duration across included commodities as of 2012. [b]Maximum duration of the expected extraction period of a copper mine, corresponding to the longest expected duration across included commodities as of 2012. [c]The time frame presented being the establishment of ecosystems with fast growing species, such as eutrophic ponds. [d]The time frame presented being the restoration of ecosystems with fast and slow-growing species, such as heathlands. [e]The time frame presented being the restoration of highly degraded ecosystems dominated by slow-growing woody species, such as ancient woodlands.

long term and in perpetuity protection of offset sites also depends on the legal and customary norms regarding property rights, contractual obligations, and land management in different jurisdictions. For example, France, a Civil law country where perpetual contractual engagements are illegal,[59] has introduced Environmental Real Obligations that, once established, can bind and guide private landholders in their land-use practices for a maximum of 99 years (Table 1). Yet, these time frames may discourage landholders from engaging with offset service provisions, notably farmers given their constraints and usual reliance on short-term contracts.[60]

Ensuring effective management

Two approaches have been proposed to recruit and retain gains: offset management services and the funding of land-use transitions (Table 2, "ensuring an effective and efficient adaptive management"). In the first approach, offset service providers are paid to manage the sites to recruit the gains over a specific time period and, when relevant, continue some level of management to retain gains as long as required (e.g., long-term weed control). This is currently the most common approach embedded in leading offset policies in the US, Australia, and within Europe, where ecological consulting companies, offset "banks," private landholders, and/or the state (for example, in the case of public-land offsets) are empowered as offset service providers. Best practice literature has promoted adaptive management based on Western ecological knowledge, with plans that include performance standards and targets. More recently, in some contexts, such as Canada, traditional or Indigenous land management practices that benefit biodiversity have also become a possible form of offset services.[34] In both cases, the literature recommends to secure management practices via various management contracts or obligations, ideally included in a covenant/easement for private land, or via stewardship agreements for public land.

The second approach proposes to invest in land-use transition as a form of offset. For example, Investment Payments for Ecosystem Services have been proposed in Europe to support farmers transitioning to organic agriculture, inspired by traditional land uses that enhance biodiversity.[33] In contrast to the first approach, payments cease once the transition is complete. For farmers targeted by this approach in Europe, the costs of retaining gains then become part of the farm's ongoing business model.[33]

In both approaches, ongoing independent monitoring, evaluation, auditing, and reporting of offset gains are recommended.[4,15] Best practice literature encourages ecologists, conservation scientists, or public authorities to conduct this evaluation and provide support to offset service providers, including expertise and research. It is also argued that offset-related data should be transparent and made available on publicly accessible offset registers to improve assessment, inform public debates, ensure accountability, and enable public

Table 2. A review of the legal and institutional mechanisms used or proposed to recruit and retain offset gains based on long-term governance needs, and their identified long-term challenges

Land security	Recruitment and retention of gains	Identified long-term risks and challenges
Legally securing the gains		
• Maintaining accessible land registry records • Building social acceptability of the offset sites at the landscape level	N/A	state and civil society: costs of developing long-term institutional resilience and manage land-use conflicts, costs of offset archives and of preserving the collective memory of the sites[a]
On public land		
Binding agreements integrating offset sites to networks of publicly protected zones	land stewardship agreements with public authorities	• possibly porous boundaries between conservation and offset activities[a] • legal limitations of setting up binding contracts beyond a few decades in some jurisdictions • state: cost of reviewing and approving contracts[a]
On private land		
Covenant/perpetual conservation easement or transfer to biodiversity conservation organization with deeds restricting land uses	• inclusion of management obligation in covenants, deeds, easement, and offset services contracts • management as part of the business model for Investment ipayments for ecosystem services	• possibly porous boundaries between conservation and offset activities[a] • legal limitations of setting up binding contracts beyond a few decades in some jurisdictions • state: cost of reviewing and approving contracts[a]
Ensuring an effective and efficient adaptive management		
Ongoing adaptive management		
N/A	• long-term adaptive management plans with performance standards and targets and/or continuation of traditional land-use practices • scientific support • public access to data	• state: costs of reviewing and approving, management plans, and of making the documentation publicly available[a] • state, research bodies, and/or civil society: costs of providing support and producing scientific knowledge[a] • long-term ecological uncertainties
Monitoring on-ground practices		
N/A	• mandatory reporting • independent monitoring and evaluation • public access to data	state, research bodies, and/or civil society: costs of evaluating management, of publishing evaluations, and of legal pursuits[a]
Securing payments for services		
Securing the capital		
N/A	• appropriate budget planning for management and monitoring • fund establishment: fund established by up-front payment (preferred) or incrementally (e.g., sinking funds or revenue transfers) • fund maintenance: participation in public, or private endowment fund	• state and civil society: costs of building the expertise that can estimate intergenerational offset budgets, and the long-term institutional safeguards against the capture of capital[a] • funds: risks of losing value through time, e.g., underestimate budget, investments in risky assets, economic or Anthropocene-related shocks

(*Continued on next page*)

Table 2. *Continued*

Land security	Recruitment and retention of gains	Identified long-term risks and challenges
Securing safeguards for unexpected changes and guarantees against risks of financial or ecological failures		
Dynamic conservation easements	• multipliers (covering time lags and uncertainties) • financial surety instruments against failures of the proponent (e.g., per formance bond, surety bond, insurance bond, bank guarantees) • financial surety instruments against financial or ecological failures of the offset project (e.g., adaptable insurance schemes, insurance pools)	• Anthropocene-related uncertainties: failure of the surety providers, uncertain legal liabilities of retaining gains, reluctance of insurances to cover long-term environmental risks; • state: costs of establishing institutional safeguards against the instrumentalization of dynamic conservation easements[a]
Monitoring financial budgets, safeguards, and guarantees		
N/A	• fund management: independent, irrevocable, and accredited trust funds or public agencies • reporting and monitoring of investment policy, of management budget plans, and of financial surety • dedicated resources for legal defense or participation to a legal defense fund	state and civil society: cost of reviewing and monitoring financial reporting and of legal pursuits[a]

Columns 1 and 2 summarize the propositions made in the academic and gray literature devoted to offset best practices (see Table S3 for references). Many of these propositions are inspired by the experience of offsetting in common law countries and may not suit in countries with other systems of law. We did not report the propositions that violate the additionality principle in these columns. Column 3 lists the long-term risks and challenges that we have identified as overlooked while reviewing the literature.

[a]This would breach the additionality principle if conservation and offset activities are not properly differentiated and sufficiently funded.

scrutiny.[4,12,61] In practice, only a minority of countries and states have adopted consistent publicly accessible offset registers.[62,63] Little to no formal monitoring and evaluation of offsets are currently being deployed as part of offset schemes, leading to a limited evidence base for determining the efficacy of existing offset schemes.[25]

Securing payments for offset services

Legally securing gains from offsetting and ensuring appropriate ongoing management and monitoring requires secure funding over decades, and potentially more than a century, if ecological restoration time frames are considered (Table 2, "securing payments for services"). Without secure offset funding, the longer-term costs are effectively externalized onto landholders, public and private conservation organizations, and future generations. This potentially results in crowding-out effects due to blurred boundaries between offsetting activities (intended to compensate for losses) and public or private conservation activities (intended to deliver gains).[64] This could discourage voluntary conservation efforts or, more critically, undermine the additionality of offset gains, and therefore reduce the ability of offset schemes to deliver NNL of biodiversity over the long term.[64,65]

Inspired by existing policy mechanisms, and experiences from mine closures and long-term pollution management, the best practice literature has focused on better anticipating these costs, mainly through promoting Trust Funds. Some have argued that Trust Funds should be independent and accredited, to properly track the allocation of offset funds (accountability) and avoid cost shifting, i.e., the use of offsetting funds to displace funding for conservation or other activities.[4,66] Others have recommended sufficient initial investments to create Endowment Funds, which potentially generate income as long as the stock market functions.[55,67]

Best practice reports also recommended financial surety instruments as safeguards for unexpected changes and guarantees against risks of financial or ecological failure, notably in Europe[55] (Table 2, "securing payments for services"). Among them, environmental insurance tools are already applied to manage mining pollution risks; yet they remain relatively new, are less regulated than other types of insurance, and might be limited for projects expanding beyond 10 years.[68] The peer-reviewed literature also promotes the use of multipliers to manage risks, notably regarding socio-political uncertainties, time lags, and additionality.[69–71] Importantly, strong legal structures of checks and balances to control financial budgets, safeguards, and guarantees have been recommended, including resources dedicated to legal defense and detailed financial reporting and monitoring, in addition to independent accredited Trust Funds (Table 2, "securing payments for services").

In practice, the costs of recruiting and retaining offset gains remain underestimated, even for short-term time frames.[4,54] For example, in VIC, Australia, the planned budget for the recruitment of offset gains covers a 10-year management period,[72] following which offset management activities fall back on pre-existing resources. A few countries and states have introduced mechanisms to secure funding for initial management costs, as well as, in some cases, some retention costs "for the long term." This includes the mandatory financial backing of "compensatory pools" (mitigation banks) in Germany for a minimum of 25–30 years,[73] endowment and maintenance funds for mitigation banks in the US,[32] or the Biodiversity Conservation Trust in NSW, Australia, which has set up a Biodiversity Stewardship Payment Fund aiming to provide an in perpetuity funding source.[52,74]

CRITICAL REVIEW AND PATHWAYS TO MOVE FORWARD

After identifying the approaches currently proposed and/or implemented for accruing and retaining biodiversity gains over "long" time frames, we now undertake a critical review of these propositions. In this section we first present the political imaginary that these approaches are derived from and perpetuate. We then discuss the implications of this imaginary. Each subsection below starts by identifying the major omissions and shortfalls from these approaches—and the imaginary they convey—and then ends by discussing potential ways forward.

Most of the proposed long-term biodiversity offset mechanisms apply a weak ecological modernist political imaginary to the realm of biodiversity offsetting.[3,75,76] The narratives of weak ecological modernization promote technocratic approaches (technology, markets, and management) as solutions to decouple the economy from its environmental impacts.[3,75,76] They struggle to engage with ecological limits and socio-political complexities, including deliberative democracy and the diversity of place-based bonds between local communities and the biosphere.[3,75,76]

Similarly, existing offset schemes and much of the best practice offset literature implicitly assumes that development can be decoupled from its biodiversity impact via technocratic approaches. They conceptualize biodiversity as gains that are assumed to be able to be produced over the long term by offset service markets or investments, retained on bounded offset sites and monitored by private entities, the state, and their experts. In doing so, they fail to engage with the ecological complexity and socio-political implications of this "production" (Table 2, column 3).

The polluter-pays principle and intergenerational costs

Omission

The best practice literature omits the long-term retention and governance costs needed for effective offsets. Consequently, these costs are imposed on conservation organizations, the state, research centers, and civil society.

One challenge for biodiversity offsetting is to ensure that the polluter pays the full cost of repairing the damage they cause. In the offset context this means internalizing the costs of both recruiting and retaining biodiversity gains, often over the long term. Yet, the World Bank's best practice offset guide highlights that "many developers … are only willing to support the up-front investment costs of the offset area (and maybe the first few years of recurrent costs), but not all the recurrent costs in perpetuity";[67] and thus advises that conservation resources should be relied upon for the long-term retention of gains.[67] Reliance on conservation-related institutions to pursue the ecological objectives of offset sites beyond a few decades is currently widespread (Table 1). This inevitably breaches the additionality principle (Box 1) by diverting future resources from conservation activities to the long-term retention of offset gains that, at best, have a net neutral impact on biodiversity when losses from development that generate the offsets are properly accounted for.

Furthermore, while best practice guidelines indicate that polluters should cover the long-term on-ground management and monitoring costs (Table 2, column 2), they do not engage with the governance costs that the proposed mechanisms impose on public authorities and civil society (Table 2, column 3). Institutionalizing best practice mechanisms effectively requires significant additional resources for factors, such as the controls, research, and stewardship building required by these mechanisms (Table 2, column 3). This also risks diverting resources away from conservation, as is already observed in some countries.[77]

The nuclear sector can act as a template for estimating the costs of long-term retention and some elements of the governance of offsets. For example, the nuclear industry already includes control costs and investments in research and technology in its estimation of the long-term waste management costs, to be paid by nuclear waste producers in some contexts.[78] Taxes on nuclear facility installation have also been used to fund additional research and studies in France;[79] and fees have already been introduced in Sweden to cover the costs of historical nuclear waste production.[80] Various institutional arrangements exist in leading countries to ensure that nuclear polluters contribute to covering the funding of public agencies, trusts, or companies dedicated to long-term management of nuclear waste.[79–81]

Making the polluter pay remains both a technical and governance challenge in both nuclear and extractive sectors. Costs can be underestimated when setting up the payment mechanisms due to a lack of knowledge regarding the actual long-term costs,[82] long-term economic or regulatory uncertainties,[68] or poor environmental governance and regulations.[83,84] Nevertheless, payments can be readjusted across time to correct past misestimates.[80] Importantly, initial investments or regular payments can also be disputed or purposely underestimated when both the proponent and public authorities embody a preference for the present and refuse to adopt costs, payments, or long-term financial assurances that would question the financial feasibility of a development project.[68,79]

Ways forward

Investments that are robustly additional to current conservation efforts are required to expand the control, research, and stewardship capacities of the state and civil society. These investments could be internalized in the costs of biodiversity offsetting, by potentially adapting methods and mechanisms already applied in other long-term sectors (e.g., nuclear and extractive activities). For target-based offsets, compensation ratios—proposed for some economic sectors to contribute toward biodiversity targets on top of compensating for a given project[36]—could also be used to recover the costs of historical impacts on biodiversity, or to correct past misestimations. Structural governance changes are needed to overcome the preferences for the present that undermine the polluter-pays principle. Appropriately pricing offsets with long-term costs and financial assurances would serve as a price signal to indicate that development projects that cause irreversible biodiversity loss and intergenerational injustices are too high a cost to be approved. Internalizing the long-term consequences of present-day decisions could enable a greater emphasis on project renouncement, considering alternatives, and enacting the avoidance step of the mitigation hierarchy.

Grappling with dynamic ecosystems in the Anthropocene

Omission

By conceptualizing biodiversity as a fixed entity that can accrue gains, current best practice approaches to offsetting do not engage with the dynamic dimension of ecosystems over the long term, nor the ecological and legal implications of the Anthropocene (Box 1).

Ecosystems are dynamic and subject to natural (e.g., speciation) and human-induced environmental change that can result in systems that comprise ecological novelty with no historical analogue.[85] The ecological time frames involved, coupled with the Anthropocene, bring into question the capacity to recruit and retain equivalent gains because of possible major shocks from extreme climate events and other landscape changes caused by human-induced climate change, or the direct anthropogenic drivers of biodiversity depletion. Therefore, while the objective of offset sites is to achieve NNL of specific species or ecological communities, this may not be ecologically feasible. Over longer time frames—particularly in view of the effects from anthropogenic climate change—recruited biodiversity gains on offset sites may no longer be directly comparable to the surrogate and corresponding ecosystem type that were lost, potentially becoming a hybrid or novel ecosystem.[85,86]

These ecological uncertainties have legal implications that may undermine the institutional capacity to secure compliance. Landscape changes may threaten the legal liabilities of service providers to recruit or retain accrued gains. While insurances are proposed to mitigate liability risks (Table 2, "securing payments for services"), some of the risks of failure may become uninsurable due to climate change and the increase in frequency of extreme weather events (for a discussion on possible consequences of climate change on insurances in general, see Wouter Botzen[87] and the Reserve Bank of Australia[88]). In the US, some have proposed more flexible legal arrangements, such as applying the Charitable trust principles to perpetual conservation easements[89] or establishing dynamic conservation easements to secure new offset sites if values on the original offset sites have degraded.[90]

Ways forward

The best practice literature needs to better engage with the dynamic dimensions of recruited gains. For example, the potential effects of anthropogenic climate change need to be addressed at the forefront of discussions on offset projects and their management plans, not as an afterthought. In addition, further ecological research is needed to clarify within which time frames, and under which conditions, biodiversity surrogates legally subject to offsetting in different jurisdictions can be recruited and retained over time, considering the ecological uncertainties imposed by climate change, and more broadly, the Anthropocene. This research could help assess the feasibility of reaching NNL for different surrogates and clarify which projects would likely result in a net loss of biodiversity, despite offset efforts. Further research is also needed in different jurisdictions to clarify the legal liabilities of offset service providers in rapidly changing landscapes. While some more flexible arrangements might be promoted to engage with long-term ecological uncertainties, strong institutional safeguards need to be built to avoid their instrumentalization for short-term land-use interests. For long-term or permanent offsets, collective reflections are also needed regarding how offset sites can support the dynamic and varying processes of biodiversity.

Governing for the long term in the Anthropocene

Omission

Current offset schemes and best practice guidelines are shaped by and for current Western politico-economic systems. They struggle to consider time horizons beyond 50–100 years and consequently are ill-prepared for the institutional implications of governing offset gains for the long term.

Current Western politico-economic systems, including capitalist economies and modern representative democracies, are not structured to consider the consequences of present-day decisions on the long-term future (over one or more centuries).[26] More fundamentally, modern liberal democracies, born in Europe, have constructed themselves through the rejection of European traditions and the idea that the present should be sacrificed for future salvation.[27]

Blind to long-term concerns, they are structurally driven by cultural, economic, and political stochastic changes, responding to financial time frames, political cycles, and planning forecasting that vary from the very short term (a few months to a few years) to the short term (up to 20 years), from an ecological standpoint (Figure 1). This preference for the present is embodied, for example, in the continuous extension of temporary storage for high-level radioactive waste resulting from the operation of commercial nuclear power plants in many countries since the 1950s, and the absence of countries with an operating deep geological disposal facility, albeit the recent progress in Finland and Sweden.[82,91] Biodiversity conservation has also been shaped by these institutional time frames. Long-term research and on-ground restoration projects rarely expand beyond 10–15 years.[92–94] It is thus not surprising to find similar institutional time frames in current offset policies and guidelines (Table 1; see also Figure 2, rows 14–24, for a few examples).

Ecological time frames necessary to recruit and retain biodiversity gains for some complex offset surrogates reach the time frames of historical periods or potentially even civilizations, if they are to account for permanent loss of some components of biodiversity (Figure 2). Furthermore, it is likely that the Western politico-economic systems and their key institutions (i.e., markets, the state, and expert bodies) will experience significant transformations or even disappear within the time frames required to recruit or retain these complex offset gains. Human institutions are not static entities—they emerge, evolve, merge, and disappear. The Western institutions that gave birth to the current Western politico-economic systems (Figure 2, rows 3–11) are relatively young from an ecological perspective. Other institutions are older—many Indigenous and traditional cultures across the globe have long-established and resilient institutions, some of which have successfully protected sacred natural sites and sustainably governed common-pool natural resources for centuries, and in some cases, for millennia.[95–100] Yet, these institutions often continue to be disregarded, marginalized, or undermined by Western formal institutions, and the field of conservation.[99–103]

Institutional changes are also likely to accelerate with the unfolding of anthropogenic environmental shocks (such as severe anthropogenic climate events or biosphere disruptions) as societies are forced to undertake transformative institutional changes or experience major unpredictable instabilities in existing social-ecological systems.[104–106] Such changes have already been observed: some institutions are adapting,[99] new forms of governance and institutions are emerging,[107] and new informal, collaborative actions are being deployed outside formal Western institutions.[108]

Despite this changing long-term context, the offset literature proposes mechanisms that are highly reliant on current formal Western institutions, implicitly assuming the future stability of these relatively young institutions over the long term. We argue that this assumption is unreasonable for long-term and perpetual offsets and might also become unreasonable under shorter time frames because of accelerating instabilities due to the Anthropocene. For example, severe economic recessions can consume the principle of secured funds.[68] More extreme shocks (due to, for example, severe climatic events, global pandemics, or wars) may also threaten the capacity of the modern state or markets to function, and even the potential collapse of Western global civilization is currently being debated.[109,110]

Ways forward

Supporting changes in offset policies that incorporate multidecadal and century-plus time frames would be a step forward. Yet, solely relying on short-lived Western institutions to secure the long-term governance of offset gains remains risky. In our view, the offset literature, policies, and practitioners could better engage in how to improve the resilience (Box 1) of offset-related institutions. Genuine, rather than instrumental, discussions between formal offset-related institutions and long-lived, resilient Indigenous and traditional governance systems could contribute to facilitating the long-term recruitment and retention of biodiversity gains. For example, offsets could be integrated into existing long-lived Indigenous and traditional social-ecological institutions. However, care needs to be taken to ensure that the additionality and polluter-pays principles are maintained, and that offsets do not destabilize these complex institutions. In addition, deeper structural reforms are required for long-term concerns and long-term governance to be considered in formal Western institutions, democratic debates, and deliberations across scales, notably when planning and development proposals are discussed (for propositions, see Rosanvallon,[27] Bourg,[111] and Takacs[112]). In many contexts, engaging with Indigenous and traditional norms, knowledge systems, institutions, and land rights claims should be essential in these structural transformations.[99,102,103]

The socio-political dimension of offset governance

Omission

Relatively few sources in the offset literature have grappled with the socio-political complexities of governing offset gains. Considerations discussed in the literature solely include how to better engage stakeholders in the offsetting process, "building acceptance" and maintaining good relationships with properties surrounding offset sites.[12,53,113]

The imaginary embedded in offset best practice literature risks repeating some of the past mistakes of the conservation field, which historically framed nature as "wild" objects that could be locked in bounded parks, placed under the control of experts and away from local communities.[114] Despite progress, the conservation field continues to struggle with engaging the human dimension of conservation—notably with formal, informal, and customary rules, social practices, power dynamics, forms of knowledge, values, place-based social-ecological relations, and complex politics across scales.[107,115,116] Similar struggles were observed in the offset literature. Yet, these socio-political dimensions are yet to be seriously addressed. For example, human conflicts over land use and access to natural resources are affecting biodiversity and its conservation;[117] protected areas, while promoted as the strongest form of protection over the long term,[118] have seen their protection status being degraded in some contexts[119–121] and their achievements being affected by human activities in their surroundings.[122] Perpetual conservation easements have already been challenged under development pressures in the US.[56] It is to be expected that offset sites risk experiencing similar challenges that could, if not anticipated, lead to the loss of recruited gains.

Ways forward

Approaches to the governance of offset sites must be expanded to build in the long-term stewardship of offset gains and to prepare for potential future land-use conflicts. We encourage the field of offsetting to collaborate further with social scientists and the humanities, public authorities, Indigenous peoples, and civil societies to accelerate transfer of the lessons already learnt regarding social-ecological resilience, democratic deliberation, and conflict management. The many learnings within conservation (and beyond) that could be applied, include conflict resolution and collaborative governance,[117] common-pool resources management,[101,123] stewardship,[124] values,[125,126] justice,[127] ecological democracy,[112] partnerships between different knowledge systems,[103] and biocultural diversity.[8] The use of deliberative platforms could enable communities and societies to explicitly discuss and refine the knowledges, actors, and institutional rules to be deployed to retain the recruited offset gains. This could help societies anchor the offset sites within their social-ecological landscapes and institutions, manage conflicts between actors, and adapt to social-ecological changes across time. Importantly, efforts to build these platforms or adapt existing ones need to be additional (yet, potentially complementary) to conservation, with their costs being factored into the estimation of offset costs.

CONCLUSION

We present an analysis of biodiversity offsetting mechanisms proposed by the best practice literature, and in use by current offset schemes, to govern offset gains over long-term time frames. While current governance mechanisms are theoretically tailored for biodiversity gains to be recruited and retained over a few years to a maximum of a few decades, these time frames do not match most ecological time frames needed to reach NNL. In practice, many offsets are likely to require governance for over a century, and in some cases, millennia, to recruit and retain biodiversity gains that offset the equivalent (significant and often permanent) biodiversity losses. However, the time frames that current Western institutions operate under, on which offsets are based, cannot ensure the longevity of these institutions. Therefore, we recommend initiating a process of incorporating long-term considerations in offset policies and of building institutional safeguards to ensure that the polluter-pays principle is properly applied to offsetting; factoring in the long-term retention, governance, and stewardship costs into the payments to be paid by the polluters. Finally, we argue that offsetting should not be discursively sold by default as delivering NNL. In our view, current NNL approaches, at best, temporarily reduce permanent damage by making polluters partially accountable for their impacts and by providing clear targets to operationalize offsets in the short to medium term. At worst, current approaches to offsetting participate in a false promise, which distracts institutional efforts from much needed transformative change centered on renouncing impactful projects, considering a greater range of alternatives, and a greater emphasis on avoidance in the mitigation hierarchy.

EXPERIMENTAL PROCEDURES

Resource availability

Lead contact

Further information and requests for resources should be directed to the corresponding author, Florence L.P. Damiens (florence.damiens@rmit.edu.au).

Materials availability

All sources used in this Perspective are listed in the References or in the Supplemental information. All sources were publicly available at the time of the analysis; however, most academic publications are behind journal paywalls.

Data and code availability

All data and sources used to produce Tables 1 and 2 and Figures 1 and 2 are available in the Supplemental information. Figures 1 and 2 were generated in Excel and PowerPoint, Version 2011.

SUPPLEMENTAL INFORMATION

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AUTHOR CONTRIBUTIONS

Conceptualization, A.G., F.L.P.D., and A.B.; investigation and visualization, F.L.P.D.; writing – original draft, F.L.P.D.; writing – review & editing, F.L.P.D., A.G., and A.B.

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Quantifying peatland land use and CO_2 emissions in Irish raised bogs: mapping insights using Sentinel-2 data and Google Earth Engine

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Ireland has > 50% of the EU's ocean-raised bogs; however, degradation through land-use activities has transformed them from carbon (C) sinks to sources. Given their significant role in climate mitigation, it is essential to quantify the emissions resulting from land use degradation of these ecosystems. A seven-class land-use classification system for Irish peatlands (LUCIP) was developed and mapped using Sentinel-2 imagery, random forest machine learning and Google Earth Engine. The results revealed that agricultural grassland comprised 43% of the land use on raised bogs, followed by, forestry (21%), cutover (11%), cutaway (10%) remnant peatlands (13%), waterbodies and built-up ~ 1% each. The overall accuracy of the map was 89%. The map was used to estimate CO_2 emissions for four classes constituting 85% of raised bogs: cutover, cutaway, grassland, and forestry using the IPCC wetlands supplement and literature-based emission factors, we estimated emissions at ~ 1.92 (± 1.58–2.27 Mt CO_2-C-yr^{-1}) and ~ 0.68 Mt CO_2-C-yr^{-1} (± 0.44–0.91 Mt CO_2-C-yr^{-1}) respectively. This is the first study to spatially quantify land use and related emissions from raised bogs. The results have revealed widespread degradation of these globally rare habitats, making them net emitters of CO_2. The map is vital for the conservation of these ecosystems through restoration efforts, and the methodology can also be applied to other regions with similar peatland land use issues.

European peatlands cover approximately 60 million ha[1,2], and a substantial proportion of this has been degraded by unsustainable land use practices, such as agriculture, forestry, and peat extraction. Consequently, almost 44% can no longer accumulate peat[3]. Tanneberger et al.[4] indicated that degraded peatlands in the European Union (EU) represent half of the globally degraded peatlands. In Ireland, peatlands cover ~ 1.46 million ha (21% of Ireland) and consist of two types of bogs: blanket bogs (~ 900,000 ha) and the globally rare Oceanic raised bog (~ 530,000 ha)[5,6]. It is estimated that they store between 60 and 75% of the national Soil Organic Carbon (SOC) stock[7–9] but land use practices have led to the degradation of about 95% of these peatlands[6,10–13].

These land use activities harm the hydrological and ecological functioning of peatland ecosystems, turning them from a net sink to a source of C[14]. It also results in a consistently lowered water table, which accelerates peat decomposition, releases dissolved organic carbon (DOC) and particulate organic carbon (POC) and alters carbon and greenhouse gas (C and GHG) fluxes[15,16]. Hence, these ecosystems, which in their natural condition are significant C stores and are crucial to the prevention of natural disasters such as landslides, fires, and floods[17], become susceptible to them[18–20]. Despite this, Irish peatlands still contribute to various hydrological and ecological functions and cultural, and socio-economic values[6,21].

The land use practices on peatlands in Ireland are similar to those in Europe, including drainage for industrial and domestic peat extraction, agriculture (mostly grasslands), afforestation and infrastructure development (roads, wind farms, airports etc.)[12,22,23]. As a result, it is estimated that less than 1% of raised bogs in Ireland are actively forming peat as of 2017[24]. This is particularly due to the intensification of land use through industrial peat extraction, afforestation and agriculture, which is a relatively recent development (since the 1940s), but has caused more damage in a short period of time[22]. The establishment of Bord na Móna (BnM), a semi-state-owned

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company, in 1946 for industrial peat extraction had a notable impact on raised bogs. Approximately 90% of the BnM landholdings are situated on raised bogs, and the majority of those (~90%) have been drained and/or opened for peat extraction[62]. BnM ceased extraction activities in 2021[25], however, there are still several medium-sized companies engaged in industrial peat extraction, including Harte, Klasmann-Deilmann, Bulrush, Clover, Erin, and Westland, as well as ~30 other small producers[11,14]. Coillte, a semi-private afforestation company established in 1989, has afforested approximately 31,000 ha of raised bogs. The provision of grants through the Common Agricultural Policy (CAP) for the reclamation of raised bog edges for agriculture has also contributed to the intensification of land use in these ecosystems. However, spatially explicit data on the extent of these activities (especially non-BnM industrial activities) and domestic peat extraction activities is non-existent[26]. The absence of such data prevents accurate quantification of emissions from managed peatlands and hinders the formulation of effective conservation strategies.

As a signatory to the United Nations Framework Convention on Climate Change (UNFCCC), Ireland has an obligation to report and account for its GHG emissions and removals and meet its emission targets for Land Use, Land Use Change, and Forestry (LULUCF), including wetlands, as outlined in the EU's 2030 climate change framework[27]. Several studies have been conducted on Irish raised bogs at small spatial scales to gain insights into the effect of land use conversion activities on C and GHG dynamics, such as losses through land, atmospheric, and fluvial emissions[28,29]. These local-scale effects can have regional and global consequences; yet information on land use status and associated emissions from these ecosystems remains poorly understood at the national, regional, and global levels[30]. To propagate local-scale emission measurements to a national scale and accurately account for peatland emissions, spatially explicit information on peatland land use is essential[14,26]. Andersen et al.[31] emphasise the importance of land use/cover data in understanding degradation and restoration. However, national and global land-use/cover maps often exclude activities such as peat extraction, forest and abandoned peat extraction sites[4]. This makes these datasets inadequate for understanding degradation through land use, monitoring conservation activities (rehabilitation, restoration, and rewetting), and assessing C and GHG emission dynamics.

To report emissions from wetlands, the Intergovernmental Panel on Climate Change (IPCC) has proposed a system consisting of three tiers: Tier 1 (T1) includes default EF and is specifically for wetlands and Tier 2 (T2) EFs are country specific and based on the emission data from case studies. The Tier 3 (T3) EFs use more complex and dynamic models. The default T1 EFs are derived from limited data available from sites with different geographical, climatic, and ecological conditions. Ireland reports emissions from peatlands based on T1 EFs except for industrial peat extraction sites and forests on drained peatlands, where country-specific EF values are being used[32]. However, the reliance on coarse spatial resolution (25 ha) CORINE (Co-ordinated Information on the Environment) land cover data and non-spatially explicit information for reporting purposes make the national emission estimates less accurate. Given these limitations, it is essential to develop peatland-specific land use maps that can be used for more accurate upscaling of emissions from site to regional, national, and global scales using IPCC methods. Furthermore, these maps are vital for supporting conservation activities, sustainable land management practices, and policy-related decision making.

This study aims to map the much-needed spatial distribution of land use on raised bogs in Ireland and quantify the corresponding C and GHG emissions[5,33,34]. The spatial extent of raised bogs was based on the DIPMv2 (Derived Irish Peat Map version 2), which is the latest peatland extent map integrating data from multiple sources[5]. Spatially explicit information on land use can be obtained using remote sensing methods. However, the persistent cloud cover inherent to the temperate maritime climate of Ireland poses a challenge to the acquisition of frequent cloud-free optical remote sensing images[36]. Consequently, it is particularly difficult to map national-scale land cover and land use. Previous attempts to map land cover at a national scale in Ireland have encountered similar difficulties and full coverage has not been achieved[36–39]. Connolly[12] successfully mapped industrial, grassland and forestry on peatlands in Ireland, including raised bogs, but was unable to map domestic peat extraction, because of medium spatial resolution of the data (23 m) and cloud cover issues.

Google Earth Engine (GEE), a planetary-scale cloud computing platform[40], integrates freely available high-resolution satellite imagery such as Sentinel-2, as well as machine learning algorithms such as random forest. By leveraging a vast archive of satellite imagery and employing temporal mosaicking functions within GEE, it is possible to obtain cloud-free imagery with wall-to-wall coverage and use it to map land use in areas where cloud cover impedes optical remote sensing[41–43]. This approach was used in this study to obtain cloud-free imagery by mosaicking annual images acquired for three years i.e., from 1st January 2018 to 31st December 2020. As a result, the first national-scale land use map of raised bog with seven classes was developed. The classes were derived from the Land Use Classification of Irish Peatlands (LUCIP), which was developed for this study through discussions with various stakeholders including NPWS (National Parks and Wildlife Service), BnM, and an ecologist. The classes in LUCIP includes cutover, cutaway, grassland, forestry, remnant peatlands, water bodies, and built-up areas. The map enabled the assessment of the spatial extent of land use in raised bogs. It is further used to estimate CO_2 emissions using site-specific EFs from case studies in Ireland[26], which are then presented along with IPCC T1 EFs. This work will provide better insight into C dynamics at the site scale, with an emphasis on the importance of high-resolution maps for area estimation and country specific EFs.

Material and methods

Study area

The study area for this research was based on the spatial extent of raised bogs derived from the DIPMv2[5]. Raised bogs are predominantly situated in the midlands of Ireland and are a distinctive feature of this inland region. They cover ~530,000 ha of the surface area and constitute ~35% of the total peatland area in Ireland and 8% of the total land surface area. Irish raised bogs represent more than 50% of oceanic-raised bogs in the EU[35].

Satellite image data

Copernicus Sentinel-2-MSI (Multi-Spectral Instrument) optical remote sensing satellite images were used in this study and the images were acquired by Sentinel 2- A and B. The Sentinel-2 sensor has 13 spectral bands, 10 of which were used in this study: Red (R), Green (G), Blue (B), Near Infrared (NIR) and Narrow NIR, three of the Vegetation Red Edge, and two of the Short-Wave Infrared (SWIR)[44]. Table 1 shows the spectral and spatial resolutions of the bands used in this study. The RGB and NIR bands have a spatial resolution of 10 m while the rest were resampled from 20 to 10 m. The sensor has a swath width of 290 km[44].

GEE provides the Sentinel-2-MSI Level-2A (L2A) image archive dating back to March 2017. This study used the atmospherically corrected products:L2AS2_SR (Sentinel-2 Surface Reflectance). They are corrected for atmospheric, slope and adjacency effects. L2A processing is based on a two-step process i.e., (1) scene classification (SC), which is used to derive a pixel classification map for vegetation, snow, soil, cloud shadows and cloud and (2) Sentinel-2 Atmospheric Correction (S2AC) which is used to convert the Top of Atmosphere (TOA) reflectance to BOA (Bottom of Atmosphere) values. The S2AC process is based on the library for Radiative transfer (libRadtran) model[46,47]. It provides cloud, haze, and water removal methods. To enhance the classification process, the vegetation and water indices were calculated and included as additional bands. The Normalised Difference Vegetation Index (NDVI) with values ranging from 0.1 to 1 indicates the presence and health of vegetation[48] (Eq. 1), while the Normalised Difference Water Index (NDWI) with values ≥ 0.5 indicating the presence of open water[49] (Eq. 2).

$$NDVI = \frac{NIR - Red}{NIR + Red} \tag{1}$$

$$NDWI = \frac{NNIR - SWIR1}{NNIR + SWIR1} \tag{2}$$

Image classification methods

A remote sensing image classification-based approach was used in this study and implemented in GEE and ArcGIS Pro desktop version 2.7 (ArcPro from here onwards). The approach consisted of accessing, pre-processing, and classifying land use using LUCIP in GEE. Accuracy assessment was conducted using ArcPro. The imagery was accessed on a national scale and constrained to Irish-raised bogs using the DIPMv2. An overview of this process is shown in Fig. 1.

Image pre-processing

Despite the high temporal resolution (five days) of Sentinel-2 (A and B), obtaining a cloud-free mosaic for wall-to-wall coverage of raised bogs in Ireland was challenging. To address this, it is important to develop an efficient cloud removal methodology. Accordingly, a temporal filter was applied to obtain imagery over three years (1st January 2018 – 31st December 2020). A selection criterion to obtain images with less than 10% cloud cover was also applied; a percentage greater than this would return cloud-contaminated images that were not useful for analysis. Based on these criteria, 1483 images were available. The remaining cloudy pixels were masked out using a cloud masking function (*masksS2clouds)* which is based on the 'QA60' quality flag band used for cloud and cirrus. Finally, the images were stacked together to generate a single cloud-free composite using the median (*ee.reducer*) composite function available in GEE. This also helped eliminate pixels with extreme values, thus removing the remaining artefacts. The final image was composed of pixels with minimal or no cloud cover.

Training sample data

The training and validation data used in this study were independent of each other. The training data was based on randomly generated sample polygons created within GEE for each land use class (Table 2). Validation sample points were generated using ArcPro. A classification schema (LUCIP) was developed to identify seven land-use

Bands	Central wavelength (µm)	Spatial resolution (m)
Band 2—Blue	0.490	10
Band 3—Green	0.560	10
Band 4—Red	0.665	10
Band 5—Vegetation red edge	0.705	20
Band 6—Vegetation red edge	0.740	20
Band 7—Vegetation red edge	0.783	20
Band 8—NIR	0.842	10
Band 8a—NNIR	0.865	20
Band 11—SWIR	1.610	20
Band 12—SWIR	2.190	20

Table 1. Characteristics of sentinel-2 bands[45].

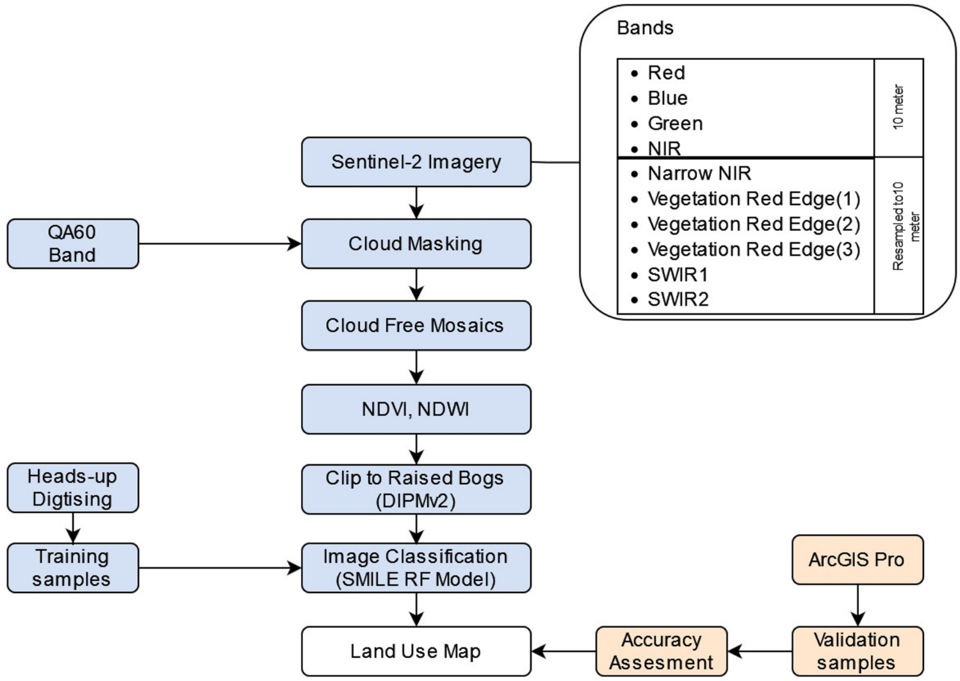

Figure 1. Data processing workflow. NIR (Near Infrared), SWIR (Shortwave Infrared), NDVI (Normalised Difference Vegetation Index), Normalised Difference Water Index (NDWI), QA60 (Quality Assessment) band for cloud and cirrus masking, and DIPMv2 (Derived Irish Peat Map version 2).

Land use class	Description
Cutaway	Land that has been subjected to industrial peat extraction, with the peat removed and/or left with a thin layer of soil, managed by BnM and other private companies with large-scale mechanised peat extraction.
Cutover	Land that has been subjected to domestic peat extraction, hand-cut, small-scale mechanised, includes bare peat, interspersed woodland, heath, and scrub.
Grassland	Agriculture grassland that is used for pasture or hay, silage, and grazing.
Forestry	Land covered with trees; afforested areas are mostly covered by evergreen tree species
Remnant Peatland	Land that has a high percentage of peat (near natural and high bog areas,) and is characterised by the presence of sphagnum mosses and other bog flora, not directly affected by human intervention. Revegetated areas of post-extraction activities.
Water bodies	Land covered with water, including natural waterways and surface water on raised bogs that have appeared after rewetting activities and/or abandonment.
Built-up/Infrastructure	Land used for human settlements and infrastructure, such as buildings, roads, windfarms etc.,

Table 2. Description of land use classes based on Land Use Classification for Irish Peatland (LUCIP) developed in this study.

classes: cutover, cutaway, grassland, forestry, remnant peatlands (high bog), and built-up/infrastructure areas (Table 2).

The collection of training data was based on the visual interpretation technique, which was used by an expert operator to generate randomly distributed sample polygons for each land use class[50]. The training data consisted of 366 polygons (148405 pixels) that were randomly distributed across the study area (Table 3).

The spectral signature of each land use class is shown in Fig. 2. The mean reflectance values across multiple Sentinel-2 bands demonstrate significant spectral separability in the visible and NIR range i.e., 0.49 to 0.78 µm. Notably, built-up areas exhibit high reflectance, whereas water has low reflectance, making them significantly distinguishable. Cutaway and grassland show high reflectance in the NIR region. Cutover and remnant peatlands, however, may exhibit some similarities, given that the cutover class includes dynamic vegetation environment. The spectral separability for most classes diminishes for longer wavelength bands, specifically at 1.61 and 2.19 µm. Nevertheless, differences in spectral reflectance between all the classes remain prominently discernible, underscoring the effectiveness of the sampling procedure employed for land use classification.

Land use class	No. of training polygons	No. of training pixels (sum per training polygon)	No. of validation points
Cutaway	37	94,672	197
Cutover	45	4345	130
Grassland	32	7320	660
Forestry	100	11,627	252
Remnant Peatland	62	28,038	121
Water bodies	64	1816	50
Built-up/Infrastructure	26	587	50
Total	366	148,405	1460

Table 3. Characteristics of randomly distributed training and validation sample data.

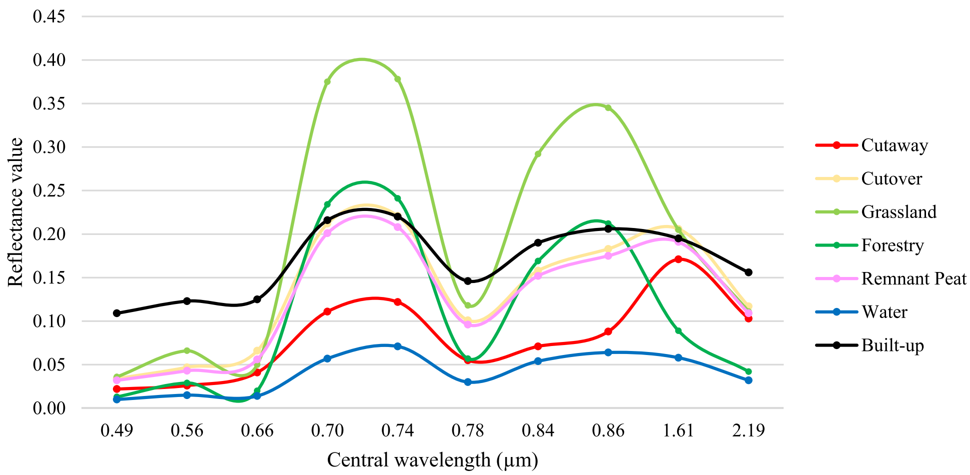

Figure 2. Spectral reflectance of the land use types across the ten spectral bands (Sentinel-2).

Classification of satellite imagery

The random forest classification model, an ensemble classifier[51,52], was trained using training data. The random forest algorithm is based on an ensemble of several decision trees, each with multiple nodes[51]. Classification was implemented using the GEE platform. A slightly improved version of the random forest model known as the Statistical Machine Intelligence and Learning Engine (SMILE) random forest algorithm was used in this study[53]. The classification model was trained using the training data, with the number of variables and number of trees being the two critical parameters. The optimal values of these parameters were determined using the square root of the number of features and trial-and-error method. Based on these procedures, the optimal number of trees was determined as 20. Each tree in the model consists of multiple nodes, and each pixel is assigned a label by each tree. The final label for each pixel is determined by aggregating the labels assigned by all trees through a majority vote[51]. The random forest model and its optimisation procedures were implemented using the GEE. The variable importance for all spectral bands, NDVI, and NDWI were also assessed. Spectral reflectance bands (2, 5, 12, and 11) were ranked higher, while NDVI and NDWI were ranked lower (see Supplementary Fig. S1 online). The accuracy of the final output map was assessed using the validation data.

Validation (accuracy assessment)

After conducting a qualitative accuracy assessment (visual evaluation), the final map was downloaded from GEE and imported into ArcPro. An overall quantitative accuracy assessment was conducted using ArcPro, with independent validation point sample data (Table 3). Yelena and Antonia[54] emphasise the importance of using higher-quality reference data derived through a sampling approach to assess the accuracy of land use maps. They further noted that the data could be based on field sampling or a higher resolution spatial resolution aerial imagery. The latter approach was used in this study since the first approach could be laborious and time-consuming for national scale mapping. The "create accuracy assessment tool" in ArcPro was used with a stratified random sampling strategy[55]. The tool generates random points, and the sample size is based on the proportion of the area for each class. This process ensures that a sufficient number of reference samples is created for each stratum (class)[55]. A total of 1460 points were obtained (Table 3). Each validation sample data point was assessed and manually labelled through the visual interpretation of very high-resolution aerial imagery (25 cm) by a single expert operator. After completion of manual labelling, a confusion matrix for accuracy assessment was generated using the "compute confusion matrix" tool in ArcPro. This was performed by comparing the classes obtained using the classification model with the ground truth data. Multiple statistics were derived from the confusion matrix to quantify the map accuracy. These include the Overall Accuracy (OA), overall agreement between classification (map), and ground truth for all classes. The User's accuracy (UA) measures the agreement between the classified pixels and the ground-truth data for a specific class from the user's perspective, whereas the Producer's accuracy (PA) measures the agreement between the classified pixels and the ground-truth data for a specific class from the producer's perspective[56]. Lastly, owing to the presence of errors in the classification results, a simple pixel counting method to calculate the land use area is not adequate. Therefore, 'good practices', as suggested by Olofsson et al.[55] were used to generate an area-based error matrix and calculate the unbiased land-use area for each class.

CO_2 emission calculations

CO_2 emissions were calculated using the IPCC T1 EFs and literature-based T2 EFs using Eq. (3). Four dominant land use classes (cutaway, cutover, forestry, and grassland), which cover ~ 85% of the total raised bog land use area (Fig. 3) were used for emission estimation. For the remaining classes (remnant peatlands, water bodies, and built-up areas), neither T1 nor T2 emission factors were available; therefore, CO_2 emissions could not be estimated. T1 default EFs from the IPCC Wetland Supplement (2013) and T2 EFs by Aitova et al.[26] which are based on case studies in Ireland for grasslands, cutover and cutaway sites were used. The EF for forestry is based on eight drained and afforested peatland sites in Ireland[57].

$$CO_2 \text{ emission } \left(tCO_2 - C\ ha^{-1}y^{-1}\right) = \text{land use area (ha)} \times \text{ EF } \left(tCO_2 - C\ ha^{-1}y^{-1}\right) \tag{3}$$

where t is tons, ha is hectares, y represents a year, and EF is the land use specific emission factor.

Results

The statistics for the area of each land use class in raised bogs obtained using the error matrix (see Supplementary Table S1 online) are presented in Fig. 3. Almost half of the raised bogs mapped in this study are covered by grassland i.e., 43% (244,100 ha). Forest covers about 21% (116,427 ha), cutaway 10% (54,302 ha) and cutover cover 11% (646,99 ha). Remnant peatlands (high bog) area covers about 13% (73,795) ha. Water bodies and built-up areas account for about 1% (1542 ha and 1358 ha, respectively). The water bodies here constitute both natural waterways included in the coarse resolution DIPMv2 and surface water on raised bog appearing possibly after rewetting activities.

The prevalence of land use activities can be seen across all raised bogs in the midlands of Ireland Fig. 4. Industrial peatland extraction sites are primarily located in the midlands (Fig. 4a) and some parts of the north (Fig. 4b and c) and south (Fig. 4f) of the midlands. Approximately 65% of these industrial extraction sites are owned by BnM. The other 35% constitute non-BnM peat extraction carried out on an industrial scale similar to BnM (Fig. 4d and e). BnM landholding and Special Area of Conservation (SAC) boundary data were used to further examine the distribution of land use to better understand the status and condition of raised bogs under different management regimes, i.e., industrial and protected (Table 4). Additionally, Coillte landholding boundary data was also used to assess land use. It owns ~ 31,000 ha of raised bog areas accounting for about one-third of the total forestry on these bogs.

The exposed peat on BnM landholdings amounts to around 42,264 ha. The rest of the cutaway bogs, totalling about 2,460 ha, are in SAC, highlighting the existence of a substantial amount of bare peat on these "protected" bogs with active cutting also taking place[58]. Cutaway bogs in midlands have interspersed forestry (Fig. 4a). The areas on the edges of these bogs represent agricultural grasslands. The remnant peatlands in the midlands and are mostly on SAC sites such as Clara Bog, Ferbane Bog, Moyclare Bog, and Raheenmore Bog (Fig. 4a). Overall, there is about 13,053 ha of the remnant peatlands located on the SAC, which is approximately 1% of the total peatland area and most of the "actively forming raised bogs" are possibly located in these sites[59]. The majority of the remnant peatlands are in the west of the midlands and are surrounded by peat-extraction activities (Fig. 4d and e). Lastly, the scattered water bodies on cutaway sites in the Midlands and some parts in the North are possible signs of some of the rewetting activities being carried out by BnM (Fig. 4a and b).

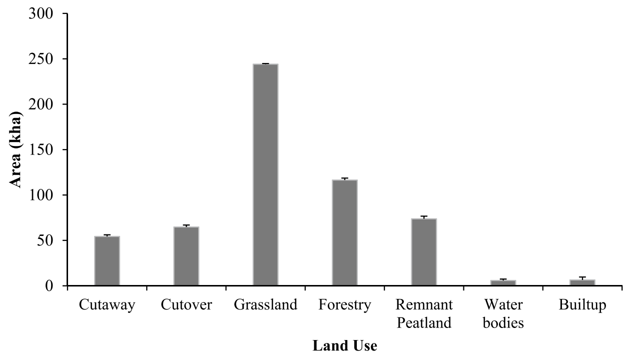

Figure 3. Land use area in kilo hectares (kha) for each class, error bars for standard errors in kha.

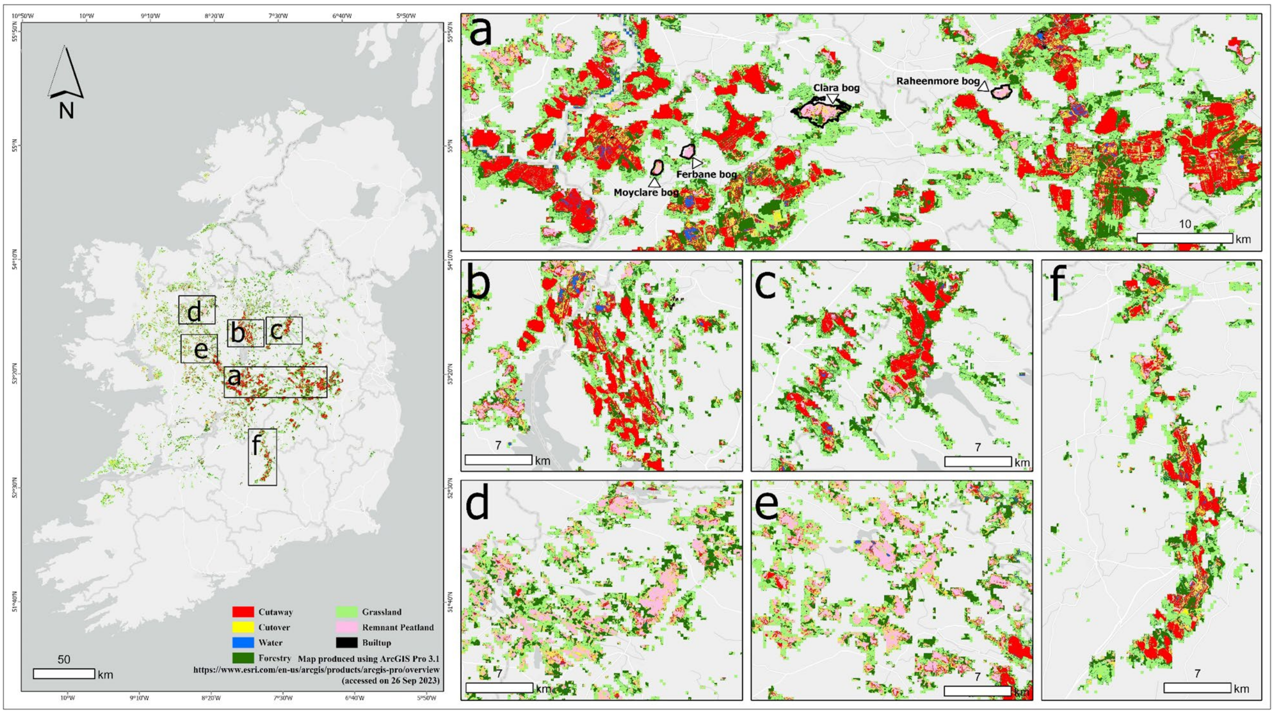

Figure 4. Land use on raised bogs. (**a**), (**b**), (**c**) and (**f**) are dominated by industrial peat extraction sites (mostly Bord na Móna), whereas (**d**) and (**e**) have a mix of remnant peatland, cutover, grassland, and forest.

Class	BnM (ha)	SAC (ha)
Cutaway	42,264	2460
Cutover	7303	4907
Grassland	2379	7318
Forestry	9067	3490
Remnant Peatland	6491	13,053
Water bodies	1580	1340
Built-up/Infrastructure	388	197
Total	69,472	32,568

Table 4. Proportion of each land use on Bord Na Mónaa (BnM) and Special Area of Conservation (SAC) under the national parks and wildlife services (NPWS). All areas are in hectares (ha).

CO_2 emissions

CO_2 emissions presented in Table 5 are calculated using Eq. (1) for the four land use classes. The area (ha) is estimated from the land use map (Fig. 4). T1 emissions were ranging between 303,710 and 1,293,730 t CO_2-C ha^{-1} y^{-1} with grassland being the highest emitters followed by forestry, cutover, and cutaway. T2 emissions were in the range of 65,705–317,330 t CO_2-C ha^{-1} y^{-1}, with the highest emissions in grassland and the lowest emissions in cutaway. The T1 emissions for grassland were four-fold higher than T2 emissions. The total CO_2 emissions

Land Use	Area (ha)	T1 (IPCC) EFs	T1 Emissions (t CO_2-C ha^{-1} y^{-1})	T2 (literature) EFs	T2 Emissions (t CO_2-C ha^{-1} y^{-1})	No. of sites for T2 EFs	References
Cutover	64,699	2.8 (1.1–4.2)	181,157	1.21 (0.4 – 2.0)	102,871	3	[26]
Cutaway	54,302	2.8 (1.1–4.2)	152,046	1.59 (1.2 – 2.0)	65,705	4	[26]
Forestry	116,427	2.6 (2.0–3.3)	302,710	1.68 (1.04 – 2.32)	195,597	8	[57]
Grassland	244,100	5.3 (3.7–6.9)	1,293,730	1.3 (0.04 – 2.55)	317,330	3	[26]

Table 5. Emissions from four dominant land use classes, with Intergovernmental Panel on Climate Change (IPCC) Tier 1 and 2 (T1 and T2) Emission Factors (EFs) with 95% confidence intervals values are shown in brackets, Emissions based on the area in hectares (ha) and EFs (in tonnes of CO_2-C per hectare per year).

from Irish-raised bogs based on the four land use classes mapped here account for 0.68 Mt CO_2-C ha^{-1} y^{-1} as per T2 and 1.92 Mt CO_2-C y^{-1} as per T1.

Accuracy assessment

The OA of the final land use map was 89% which is computed from the diagonal line of the confusion matrix (Table 6), representing the number of correctly classified classes. A total of 1303 of 1460 points were correctly classified. The UA ranges from 70% (water and cutover) to 96% (forest), and PA ranges from 64% (built-up) to 97% (cutaway).

The results show the highest PA for cutaway (97%) and grassland classes (93%) while remnant peatlands (75%) and built-up (64%) have the lowest PA. Forestry (97%), grassland (94%) and remnant peatlands (91%) all show high UA, while built-up (68%), cutover and water (70%) show low UA. The lower UA of the cutover class (70%) can be attributed to the presence of heterogeneous vegetation, resulting in a mosaic landscape following the abandonment of extraction sites. As a result, this class is prone to misclassification, particularly with remnant peatlands (another landscape characterised by heterogeneity) (Fig. 2). The lower UA of water bodies (70%) and misclassification with forestry can be attributed to overlap in spectral signatures in partially vegetated and surface water areas, as shown in Fig. 4.

Discussion

The degradation of Irish-raised bogs due to centuries of human exploitation is widely acknowledged[6,12,13]. Nevertheless, a significant knowledge gap exists in the absence of "robust aerial data" for accurate assessment of land use on the raised bog[14,26]. This gap in spatial data is addressed through the development of the LUCIP taxonomy and its implementation in GEE using Sentinel-2 data. This study provides the first high-resolution wall-to-wall coverage of land use on raised bogs in Ireland. The robust methodology presented here facilitates an accurate assessment of the magnitude and extent of land use and CO_2 emissions on these ecosystems. It utilises cloud computing (GEE), temporal mosaicking, and machine learning (random forest and high-resolution remote sensing imagery (Sentinel-2)) to overcome the issue of persistent cloud cover in Ireland. The accuracy assessment results (overall accuracy of 89%) showed good agreement between the map and the reference data.

Currently, the Irish National Inventory Report (NIR) only considers peat extraction activities (industrial/domestic) in the "managed wetlands" category for all peatlands (blanket and raised bogs). This area is reported as 70,020 ha, of which 400 ha is domestic cutover with the remainder being industrial cutaway, and emissions calculations in the NIR are also reliant on these area estimates[32]. In literature, this figure is ~ 80,000 ha, which is mainly the BnM landholding[12,14,32,60]. However, the findings of our study which focused only on raised bogs, indicate that peat extraction (cutaways and cutovers) is considerably more prevalent than currently reported and extends to approximately 119,000 ha. This is 70% higher than the NIR-reported "managed wetland" area figures for all peatlands. Hence, we address the overall ambiguity in exisiting land use estimates by providing accurate spatially explicit land use information derived from robust remote sensing methods.

The results depict heterogeneous land use in raised bogs across Ireland. The midland raised bogs (Fig. 4a, b, c, and f) are dominated by industrial mining activities as well as conversion to grassland and forestry. The more peripheral raised bog areas to the west, northwest, and southwest of the midlands are dominated by conversion to grassland and forestry. In general, the most extensive land use on raised bogs is agricultural grassland which is distributed across the region. Grasslands mainly occur on the margins of cutaway, cutover and remnant peatlands. The remnant peatland class, which represents the remaining areas of the raised bogs, are not in pristine condition, and are more abundant towards the North and West of the midlands, away from the areas of intensive industrial peat extraction activities. The BnM Peatland Climate Action Scheme (PCAS) aims to restore degraded peatlands within BnM landholding and is a good start for mitigation and adaptation, which are more intact raised bogs in the north and west that could be targeted for active restoration by policymakers, facilitating carbon retention in these ecosystems. It is also pertinent to mention that the PCAS was initiated at some of the former industrial peat extraction sites during the timeframe of this study. Most of these areas are still bare peat which means the data produced in this study could be used as baseline data for tracking and monitoring the PCAS over time.

Class	A	B	C	D	E	F	G	Total	UA (%)
Cutaway (A)	**164**	12	1	8	2	10	0	197	83
Cutover (B)	0	**91**	0	4	15	19	1	130	70
Water (C)	1	0	**35**	8	2	0	4	50	70
Forest (D)	1	2	0	**244**	4	1	0	252	96
Grassland (E)	2	1	1	12	**624**	6	14	660	94
Remnant Peatland/High Bog (F)	1	2	0	2	5	**111**	0	121	91
Built-up (G)	0	0	0	3	13	0	**34**	50	68
Total	169	108	37	281	665	147	53	**1303**	**OA (%)**
PA (%)	97	84	94	86	93	75	64		89.2

Table 6. Result of accuracy assessment for the seven land use classes, including Overall Accuracy (OA), User's Accuracy (UA), and Producer's Accuracy (PA). The emboldened diagonal elements represent accurately classified areas.

Overall, the maps show that the current level of human-induced degradation of these raised bogs through land-use change requires immediate action for sustainable management of these ecosystems.

On BnM landholdings, industrial extraction activities have gradually ceased over the past two decades, with an announcement of complete cessation in 2021. The results of this are beginning to be observed in the data. At the Blackwater site (Co. Offaly) site (Fig. 5), areas are classified as remnant peatlands, which is an indication of revegetation after the cessation of extraction activities (pre-2000) and subsequent rewetting in 1999[61]. These sites are going through a transformation with land use conversion to forestry or a diverse mosaic of vegetation communities composed of heather, shrubs, grasses, and interspersed larger plants. The forestry areas in Fig. 5, are on Coillte landholdings and are highlighted with a grey outline. Other areas with surface water are possibly signs of rewetting activities and are represented by surface water here (Fig. 5). Vegetation cover at Blackwater has increased over the years, albeit slowly, with Sphagnum mosses and other bog species recolonising the area i.e., sparse remnant peatlands patches among the prevalent bare peat (cutaway) (Fig. 5). This recovery process is not only important for carbon sequestration and climate change mitigation but also for the restoration of the unique biodiversity and ecosystem services provided by peatlands. An SAC site is outlined (white dotted line) in the bottom right (Fig. 5) and shows a good example of what is considered a “near natural” raised bog e.g., intact centre but degraded margins where substantial cutting has taken place and areas converted to grassland. These changes can be seen using Sentinel-2 which demonstrates the utility of this methodology for tracking and monitoring land use change in raised bogs over time.

The EU has established a range of regulations and initiatives that directly or indirectly require restoration and sustainable management of peatlands. These include the Habitats Directive (Council Directive 92/43/EEC), Water Framework Directive (Directive 2000/60/EC), EU Biodiversity Strategy for 2030, Common Agricultural Policy (CAP), Natura 2000 Network (Directive 2009/147/EC), LIFE Programme, EU Climate Adaptation Strategy, and more recently the Nature Restoration Law which includes restoration of peatlands by binding targets and net zero CO_2 emissions from these ecosystems by 2050. The effective implementation of these initiatives is only possible through robust mapping, tracking, and monitoring[62] methodologies such as those proposed in this study.

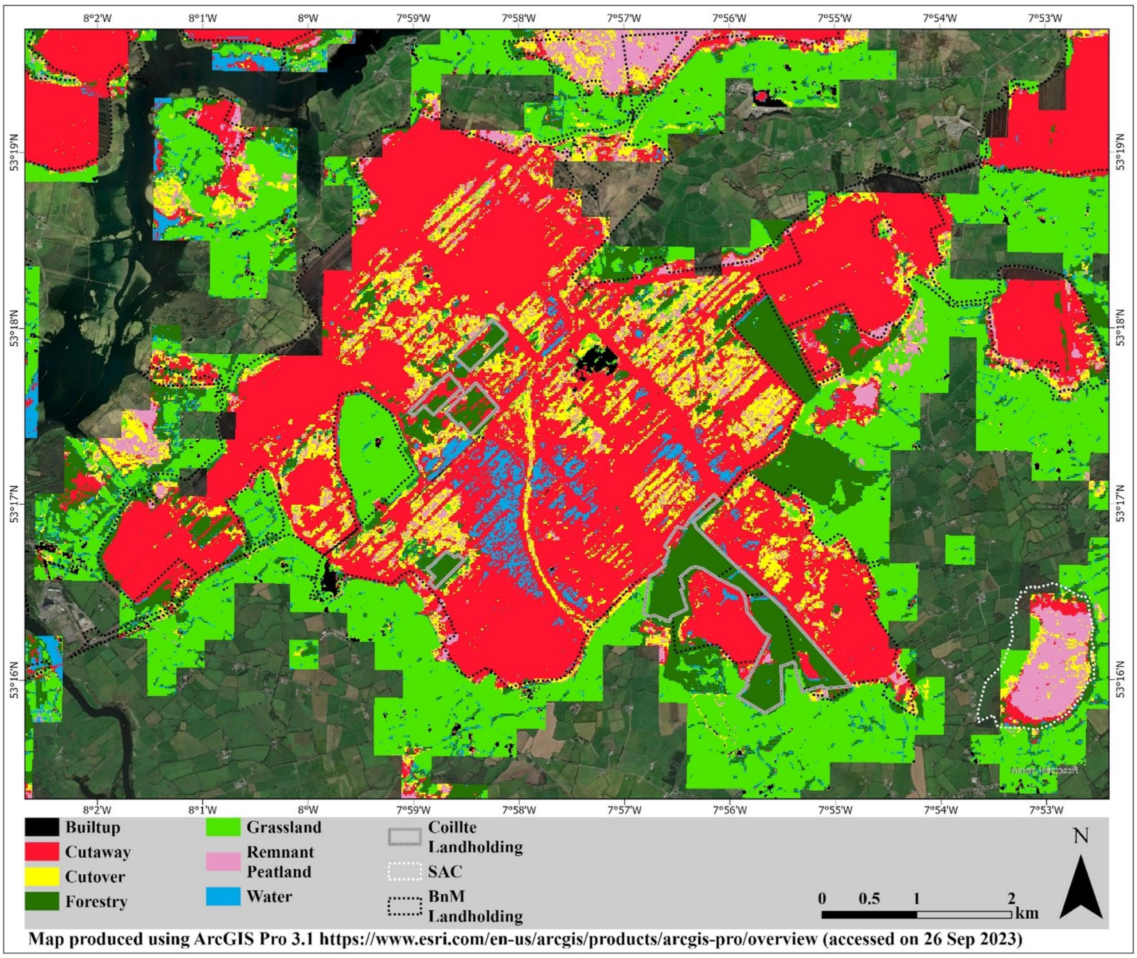

Figure 5. Typical example of a former industrial bog complex mapped in this study. The areas outlined by the black dotted lines are within the BnM (Bord na Móna) landholdings, whereas the white dotted lines in the southeast section of the map show a bog under SAC (Moyclare Bog). The grey boundaries in the BnM landholdings and outside of it are Coillte landholdings.

The map produced here serve as an important indicator for determining the baseline status and condition of these ecosystems as well as providing a quantification of CO_2 emissions hotspots. By providing a detailed map of BnM/non-BnM industrial activities and domestic extraction activities, this study not only highlights these activities in a spatial context but also estimates emissions from them. The emissions calculated in this study based on IPCC T1 and Ireland-specific T2 EF show a substantial difference. The IPCC default emission factor is higher than the Irish T2 EF resulting in higher emission estimation. One of the limitations of using IPCC T1 EFs is that these EF are based on limited case studies with diverse geographical locations, climatic conditions and ecology not necessarily suited to Irish Peatlands. The EFs proposed by Aitova et al.[26] and the EFs from the study by Jovani-Sancho[57] are based on measurements from specific sites in Ireland, the United Kingdom and Germany, and may not be a true representatives of other sites in the country. For example, T1 EFs for grasslands (5.3 t CO_2-C ha^{-1} y^{-1}) are mostly based on study sites from Germany, which are under more intensive management practices compared to Ireland[26,63]. This may lead to a substantial difference when comparing T2 EFs for grasslands in Ireland (1.30 t CO_2-C ha^{-1} y^{-1})[26]. While these EFs could be refined specifically for Ireland, their use by Aitova et al.[26] is a significant improvement compared to the T1 EFs. Finally, the delineation of raised bogs in this study relies on an existing peatland extent map i.e., DIPMv2. Although, DIPMv2 is most current peatland map in Ireland, with an overall accuracy of 88%, it tends to underestimate the presence of peatlands with areas smaller than 7 ha[5]. This study can be expanded to these missing areas if the DIPMv2 is updated in the future.

Nevertheless, this study demonstrates the robustness and utility of remote sensing methods to accurately map the land use on peatlands and to integrate these data with the latest T2 EFs thus refining estimates of CO_2 emissions from different land use on Irish peatlands. The LUCIP implemented in GEE facilitates the development of highly accurate land use maps that can aid the refinement of national-scale T2 reporting in these globally rare ecosystems. These integrated spatial datasets can help inform decision-making for sustainable land management practices and conservation. Furthermore, detailed habitat mapping of the remnant peatland class using a high-resolution dataset and integrated Sentinel-1 and 2 approach could be useful for monitoring active raised bog areas in SAC[42,64]. Future work using the LUCIP could address the large knowledge gap regarding land use type and extent on blanket bogs, which account for ~ 70% of peatlands in Ireland and have not been studied at this level in Ireland. It is important that the EFs and emissions are assessed for these areas to identify C and GHG emission hotspots and areas for targeted restoration.

Conclusion

In this study, a spatially explicit dataset of land use on Irish raised bogs was created by integrating the DIPMv2 and Sentinel-2 satellite images collected between 2018 and 2020. Overall, the accurate results (OA = 89%) of this study provide valuable insights into the spatial extent of land use in raised bogs in Ireland. These data were integrated with T2 EFs to refine the estimation of CO_2 emissions from the four major land classes on raised bogs. These spatial data on land use can inform policies on land use and emissions at a national scale. The map also enhances the current understanding of the extent and scale of different land uses (especially peat-extraction activities) in a spatial context. The state and condition of raised bogs in Ireland present a pressing concern due to their substantial CO_2 emissions. Urgent measures are required to address this issue, including (i). mitigating emissions and (ii). implementing sustainable management practices to promote carbon sequestration within these ecosystems and prevent additional degradation. This spatial information can be used to inform the development of more sustainable approaches to peatland management in the country, the decision-making process for developing such policies and effective strategies to mitigate these management impacts.

Data availability

The datasets used and/or analysed during the current study are available from the corresponding author upon reasonable request.

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Author contributions
W.H. lead the preparation, creation and/or presentation of the published work, specifically writing the initial draft. He took a lead role in the development and design of the methodology using Remote Sensing and GIS analysis in both GEE and ArcPro as well as in data curation. Both W.H. and J.C. conceptualised the study. R.I. contributed to the emission calculations. Both M.S. and J.C. contributed to the review and editing of the manuscript.

Competing interests
The authors declare no competing interests.

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Hydro-G

An Coimisiún Pleanála PAX07.323761

Expert Opinion

for

Barnaderg Gortbeg GWS Observation & Objection

in the context of

European Union (Drinking Water) Regulations 2023 (S.I. No. 99 of 2023)

Cooloo Wind Farm, Co. Galway

Private Development - REDIII Application

in the groundwater and surface water catchments of

Mid Galway PWS

Barnaderg Gortbeg GWS

Briarfield GWS

Lough Corrib PWS

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Report Title: An Bord Pleanála PAX07.323761. Barnaderg Gortbeg GWS - Public & Group Water Supply Impact Assessment. Expert Opinion. Barnaderg Gortbeg GWS Observation & Objection.

Date: 20th November 2025

Prepared by: Pamela Bartley

Dr. Pamela Bartley B.Eng, M.SC., Ph.D.

Contents

List of Abbreviations

BH	Borehole
EPA	Environmental Protection Agency
CALCDA	Climate Action and Low Carbon Development Act (2015)
GSI	Geological Survey of Ireland
GW	Groundwater
HES	Hydro Environmental Services, Dungarvan. Consultants to MKO.
HSE	Health Service Executive
MKO	EIAR Authors
NFGWS	National Federation of Group Water Schemes
PWS	Public Water Supply
WTP	Water Treatment Plant
ZOI	Zone of Influence
ZOC	Zone of Contribution

Executive Summary

- Dr. Pamela Bartley of Hydro-G was commissioned by the Barnaderg Gortbeg GWS to prepare this report in support of the Objection to a proposed High Risk & High Hazard development in the vicinity of groundwater and surface water supplying their Group Water Supply groundwater spring and borehole abstraction locations. The author of this report is an expert PWS water supply engineer with karst aquifer expertise who supervised water supply borehole drilling at the Barnaderg Gortbeg GWS site and within the compound of the nearby Mid Galway PWS. The variability in the karst of this area is phenomenal. The largest groundwater strike of my drilling supervision career was at Barnaderg GWS. Amongst the most mediocre karst conduit groundwater strikes of my career was at the nearby Mid Galway PWS WTP compound.

- This report presents information for An Bord Pleanála in relation to a 'Private Development - REDIII Application' by Neoen Renewables Ireland Limited named Cooloo Wind Farm (ABP Reference No. PAX07.323761)**.** No quantitative Risk Assessment has been presented by the applicant with respect to the onerous obligations, when catchment changes are proposed, of the European Union Drinking Water Regulations 2023 (SI 99 of 2023).

- The applicant proposes construction in the lands overlying the karst conduit groundwater system supplying water to the Group Water Scheme sources Barnaderg Gortbeg and Briarfield, the latter is not mentioned at all in the EIAR. In addition, the applicant proposes construction in the lands contributing groundwater and surface water to the Mid Galway PWS. The agents for this turbine project propose abnormally excessive loads and infrastructure in the Groundwater Body (GWB) and catchment of the Mid Galway PWS, Barnaderg Gortbeg GWS and Briarfield GWS and Lough Corrib, although the latter is remote from the proposal.

- Whilst the agents cite a 2012 Source Protection Zone report for the Mid Galway Scheme, the GSI and the EPA (2012) state very clearly that "<u>Source Protection Zones are a landuse planning tool which enables a more objective, geoscientific assessment of the risk to groundwater **quality** to be made</u>". The emphasis is on quality: A Source Protection Zone is defined by a 100-day time of travel to the source and is designed to protect the source from microbial and viral contamination (DELG/EPA/GSI 1999). In this conduit karst groundwater setting the potential for collapse of surface karst into subterranean karst is high when the scale of the abnormal and excessively abnormal loads are considered. The issue is that all groundwater in this GWB has the potential to flow to the Mid Galway PWS, Barnaderg Gortbeg GWS, Briarfield GWS and Lough Corrib. Even groundwater outside the 100-day time of travel Source protection Zone, mapping for microbial and viral contamination, can travel to the named PWS sources.

- No defensible assessment of groundwater flow systems has been submitted to An Coimisiún Pleanála regarding the groundwater system beneath the areas proposed for excessively abnormal loads, including all haul roads, crane pads, foundations and turbine masts. A Geotechnical Karst Risk Assessment (GDG, 2025) in "support of the application". However, that Geotechnical Karst Risk Assessment was completed by geologists and not hydrogeologists. This is evident in their opening quote from Drew (2018) in which a "simple" definition of karst is presented in favour of Drew's (2018) "more sophisticated and hydrogeologically orientated definition of what is meant by karst": An integrated mass transfer system in soluble rocks with a permeability structure dominated by conduits dissolved from the rock and organised to facilitate the circulation of fluids." The Geotechnical Karst Risk Assessment (GDG, 2025), in support of the application, fails to convey the connection between the surface expressions of karst on the landscape with the known conduit system conveying large volumes of groundwater in the immediate vicinity of the PWS sources and two GWS sources. Over 10,000 m3/d of groundwater is discharged in the vicinity of the proposed development. Subterranean conduits are the mechanism of that groundwater flow system. This is not acknowledged by the geotechnical engineers, who by their nature are interested in solid geology and not conduit groundwater systems.

- Turbines and blades will be maintained with persistent chemicals, details for which are absent from the baseline groundwater and surface water monitoring data. The Hub of each turbine, at c.100m above ground, will contain lubricant to ensure efficient operation of the three rotating blades on each of the masts. The Drinking Water Regulations (2023) and the Groundwater Regulations (20120, as amended 2016) specify Parametric Values for chemicals and lubricants associated with the maintenance of Turbine blades and masts. No baseline information is presented in the EIAR for those parameters.

- The purpose of this report is to present expert hydrogeological information for An Coimisiún Pleanála's consideration with respect to the hydrogeological environment, Drinking Water Regulations and the potential for impact arising from the proposed development. The construction area is connected to groundwater and surface water that are sources for a significant PWS and significant GWS boreholes and springs. The conclusions of no potential for impact are not justified by virtue of the fact that no specific foundation designs are presented in the EIAR for EIA and no mapping for mains distribution networks are presented.

- The Risk Impacts outlined in the Geotechnical Karst Risk Assessment (GDG, 2025) include "Detailed ground investigation, mitigation through use of grouted piled foundations, or bridging cavities with concrete, or geogrid and coarse granular fill if appropriate". Sanctioning grouting in response to collapsing caves is not advised. Sanctioning the placement of excessive and abnormally excessive loads over conduit karst supplying 1000's of homes with no water supply contingency is not advised in the interest in public health and safety.

- Whilst CALCDA demands that An Coimisiún Pleanála must enable furtherance of Ireland's Climate Action Plan, the words "IN SO FAR AS PRACTICABLE" are KEY words that must be remembered by all parties. The potential to affect the QUALNTITY of groundwater supply to 1000's of homes and farms rules out the "IN SO FAR AS PRACTICABLE" option of the CALCDA. The rights of the public to have safe water delivered to their homes and farms is a Human Right that must be maintained.

Statement of Expertise Pamela Bartley B.Eng., MSc., Ph.D

Pamela is a water focussed civil engineer. After more than 25 years of field based practice in borehole drilling, groundwater monitoring and abstraction point management she can be considered a karst hydrogeology specialist: her Ph.D was a field based-karst limestone environment study and in the years after she completed CPD training with the GSI at their karst specialist course run in the Burren. Pamela is qualified and IOSH certified to act as PSDP (Project Supervisor Design Phase) & PSCS (Project Supervisor Construction Stage) as defined by the Construction Regulations. The company is a registered Irish Water Supplier (no. 1855) and Pamela Bartley is HSQE approved within Irish Water and is one of their Hydrogeologist Framework service providers.

Upon completion of a Diploma in Water and Wastewater Technology at Sligo RTC, she completed a degree in Civil Engineering at Queens University, Belfast and then completed a Master of Science in Environmental Engineering followed by a hydrogeological focussed Ph.D. on Karst Groundwater Impact: both postgraduate degrees were completed within the school of Civil Engineering at Trinity College, Dublin.

Her key work areas are groundwater impact and groundwater use. She specialises in the engineering of groundwater from large scale water supply boreholes for PWS, GWS, Motorway Service Stations & Hotels. Other work areas include evaluation of discharges to groundwater and surface waters for compliance with Irish Regulations and the hydrological and hydrogeological assessments required for EIARs for quarries. She has a skillset in the assessment of groundwater quality for water treatment process parameters and working in collaboration with water treatment plant designers.

Pamela has successfully completed post doctorate formal course training in the areas of:

- PSDP & PSCS (IOSH certified, 2016).
- Karst Hydrogeology (GSI, 2013).
- Planning & Development Act (IE, 2010) & Expert Witness (IE, 2011).
- On Site Wastewater & Water Services Amendment Act 2012 (IE, 2012 & Dublin 2012).
- Zero Discharge Willow Wastewater Systems Design Courses (Denmark 2008 & 2011 & Ireland 2012).
- Surface Water Regulations 2009 (DoE, 2010 & 2011).
- Sustainable Drainage (Wallingford/CIRIA, 2005 & 2008).
- Source Protection Zone Delineation (IGI/GSI, 2007).
- Groundwater & Contaminant Microbiology (IGI/GSI, 2006).
- Site Suitability Assessment (FETAC, 2002) & Applied Groundwater Modelling (ESI, UK, 2000).

Pamela's water supply borehole expertise has been gained in the field by her personal supervision of drilling and designing required subsurface completions for large scale abstractions for DBO2's East Galway Group Water Scheme BHs: Ballinabanba GWS; Barnaderg GWS; CBC GWS; Kiltiernan GWS and Ballyaneen GWS as well as many PWS groundwater well sources for Galway County Council, Clare County Council and later for Irish Water in Counties from Donegal to Galway and the Roscommon border. Amongst many other private sites, she has completed successful potable boreholes for Kilronan Castle in Roscommon; Lakeland Dairies, Co. Cavan; The Killeshin Hotel, Co. Laois; The Loughrea Hotel; The Charleville Park Hotel and the Motorway Service Stations at the Obama Plaza, Galway Plaza and the Supermacs Service station in Tipperary. She has developed competency in review of camera surveys of boreholes in need of rehabilitation and design of subsequent programmes to improve yield.

As a result of work in evaluating planning appeals, Pamela has become specialist in planning evaluations in the context of enacted Irish Regulation and EU Directives concerning the water environment such as the Groundwater Regulations (S.I. No. 9 of 2010 & Amendment Regulations S.I. No. 366/2016), Surface Water Regulations (S.I. No. 272 of 2009 & Amendment Regulations S.I. No. 386 of 2015), Water Framework and Habitats' Directives. She has been an invited guest speaker at An Bord Pleanála, The Irish Concrete Federation, The Health Service Executive, Environmental Health Officers National Conference, The Irish Planning Institute's National Conference, The International Association of Hydrogeologist's National Conference (Irish Branch) and has delivered hydrogeological lectures to the public during Science Week. In the past, she has held full time lecturing positions in third level institutions (WIT & CIT, 1996 – 1999), delivered practical laboratory instruction in the assessment of subsoils for the FETAC Site Assessor programme and also demonstrated hydraulics laboratory and practical field survey tutorial modules at Trinity College Dublin (1996). Pamela is a qualified and certified 'Site Assessor' and has been an interviewer of examination candidates in respect of eligibility for the Site Suitability FETAC Qualification.

Pamela Bartley's company is Bartley Hydrogeology ltd., registered to trade as Hydro-G. The company holds professional indemnity insurance of €2million for each and every claim in each period and the company holds both employers, public and products liability insurances (Employers Liability : €13,000,000 any one claim/unlimited any one period of insurance, Public Liability : €6.5 million, Products Liability : €6.5 million). Pamela is an expert provider to Uisce Eireann on the Hydrogeologists Framework Panel and Supply Demand Balance Programme.

1.0 Introduction

In September 2025 the Cooloo Wind Farm, Co. Galway, was presented to An Coimisiún Pleanála for their consideration under the mechanism of 'Private Development - REDIII Application Development' with an application code PAX07.323761. The Project description is provided by agents for the applicant, as follows:

i. 9 no. wind turbines with the following parameters:

a. Total turbine tip height of 180 metres;

b. A rotor blade diameter of 150 to 162 metres;

c. A hub height of 99 to 105 metres;

ii. Permanent turbine foundations, hard-standing and assembly areas;

iii. Underground electrical (33kV) and communications cabling;

iv. 1 no. temporary construction compound (including site offices and welfare facilities);

v. A meteorological mast with a height of 100 metres, security fencing and associated foundation and hard-standing area;

vi. 1 no. new site entrance on the R332 in the townland Lisavally;

vii. 1 no. new access and egress point off the L6056 Local Road in the townland of Dangan Eighter;

viii. 1 no. new access and egress point on to an existing access track in the townland of Dangan Eighter;

ix. 2 no. new access and egress points off the L6301 Local Road in the townland of Cooloo and Lecarrow;

x. Upgrade of existing site tracks/roads and provision of new site access roads, clear span crossings, junctions and hard-standing areas;

xi. A new temporary access road from N63 national road and to R332 Regional Road in the townland of Slievegorm to facilitate the delivery of turbine components and other abnormal sized loads;

xii. Demolition of an existing derelict house and adjacent outbuilding in the townland of Cooloo;

xiii. Peat and Spoil Management Areas;

xiv. Tree felling and hedgerow removal;

xv. Biodiversity Management and Enhancement measures;

xvi. Site Drainage;

xvii. Operational Stage site signage; and

xviii. All ancillary apparatus and site development works above and below ground, including soft and hard landscaping.

The applicant is seeking a ten-year planning permission. Current and future wind turbine generator (WTG) technology will ensure that the wind turbine model, chosen for the Proposed Project, will have an operational lifespan greater than the 35-year operational life that is being sought as part of the planning application.

Dr. Pamela Bartley of Hydro-G was commissioned to assess the risk to the quality and quantity of the Barnaderg Gortbeg GWS water sources. However, given that the Barnaderg Gortbeg GWS is intrinsically connected to the Uisce Eireann Mid Gawly PWS both schemes are considered in this assessment.

The author of this report is an expert PWS water supply engineer with karst aquifer expertise who supervised water supply borehole drilling at the Barnaderg Gortbeg GWS site and within the compound of the nearby Mid Galway PWS. The variability in the karst of this area is phenomenal. The largest groundwater strike of my drilling supervision career was at Barnaderg GWS. Amongst the most mediocre karst conduit groundwater strikes of my career was at the nearby Mid Galway PWS WTP compound.

The proposal before An Coimisiún Pleanála in case PAX07.323761 concerns a network of haul roads, crane pads, construction pads, foundations and associated infiltration devices in the lands overlying the karst conduit groundwater system supplying water to the Group Water Scheme sources Barnaderg Gortbeg and Briarfield, the latter is not mentioned at all in the EIAR. In addition, the applicant proposes construction in the lands contributing groundwater and surface water to the Uisce Eireann Mid Galway PWS, which is a very large abstraction that is in the public record of EPA Abstraction Register in excess of that considered in the EIAR reported to An Coimisiún Pleanála. This has significance in the context of encroachment of a larger portion of the proposed development area into the zone of influence of the abstractions. The agents for this turbine project propose excessive and abnormally excessive loads and infrastructure in relatively close proximity to and in the same Groundwater Body (GWB) and the same catchment of the groundwater abstraction sources for Mid Galway PWS, Barnaderg Gortbeg GWS and Briarfield GWS.

The proposal before An Coimisiún Pleanála does acknowledge the fact that at the construction sites proposed for the 9 individual turbine footings (likely 23m diameter of concrete, likely in 30m diameter excavations) will require pumping of cement into deep foundations (5 to 10m depth) on lands that are connected to Mid Galway PWS and both the Barnaderg Gortbeg and Briarfield GWSs. The proposal before An Coimisiún Pleanála does acknowledge the hazard presented by the widespread evidence for surface karst (Appendix 8-2) and that those hazards might require pumping concrete into piled foundations beneath turbines AND beneath floating roads. However, the karst risk assessment is superficial and does not address the groundwater impact potential of karst in any way.

Part 3 of the European Union (Drinking Water) Regulations 2023 provides comprehensive instructions on Risk Assessment and obligations in respect to the catchments and controls for Public Water Supply Sources. The agents for the applicant have not exercised the legislative obligation considering the scale of PWS that could potentially be affected. The EPA Register of Abstractions is available to all members of the public and professionals in the assessment of risks posed to Public Water Sources. The EPA has published the register in a way that it is querriable by GWB name and its WFD Code. On the basis of the obligations set out in Part 3 of the European Union (Drinking Water) Regulations 2023, it is incumbent on applicants and planning authorities to complete detailed studies to complete Risk and Impact assessments in the context of PWS Abstractions.

In a karst conduit groundwater system such as this, risks posed include impacts on the quality of the water presented to the GWS for treatment before issue to their members and quantitative risks posed by potential interruption of water flow in conduits that could collapse or be filled with grout, as is one of the mitigation measures proposed by the applicant.

2.0 Groundwater Receiving Environment & PWS

The development area proposed for the construction site to enable turbines, roads, spoil heaps and underground cabling overlie the Clare Corrib Groundwater Body (WFD Code IE_WE_G_0020). The GSI data and maps server map groundwater characteristics as follows:

- Groundwater Flow Regime 'Karstic (KA)'.
- Aquifer type = Regionally Important Conduit Karstified Aquifer.
- Groundwater Flow Path Velocities (GSI, 2004) mapped in the East to West flow domain, which is the direction of flow applicable to this application and within the application area = 100m to 400m per hour in some cases. This means that groundwater flow velocities are 2.4 to 9.6 km per day. The GSI (2004) GWB Descriptor Sheet for the GWB is presented as Appendix A to this report.

No defensible assessment of groundwater flow systems has been submitted to An Coimisiún Pleanála regarding the groundwater system beneath the areas proposed for excessively abnormal loads, including all haul roads, crane pads, foundations and turbine masts. A Geotechnical Karst Risk Assessment (GDG, 2025) in "support of the application". However, that Geotechnical Karst Risk Assessment was completed by geologists and not hydrogeologists. This is evident in their opening quote from Drew (2018) in which Drew's "simple" definition of karst is presented in favour of the very next sentence in Drew's (2018) Karst of Ireland textbook, which defines a "more sophisticated and hydrogeologically orientated definition of what is meant by karst", as follows:

"An integrated mass transfer system in soluble rocks with a permeability structure dominated by conduits dissolved from the rock and organised to facilitate the circulation of fluids."

The Geotechnical Karst Risk Assessment (GDG, 2025), in "support of the application", fails to convey the connection between the widespread evidence of surface expressions of karst on the proposed project's landscape with the known conduit system conveying large volumes of groundwater in the immediate vicinity of the PWS sources and two GWS sources.

Over 10,000 m3/d of groundwater is abstracted for public consumption each day in the vicinity of the proposed development. The Source Protection Report for the Mid Galway PWS scheme (EPA, 2012) is presented as Appendix B to this report. Whilst the karst conduit system is well described in EPA (2012), and each of the GWSs are also documented and evaluated, An Coimisiún Pleanála is advised that the Mid Galway report did not have a focus on the actual application area's subterranean Karst systems. Therefore, the level of detail is not available for the applicant's proposed development area. EPA (2012) is provided as an example only of how much work and risk is involved in this hydrogeological setting. As stated, the applicant's agents approached the situation from a geotechnical rather than hydrogeological perspective.

Subterranean conduits are the mechanism of that groundwater flow system. This is not acknowledged by the geotechnical engineers, who by their nature are interested in solid geology and not conduit groundwater systems. The many 'potential turloughs' and dolines mapped by the wind industry expert service provider, GDG (2025), are not explained as links to the underlying groundwater conduit system. Only one turbine location was surveyed in the Geotechnical survey reported in the GDG (2025) report on karst. The method applied is not the method that those searching for groundwater conveying karst conduits seek. The preferred method is EM.

Turloughs are a groundwater feature. Turloughs are surface expressions of groundwater moving from the conduit groundwater flow system upwards, often in vertical shafts, to ground level in ephemeral lakes. The proposed construction area is between Horseleap Lough, Summerville Lough and Levally Lough. An underground conduit groundwater flow system connects those Loughs. This is documented in EPA (2012), which is Appendix B to this report. Never have excessive and abnormally excessive loads been applied to the landscape of east Galway and there are no site testing data presented for the applicant in which the shear loading capacity is demonstrated for the lands proposed for haul roads or the 9 crane pads and 9 turbine pads suggested.

3.0 The Clare Corrib Groundwater Body - Details relating to Sources of Water Schemes

The publically available EPA published register of abstractions, under the Abstraction & Impoundment Regulations, presents as follows:

- The Barnaderg Gortbeg GWS groundwater source is registered to supply 900 m3/d to the public from the Clare Corrib GWB. This water supply scheme was developed by the local community in 1970. There is no Plan B for the scheme. Uisce Eireann have not identified the adjacent Mid Galway Scheme as a scheme that has funding to expand. In any case, if the Barnaderg Gortbeg sources of water were impacted by the proposed development, so too would Mid Galway. The connectivity is documented in the EPA (2012) report appended here as Appendix B. The Barnaderg Gortbeg GWS manages 110 Km of pipe network distributing water to 1,500 connections and 940 Customers in the vicinity of the proposed development.

- The Brierfield and District Group Water Scheme Society Limited is registered to supply 91 m3/d to the public from the Clare Corrib GWB.

- The Uisce Eireann Mid Galway PWS is registered to supply 5,146 m3/d to the to the public from the ABBERT_030 river. An Coimisiún Pleanála is advised that all groundwater spring discharges are assigned as surface water system connectivity. Hence the Abbert River registered source. It is, however, a surface water system from which Uisce Eireann abstracts 5,146m3/d but the surface water is fed by groundwater springs. There is also a groundwater supply borehole at the site that assists in water treatment processes.

Groundwater and Surface Water are connected in this karst system. Hence the concern regarding the applicant's agent's presentation that:

"The topography of the Proposed Wind Farm site is undulating with gentle slopes typical of a low-lying raised bog setting with surrounding local hills. The elevation of the Proposed Wind Farm site ranges from approximately 65m OD (metres above Ordnance Datum) to 80m OD, with slopes falling to the north and southeast from a high point located centrally with the Proposed Wind Farm site which also coincides with a surface water catchment topographic divide between the Grange River to the north and the Abbert River to the south". & "The Proposed

Wind Farm site is drained by several 1st order watercourses that emerge from the peatland areas. There is also a high density of man-made drainage associated with the peatland and grassland areas. The man-made drainage density is evident on the OSI 6", 25" mapping and aerial imagery" (Appendix 9-1 Flood Risk Assessment, EIAR 2025 Cooloo Wind Farm).

The potential for organic matter release from the bogs, during all phases of the project, to the drainage system has potential to react with the chlorination systems of the Water Treatment Plants (WTPs) and has potential to create Trihalomethanes.

The Drinking Water Regulations (2023) and the Groundwater Regulations (20120, as amended 2016) specify Parametric Values for chemicals and lubricants associated with the maintenance of Turbine blades and masts. No baseline information is presented in the EIAR for those parameters**.**

4.0 In appropriate Use of Information and Implications

Whilst the agents cite a 2012 Source Protection Zone report for the Mid Galway Scheme, the GSI and the EPA (2012) state very clearly that "Source Protection Zones are a land use planning tool which enables a more objective, geoscientific assessment of the risk to groundwater **quality** to be made". The emphasis is on **quality**: A Source Protection Zone is defined by a 100-day time of travel to the source and is designed to protect the source from microbial and viral contamination (DELG/EPA/GSI 1999). It is wholly inappropriate for wind farm applications to attempt to portray that their proposed development area does not wholly overlap a Source Protection Zone for a PWS or a GWS. Some of the Turbines proposed do overlap the mapped Source Protection Zone. However, ALL of the turbines proposed overlap the groundwater system feeding the Mid Galway and Barnaderg Gortbeg GWS sources. The connectivity to Brierfield GWS is also an issue.

In this conduit karst groundwater setting the potential for collapse of surface karst into subterranean karst is high when the scale of the abnormal and excessively abnormal loads are considered. The issue here is that all groundwater in this GWB has the potential to flow to the Mid Galway PWS, Barnaderg Gortbeg GWS and Briarfield GWS. Even groundwater outside the 100-day time of travel Source protection Zone, that was mapped by the EPA and GSI (2012) for microbial and viral contamination, can travel to the sources for Mid Galway PWS, Barnaderg Gortbeg GWS and Briarfield GWS. Therefore, the issue of QUANTITATIVE IMPACT is more relevant and this has not been adequately assessed in the context of interruption of PWS in either the Water Chapter or the Geotechnical Risk Assessment.

Neither have the Biodiversity Assessments considered the potential impacts of the groundwater conduit system collapse, or deep peat slides, blocking the Poor Status drainage network, so well described and mapped in the Triturus (2025) Baseline Aquatic Survey (Appendix 6-3). An Coimisiún Pleanála is invited to include this in their brief to their own ecologist: What would be the effect on the Lough Corrib SAC and SPA to which the drainage system of the proposed development area is connected to?

Returning to water, the EPA (2012) was completed for a stated abstraction of 4,000 m3/d. In the intervening 13 years since the work was completed, the abstraction has increased to over 5,000 m3/d. For the operational 35 year lifespan proposed, the abstraction will increase again and again. Therefore, the mapped zones of contribution will increase farther into the turbine foundation areas. The same is true for the zone feeding Barnaderg Gortbeg GWS.

An Coimisiún Pleanála is invited to include this in their brief to their own hydrogeologist – how to forecast the increasing scale of impact into the future.

5.0 Business Focussed, Not People or Environment Focussed, Mitigation Measures Proposed

- The Mitigation Measures proposed in the Geotechnical Karst Risk Assessment provide valuable insight into the focus of the Environmental Impact Assessment completed by the agents for the wind industry. In the GDG (2025, Appendix 8-2 of the EIAR), the 'Karst Risk Assessment' Appendix 1 presents all the potential risks to the client's infrastructural investments.

- There is no follow through regarding the required Mitigation required to provide an alternative source of water to 1000's of local homes (Mid Galway's 5,146 m3/d; Barnaderg Gortbeg's 900m3/d and Brierfield GWS's 91 m3/d).

- The potential scenarios of Hazard posed by the karst environment are correctly identified and listed in the GDG (2025) Appendix 1 Table in Appendix 8-2, as follows:
  - Rapid collapse of sinkhole/doline cavity
  - Subsidence of soils overlying suffusion or buried dolines
  - Cavities / Voids
  - Variable rockhead
  - Solutionally Weathered Rock

- The 'Risk Impact' entitled column of the Table in the GDG (2025) Appendix 1 of Appendix 8-2 of the EIAR includes a strange mix of required construction efforts and in response to karst uncertainties, include as follows:

  - "Detailed ground investigation, mitigation through use of grouted piled foundations, or bridging cavities with concrete, or geogrid and coarse granular fill if appropriate". The ship will have sailed if permission is granted for a Wind Farm on speculative reasons that the mitigation is detailed ground investigation. In addition, suggesting grouting in this particular environment is not advised because large volumes of grout have the potential to clog conduits and stop groundwater flowing to the Mid Galway PWS, Barnaderg GWS and Brierfield GWS.

  - In relation to Access Roads in the bogs, which will have excessively abnormal loads placed over deeper bog than the applicant's agents have managed to push their probes through, the 'Risk Impact' of subsidence and piled foundations is not design according to the site investigations. The true response would have been a CONCLUSION THAT THE SELECTED AREA IS UNSUITABLE FOR THIS TYPE OF DEVELOPMENT. Sanctioning the placement of excessive and abnormally excessive loads over conduit karst supplying 1000's of homes with no water supply contingency is not advised in the interest in public health and safety.

- The Mitigation Measures proposed in Chapter 18 of the EIAR propose surface water monitoring for a list of parameters that do not include the potential emissions from the materials that will arise from construction and maintenance during operation (Table 9-8 of the Water Chapter is referred to in Table 18-1 Mitigation Measures, specifically MM3).

- The Mitigation Measures proposed in Chapter 18 of the EIAR do not present Mitigation for Interruption of Public Water Supply. A simple email request to 'Data Requests' at Uisce Eireann will result in sharing of maps for the entire area of interest: the Grid Connection, the haul routes and the construction area. The potential for construction of the Grid Connection to intersect the water supply mains is high. No Mitigation Measures are proposed. The same applies to the water mains distribution network for the GWSs.

- There are many issues with the Mitigation Measures Proposed. However, most significantly, there is no Mitigation Measure proposed in relation to the potential for Human Health Impact on the people who receive groundwater and groundwater fed Surface Water from the three local PWS and GWS sources in the immediate vicinity of the proposed development area. As previously outline by Hydro-G and as published by the GSI in their description of the groundwater flow mechanism in the Clare Corrib GWB. Relative to the PWS and GWS abstraction source locations, the proposed haul roads, construction pads, crane pads and turbine erection sites are within the 9km published groundwater flow path length (GSI, 2004). There are no Mitigation Measures proposed for true risks to the source waters for public and GWS supply relating to issues, as follows:

    - Increased turbidity in the karst conduit or surface water system. Increased turbidity has the potential to affect the disinfection process in the WTPs and thereby compromises the sterility and safety of the water supplied to the public. There is no information presented by the applicant for baseline turbidity in surface waters or groundwaters of the area.
    - Increased Dissolved Organic Carbon in groundwater or surface waters. Construction in peatlands has the potential to exacerbate release of Dissolved Organic Carbon and this constituent is a driver on increased Trihalomethane formation potential in water supplied to the public after the statutory obligation of chlorination prior to discharge to the water mains. No Silt buster will remove DISSOLVED organic carbon in waters discharging from the site. There is no information presented by the applicant for baseline Dissolved Organic Carbon in surface waters or groundwaters of the area.
    - There is no information presented by the applicant for baseline lubricants and oils that will be in each hub and supplemented in the lifetime of the development, no information on hydrocarbon baseline, no details for the baseline surface water and groundwater constituents relatable to the proposed surface finishes of the coated turbines or those constituents that will be used in the cleaning of the turbine infrastructure.

Without baseline data, how can environmental compliance and public health impacts be policed in the lifetime of the proposed project?

6.0 Hydrogeological Impact Assessment Components

For all hydrogeological assessments, it is best practice to apply the Source > Pathway > Receptor Model of assessment of potential impact**.**

6.1 Sources

The potential sources of impact in any construction project of this nature, and indeed applicable to the Cooloo Wind Farm's proposal for Co. Galway, includes as follows:

- Water runoff from the construction site hardstandings and crane pads,
- Dewatering of trenches and excavations for foundations,
- Rainfall runoff on the peat, earth and rock extracted to enable each foundation base to be constructed.
- Cement being transported in trucks along the recently constructed haul roads,
- Cement being pumped from cement trucks,
- The transport and storage of steel reinforcement bars and rafts for the concrete foundations to each turbine, specified as 4-5m below ground level.
- Wastewater arisings from the people involved in the construction activities.
- Operational replacement of hub lubricants and hydrocarbons.
- Operational use of cleaning materials and de-icers.

The typical scale of a Turbine base pad construction area is presented as Plate A. Note that the turbine rotor lengths dictate some site dimensions. Turning distances for the unusually long trucks is also a constraint dictating the dimensions required to accommodate safe working areas. There will be the equivalent of c. 4 domestic resident sites area for each turbine (4 x 0.5 acre = 2 acres = c. 1 ha of excavation for each of the 8 turbines). This presents silt and runoff burden that presents a threat to the Mid Galway PWS and GWSs nearby.

Plate A Turbine base construction pads (9 no. proposed). Note the scale of each of the three rotors relative to the construction workers.

As is shown in the DWGS for the application, there will be extensive areas of Spoil Management and water management treatment systems adjacent to each of the proposed 9 turbines, the proposed substation construction site and along all trench excavation rotes. All water management will be by Infiltration into the epikarst of the underlying Clare Corrib Groundwater Body and the Regionally Important Karst aquifer feeding Lough Corrib and multiple GWS BHs: refer to Drainage Drawings and BH Logs.

6.2 Pathway

In this karst limestone aquifer type, although mapped as Conduit karst, the epikarst plays the dominant role in conveyance of the abundant rainfall to surface water systems. This is known and understood by all hydrogeologists.

6.3 Receptors

The receptors within range of impact arising from the construction of the proposed windfarm, construction pads, hardcore standings, roads and infiltration drains include, as follows:

1. Mid Galway PWS
2. Barnaderg Gortbeg GWS
3. Briarfield GWS
4. Lough Corrib SAC and SPA

7.0 Building on Bogs over Conduit Karst – Hydrological Impact and Carbon Sequestration

There is a reason that the bogs of the proposed development area are there: poorly drained depressions in low permeability glacial till are ultimately filled with peat. The clay underlying the bogs is essential to their sustainability, cutaway or not. Integrity of the clay containment is essential to any restoration or rewetting. Turbine foundations, even on the margins of bogs, will destroy that integrity with all the implications for biodiversity/carbon storage. Even if not designated legally, they are Groundwater Dependent Terrestrial Ecosystems (WFD) and worthy of protection as listed habitats (which include 'degraded bog'). In Annex III of the parent EIA DIRECTIVE (2011/92/EU) on the assessment of the effects of certain public and private projects on the environment, Annex III clearly states that: "The environmental sensitivity of geographical areas likely to be affected by projects must be considered, having regard, in particular, to:

(a) the existing land use;
(b) the relative abundance, quality and regenerative capacity of natural resources in the area;
(c) the absorption capacity of the natural environment, paying particular attention to the following areas: (i)wetlands; (vi) areas in which the environmental quality standards laid down in Union legislation have already been exceeded;"

Attention is drawn here to the legal obligation to consider "the absorption capacity of the natural environment". A significant portion of the land on which the turbines are proposed are bogs (wetlands of a sort). Professor Paul Johnston of Trinity College Dublin is on government record in stating that "Beyond all scientific doubt, building turbines in peat will negatively affect biodiversity and increase carbon loss from this habitat through the required drainage, foundations and infrastructure. Damage arising from construction releases more carbon from the peatland. The long-term sustainable approach is the restoration of bog wetlands. A strategy of restoration, rather than any construction whatsoever, will provide a reduction in carbon emissions from the peatland in perpetuity. The societal benefits will be better water quality, reduction in flood events, a reversal of biodiversity loss and more opportunities for people to connect with nature resulting in better physical/mental health outcomes, as recognised in the Climate Action Plan, a derivative of the Paris Agreement. Moreover, since 1987,Ireland has been a signatory of the international Ramsar convention which provides for the protection and promotion of wetlands including peatlands. The case that windfarms in peatlands are incompatible with these requirements is rarely even considered appropriately in EIARs. The existing and growing resistance to terrestrial windfarms due to their environmental impact is frequently justified and exacerbated by inadequate EIARs which result in extra delays and costs as well as in poor planning decisions. This conflict between the requirements of environmental legislation and the need for increased wind power is unsustainable. When it comes to protecting our environment and its increasingly important ecosystem services on which the human race depends".

Moreover, streams are the headwaters of the Clare River and hence supply sources for the Corrib SAC. All tributary streams to the Corrib are salmonid. Hence a windfarm in the headwaters of the catchment represents a risk to that water supply and ecology, especially in quality, notwithstanding the same tributaries are ancillary to an arterial drainage scheme. However, under Nature Restoration, such arterial drainage is itself under review for rehabilitation to more natural conditions (OPW) – building turbines should not be allowed to impede this restoration. The generic drainage system depicted in the report for draining roads and hardstands is unlikely to work since the low permeability soils will accelerate this drainage into the existing network – soil infiltration is likely to be poor, but no field assessment was made. Moreover, the proposed system with 'silt traps' is unlikely to work in detaining colloidal solids which, themselves carry Dissolved Organic Carbon (DOC) arising from the extensive excavations/roads on site, as well as from windfarm enhanced drainage from the peatbogs. Such losses conflict with the role of wind farms as climate mitigation devices.

8.0 Maladaptation

Maladaptation refers to actions or strategies that, while intended to address the challenges posed by climate change, inadvertently exacerbate the problem, or create new vulnerabilities. This can occur when adaptation measures are poorly planned, misaligned with the local conditions, or fail to account for long- term consequences.

The Ireland National Adaptation Framework – National Adaptation Plan 2025 (NAP 2024) states as follows:

- p.42, "Avoiding Maladaptation: Ensure that adaptation actions do not inadvertently create new vulnerabilities or exacerbate existing ones."

- "Consideration of Climate Mitigation: Ensure that climate mitigation outcomes are considered alongside adaptation planning where appropriate."

- p. 47, As part of its annual review, the CCAC also considers developments made in terms of supporting a just transition in terms of both mitigation and adaptation – noting in its 2023 review the need to accelerate the integration of the just transition principles across all mitigation and adaptation policy development and implementation".

9.0 Discussion – Safe Drinking Water Supply – A Human Right

In response to Mr. John McGuiness' PQ 103 question in the Oireachtas on the 5th of November 2024, Mr. Eamon Ryan admitted that Ireland's onshore Wind Targets were not tested using geospatial techniques (Wind Energy Generation – Tuesday, 5 Nov 2024 – Parliamentary Questions (33rd Dáil) – Houses of the Oireachtas & https://www.oireachtas.ie/en/debates/question/2024-11-05/103/#pq_103). The fact that Mr. Eamon Ryan admitted that they did not use geospatial techniques means that the government has not proven that their targets are logistically feasible given the constraints presented by Conservation Objective sites, the nature of groundwater as a source of supply in rural Ireland and the nature of housing development. Instead, wind energy targets were chosen by the then government based on modelling emissions and power systems. Therefore, Mr. Ryan's team decided that they wanted a certain emission reduction and set their target to that desire, regardless of any consideration of constraints posed by threats to Ireland's rivers, aquifers, water supply water to rural communities, Conservation Objective Natura 2000 sites and their endangered or protected species and habitats, nor were Housing Density nor Human Health implications considered in the selection of the onshore wind targets. It is for that reason that the results of the Strategic Environmental Assessment on Renewable targets cannot be published or defended by the Government.

The case before An Coimisiún Pleanála is a proposed High Risk & High Hazard development in the vicinity of groundwater and surface water supplying the Barnaderg Gortbeg GWS's groundwater spring and borehole abstraction locations. In the absence of any information being presented to An Bord Pleanála in relation to surface water and groundwater concentrations of those chemicals and lubricants associated with the maintenance of turbine masts and blades, as specified in the Drinking Water Regulations (2023) and Groundwater Regulations (2010, as amended 2016) it would seem that an EIA by An Coimisiún Pleanála is not possible. All of the parameters presented in Appendix 9-2 and 9-3 of the Water Chapter are chemicals associated with agricultural and domestic wastewater impacts. Therefore, the baseline quality of the waters has not been established in the area for groundwater and surface water turbidity (a parameter that will affect safety of supply), oils, lubricants and other chemicals that will be used to maintain, operate and repair the hubs and the coatings on the mast and blades of each turbine. Given that the groundwater of the proposed development area is connected to the Mid Galway and Barnaderg Gortbeg GWS sources, a baseline chemical analysis of parameters is required for the chemical constituents of relevance to the operation of the proposed development. Then, when the baseline is presented and the potential loadings are applied, An Coimisiún Pleanála must make a determination on the basis of whether the future chemical concentrations are acceptable in the context of environmental and public health impacts.

Notwithstanding potential water quality impacts, quantitative impact potential has not been acknowledged in any way by the applicant's agents. The hazards posed by subsidence in karst or collapse of caves has been listed. But the only impact considered is how the turbines might be affected.

Overall, the information presented by the applicant is lacking and there are gross omissions of factual information with respect to the Mid Galway PWS, Barnaderg Gortbeg GWS, Briarfield GWS and Lough Corrib SAC, SPA and Galway City's and Tuam's and environs' source of PWS. The proposal presents a construction period of up to 2 years if there are no delays caused by accidents or unfavourable weather. The lands proposed by the applicant are within the EPA WFD catchment of, and Zone of Contribution to, Lough Corrib: the PWS supply for water to Galway City, Tuam and north east Galway. The multinational and educationally driven economy of Galway city and Tuam is wholly reliant on Lough Corrib as its source of PWS. The proposed development area is also in the groundwater system feeding the nearby Mid Galway PWS and Barnaderg Gortbeg GWS. The applicant's agents have incorrectly used a land use planning map for microbial time of travel and a volume of water abstraction that is 13 years out of date.

With respect to An Coimisiún Pleanála's obligations under s15(1) of the Climate Act is to address "the climate emergency", the rights of the public to have safe water delivered to their homes and farms is a Human Right. As stated by Mr. Justice Humpries in the Coolglass Judgment: 15(1), like any other domestic provision, must be interpreted consistently with EU and European Convention on Human Rights ("ECHR") law.

10.0 Recommendation

It is recommended that An Coimisiún Pleanála refuse permission to the said development for the reason that the proposal presents a risk to public health by the pathway of groundwater abstracted for the purposes of Public Water Supply at the Mid Galway source(s), the Barnaderg Gortbeg GWS and Briarfield GWS. The rights of the public to have safe water delivered to their homes and farms is a Human Right that must be maintained.

Pamela Bartley

Signed: ________________________________ Date: 20th November 2025

Dr. Pamela Bartley BEng, MSc, PhD

Appendix A GSI (2004) GWB Description Sheet

Clare-Corrib GWB: Summary of Initial Characterisation.

Hydrometric Area Local Authority	Associated surface water features	Associated terrestrial ecosystem(s)	Area (km^2)
30 Galway, Mayo Roscommon Co.Co's	**Rivers**: Abbert River, Black River, Cregg River, Dalgan River, Grange River, Killaclogher River, Kilshanvy River, River Clare, River Nanny, Sinking River, Togher River, Waterdale River **Lakes**: Corrib	000296 LISNAGEERAGH BOG AND BALLINASTACK TURLOUGH 000247 SLIEVE BOG 001237 BOYOUNAGH TURLOUGH 000224 ALTORE LAKE 000301 LOUGH LURGEEN BOG/GLENAMADDY TURLOUGH 000215 RATHBAUN TURLOUGH 001282 KILTULLAGH LOUGH 000263 DRUMBULCAUN BOG 000297 LOUGH CORRIB 000323 RICHMOND ESKER NATURE RESERVE 000289 KNOCKAVANNY TURLOUGH 000295 LEVALLY LOUGH 001254 DERRINLOUGH BOG 001255 DERRYNAGRAN BOG AND ESKER 000282 KILLOWER TURLOUGH 000331 TURLOUGH O'GALL 000234 BELCLARE TURLOUGH 001319 SUMMERVILLE LOUGH 001294 LOUGH HACKET 001288 KNOCKMAA HILL 000385 ROSTAFF TURLOUGH 002038 CASTLE HACKETT SOUTERRAIN 001322 TURLOUGH MONAGHAN 001788 TURLOUGHCOR 001280 KILLACLOGHER BOG 000307 LOUGH TEE BOG 001709 TIAQUIN BOG 000311 MONIVEA BOG 000287 KILTULLAGH TURLOUGH	~1422

Topography	The land surface is characterised by small hills and low ridges, with ground elevations ranging from 10-160 mAOD. The topographic surface slopes gently westwards. Elevations are highest (100-160 mAOD) in the north (south of Ballyhaunis, west of Ballinlough) and south (just north of Monivea). To the west of a line running north-south from Claremorris to Athenry the elevation is 10-40 mAOD, and to the east of this line, the elevation is 40-70 mAOD.	
Geology and Aquifers	**Aquifer categories**	The main aquifer category in this GWB is: **Rk^c:** Regionally important karstified aquifer dominated by conduit flow. There are some small areas (in the vicinity of Headford) with an aquifer category of: **Ll**: Locally important aquifer which is moderately productive only in local zones.
	Main aquifer lithologies	This GWB is composed primarily of Dinantian Pure Bedded Limestones. There are some small areas (in the vicinity of Headford) of Dinantian Pure Unbedded Limestones.
	Key structures	Few faults are mapped in this area; this may reflect the lack of major variation in the rock lithology. The dips over the GWB area are generally less than 10^o, except near faults, where steeper dips result from fault drag. Shallow synclines aligned with the axes in an E-W direction cross the GWB.
	Key properties	**Karstification** is widespread in this GWB. Recorded karst features number 219, but are considered to represent only a fraction of existing features. A histogram showing the different types of karst features currently in the database is provided in Figure 3. **Transmissivity and Storativity:** Well yields are variable, being distributed through all the well yield categories. Using 60 wells located in the GWB, 59% are either "excellent" (>400 m^3/d) or "good" (100-400 m^3/d), and 23% are either "poor" (<40 m^3/d) or "failed", with the remainder "moderate" (40-100 m^3/d). The median yield is 131 m^3/d. Histograms showing the distribution of well yields and productivity are given in Figures 4 and 5. Note: productivity is an index relating specific capacity to yield - the higher the productivity the higher the transmissivity. Productivity values are distributed throughout all the productivity categories, indicating the variability of the aquifer properties throughout the GWB. Analysis of the areal distribution of the data suggests that it is difficult to predict the aquifer properties in any particular place, with a few possible exceptions. For instance, in the vicinity of Tuam the well yields that are "excellent" are accompanied by several large springs, and just north of Monivea there is a cluster of "failed" wells (also due in part to silting up of the boreholes) which suggests that there may be an increase in yield from south to north across the GWB. Water table levels have high annual variations, which indicates that the storage is low - approximately 0.01-0.02 (Daly, 1985). The springs in the GWB also reflect the low storativity as many of the spring flows rise and fall quickly in response to rainfall events. Furthermore during prolonged drought many springs cease to flow and well yields drop significantly.
	Continues next page	**Groundwater velocity:** Tracer tests indicate variable groundwater velocities. Furthermore, tracer test data illustrates anisotropy in the transmissivity, with higher east-west transmissivity. Groundwater velocities in the E-W domain are in the order of 100-450 m/hr, as evidenced by the following tests: Lassanny Swallow hole to Ballyhaunis spring (440m/hr); Ballyglunin Cave to Aucloggeen Spring (200m/hr). Groundwater velocities in the N-S domain are in the order of 6-35m/hr, as evidenced by the following tests: L.Hackett to Kilcoona spring (35m/hr); Pollnahallia to Bunatober spring (6m/hr). Extensive conduit systems exist, as exemplified by the Ballyglunin Cave system. The mapping of this system indicates conduit development along the N-S and W-E joint sets, with an overall dip to the west (Drew and Daly, 1993).

		Groundwater flow directions and gradients: Overall, flow directions are to the southwest, with all groundwater discharging to L. Corrib. Although, there are six surface water catchments within the GWB, a *key* aspect is that groundwater can flow across the surface water divides and beneath surface water channels, as evidenced by the tracer test data. Examples of this key property are listed as follows: 1) water that sinks at Ballyglunin Cave emerges at Aucloggeen Spring, which crosses two surface water catchments. 2) water sinking along an losing stretch of the River Clare remerges as the headwater of the Black River. 3) recent tracing tests in the Ballinlough area of Roscommon indicate a link across the Shannon RBD into the Western RBD, from Coolcam (Roscommon) to Meeltraun (Mayo). 4) water along an losing stretch of the Sinking River flows about 10 km underground to join the River Clare. Drew (1976 (a)) suggests that groundwater flow is concentrated along the axes of shallow synclines. Gradients are variable, irregular due to the uneven distribution of transmissivity and are in the order of 0.01-0.002 (Drew and Daly, 1993; Daly, 1985)).
	Thickness	The Dinantian Pure Bedded Limestones are generally over 100 m thick. Most groundwater flows in an epikarstic layer a couple of metres thick and in a zone of interconnected solutionally-enlarged fissures and conduits that extends approximately 30 m below this. Deeper inflows can occur in areas associated with faults or dolomitisation.
Overlying Strata	**Lithologies**	Till is the dominant subsoil type, covering approximately 65% of the GWB. Cutover Peat comprises 23% of the area, sand/gravel covers approximately 3% and alluvium 2%. A full breakdown of the subsoil lithology is given in Table 1. A large proportion of the sand/gravel forms a random hummocky topography, although long sinuous, braided ridges of sand/gravel (eskers) have also been deposited especially in the east. A small portion of the north eastern area of the GWB around Cloonfad is described under the Roscommon Groundwater Protection Scheme (Lee and Daly, 2003) The till in this area is described as “SILT” (BS 5930), and is classed as “Moderate” permeability. There are also areas of “clayey” till, often underlying areas of raised bog (Drew and Daly, 1993). The thin till cover over much of the west part of the area is generally free draining (Daly, 1985).
	Thickness	East of a line linking Athenry – Tuam – Dunmore, the subsoil is “generally thicker” (Daly, 1985; Drew and Daly, 1993). This is supported by the occurrence of rock at or near surface, which is generally restricted to the western and southwestern part of the GWB. Analysis of the available depth to bedrock borehole data is limited as most of the data are clustered in three main areas: western, northeastern and central (area around Tuam) parts of the GWB. Nevertheless the data show a *general* increase in subsoil thickness in an easterly direction: average depth to bedrock increases from 4 m to 9 m from the west to east. In addition, there are instances of depth to bedrock greater than 20 m around Dunmore (northeast of GWB). However, there are also pockets of deeper till in the southwestern part of the GWB.
	% area aquifer near surface	50% of the GWB to the west of the line Athenry – Tuam – Dunmore is only covered by shallow till. 4% of the total GWB area has rock at or near surface.
	Vulnerability	The vulnerability for a small portion of the north eastern area of the GWB around the area of Cloonfad is described in the County Roscommon Groundwater Protection Scheme (Lee and Daly, 2003). In this area the vulnerability classification is variable dependent on the depth to bedrock. For the rest of the area. *[Information to be added at a later date]*
Recharge	**Main recharge mechanisms**	Both point and diffuse recharge occur in this GWB. Diffuse recharge occurs over the GWB via rainfall percolating through the permeable subsoil. Despite the presence of peat and till, point recharge to the underlying aquifer occurs by means of swallow holes and collapse features/dolines. Dolines have been recorded even in areas of thick peat deposits (Hickey et al, 2002). Point recharge occurs via many small sinks that are present in the low permeability till areas where the subsoil is breached. Recharge also occurs along ‘losing’ sections of streams. There are well defined stretches of the River Clare, Sinking River and Abbert River that are losing (Daly, 1985; Drew and Daly, 1993).
	Est. recharge rates	*[Information to be added at a later date]*
Discharge	**Large springs and large known abstractions (m^3/d)**	Large Springs: Corrandulla GWS (6764 m^3/d), Kilbannon GWS (5995 m^3/d), Mullacultra GWS (3270 m^3/d), Barnaderg Group Scheme (5000 m^3/d), Ballyhaunis WSS (12000 m^3/d), Tobernanny, Gortgarrow, Lettera Large known borehole abstractions: Gallagh GWS (523 m^3/d), Rusheens Tuam GWS (114 m^3/d), Roadstone Ltd (227 m^3/d), Belclare (114 m^3/d). *[Information to be added to and checked]*
	Main discharge mechanisms	The main groundwater discharges are to the streams, rivers and large springs found within the body. The large springs at Kilcoona, Bunatober and Aucloggeen and others issue from the bottom of a limestone scarp that is thought to represent an ancient shoreline of L. Corrib. Further these springs are likely to represent overflow springs and deeper groundwater flow discharges to outlets beneath the present day L. Corrib (Drew, 1993). In winter groundwater will fill the turloughs found in the area and partly discharge via the artificial channels that were installed to alleviate flooding.

	Hydrochemical Signature	The groundwater has a calcium bicarbonate signature. Two groundwater provinces are suggested by Drew and Daly (1993). Firstly, there is a shallow groundwater component that is characterised by high suspended solids and relatively low electrical conductivities (300-400 µS/cm). Springs that are fed by this component typically have a "flashy" throughput and often cease to flow during prolonged drought. Secondly, there is a deeper groundwater component that is characterised by relatively non-turbid groundwater with higher electrical conductivities (>450 µS /cm). Springs fed by this deeper component often have smoother hydrographs where there is a gradual change in discharge. Several large springs comprise both flow components, examples are Lettera, Tobernanny and Bunatober springs.
Groundwater Flow Paths		These rocks are generally devoid of intergranular permeability. Groundwater flows through fissures, faults, joints and bedding planes. In pure bedded limestones these openings are enlarged by karstification which significantly enhances the permeability of the rock. Karstification can be accentuated along structural features such as fold axes and faults. Groundwater flow through karst areas is extremely complex and difficult to predict. As flow pathways are often determined by discrete conduits, actual flow directions will not necessarily be perpendicular to the assumed water table contours, as shown by several tracing studies (Drew and Daly, 1993). The tracer tests show that groundwater can flow across surface water catchment divides and beneath surface water channels. Flow velocities can be rapid and variable, both spatially and temporally. Rapid groundwater flow velocities indicate that a large proportion of groundwater flow occurs in enlarged conduit systems. Groundwater flow in highly permeable karstified limestones is of a regional scale. Flow path lengths can be up to a several kilometres, for example 9.6 km from Ballyglunin Cave to Aucloggeen Spring. Overall, groundwater flow will be towards the River Clare and L. Corrib, but the highly karstified nature of the bedrock means that locally groundwater flow directions can be highly variable.
Groundwater & Surface water interactions		The area is drained by the River Clare and its tributaries, however the present day drainage network has been changed significantly by arterial drainage that took place early in the nineteenth century. Figures 1 and 2 show the pre/post arterial drainage network. According to Coxon and Drew (1983), much of the current stream network is a storm runoff system that is inactive during summer months. Thus, prior to drainage, streams sank underground via the turloughs present in the GWB. Many of the streams have well defined losing stretches where they lose water to the underground system (Daly, 1985). There is a high degree of interconnection between groundwater and surface water in karstified limestone areas such as in this GWB. Even though large areas of peat and tills overlie the body, collapse features in these areas provide a direct connection between the surface and the groundwater systems. The close interaction between surface water and groundwater in karstified aquifers is reflected in their closely linked water quality. Any contamination of surface water is rapidly transported into the groundwater system, and vice versa. Furthermore, there are a number of terrestrial ecosystems within this GWB with varying dependence on groundwater.

Conceptual model

- The north, south and west groundwater divides of this GWB are topographic highs that coincide with surface water catchment boundaries. It is bounded to the east by Lough Corrib.
- The topography is undulating with ground elevations ranging from 10-160 mAOD. A large proportion of the body is overlain by till, which thickens in an easterly direction.
- The area is principally drained by the River Clare and its tributaries, however the present day drainage network has been changed significantly by arterial drainage that took place early in the nineteenth century. Much of the current stream network is a storm runoff system and is inactive during summer months. Prior to artificial drainage, streams sank underground via a few turlough sinks in the GWB.
- Within the GWB, surface water catchments are often bypassed by groundwater flowing beneath surface water channels and across surface water catchment divides.
- A large number of karst features occur within the body. These include turloughs, caves, dolines, swallow holes and springs.
- The GWB is composed primarily of high transmissivity karstified limestone (**Rk**^{c}). Transmissivity and well yields are variable. Storage in the GWB is low.
- Groundwater flows through a network of solutionally enlarged bedding planes, fissures and conduits.
- Rapid groundwater flow velocities have been recorded through groundwater tracing. The tracing indicates an anisotropy in the transmissivity, with faster groundwater flow velocities and higher transmissivity in an E-W direction, which may be linked to shallow E-W trending synclinal axes and steeper E-W hydraulic gradients.
- Recharge in this GWB occurs via losing streams, point and diffuse mechanisms. Despite the presence of peat and till, point recharge to the underlying aquifer occurs by means of swallow holes and collapse features/dolines.
- The groundwater in this body is generally unconfined but may become locally confined beneath thick, low permeability subsoil. Most of the groundwater flow occurs in the upper epikarstic layer and in a zone of interconnected solutionally enlarge bedding planes and fissures, generally extending to a depth of 30 m.
- In general, the degree of interconnection in karstic systems is high and they support regional scale flow systems. Flow paths have been measured up to 10 kilometres in length.
- Some areas in this GWB are of extreme vulnerability due to the thin nature of the subsoil, as well as the frequency of karst features, allowing point recharge. Groundwater storage in karstified bedrock is low and the potential for contaminant attenuation in such aquifers is limited.
- The main discharges are to the rivers, large springs and L. Corrib. In winter groundwater discharges to the many turloughs and transmitted via the artificial channels that were installed to alleviate flooding.
- There is a high degree of interaction between surface water and groundwater in this GWB. There are a number of terrestrial ecosystems within this GWB which have varying dependence on groundwater.
- There are potentially two groundwater provinces within the GWB but this is uncertain. The groundwater has a calcium bicarbonate signature.

Attachments

Figures 1, 2, 3, 4 and 5.

Instrumentation

Stream gauges: 30002, 30003, 30004, 30006, 30007, 30010, 30011, 30012, 30013, 30014, 30015, 30020, 30022, 30023, 30024, 30025, 30026, 30029, 30030, 30032, 30040, 30045, 30053, 30055, 30071, 30101, 30103.
EPA Water Level Monitoring boreholes: Lackagh, GAL287, Tuam (Coca Cola), GAL291, Shrule, MAY085
EPA Representative Monitoring points:

Information Sources

Daly, D. (1995) *A report on the Flooding in the Glenamaddy area.* Groundwater Section Report File 2.2.7. 34pp.
Daly, D. (1992) *A report on the Flooding in the Claregalway area.* Groundwater Section Report File 2.2.7. 12pp.
Daly, D. (1985) *Groundwater in County Galway with particular reference to its Protection from Pollution.* Geological Survey of Ireland report for Galway County Council. 98pp.
Drew D.P. and Daly D. (1993) *Groundwater and Karstification in Mid-Galway, South Mayo and North Clare.* A Joint Report: Department of Geography, Trinity College Dublin and Groundwater Section, Geological Survey of Ireland. Geological Survey of Ireland Report Series 93/3 (Groundwater), 86 pp
Drew, D.P. (1973a) *Hydrogeology of the north Co. Galway – south Co. Mayo lowland karst area, Western Ireland.* International Speleology 1973, III, Sub –section Ca.
Drew, D.P. (1973b). *Ballyglunin core Co. Galway and the hydrology of the surrounding area.* Irish Geography Vol. 6, No. 5. pp 610-617.
Doak, M. (1995) *The Vulnerability to Pollution and Hydrochemical Variation of Eleven Springs (Catchments) in the Karst Lowlands of the West of Ireland*. Unpublished M.Sc. thesis, Sligo Regional Technical College.
Hickey, C., Lee, M., Drew, D., Meehan, R. and Daly D. (2002) *Lowland Karst of North Roscommon and Westmeath*. International Association of Hydrogeologists Irish Group. Karst Field Trip October 2002. Unpublished IAH Report.
Lee, M. & Daly D. (2003) *County Roscommon Groundwater Protection Scheme*. Main Report. Roscommon County Council & Geological Survey of Ireland, 54pp.
Hickey, C., Lee, M., Drew, D., Meehan, R. and Daly D. (2002) Lowland Karst of North Roscommon and Westmeath. International Association of Hydrogeologists Irish Group. Karst Field Trip October 2002. Unpublished IAH Report.

Disclaimer

Note that all calculation and interpretations presented in this report represent estimations based on the information sources described above and established hydrogeological formulae.

Figure 1 Pre Arterial Drainage.

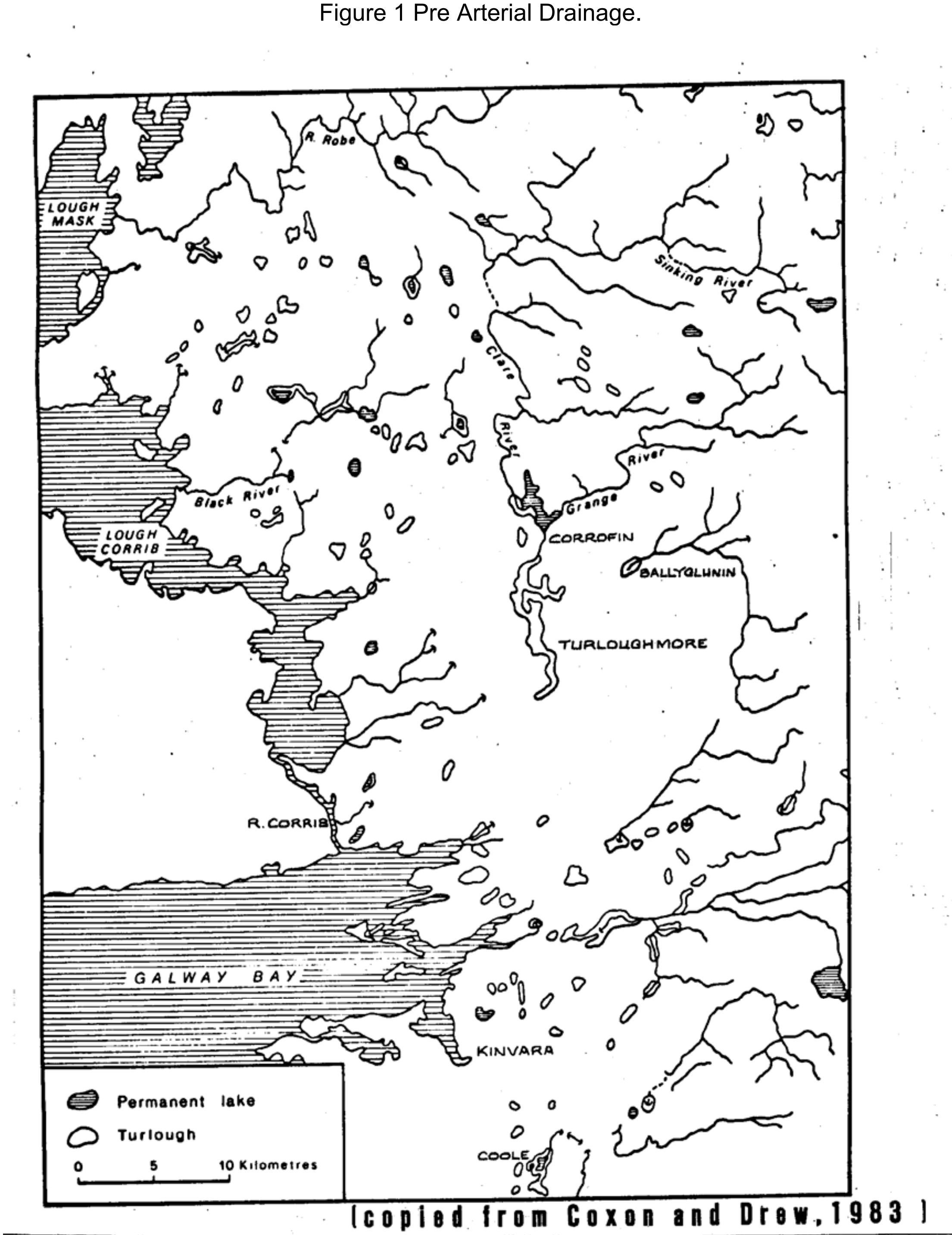


Figure 2 Post Arterial Drainage

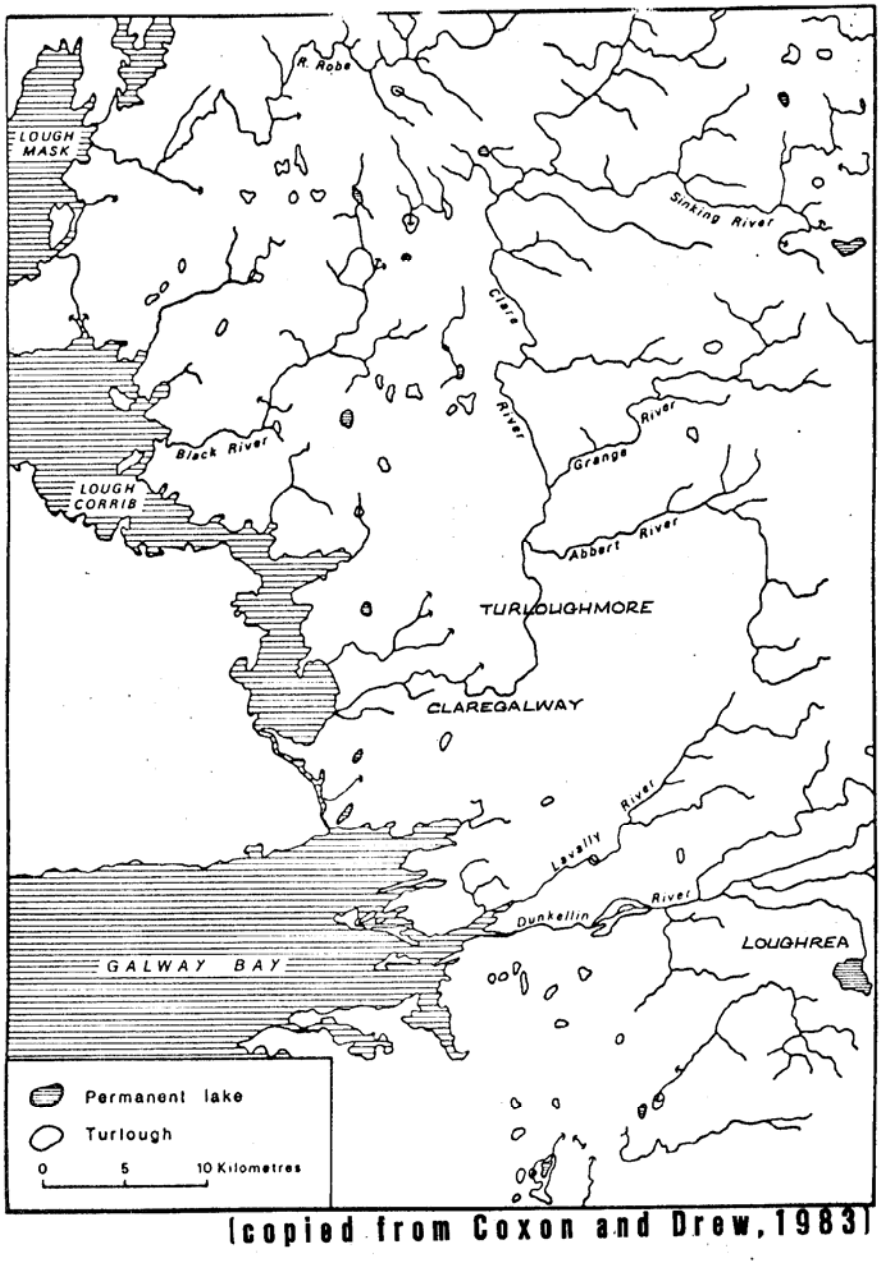


Figure 3 Histogram of Karst features in Clare-Corrib GWB

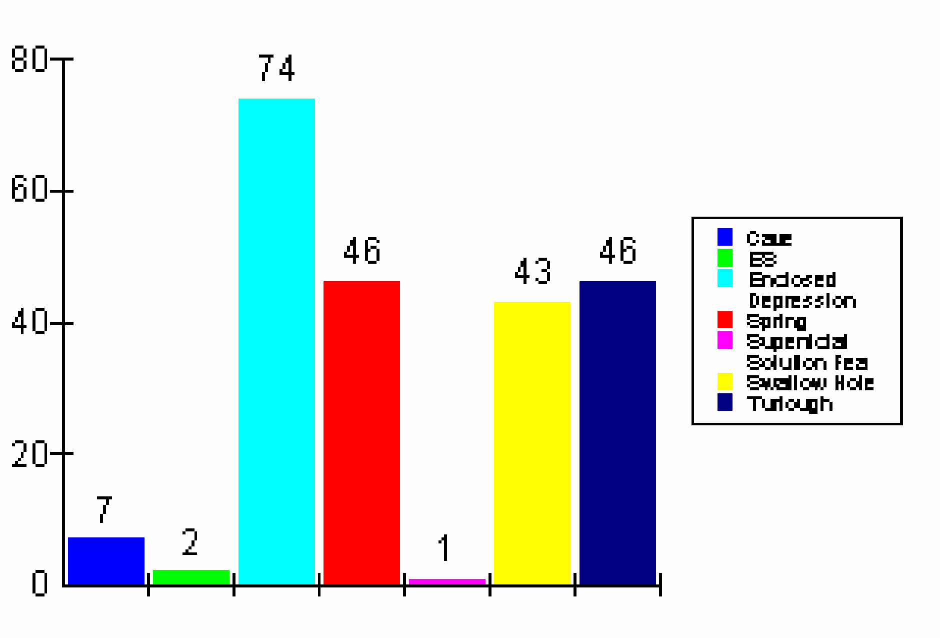


Figure 4 Histogram of Well Yields in Clare-Corrib GWB

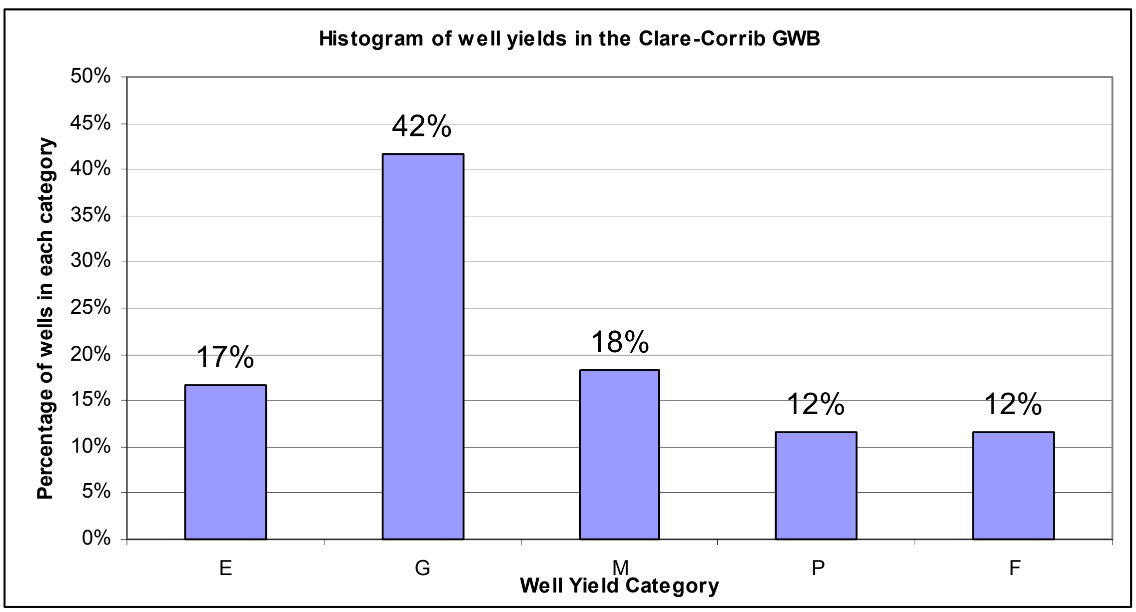


Figure 5 Histogram of Well Productivities in Clare-Corrib GWB

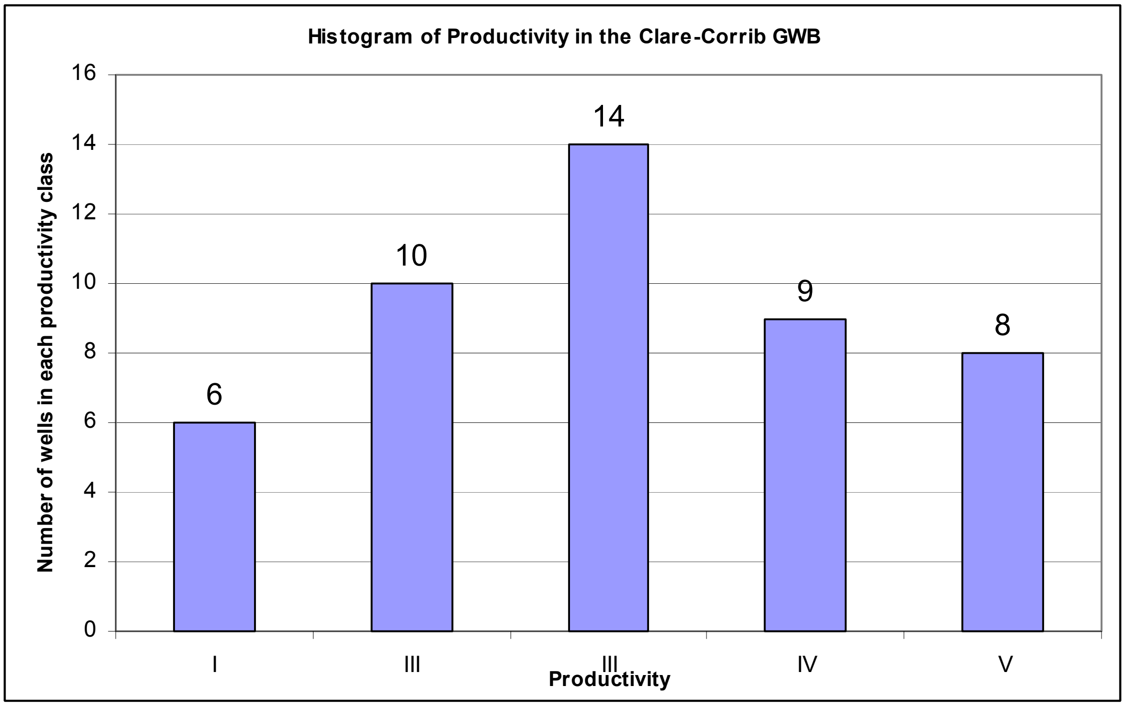
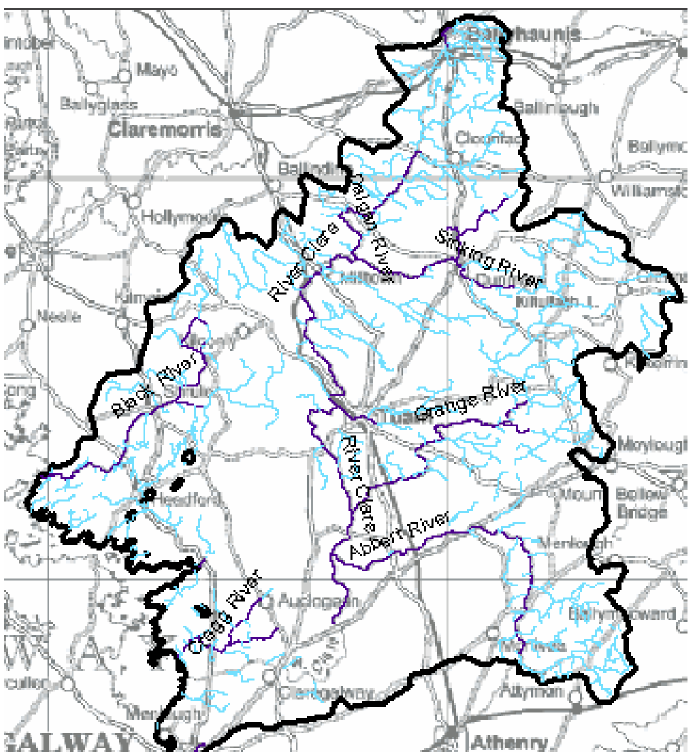


Table 1. Subsoil types in Clare-Corrib Groundwater.

PAR_MAT	Full name	Area sq m	% of GWB
TLs	Limestone Till	881175858	59.9%
TGr	Granitic Till	355611	0.0%
TDSs	Devonian Sandstone Till	72907274	5.0%
RsPt	Raised Peat	15612	0.0%
Rck	Rock	7076384	0.5%
nodata	nada	6512889	0.4%
Mrl	Marl	781353	0.1%
Made	Made Ground	7776478	0.5%
Lk_isle		513	0.0%
Lake		3857021	0.3%
L	Lake sediments undifferentiated	10777977	0.7%
KaRck	Karstified limestone bedrock at surface	53547458	3.6%
GLs	Limestone sands and gravels (Carboniferous)	45700893	3.1%
Esk	Eskers	1989472	0.1%
Cut	Cutover Peat	343496766	23.4%
BktPt	Blanket Peat	2558408	0.2%
BasEsk	Basic esker sands and gravels	5158629	0.4%
A	Undifferentiated alluvium	26211636	1.8%

Clare-Corrib GWB (For reference only)



List of Rock units in Clare-Corrib GWB

Unit Name	Code	Description	Rock Unit
Ardnasillagh Formation	AS	Dark cherty limestone, thin shale	Dinantian Pure Bedded Limestones
Aughnanure Oolite Formation	AU	Cross-bedded massive oolitic limestone	Dinantian Pure Bedded Limestones
Ballysteen Formation	BA	Dark muddy limestone, shale	Dinantian Lower Impure Limestones
~~Boyle Sandstone Formation~~	~~BO~~	~~Sandstone, siltstone, black mudstone~~	~~Dinantian Mixed Sandstones, Shales and Limestones~~
~~Cloonfad Felsite~~	~~CfFe~~	~~Felsite~~	~~Granites & other Igneous Intrusive rocks~~
Cong Canal Formation	NL	Medium to thick-bedded pure limestone	Dinantian Pure Bedded Limestones
Cong Limestone Formation	CO	Thick-bedded pure limestone	Dinantian Pure Bedded Limestones
Coranellistrum Formation	CT	Medium to thick-bedded pure limestone	Dinantian Pure Bedded Limestones
Illaunagappul Formation	IL	Limestone, thin shale partings	Dinantian Pure Bedded Limestones
Kilbryan Limestone Formation	KL	Dark nodular calcarenite & shale	Dinantian Lower Impure Limestones
Knockmaa Formation	KA	Thick-bedded pure limestone	Dinantian Pure Bedded Limestones
Lucan Formation	LU	Dark limestone & shale (Calp") "	Dinantian Upper Impure Limestones
Oakport Limestone Formation	OK	Pale grey massive limestone	Dinantian Pure Bedded Limestones
Oldchapel Limestone Formation	OC	Dark fine limestone & calcareous shale	Dinantian Pure Bedded Limestones
~~Owenriff Member~~	~~OUor~~	~~Dark limestone with thin shales~~	~~Dinantian Lower Impure Limestones~~
Two Mile Ditch Member	KAtm	Thick-bedded limestone, clay wayboards	Dinantian Pure Bedded Limestones
Visean Limestones (undifferentiated)	VIS	Undifferentiated limestone	Dinantian Pure Bedded Limestones
Waulsortian Limestones	WA	Massive unbedded lime-mudstone	Dinantian Pure Unbedded Limestones

Appendix B Establishment of Groundwater Source Protection Zones Mid-Galway Public Water Supply Scheme (May 2012)

Establishment of Groundwater Source Protection Zones

Mid-Galway Public Water Supply Scheme

Rev. A

May 2012

Prepared by:

Henning Moe and Michal Smietanka, CDM

With contributions from:

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And with assistance from:

Galway County Council

Project description

Since the 1980s, the Geological Survey of Ireland (GSI) has undertaken a considerable amount of work developing Groundwater Protection Schemes throughout the country. Groundwater Source Protection Zones are the surface and subsurface areas surrounding a groundwater source, *i.e.* a well, wellfield or spring, in which water and contaminants may enter groundwater and move towards the source. Knowledge of where the water is coming from is critical when trying to interpret water quality data at the groundwater source. The Source Protection Zone also provides an area in which to focus further investigation and is an area where protective measures can be introduced to maintain or improve the quality of groundwater.

The project "Establishment of Groundwater Source Protection Zones", led by the Environmental Protection Agency (EPA), represents a continuation of the GSI's work. A CDM/TOBIN/OCM project team has been retained by the EPA to establish Groundwater Source Protection Zones at monitoring points in the EPA's National Groundwater Quality Network.

A suite of maps and digital GIS layers accompany this report and the reports and maps are hosted on the EPA and GSI websites (www.epa.ie; www.gsi.ie).

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1 Introduction

Groundwater Source Protection Zones (SPZ) have been delineated for the Mid-Galway public water supply scheme according to the principles and methodologies set out in 'Groundwater Protection Schemes' (DELG/EPA/GSI, 1999) and in the GSI/EPA/IGI Training course on Groundwater SPZ Delineation.

The Mid-Galway Public Water Scheme (PWS) is sourced from an unnamed stream in the townland of Derreen, Co. Galway. In 2010 and 2011, the PWS pumped and distributed an estimated 4,000 m^3/d on average to households connected to the scheme.

The objectives of this report are as follows:

- To outline the principal hydrogeological characteristics of the area surrounding the PWS.
- To delineate source protection zones for the sources of water to the PWS.
- To assist the Environmental Protection Agency and Galway County Council in protecting the water supply from contamination.

The protection zones are intended to provide a guide in the planning and regulation of development and human activities to ensure groundwater quality is protected. More details on protection zones are presented in 'Groundwater Protection Schemes' (DELG/EPA/GSI, 1999).

The maps produced are based largely on the readily available information in the area, a field walkover survey, water level monitoring during normal pumping operations, and on mapping techniques which use inferences and judgements based on experience at other sites. As such, the maps cannot claim to be definitively accurate across the whole area covered, and should not be used as the sole basis for site-specific decisions, which will usually require the collection of additional site-specific data.

The authors wish to acknowledge the contributions made by the caretakers of water supply facilities at the Mid-Galway PWS, the Barnaderg group water scheme (GWS), and the Brierfield GWS.

2 Methodology

The methodology applied to delineate the SPZ consisted of data collection, desk studies, site visits, field mapping of geological exposures, mapping of geomorphology and karst features, well audits, water level recording, flow measurements, tracer testing, as well as subsequent data analysis and interpretation. The work was carried out between June 2010 and October 2011.

3 Location, Site Description and Spring Protection

As shown in **Figure 1**, the Mid-Galway PWS is located approximately 4 km to the northeast of Abbey village and 3.5 km south of Barnaderg village. The source of the water for the PWS is an unnamed stream which flows south from Horseleap Lough to the Abbert River. For ease of reference, this stream is referenced as the Derreen stream, named after the townland that the PWS is located in and which provides water to the PWS. Derreen stream is intermittent in its upper reaches between the Barnaderg GWS and Horseleap Lough.

The PWS is contained within a fenced-in area that holds a new (2011) reservoir, treatment facility, and pumphouse. The water is filtered and disinfected at source prior to distribution. Photographs of the PWS and general points of interest are included in **Appendix A**.

Figure 1: Location Map with Points of Interest

4 Summary of Sources

Table 1 provides a summary of the PWS. The average quantity of water abstracted and distributed in 2010/2011 was 4,000 m^3/d but abstraction records indicate this can range with demand from 2,500 to 5,500 m^3/d.

Table 1: Source Details

	Mid-Galway PWS
Reporting Code	IE_WE_G_225_07_003
Groundwater Body	Clare-Corrib (IE_WE_G_0020)
Grid reference	153928E, 244679N
Townland	Derreen
Source type	Surface water (originating mainly as groundwater)
Owner	Galway County Council
Elevation (Ground Level - GPS)	54 mOD
Average daily abstraction (m^3/d):	4,000
Estimated median discharge (m^3/d)*	19,000

Note:
** - Estimated from EPA flow records for the measurement period between October 2009 through June 2011.*

The PWS sources its water from an intake on an unnamed stream which flows between Horseleap Lough (see **Figure 1**) and the Abbert River. The stream's flow has been monitored by the EPA since October 2009 when an automatic flow recorder (a Time of Flight ultrasonic device) was installed by the bridge approximately 20 m downstream of the PWS intake. As such, the device records flows which are influenced by the abstractions from the PWS. A second, smaller abstraction also takes place at the Barnaderg GWS, located approximately 700 m upstream of the PWS (see **Figure 1**). Until late 2011, the GWS sourced its water from a spring which contributes overflow to the Derreen stream. The GWS presently produces water from a new well drilled less than 100 m from the spring, drawing on the same groundwater that otherwise discharges naturally to the spring. The total average abstraction from the GWS in 2010-2011 was approximately 900 - 1,000 m^3/d.

Estimated flows are shown in **Figure 2** for the period between October 2009 and June 2011. There are data gaps, particularly in the first few months of operation, however, the estimated flow ranged from 30 l/s (2,590 m^3/d) in early September 2010 to approximately 4,000 l/s (345,600 m^3/d) during the flood events of November 2009. The flow records are characterised by dry- and wet-weather extremes. In order to reduce potential skewing of flow statistics by extreme events, median flows have been defined rather than arithmetic averages. For the measurement period referenced above, the median flow is 168 l/s (14,515 m^3/d). This increases to 225 l/s when abstractions from the PWS and the Barnaderg GWS are added. When only daily maxima values are used (i.e. by removing potential streamflow reductions from abstractions), the median flow becomes 220 l/s (19,000 m^3/d), and the bi-weighted mean is very similar, at 214 l/s. A value of 220 l/s is, therefore, considered a more representative flow to be used for purposes of delineating zones of contribution to the PWS. It is represented primarily by groundwater discharges into the stream from: a) individual springs; and b) diffuse seepages along the stream bed and bedding planes on adjacent stream banks. Surface water contributions only become important at much higher flows, and originate as runoff in ditches, overflow from Horseleap Lough, as well as overflow from a topographic depression just east of Horseleap (which joins the outflow from the lake near the Horseleap Bridge).

A rare opportunity was afforded in early September 2010 to observe a sudden hydraulic 'transformation' of the hydrological system in response to a single, individual storm event. As indicated in **Figure 3**, 51 mm rainfall event was recorded on September 6th at a nearby rainfall station at Glenamaddy, less than 20 km to the north-northeast of the PWS.

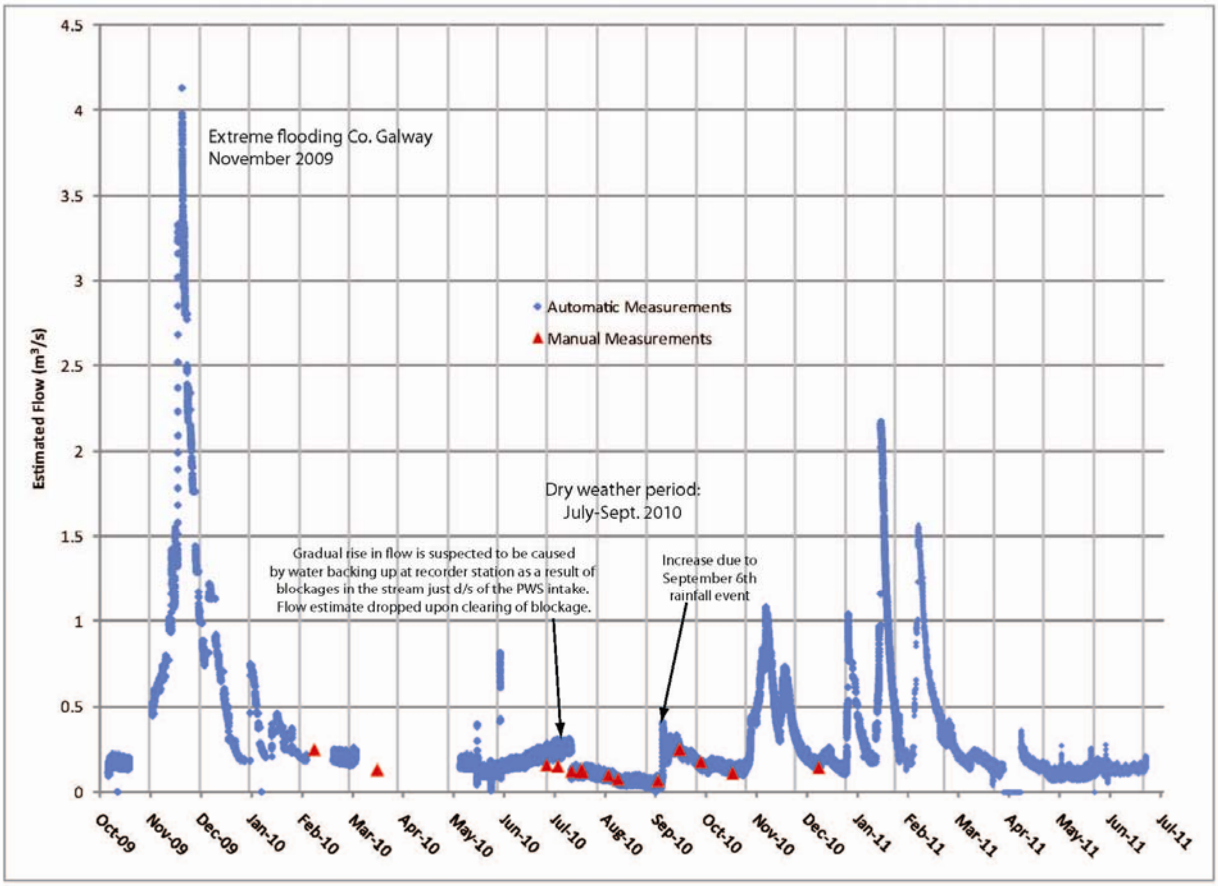


Figure 2: Estimated (Measured) Flow in the Derreen Stream October 2009 – July 2011

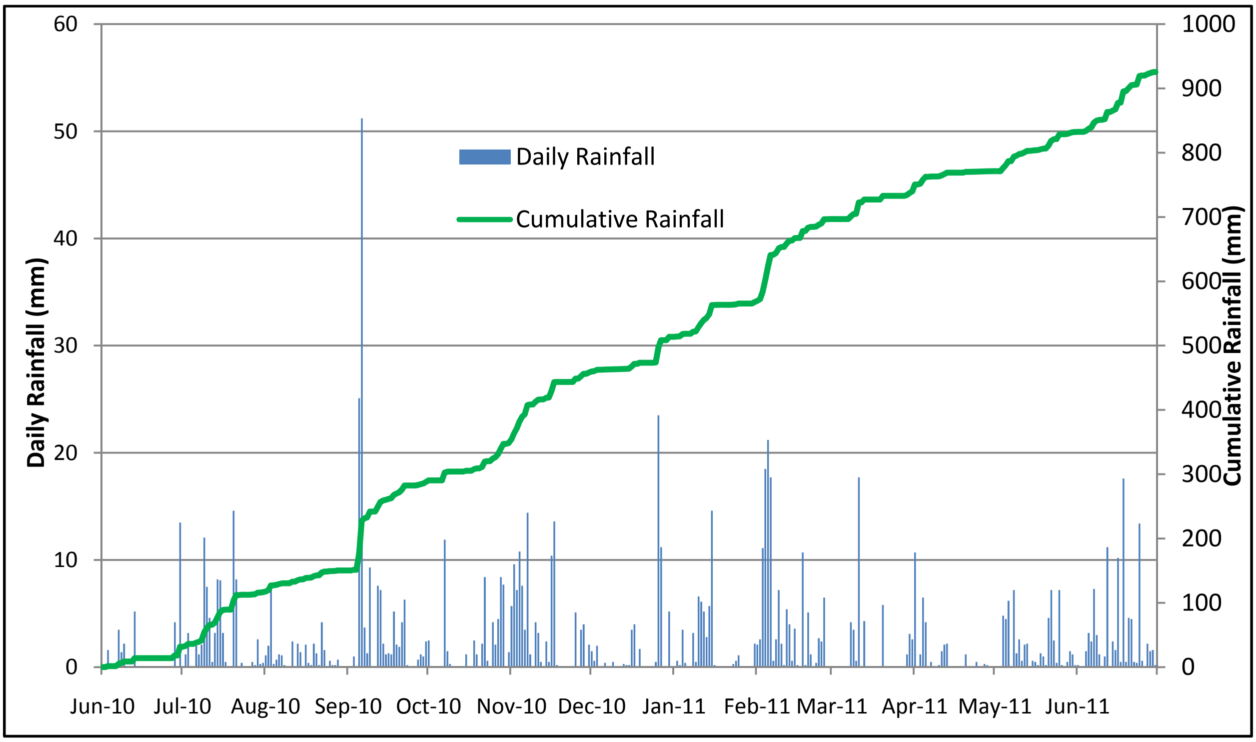


Figure 3: Daily and Cumulative Rainfall at Glenamaddy, June 2010 to July 2011

The hydrological changes that resulted are summarized in **Figure 4** along the Derreen stream, where manual flow measurements of individual discharge points and streamflow were made on September 3rd (the end of the extended dry weather period) and September 16th (post-September 6th storm event). The September 16th measurements are consistent with similar measurements by the EPA in March 2008, which are reproduced in **Figure 5,** although spring discharges and inflows from ditches in the wooded area near the PWS were much larger on March 6th, 2008 presumably because antecedent ground conditions were more saturated.

General observations from site visits on different dates testify to a dynamic groundwater flow system where individual discharge points appear and disappear as a function of the hydrological conditions that preceded or existed on the dates of measurement/visit. These types of springs are typically known as 'overflow' springs, and typically point to the presence of a complex system of underground conduits. As noted by the red text in **Figure 4**, two additional springs were active on February 14, 2011 on the east bank of the Derreen stream. These springs appeared after heavy rainfall events in January and early February 2011, whereby water levels built up over time before reaching ground surface at these locations (note, 3-4 metres above stream level). Their combined measured discharges were approximately 80 l/s (10% of the total measured flow in the Derreen stream on that day).

The area between Horseleap Lough and the PWS undoubtedly represents an important groundwater discharge area. It occupies a relatively low topographic position adjacent to the Abbert River and, indeed, the Abbert River may be acting as a hydraulic boundary to groundwater flow. This, however, has not yet been conclusively demonstrated. Drew (1973) identified a shallow conduit system that passes beneath and across the Abbert River at Ballyglunin, approximately 7.5 km to the southwest of the PWS. A similar situation could exist closer to the Mid-Galway PWS.

The groundwater discharges associated with the Derreen stream are small compared to the Pollifrin Spring, shown in **Figure 6**, which is located approximately 2.2 km to the east-southeast of the PWS. It consists of three discrete but connected discharge points, and is by far the largest of all discharges in the study area. Pollifrin is a source of water for the Brierfield GWS, with an average daily abstraction of 100 m^3/d. Given its location and based on results of dye tracer testing (see Section 8), Pollifrin is considered to be part of the same hydrogeological system that supplies water to the Mid-Galway PWS and the Barnaderg GWS. Unfortunately, there are no historical flow records from Pollifrin. Manual spot measurements of the outflow channel that carries water to the Abbert River yielded a range of flows between 30 l/s (2,592 m^3/d) on August 5, 2010 and 2,623 l/s (226,627 m^3/d) on January 17, 2011. The latter includes an estimated contribution of 200 l/s (17,280 m^3/d) from surface runoff (i.e. inflow from ditches). The Pollifrin spring appears to be subject to the same extreme behaviour as the Derreen stream. From the few measurements that exist, the median flow (discharge) is estimated at 411 l/s (35,510 m^3/d). Combined with the records from the PWS, the total median discharge for the entire groundwater discharge system is estimated to be 631 l/s (54,518 m^3/d).

4.1 Topography, Surface Hydrology, Landuse

The PWS is situated approximately 54 mOD at the edge of a forested area which is surrounded by agricultural (pasture) land. Topography rises gently in an east-northeasterly direction to elevations of approximately 80-90 mOD in the vicinity of Moylough (see **Figure 1**). The roughly triangular area between the PWS, Moylough and Menlough (to the south of Moylough) forms a gently rolling limestone 'plateau' which is generally devoid of surface drainage features but incorporates numerous small enclosed depressions that pond rainwater following high intensity or long duration rainfall events. The general study area is demarcated by limestone hills at Oakwood (160 mOD, near Abbeyknockmoy, south of the Abbert River), Knock (115 mOD, near Barnaderg village), and Mountbernard (125 mOD, some 11 km east of Monivea village).

The PWS is located in the Western River Basin District, within the Clare River catchment. Regional drainage is to the west-southwest, towards the Clare River. Local drainage, including the Derreen Stream, is towards the Abbert River which in turn flows into the Clare River. Other significant surface water features within the study area are Horseleap Lough to the east-northeast of the PWS and Summerville Lough to the west of Moylough. Whereas the Abbert River is a regional drainage feature, the two loughs are local features with small catchment areas.

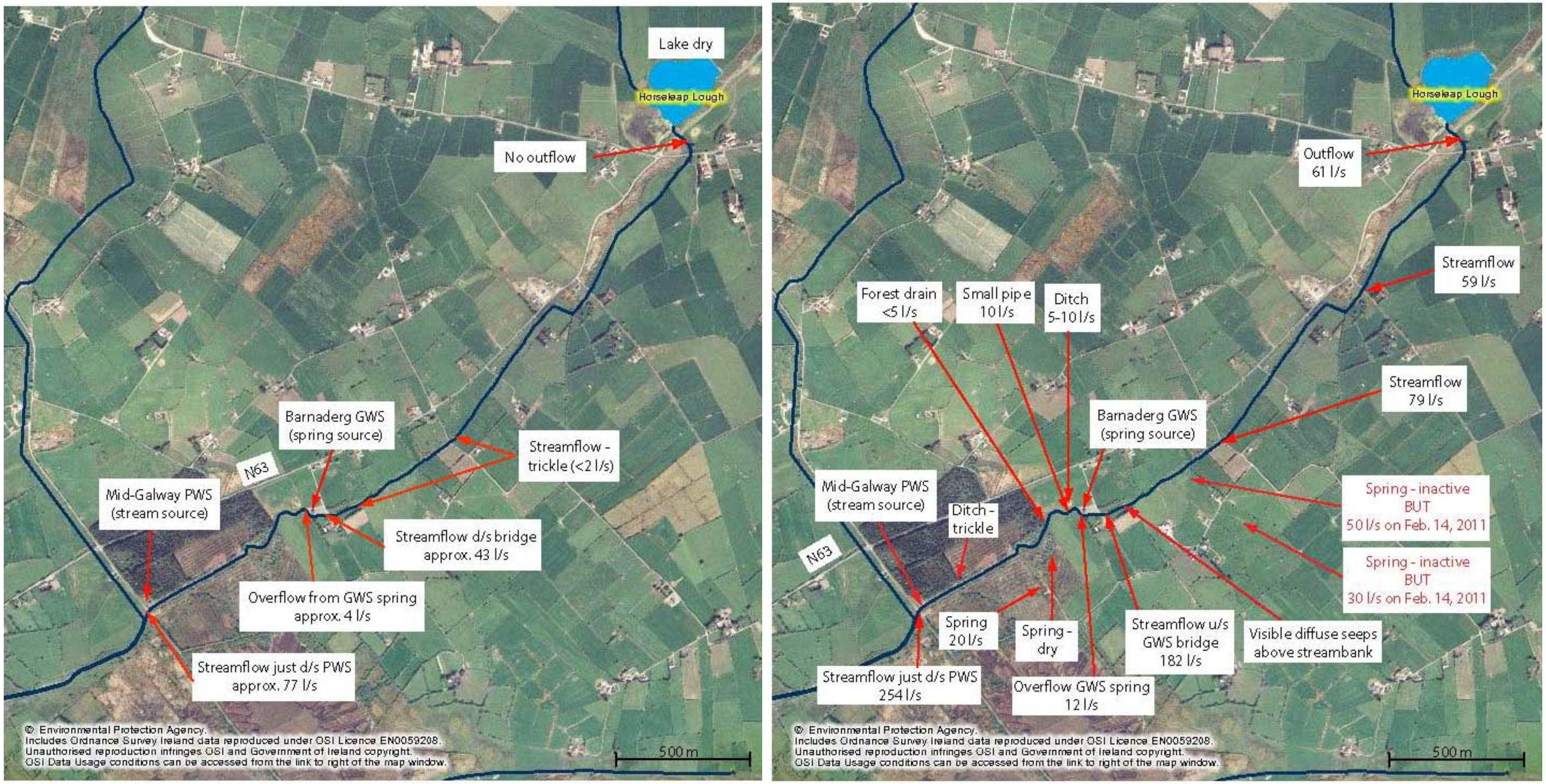
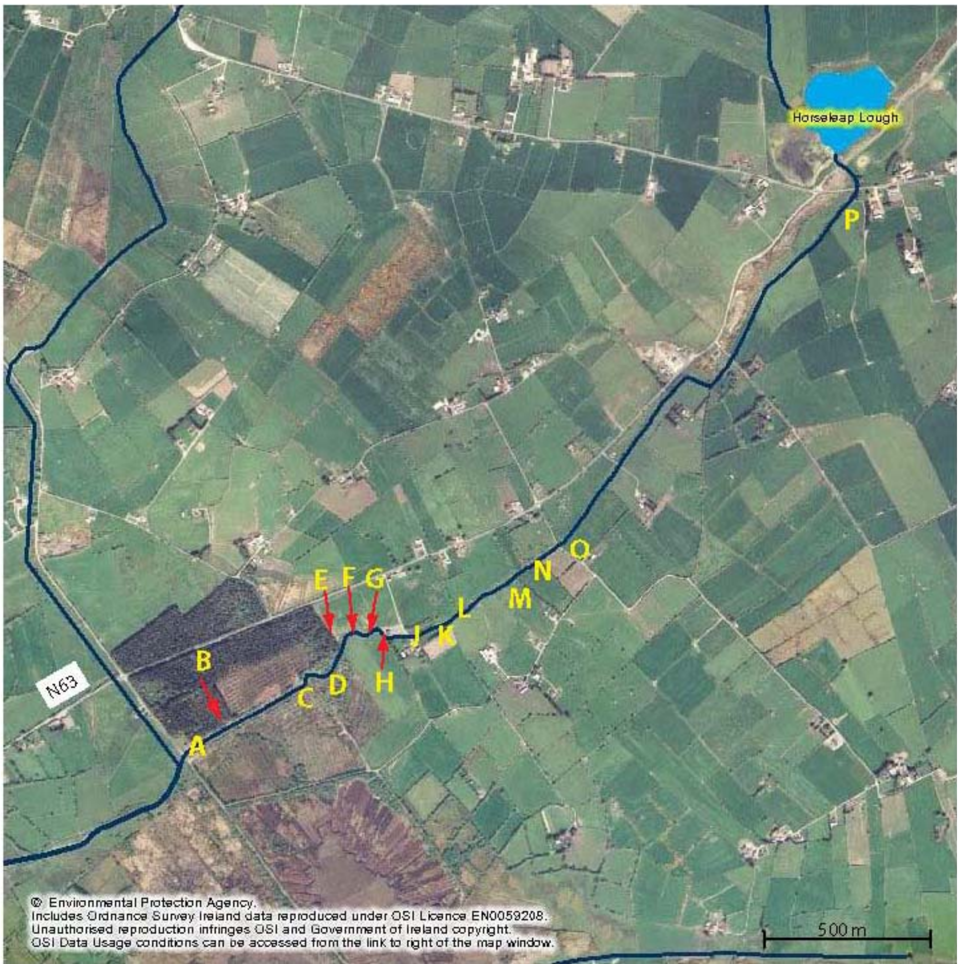
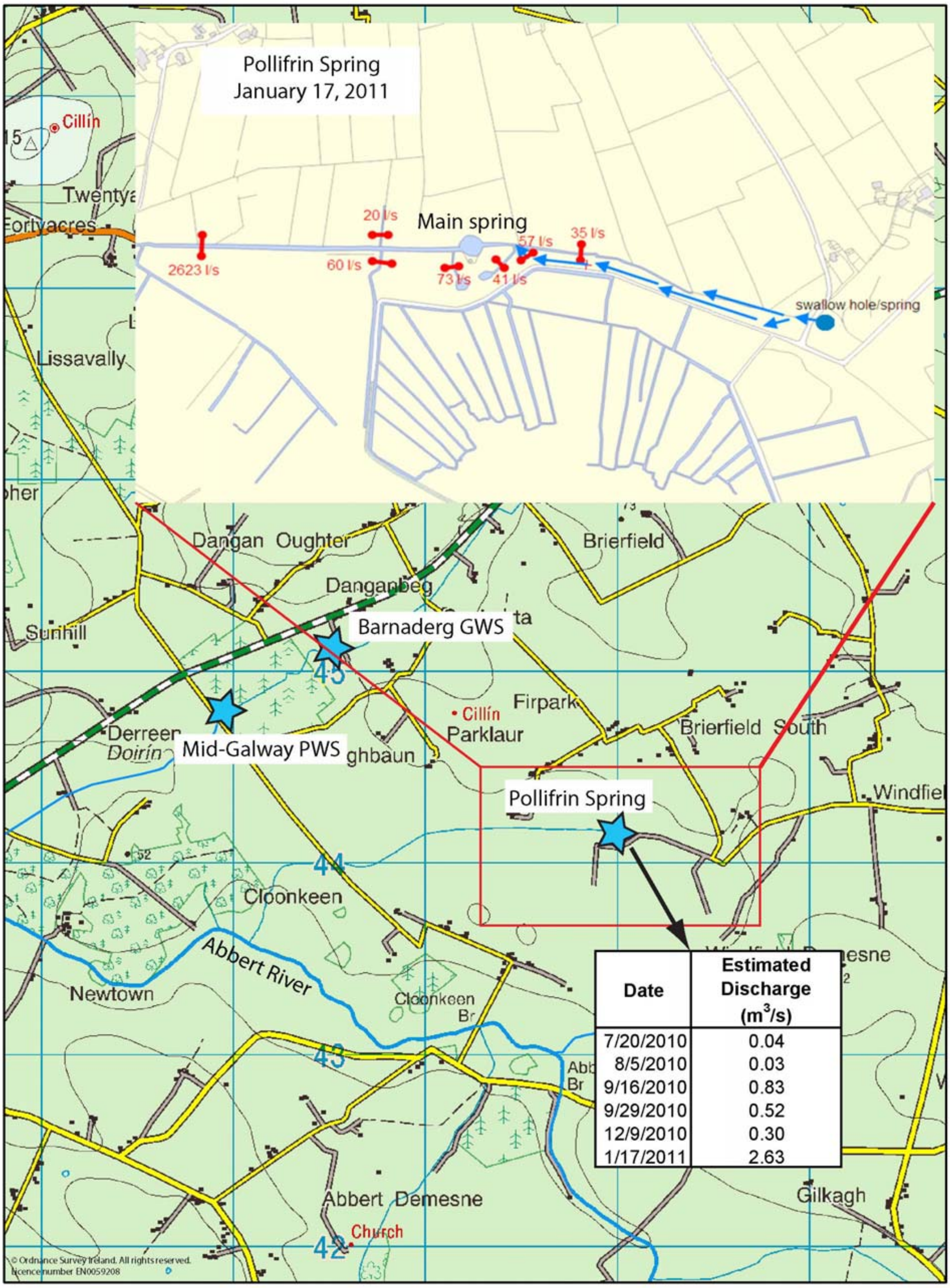


Figure 4: Flow Contributions to Derreen Stream on September 3rd and 16th, 2010



Location	Flow m³/s	EC	Ph	Temp	Description
A	0.3316	703	7	10.5	Main channel, just u/s of Mid-Galway PWS
B	0.0363	693	7.12	10.2	Inflow (ditch)
C	0.0858	709	6.76	10.2	Spring contribution
D	0.0158	708	6.94	10.2	Spring contribution
E	0.0055	790	7.46	9.7	Inflow (ditch)
F	0.007	728	7.09	10.2	Inflow from covered spring via pipe
G	0.0023	712	7.06	9.2	Spring
H	0.006	708	6.81	10.2	Overflow from spring at Barnaderg GWS
J	0.188	715	6.82	9.9	Main channel
K	0.0866	708	6.76	10.1	Diffuse discharges from the stream bank
L	0.1014	700	7.26	9.6	Main channel
M	--				Spring, no flow
N	0.035	680	7.03	9.4	Seep via ditch
O	0.057	661	7.51	9.1	Main channel
P	0.0368	604	8.15	8.6	Outflow from Horseleap Lough

Figure 5: Flow Contributions to Derreen Stream on March 6, 2008



Date	Estimated Discharge (m^3/s)
7/20/2010	0.04
8/5/2010	0.03
9/16/2010	0.83
9/29/2010	0.52
12/9/2010	0.30
1/17/2011	2.63

Figure 6: Spot Measurements of Discharges from Pollifrin Spring

5 Hydrometeorology

Establishing groundwater source protection zones requires an understanding of general hydrometeorological patterns across the area of interest. The information presented below was obtained from Met Éireann.

Annual Average Rainfall: 1,057 mm. The contoured map of rainfall data in Ireland (Met Éireann website, data averaged from 1961–1990) shows that the source is located between the 1,000 mm and the 1,200 mm average annual rainfall isohyets. The closest meteorological (rainfall) station is at Glenamaddy (Gortnagier) approximately 15 km away to the north, with a 30-year average annual rainfall of 1,057 mm. For the study period between June 2010 and June 2011 (see **Figure 3**), the total rainfall was 850 mm.

Annual evapotranspiration losses: 450 mm. Potential evapotranspiration (P.E.) is estimated to be 475 mm/yr (based on data from Met Éireann). Actual evapotranspiration (A.E.) is estimated as 95% of P.E., to allow for seasonal soil moisture deficits.

Annual Average Effective Rainfall: 607 mm. The annual average effective rainfall is calculated by subtracting actual evapotranspiration (450 mm) from rainfall (1,057 mm). The 30-year average potential recharge to groundwater is therefore 607 mm/year.

Reference is made to Section 9 on recharge which estimates the proportion of effective rainfall that enters the groundwater system.

6 Geology

This section outlines the relevant characteristics of the geology of the immediate study area. It provides a framework for the assessment of groundwater flow and source protection zones. The geological information is based on:

- Geology of South Mayo. Bedrock Geology 1:100,000 Map series, Sheet 11, Geological Survey of Ireland (McConnell et al, 2002);
- Geology of Longford-Roscommon. Bedrock Geology 1:100,000 Map series, Sheet 12, Geological Survey of Ireland (Morris et al, 2003);
- Field mapping of bedrock outcrops, karst features, and Quaternary deposits;
- Discussions with Markus Pracht of the bedrock section of the Geological Survey of Ireland.

6.1 Bedrock

As indicated in **Figure 7**, the bedrock in the entire study area has been mapped by the GSI as Dinantian Pure Bedded Limestone. Outcrops of bedrock are generally scarce, but consist of pale grey, thin bedded (<1 m) limestones that are nearly horizontally bedded.

6.2 Karst Features

Important karst features have been mapped (see **Figure 7** and **Appendix B**) during walkover surveys. Besides the springs highlighted between Horseleap Lough and the PWS, the most significant karst features within the study area include two turloughs (Cloonoran and Loch Na Lasrach, both near Moylough), active swallow holes (e.g. Moylough Castle, Loch Na Lasrach and Ballynamona), as well as the large spring(s) at Pollifrin. Within the elevated limestone plateau that was referenced in Section 4, there are literally dozens of enclosed depressions (too many to map individually as part of this project).

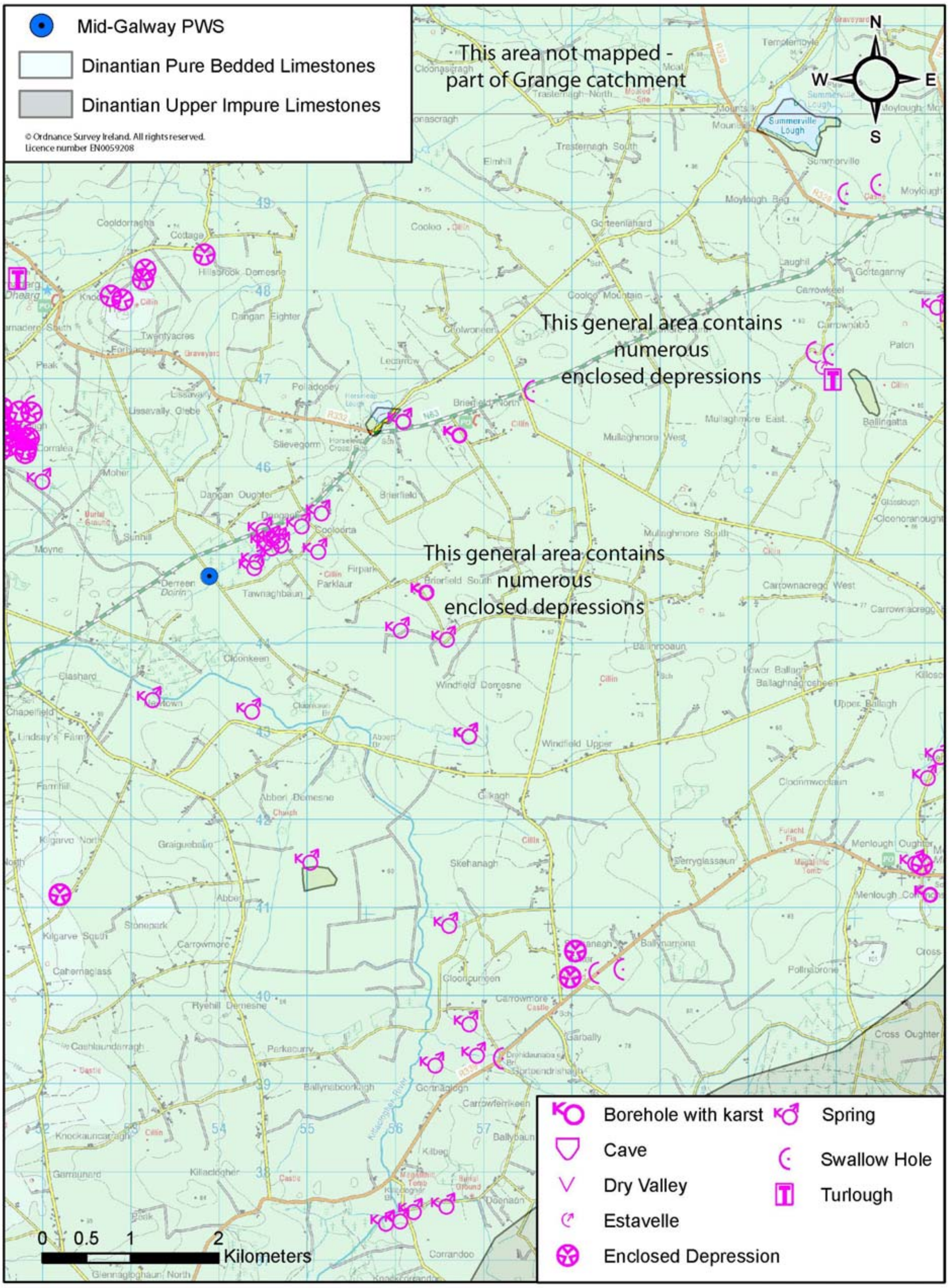


Figure 7: Bedrock/Rock Unit and Karst Features Map

In addition, there is evidence of kart conduits in at least three boreholes, including the well that was drilled adjacent to the Barnaderg GWS spring (Hydro-G, 2011). Until the autumn of 2011, the GWS abstracted an estimated 1,000 m^3/d from the Barnaderg spring which now overflows into the Derreen stream. The new well drilled in 2011 has since become the primary source of water for the GWS. The borehole is approximately 53 m deep. Drilling was stopped when a major conduit was encountered which produced 'sufficient' quantities of water to meet the demands of the GWS. During air-lifting and test pumping of the borehole, an immediate response was observed in the water levels and overflow at the GWS spring source, proving a direct connection between the spring and the deeper conduit intersected by the borehole (Bartley, 2011). Whether or not the deeper conduit is the principal 'feeder' to the Barnaderg spring is not known. Similar instantaneous water level changes were also noted in a disused borehole approximately 150 m to the west of the new borehole, suggesting the presence of a deeper conduit system in the PWS discharge area generally.

6.3 Depth to Bedrock

Soils are thin (<3 m) across much of the study area but depth to bedrock increases along eskers and moraine ridges (see below) as well as within the peat areas of Horseleap Lough, Summerville Lough, Loch Na Lasrach and the Abbert River, as well as small, internal drainages within the limestone plateau area (where water ponds and partly recharges the underlying aquifer). At the new borehole at the Barnaderg GWS, till and alluvial sediments were found to be nearly 10 m thick, and is presumably associated with the linear NE-SW trending esker at Horseleap Lough.

6.4 Soil and Subsoil Geology

Mapped soils within the study area, see **Figure 8**, include deep, well drained mineral soils (BminDW) across much of the study area with pockets of shallow peaty soils surrounding the previously referenced loughs and peat areas. Shallow, well drained mineral soils (BminSW) are associated with linear esker deposits, whilst lacustrine soils (clays/marl) are associated with the Loch Na Lasrach turlough.

Mapped subsoils, see **Figure 9**, consist primarily of glacial limestone-derived till (TLs) and cutover peat (cut). Other subsoil types mapped in the study area include linear esker deposits stretching from the PWS to Summerville Lough, re-worked gravel deposits derived from the limestone till, and lacustrine clays at the Loch Na Lasrach turlough. Subsoil permeability, as mapped by Teagasc, is 'moderate' across the limestone till areas, 'high' along the esker deposits, and 'low' in the pockets of peat and lacustrine clays. Window sampling was carried out at the eastern end of Summerville Lough to examine the nature of subsoils adjacent to the peat area that drains to the swallow hole at Moylough Castle. The logs of 9 shallow (<5 m deep) boreholes are reproduced in **Appendix C**, and indicate a range of subsoil grades and layering of peat, clay, silt, sand and gravel. The peat is believed to be relatively thin. In addition to surface drainage from the peat towards the swallow hole, it is also possible that subsurface drainage takes place via sandy deposits.

During field mapping of karst features, an interesting subsoil feature was noted at the northern end of the Loch Na Lasrach turlough. As indicated on **Figure 10**, a drainage channel has been partly excavated by local residents in an attempt to alleviate flooding in the turlough, whereby the flood water would drain north towards the low-lying area near Cloonoran Turlough. The dug channel takes advantage of a natural, linear depression which, according to local residents, is filled with 'sandy material'. Exposures at the base of the main meltwater channel indicate the presence of well drained, permeable till. On the basis of the local geomorphology, the natural, linear depression is interpreted to be a glacial outwash channel. It is flanked to the east by a parallel high moraine ridge and aligns with N-S trending deposits to the south of the turlough. There are three other, but more subtle, parallel outwash channels between Loch Na Lasrach and Lakeview that also extend to the north. Observations of relative elevations suggest that the main outwash channel is in direct hydraulic communication with the Loch Na Lasrach turlough, certainly when water levels are high.

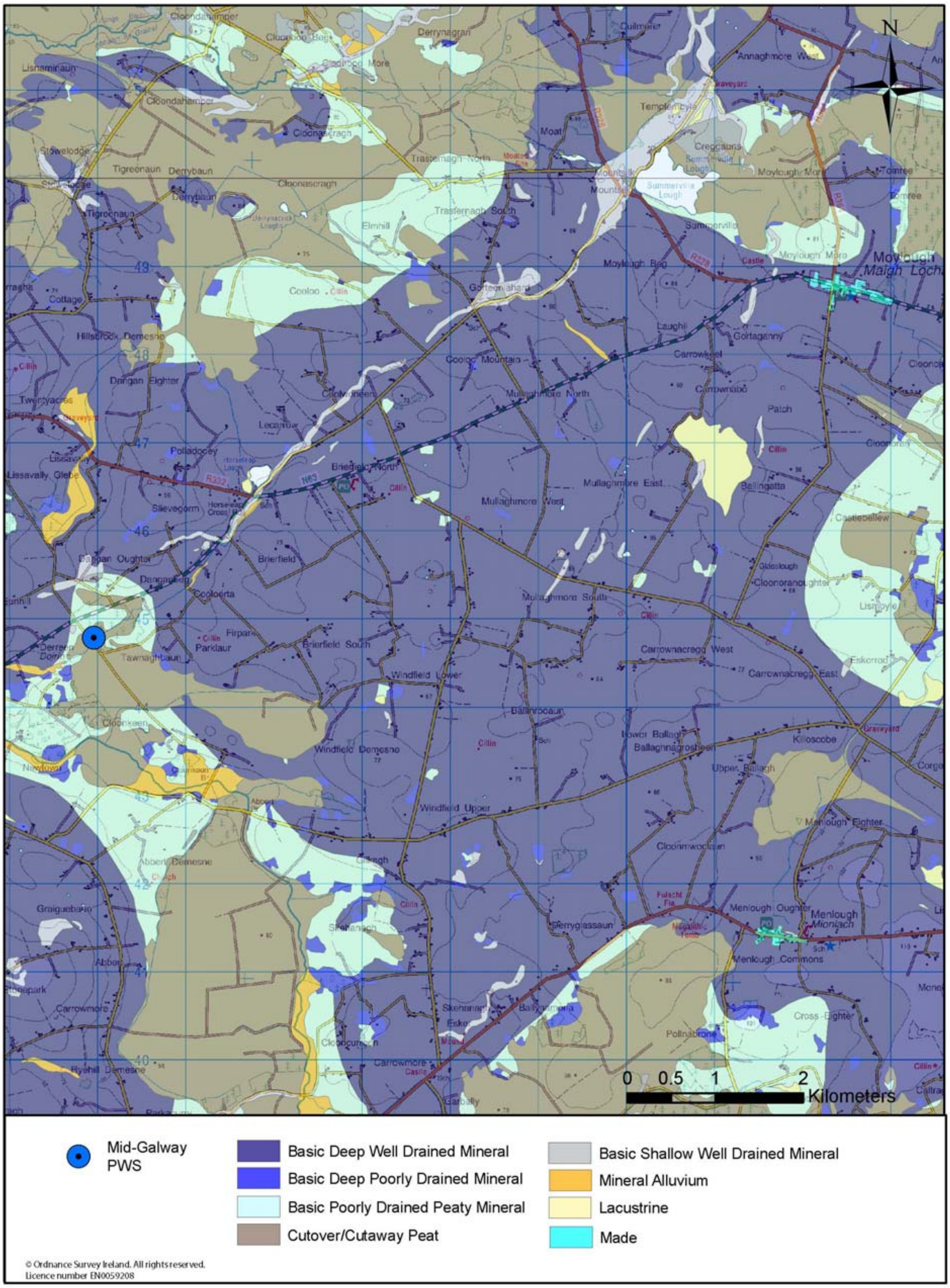


Figure 8: Soils Map

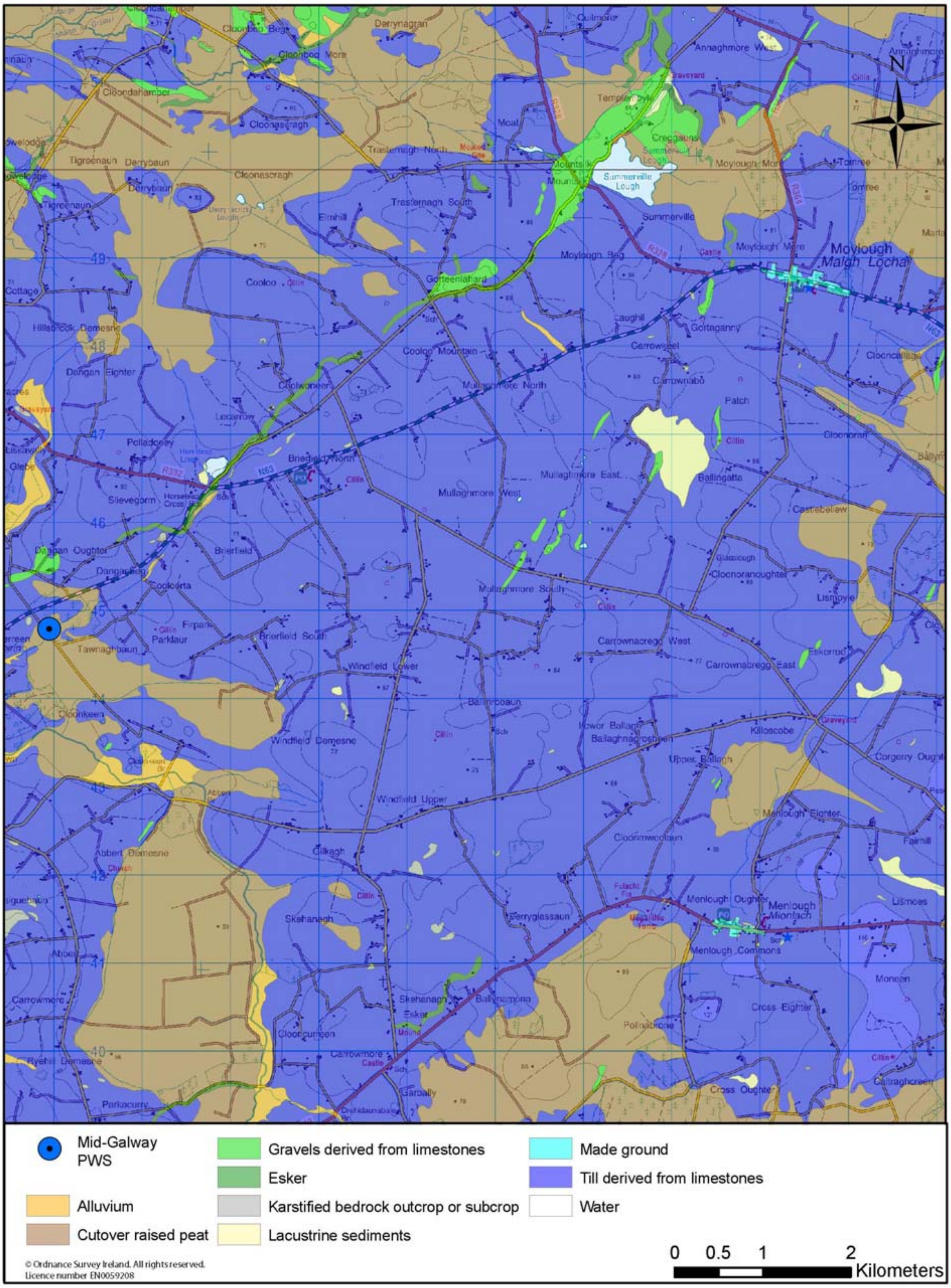


Figure 9: Subsoils Map

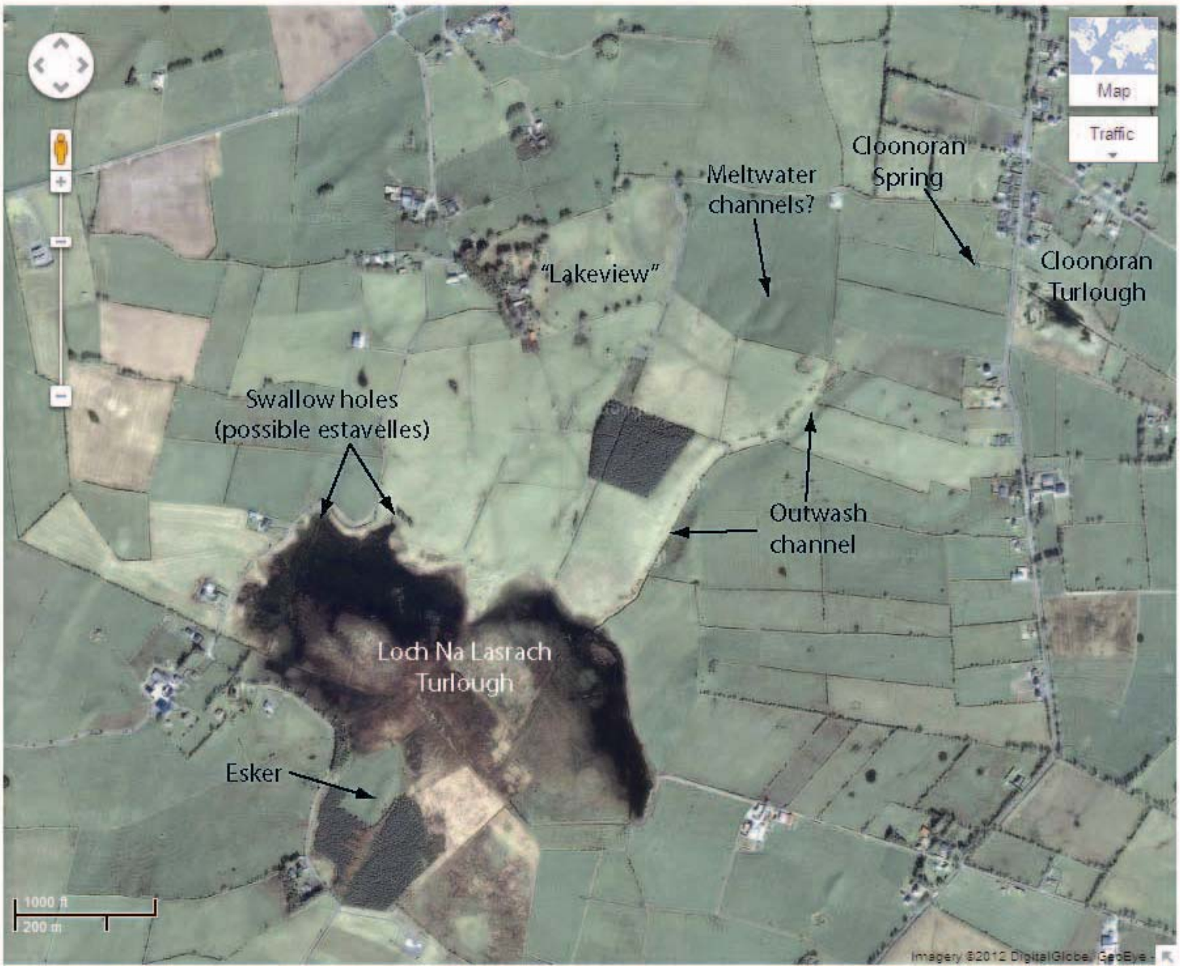


Figure 10: Outwash Channel from Loch Na Lasrach

This implies that some water escapes from the turlough as shallow groundwater in a northerly direction via the outwash deposits. The meltwater channel curves to the northeast towards the spring that supplies water to the Cloonoran turlough to the south of Moylough, which in turn overflows and drains further east towards Mountbellew, and ultimately to the Suck River. This implies that Loch Na Lasrach is part of the western headwaters of the Suck River and, by inference, also the Shannon River.

7 Groundwater Vulnerability

Groundwater vulnerability is dictated by the nature and thickness of the material overlying the uppermost groundwater 'target', which in the case of the Mid-Galway PWS is the limestone aquifer. As such, vulnerability relates primarily to the permeability and thickness of subsoil. A detailed description of the vulnerability categories can be found in the Groundwater Protection Schemes document (DELG/EPA/GSI, 1999) and in the draft GSI Guidelines for Assessment and Mapping of Groundwater Vulnerability to Contamination (Fitzsimons et al, 2003).

A groundwater vulnerability map for County Galway has been developed by the GSI. As shown in **Figure 11**, vulnerability is mapped as 'extreme' and 'high' within most of the study area, 'moderate' where subsoils are thick (e.g. esker ridges), and 'low' where peat and lacustrine clays are present. In the immediate vicinity of the PWS, vulnerability is mapped as 'moderate' and 'low' on account of peaty subsoils and greater depths to bedrock.

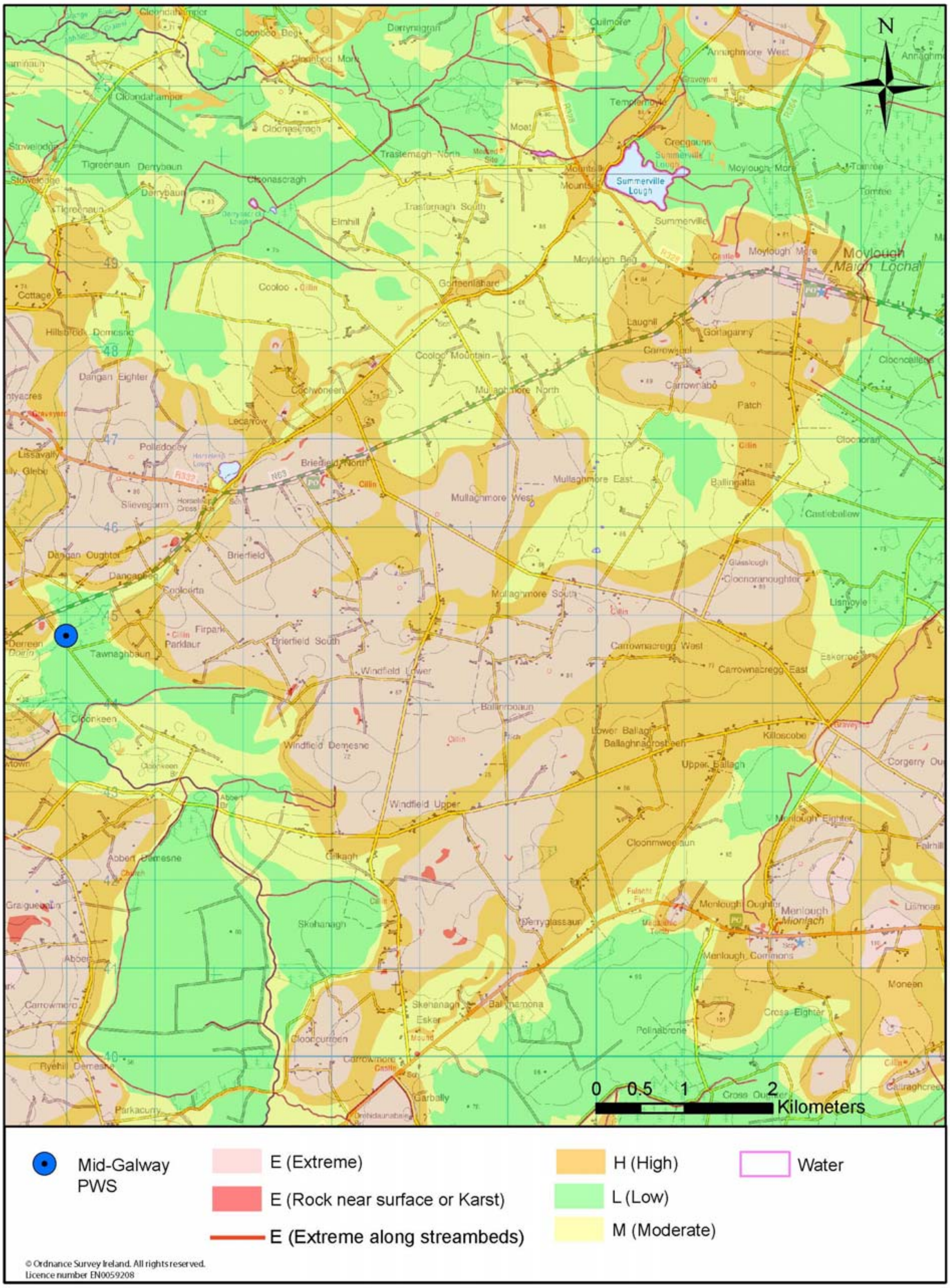


Figure 11: Groundwater Vulnerability Map

8 Hydrogeology

This section describes the current understanding of the hydrogeology of the study area of the PWS. Hydrogeological and hydrochemical information was obtained from the following sources:

- GSI and EPA websites and databases;
- County Council Staff and drinking water returns;
- Met Eireann rainfall and evapotranspiration data;
- Field mapping, tracer testing and measurements.

8.1 Groundwater Body and Status

The main spring that supplies the PWS is located within the Clare-Corrib groundwater body (GWB) which has been classified by the EPA as being of "Poor" status (due to elevated phosphorus concentrations). The groundwater body descriptions are available from the GSI website: www.gsi.ie and the 'status' is obtained from the Water Framework Directive website: www.wfdireland.ie/maps.html.

8.2 Groundwater levels, flow directions and gradients

The limestone bedrock in the area is karstic as evidenced by general spring characteristics and mapped karst features. As such, fissures and conduits dictate flow patterns, directions and rates. These flows vary in space and time as a function of changes in hydrometeorological conditions. General topographic and drainage considerations suggest that groundwater flow is from northeast to southwest. To establish flow directions, travel times, and zones of contribution(s), 7 dye tracer tests were conducted from 7 dye injection locations between June 2010 and April 2011, and again in October 2011, specifically targeting detection in the Derreen stream and the springs at the Barnaderg GWS and Pollifrin. Summarised in **Appendix D**, five tests were positively traced to one or more of these locations, as follows:

- An actively draining swallow hole near Moylough Castle was traced to Barnaderg GWS and the Mid-Galway PWS. Pollifrin was not sampled for this test, hence, it is not known if the dye discharged at this location.
- Using tankered water for dye flushing purpose, a recently (2009) opened surface collapse feature at Mullaghmore North was traced to Barnaderg GWS and the Mid-Galway-PWS, with a suspected/marginal detection also at Pollifrin.
- An actively draining swallow hole at the Loc Na Lasrach turlough resulted in confirmed traces to the Mid-Galway PWS and Pollifrin.
- Using tankered water for dye flushing purposes, a doline located at Windfield Demesne was traced to the Mid-Galway PWS and Pollifrin.
- An actively draining swallow hole at Ballynamena was traced to the Mid-Galway PWS, with a suspected/marginal detection also at the spring at the Barnaderg GWS. The dye was not detected at Pollifrin.

Two traces did not yield any results, i.e. the dyes were not detected in any of the sampling locations. These traces were injected in an active swallow hole at Carrowmanagh, approximately 3 km to the northwest of the PWS, and a doline at Annaghmore, approximately 3 km north of Moylough village. One test, from the active swallow hole at Ballynamena, was repeated in October 2011 due to inconclusive results during a first attempt in April 2011.

It should be pointed out that detections of dye at the Mid-Galway PWS are attributed to the sampling that was carried out along the Derreen stream, both at selected upgradient springs and diffuse seepages as well as by the PWS itself. Results point to a complex flow system with contributions to the Mid-Galway PWS from both proximal and distal locations to the northeast, east, and southeast. The results further demonstrate that the general area that incorporates the PWS, the Barnaderg GWS, and the Pollifrin spring can be considered part of the same groundwater flow system (see Figure 1 and also Section 9).

With evidence of flow from the Loch Na Lasrach turlough to the Mid-Galway PWS (and Pollifrin), it is concluded that the turlough is part of the ZOC of the PWS which drains to the Abbert River which in turn flows into the Clare River. In Section 6.4, it was demonstrated that the turlough also contributes to the Suck River catchment. By inference, the turlough is situated at the natural groundwater divide between the Shannon and Western River Basins.

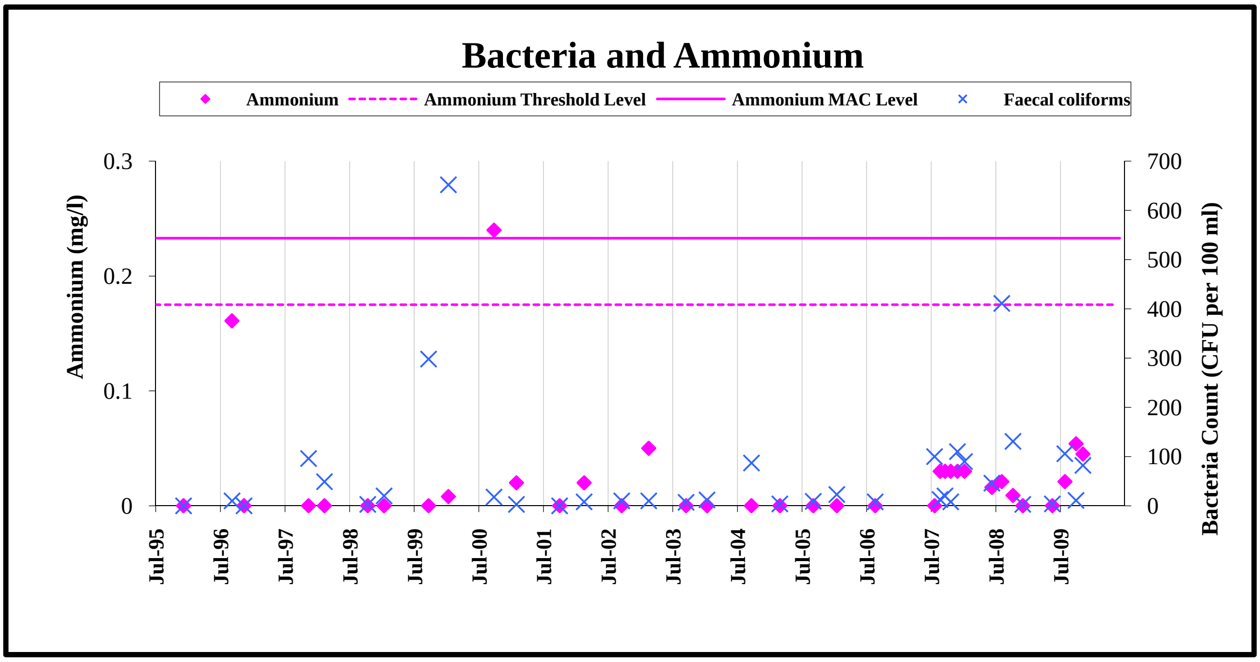
The established southwest and westerly groundwater flow components to the Mid-Galway PWS contrast with the demonstrated north-northeasterly flow gradients associated with the Mountbellew PWS (CDM 2011) and Caltra GWS (CDM 2012a).

8.3 Hydrochemistry and Water Quality

The Mid-Galway PWS was monitored by the EPA annually between 1995 and 1998, semi-annually between 1995 and 2006, and has been monitored quarterly from 2006 to present. The PWS was included in the EPA operational chemical network in late-2006. The sample point is in the pump house, prior to treatment. Existing laboratory results have been compared to these thresholds or standards: EU Drinking Water Council Directive 98/83/EC Maximum Admissible Concentrations (MAC); the European Communities Environmental Objectives (Groundwater) Regulations 2010, which were recently adopted in Ireland under S.I. No. 9 of 2010.

The water quality data are summarised graphically in **Figures 12 to 15**, representing up to 36 samples in total (until the end of 2009), and results are highlighted as follows:

- The water is hard (average 352 mg/l $CaCO_3$). Field conductivity ranges between 559 and 825 µS/cm with an average of 721 µS/cm. The average field pH is 7.1 and the hydrochemical signature of the water is calcium bicarbonate.
- Faecal coliforms are detected periodically with gross contamination (>100 CFU per 100 ml) on 7 occasions in the available dataset, tending to occur in late summer.
- There has been only one exceedance of EPA's status Threshold Value of 0.175 mg/l for ammonium. The general apparent absence of ammonium pre-2007 reflects the use of different detection limits, at 0.008 and 0.03 mg/l. EPA's analytical protocols have changed with the introduction of the Water Framework Directive related monitoring programme at the end of 2006, whereby detection limits were generally lowered for many substances (ammonium detection limit is 0.007).
- Concentrations of nitrate (as NO_3) range from 3 mg/l to 29 mg/l with a mean of 14 mg/l, and with a possible downward concentration trend in the past 3-4 years. These values are well below the groundwater quality standard of 50 mg/l and the EPA status Threshold Value of 37.5 mg/l for “Good” chemical status.
- Chloride concentrations range from 10 mg/l to 26 mg/l with a mean of 20 mg/l. which is below EPA's status Threshold Value of 24 mg/L for “Good” chemical status. Like nitrate, chloride concentrations appear to show a decreasing trend in the past 3 years or so.



Note- the zero concentrations of ammonium shown pre-2007 reflect the use of higher detection limits compared to post-2006 data.

Figure 12: Bacteria Counts and Ammonium Concentrations

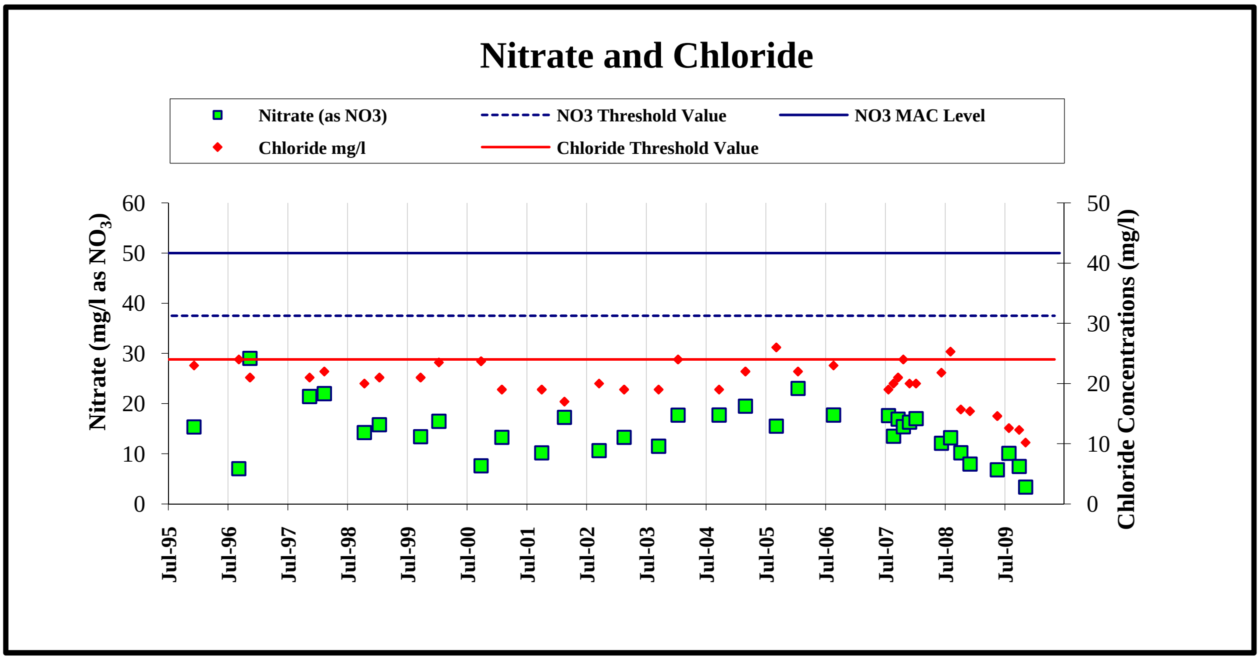
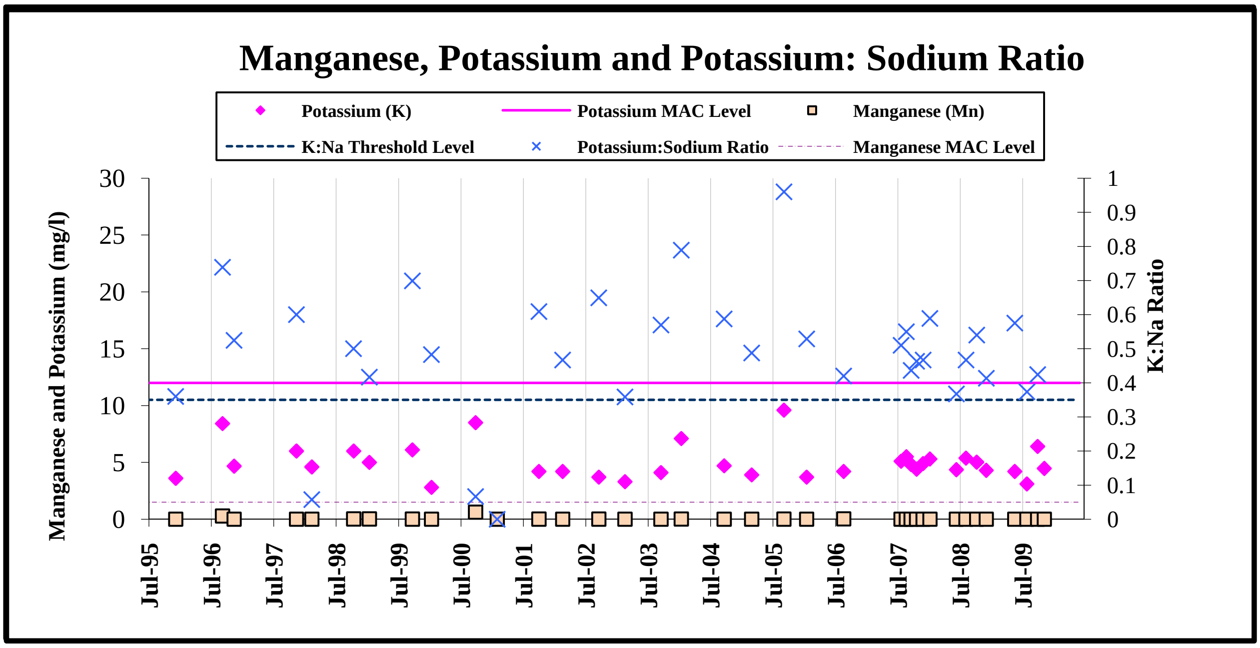
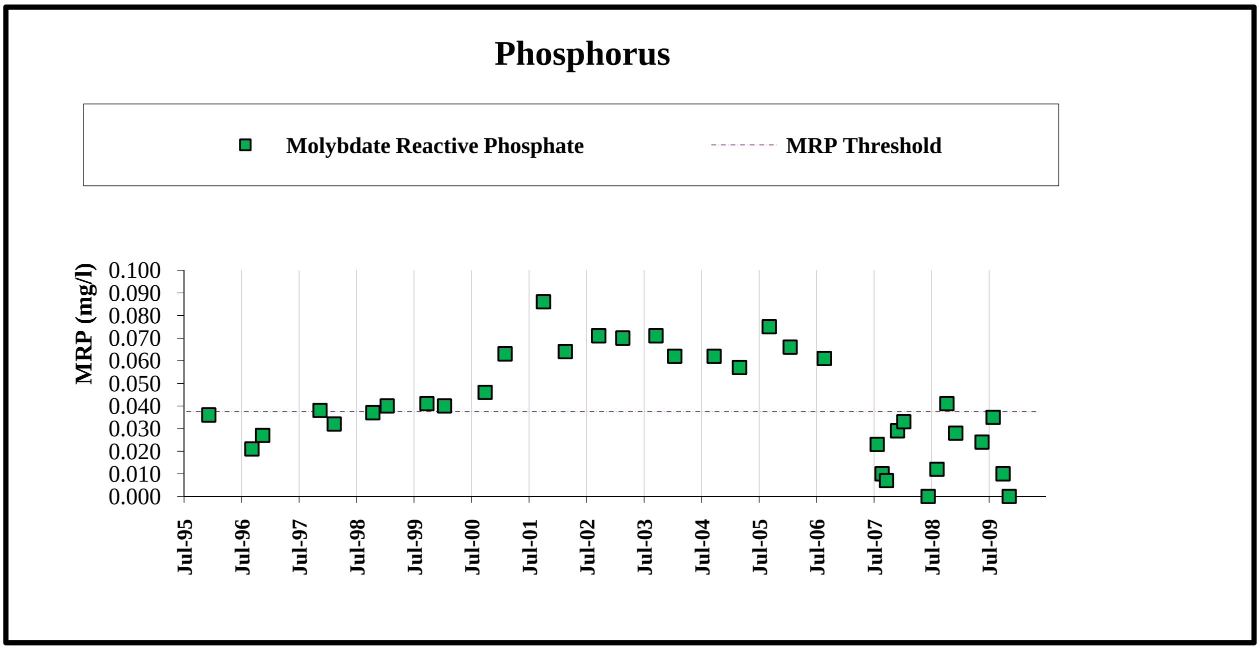


Figure 13: Nitrate and Chloride Concentrations



Note - zero concentrations of Mn implies it was not detected above its detection limit.

Figure 14: Manganese and Potassium Concentrations and K/Na Ratios



Note - zero concentrations of MRP implies it was not detected above its detection limit.

Figure 15: MRP Concentrations

- The range of reported concentrations of Molybdate Reactive Phosphate (MRP), or orthophosphate, is between non-detect (<0.009 mg/l) and 0.875 mg/l. The latter value occurred in October 2007 and stands out from the rest of the data (therefore, not included in the graph below). Excluding the single high value, the average MRP concentration over the reporting period was 0.064 mg/l (as P), which is above the EPA status Threshold Value for “Good” groundwater status of 0.035 mg/l P. Between 2000 and 2006, concentrations generally exceeded the threshold, and since 2006, there has been a marked improvement in related concentrations (see **Figure 15**).

- Sulphate, magnesium and calcium concentrations are within normal ranges. The potassium/sodium ratio is high, frequently exceeding its threshold value of 0.35, possibly on account of generally low concentrations of sodium. There have been several exceedances of relevant threshold values for iron, particularly in the period 2000 through 2006, and may be indicative of organic pollution.

- The concentrations of all other trace metals are low and/ or below laboratory detection limits.

- There have been two detections each of MCPA and mecoprop (active ingredients in herbicides) in post-2006 samples, but the detections were below drinking water standards. The concentrations of all organic compounds to date are below respective laboratory limits of detection, with the exception of one unconfirmed detection of total petroleum hydrocarbons of 60 µg/l in 2009, above the drinking water standard of 10 µg/L.

In summary, groundwater quality at the PWS shows elevated MRP concentrations and is periodically impacted from bacteriological contamination. A water quality improvement has occurred since 2006/2007, with a decrease in concentrations of parameters that are indicative of organic waste sources (e.g. nitrate, K/Na ratio, iron, manganese, chloride). The precise cause for the improvement is not known, however, a general decrease in nitrate and phosphate concentrations in the years 2007-2009 has been referenced nationally (EPA, 2010) and may be linked to above average rainfall (and recharge) conditions in the wet years of 2008 and 2009.

8.4 Aquifer Characteristics

The presence of karst features within the study area provides evidence for karstification of the limestone aquifer that supplies groundwater to the Mid-Galway PWS. The established links between dye injection points and the downgradient springs are characteristic of the regional aquifer system that stretches across much of County Galway and which gives rise to numerous springs used for public water supply. This limestone aquifer has been classified by the GSI as an *Rkc* aquifer – a *regionally important karstic aquifer, dominated by conduit flow.* Flow rates of between 750 m/d and 1,500 m/d through the karst system have been established from the tracer tests at Moylough Castle and Loch Na Lasrach. The tests were carried out under very different hydrological conditions (dry and wet, respectively), which may account for the difference in measured flow rates. The associated flow gradients are 0.002 and 0.004, respectively. There are few locations where the limestone is exposed, so it is difficult to judge the degree to which the epikarst is present and/or developed. The epikarst is the upper, more fractured and weathered zone in karstified rocks. It is particularly important to groundwater recharge estimation, as it determines the distribution of recharge, specifically diffuse recharge, and can be visualised as a perched aquifer system channelling infiltrating water to points of entry into the deeper groundwater flow system.

9 Zone of Contribution

The Zone of Contribution (ZOC) of a natural spring or other discharge point (e.g. abstraction borehole) is the hydrogeological catchment area(s) of the source that is required to support the natural discharge or abstraction from long-term recharge. As such, the *size* of the ZOC is controlled by the total discharge (outflow) at the source and groundwater recharge (inflow) to the source. The *shape* of the ZOC is controlled by groundwater flow patterns and gradients, as well as subsoil and aquifer permeabilities. As each of these elements is subject to some uncertainty, ZOC delineation typically involves water balance calculations (see Section 9.3) and conceptualising the groundwater flow system, as described below.

9.1 Conceptual Model

Illustrations of the conceptual hydrogeological model of the groundwater flow system associated with the Mid-Galway PWS are provided in **Figures 16 and 17.** Groundwater discharges from a karstified limestone aquifer where flow is concentrated in conduits that converge and discharge in the area between the PWS, Barnaderg GWS, and the Pollifrin spring. Established flow directions are from higher ground to the northeast, east and southeast. The presence of springs on both sides of the Abbert River suggests that the river may act as a hydraulic barrier. However, this has not been conclusively demonstrated. Evidence of deeper conduits in the area of the Barnaderg GWS would indicate that conduits may be able to transport groundwater past and possibly beneath the Abbert River, similar to the situation described at Ballyglunin by Drew (1973).

Point recharge to the karstified limestone aquifer occurs at swallow holes and enclosed depressions, some of which have been used to trace dye materials to the PWS. Although swallow holes have the same hydrological function of draining water into the aquifer, the mapped swallow holes in the study area occur in very different physical settings:

- Swallow holes near Moylough Castle drain a large peat bog near Summerville Lake. There are drainage channels directly connected to the lake. Gradients are very shallow, but the peat area and the lake drain to the swallow holes near the castle, for most of the year (flows into the swallow holes ranging from ‘dry’ to 20 l/s were measured as part of this study);

- Swallow holes at the Loch Na Lasrach turlough drain surface water when turlough levels recede. During rainfall events, the turlough collects surface runoff from surrounding land, including 5-10 m high moraine ridges. The surface catchment of the turlough is small compared to the quantity of water that is held in the turlough. It also occupies high ground, at an elevation of approximately 80 mOD. Local residents have indicated that the swallow holes at the northern end of the turlough periodically supply water into the turlough, whereby the swallow holes would serve as estavelles. Unfortunately, this has not been possible to confirm or witness directly during this study. Given the high elevation of the turlough compared to surrounding land, the only feasible ‘driver’ for this situation (i.e. topography) would be groundwater inflow from the north.

- Swallow holes at Ballynamona drain a small, unnamed stream which originates on higher peaty, forested ground (flow into the swallow hole ranging from 5-20 l/s were measured as part of this study). The inflowing stream fluctuates significantly with rainfall, and looses water along its path before reaching the swallow hole, thus recharging the aquifer along the way.

Diffuse recharge occurs across the broader ‘limestone plateau’ indicated on **Figure 16**. The plateau (70-90 m OD) is devoid of surface drainage features, which may be explained by ‘efficient’ recharge of rainwater. A significant area of the plateau is covered by thin subsoils (generally <3 m) which would result in high and efficient diffuse recharge into the underlying limestone aquifer, especially where the epikarst is well developed. The plateau occupies a roughly triangular area between the PWS, Moylough village, and Ballynamona. Lower recharge rates and quantities are expected where subsoils are thicker and/or of lower permeability, such as the areas near Summerville Lough and Loch Na Lasrach. The topography in these areas are dominated by gently undulating hills of shallow till resting on karstified bedrock, with eskers and ice marginal moraines deposited occasionally as 5-10 m high linear ridges. Esker and moraine ridges are not believed to bear any relationship to groundwater flow directions in the underlying limestone aquifer. They do, however, influence recharge patterns, whereby runoff from the ridges collects in numerous small internal drainage basins, where the ponded water infiltrates slowly to the limestone aquifer. The lowest groundwater recharge rates within the study area would be associated with the peat areas. However, as indicated previously, surface water associated with peat areas also drains to individual, mapped swallow holes near Summerville Lough, Loch Na Lasrach, and Ballynamona.

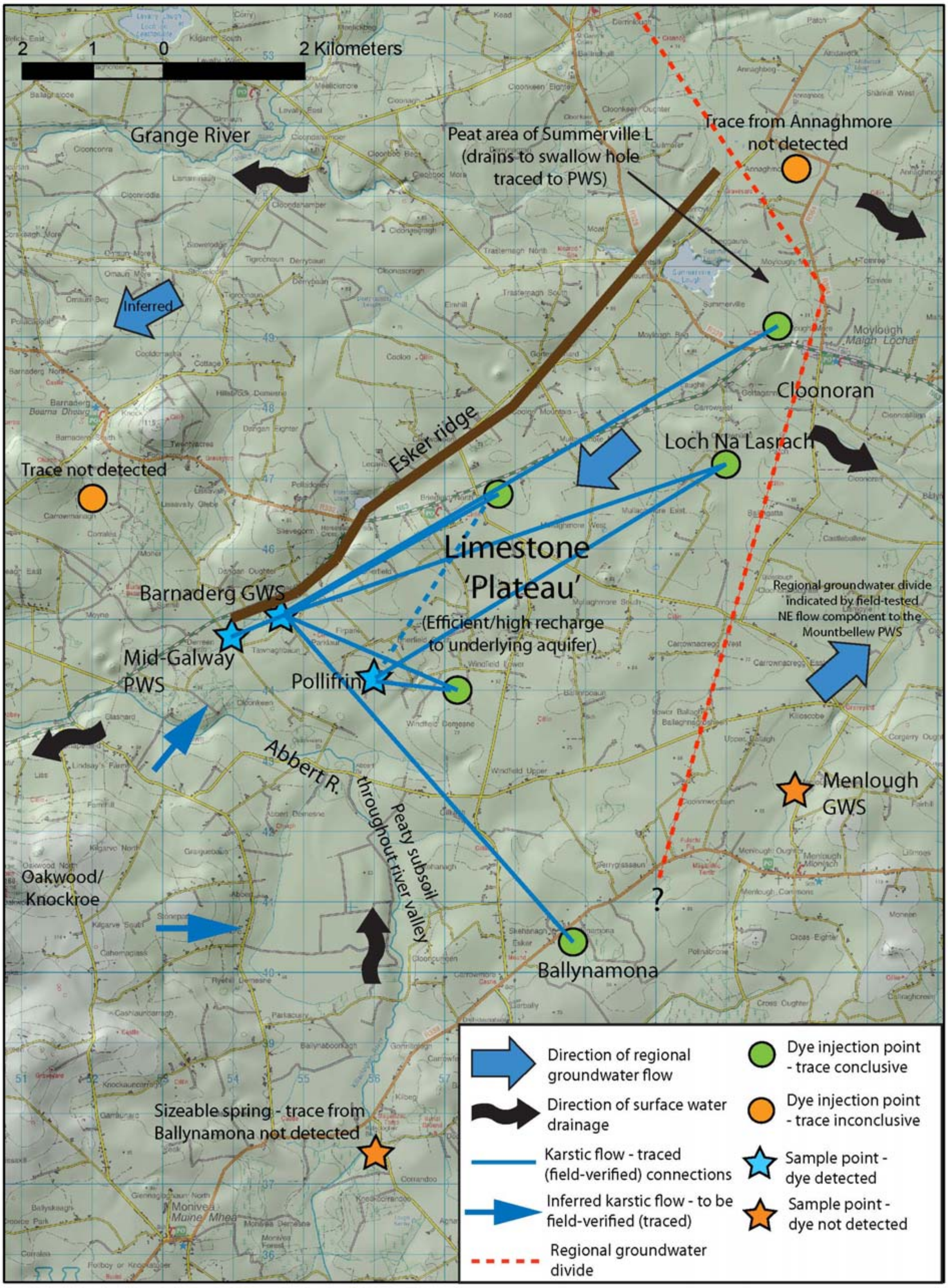


Figure 16: Conceptual model with results of tracing – plan map

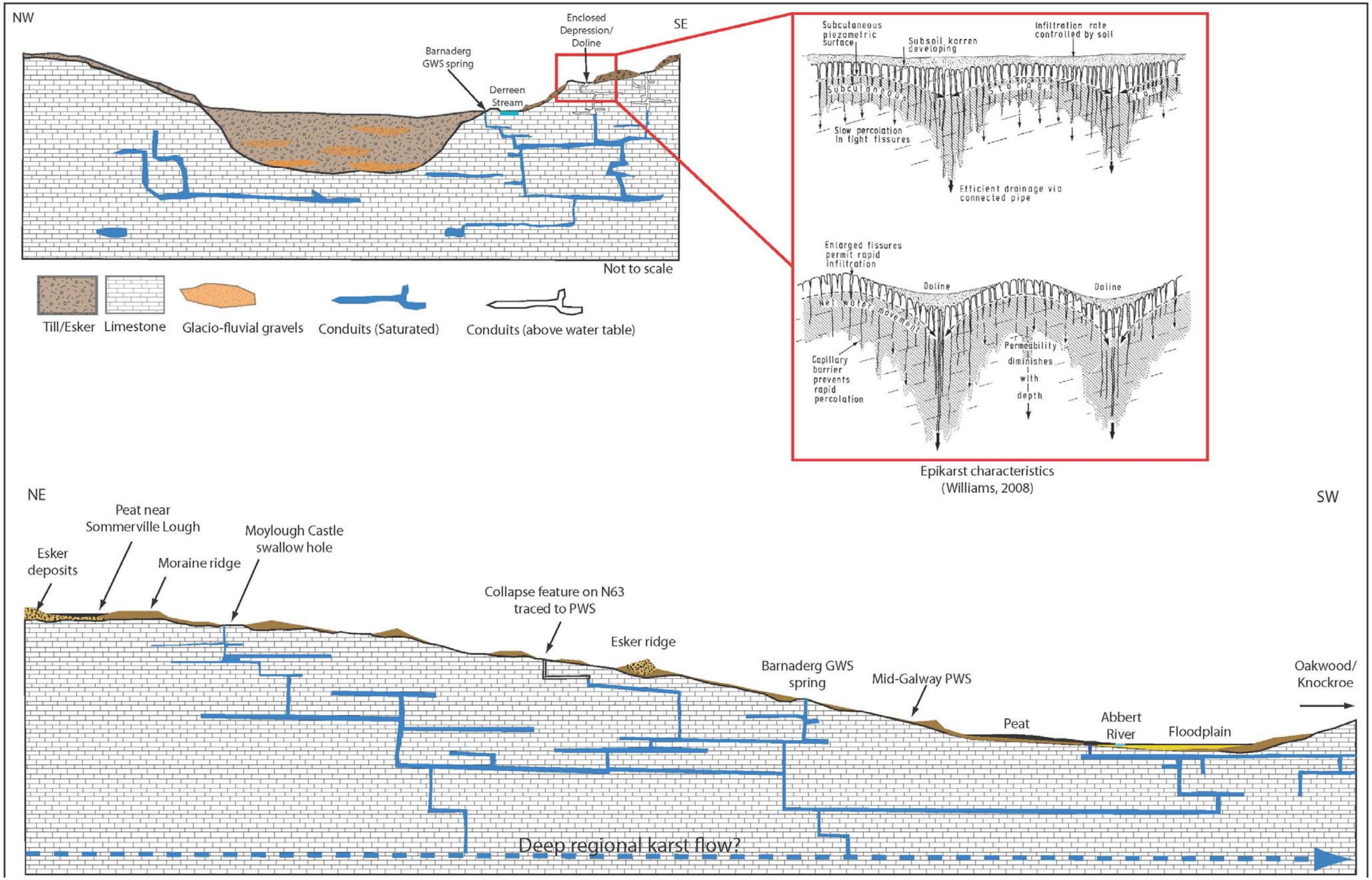


Figure 17: Conceptual model – cross-section

Groundwater discharges occur at springs and as diffuse seepages from shallow bedrock presumed to represent epikarst. A good example of the latter is observed just upstream of the bridge that crosses the Derreen stream adjacent to the Barnaderg GWS. Seepages occur from apparent bedding exposed 1-2 m above the stream water level. The epikarst is suspected to be a significant contributor to the extreme changes in discharges that are observed at the PWS and Pollifrin springs during rainfall events. The epikarst may be less developed or absent beneath some areas that are covered by thicker till deposits, as calcareous tills can buffer the pH of infiltrating water.

Below the epikarst, groundwater flow takes place in conduits at different ‘levels’ (depths/elevations), as evidenced in the recently drilled borehole at the Barnaderg GWS. These conduits fill and empty in time as a function of specific hydrological conditions. Their interactions and the water levels/pressures within them give rise to the time-varying discharge rates measured and observed at individual discharge points. The conduit flow system is characterized by high transmissivity, low storage, fast travel times, and little or no attenuation of pollutants aside from mixing and dilution. Flow rates up to 1,500 m/d were measured from the tracer tests described in Section 8.4.

Where sand and gravels deposits are present, these provide for groundwater storage which can drain/recharge to the underlying limestone aquifer during prolonged dry weather conditions, such as those experienced during the summer of 2010. A southwest to northeast trending esker system is visible from the PWS to Summerville Lough, roughly parallel to the N63 at Horseleap Lough. Sand and gravel deposits are, therefore, present above the limestone aquifer in the main groundwater discharge area between the PWS and the Barnaderg GWS. The drilled borehole adjacent to the Barnaderg GWS encountered approximately 10 m of till and esker-type deposits above bedrock, including a 4 m thick, permeable sand and gravel layer (Bartley, 2011). With such deposits overlying the limestone aquifer at this location, and with groundwater levels higher in bedrock, the hydraulic responses in the limestone aquifer at the Barnaderg GWS location would be expected to be buffered by the sand and gravel deposits. Such buffering effects are, however, not apparent and as a result, the precise discharge mechanism and setting of the limestone springs are not well understood. Potential discharge scenarios may involve rapidly varying depths to bedrock (i.e. subsoil ‘windows’).

9.2 Boundaries

Groundwater flows by gravity to the discharge points along the Derreen stream. All areas at a higher elevation than the Mid-Galway PWS are, therefore, potentially within the ZOC. The delineated ZOC, shown in **Figure 18**, was developed from a combination of tracer test results, topographic interpretations, and water balance considerations (see Section 9.3). Specifically, the shape of the ZOC is influenced by the following main considerations:

- Positive dye tracer lines;
- Inferred high rates of diffuse recharge across the limestone plateau (indicated in **Figure 16**);
- Presence of springs to the east of the limestone plateau, near Moylough and Menlough villages, which require their own contributing areas;
- Peat areas that drain to swallow holes which have been traced to the Mid-Galway PWS.

The **western boundary** in vicinity of the PWS is defined by surface drainage and groundwater discharges that contribute flow to the Derreen stream at and upstream of the PWS. To the north of the PWS, the western boundary extends along Slievegorm hill. A tracer test from an active swallow hole to the west of this hill did not result in a positive detection at the PWS and is therefore excluded from the ZOC. To the south of the PWS, the western boundary is defined by Pollifrin spring and broadly follows the margins of lower-permeability sediments along the Abbert River (which include peat and marl, i.e. low recharge). Until proven otherwise, it is inferred that the Abbert River is a hydraulic boundary.

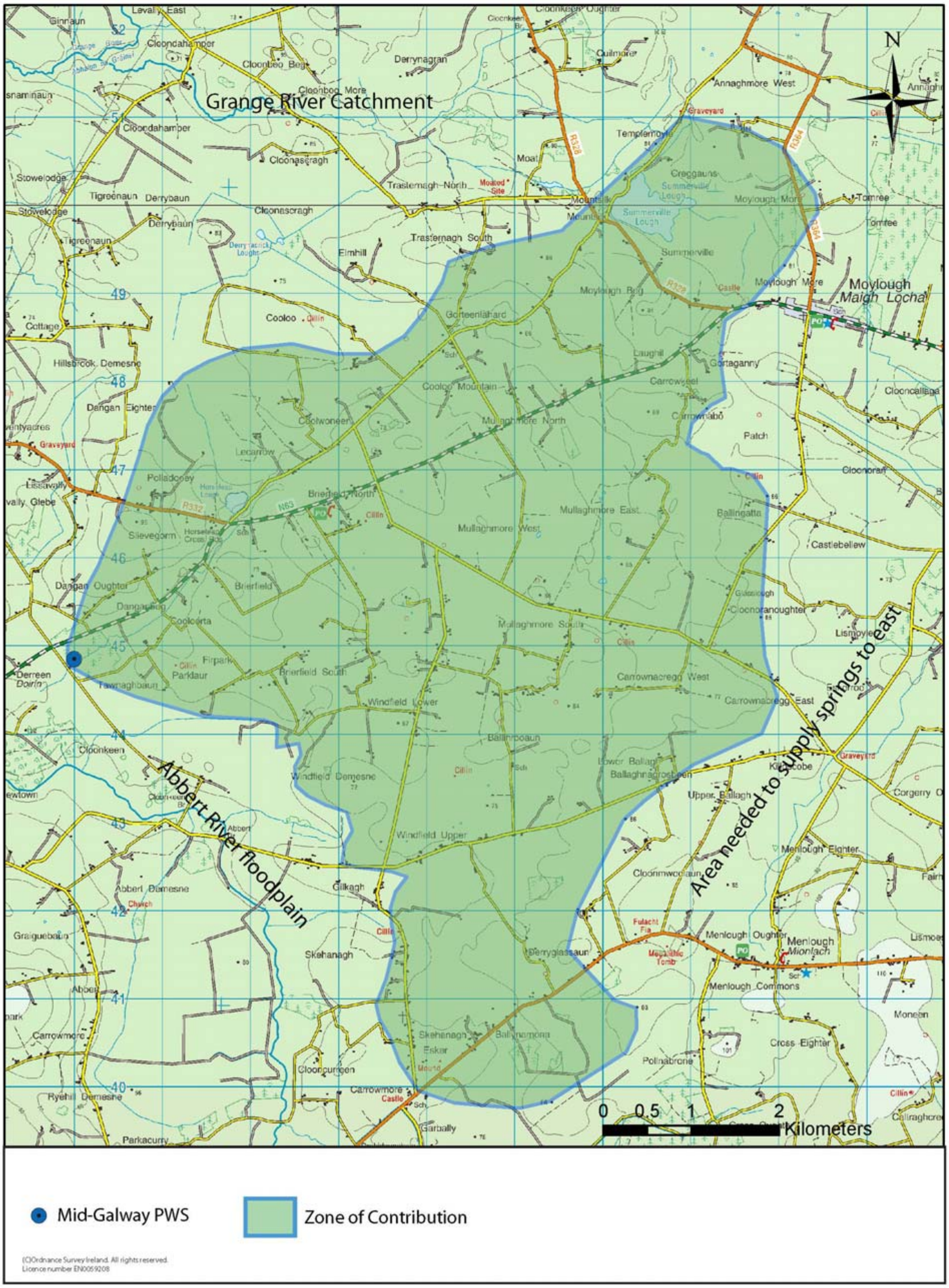


Figure 18: Estimated Zone of Contribution

The **northwestern boundary**, which extends past Summerville Lough, is constrained by several small springs that give rise to the headwaters of the Grange River. The boundary is, therefore, taken to be the topographic catchment divide of the Grange River. The ZOC incorporates the esker system between the PWS and Summerville Lough, as this is believed to be in hydraulic contact with the limestone and is oriented in the same structural direction (southwest to northeast) as the established tracer lines that run sub-parallel to the N63 (see **Figure 16**).

The **northern boundary** extends to a topographic divide near Annaghmore. At Annaghmore, dye injection into a free draining doline did not result in detections at any of the locations monitored, including the PWS. The **eastern boundary** is broadly constrained by consideration of the probable catchment areas for the springs at Cloonoran and Menlough, as well as the delineated ZOC of the Mountbellew PWS (CDM, 2011). The Cloonoran spring supplies water to the Cloonoran turlough which drains east. Menlough springs, including the spring that supplies water to the Menlough GWS, drain in a northerly direction. The swallow hole at Lismoes, just east of Menlough, was traced north to the Mountbellew PWS, from where drainage continues to Mountbellew and the Suck River. The inferred eastern ZOC boundary, therefore, represents a divide between groundwater flow to the southwest (in the Mid-Galway groundwater catchment) and northeast (in the Menlough/Mountbellew groundwater catchments), thus marking the divide also between the Western and Shannon River Basin districts.

The **southern boundary** incorporates the surface catchment of the stream that drains into the Ballynamona swallow hole, and which was traced to the Barnaderg GWS. This stream loses water along its course before reaching the swallow hole and so the surface catchment of the swallow hole is also inferred to be part of the groundwater catchment of the PWS (hence, included in the ZOC). Furthermore, there are numerous enclosed depressions/dolines in the area of Skehanagh and Winfield, between Ballynamona and the PWS, and it is inferred that these are part of a groundwater pathway between Ballynamona/Skehanagh and the PWS discharge area generally. The location of the **southwestern margin** of the ZOC (near Carrowmore) is constrained by the presence of several springs located further southwest along the Killaclogher River (which becomes the Abbert River further north). The largest of these springs was monitored during a dye tracer test from Ballynamona, but did not yield a positive detection.

9.3 Recharge and Water Balance

The term ‘recharge’ refers to the amount of water that infiltrates into the ground and replenishes an aquifer. As such, it is an important part of the water balance of a groundwater flow system. For the SPZ project, recharge is estimated using Guidance Document GW5 (Groundwater Working Group, 2005), from which a bulk recharge coefficient (R_c) is defined for an area that is described by combinations of groundwater vulnerability, subsoil permeability and soil type. The R_c is then applied against the annual average effective rainfall defined in Section 5 to derive annual average recharge (in mm/yr).

The estimation of a realistic R_c is important as it influences the size of the ZOC to the source and, therefore, the Outer Source Protection Area (see Section 10). The R_c that is defined for the Mid-Galway PWS area is directly related to the conceptual hydrogeological model presented in Section 9.1 as well as the boundary discussions in Section 9.2. For the ’extreme’ groundwater vulnerability scenario which occurs throughout much of the study area, including the ‘limestone plateau’, an R_c of approximately 90% can be expected (i.e. 90% of effective rainfall infiltrates into the groundwater system). For the other vulnerability scenarios, which involve greater subsoil thicknesses and/or a range of subsoil permeabilities, lower R_c values apply.

The ZOC shown in **Figure 18** is based on the estimated median combined total discharge measured at the Mid-Galway PWS and Pollifrin spring of 631 l/s (54,518 m^3/d). It has a total area of approximately 49.8 km^2 which, on the basis of general catchment characteristics, was derived from an area-weighted recharge coefficient (R_c) of 66%, as indicated below. Using the meteorological statistics in Section 5, the average annual recharge over the ZOC is estimated to be 402 mm/yr, as follows:

Average annual rainfall (R) (see Section 5)	1,057 mm
Estimated P.E. (see Section 5)	475 mm
Estimated A.E. (95% of P.E.)	450 mm
Effective rainfall (ER = R-AE)	607 mm
Potential recharge (equal to ER)	607 mm
Rc for 'extreme' vulnerability areas (41% of ZOC area)	90%
Rc for 'high' vulnerability areas (27% of ZOC area)	70%
Rc for 'moderate' vulnerability areas (24% of ZOC area)	40%
Rc for 'low' vulnerability areas (8% of ZOC area)	10%
Bulk recharge coefficient for ZOC	66%
Annual recharge rate	402 mm

It follows that the remaining 34% of the water balance is represented by surface runoff which is generated along the surface catchments of Horseleap Lough, Summerville Lough and Loch Na Lasrach. Some proportion of the runoff may recharge into the aquifer via swallow holes and/or collect in and recharge via numerous small, internal drainage basins within the limestone plateau.

As mentioned above, the defined ZOC reflects dye tracer test results as well as an area needed to support the representative discharge from the groundwater system, which is derived from a combination of the EPA gauging station near the Mid-Galway PWS and spot-measurements at Pollifrin. It does not reflect peak discharges. Estimates of the representativeness of spring discharges and stream flows using arithmetic means are likely to be inaccurate given the occurrence of extreme high discharges and flows. Hence, the median/bi-weighted flow value was used which gives less weight to extreme values in the dataset.

The positive dye traces provide important controls on the shape and extent of the ZOC. Despite these controls, there remain two primary areas of uncertainty that, on the basis of additional study, could yet influence the definition of the ZOC:

a) the hydraulic interaction between the karstified aquifer and the Abbert River;
b) the 'robustness' of the presently estimated median flow of the Pollifrin spring.

The Abbert River is potentially, but not yet conclusively demonstrated to be, a hydraulic boundary for southwesterly groundwater flow in the general study area. As a hydraulic boundary, it would help explain the emergence of springs and seepages on the eastern bank of the river. With the possibility of groundwater flow also from the Oakwood/Knockroe hill area (see Figure 1) towards the river (i.e. from the west), a hydraulic boundary at the river would also help to explain the presence of small springs on the western bank of the river. However, the possibility that flow crosses the river, either via a deep regional conduit system (to the southwest) or in the manner described at Ballyglunin (Drew, 1973) (e.g. to the northeast from Oakwood/Knockroe) cannot be ruled out. The former is difficult to ascertain without significant drilling and dye tracer testing. The latter can be tested, especially during low flow conditions, by injecting dye materials in dolines that have been mapped at Knockroe to see if they emerge at discharge points on the opposite side of the Abbert river (e.g. at Pollifrin). This was planned during the study described herein, but permission was not granted by landowners to access the required locations for dye injection purposes within the study period. In this regard, recommendations for additional work are included in Section 13.

As for the estimated median flow of the Pollifrin spring, additional measurements are needed to strengthen the flow statistics from this important discharge source. A median discharge of 411 l/s has been estimated on the basis of six measurements only, although they do include a broad range of values during dry and wet weather conditions, and the magnitude of the median flow is 'conceptually right' from observations made during field visits. If anything, the referenced median discharge is likely on the high end of the scale, which means the resulting ZOC is conservatively large. As stated in Section 13, flow measurements from Pollifrin should be made on a routine basis.

10 Source Protection Zones

The Source Protection Zones are a landuse planning tool which enables a more objective, geoscientific assessment of the risk to groundwater quality to be made. The zones are based on an amalgamation of source protection areas and the groundwater vulnerability. The source protection areas represent the horizontal groundwater pathway to the source, while the vulnerability reflects the vertical pathway. Two source protection areas are typically delineated, the Outer Source Protection Area (SO) and the Inner Source Protection Area (SI).

The SO encompasses the entire ZOC to the PWS. The SI is defined by a 100-day time of travel to the source and is designed to protect the source from microbial and viral contamination (DELG/EPA/GSI 1999). Actual flow velocities ranging from 750-1,500 m/d have been demonstrated from dye tracer testing in the study area which means that, once pollutants enter the conduit system, they can reach the PWS within a few days from the distant parts of the ZOC. For this reason, the entire ZOC is defined as an SI. This is especially critical in the 'extreme' and 'high' vulnerability areas, and within the surface catchment areas of swallow holes.

The resulting groundwater Source Protection Zones are shown in **Figure 19**. Within the ZOC, the SI is designated as SI/Extreme (41%) SI/High (27%), SI/M (24%) and SI/L (8%).

11 Potential Pollution Sources

Potential sources of groundwater pollution within the ZOC are mainly associated with farmyards, landspreading of slurry, livestock grazing close to karst features such as swallow holes (especially), as well as onsite wastewater treatment systems (OSWTS). These are located and/or practiced throughout the ZOC. In addition, there are sand and gravel quarries along the esker deposits. There are no industrial or commercial activities that can be described as high risk activities.

12 Conclusions

The Mid-Galway PWS sources its water from the Derreen stream which represents a mix of groundwater and surface water. Several springs and streambank seepages contribute flow to the Derreen stream between the PWS and Horseleap Lough. The water that is discharged originates from both proximal and distal locations, including swallow holes as far away as Lough Na Lasrach and Moylough Castle. Groundwater flows through fissures, fractures and open conduits in a karstified limestone aquifer that facilitates very fast transport of water. Dyes have been traced from injection points up to 9 km from the PWS, at flow rates ranging from 750 m/d to 1,500 m/d.

The delineated ZOC extends to the northeast, east and southeast from the PWS. It incorporates the springs at Pollifrin and Barnaderg GWS, as both of these are part of the same groundwater flow system that supplies water to the PWS. The size of the ZOC has been estimated from water balance considerations and covers a total area of approximately 49.8 $km^{2.}$ Its' shape is influenced by dye tracer test results, primarily from injection points to the east-northeast. The ZOC of the PWS alone, i.e. excluding Pollifrin, is in reality a subset of the ZOC shown in **Figure 18**, but cannot be 'extracted' or parsed out with any degree of certainty unless a significant additional body of field work, notably flow measurements and dye tracer testing, was carried out. The hydraulic relationships between the springs would need to be examined in terms of their hydraulic responses to rainfall events, and roles as underflow or overflow springs.

Groundwater flow and ZOCs in karstified aquifers are difficult to predict at best, and will change in time with hydrometeorological conditions. Consequently, some uncertainty will always remain with ZOC delineation, including that presented in this report. Although the existing tracer tests provide good control points for the shape of the ZOC, there are areas of uncertainty that remain, notably the hydraulic influence of the Abbert River on groundwater discharges and the estimate of median discharge from the Pollifrin spring. Recommendations for additional work are included in Section 13.

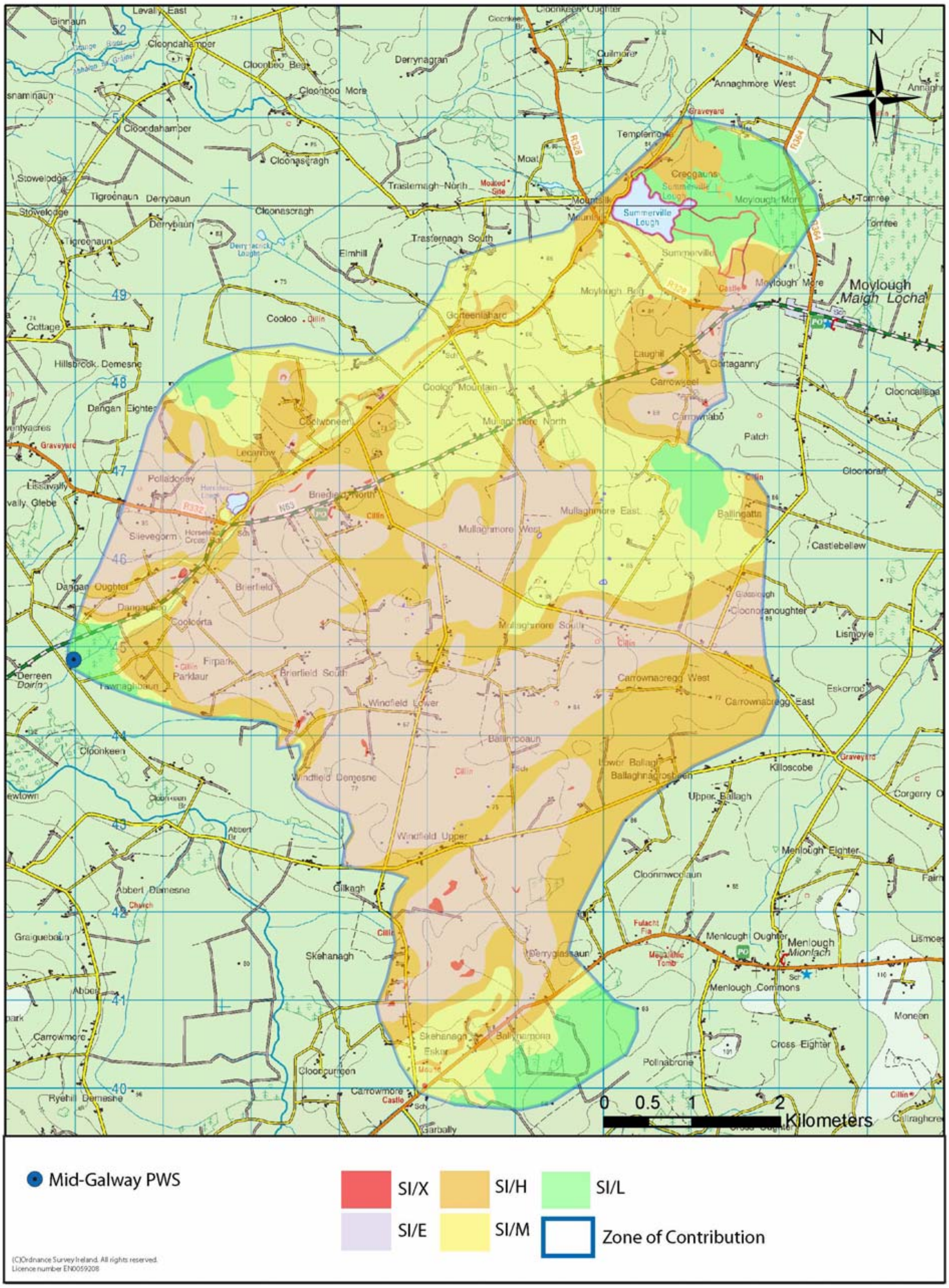


Figure 19: Source Protection Zones

Water quality data from the Mid-Galway PWS shows historical and periodic evidence of contamination by organic waste sources. The greatest risk of pollution appears to be associated with farmyards, landspreading of slurry, livestock grazing near point locations of groundwater recharge, and likely also private onsite wastewater treatment systems.

13 Recommendations

Given the vulnerability of the Mid-Galway PWS to contamination, good agricultural practice relating to landspreading and slurry storage should be followed within the delineated ZOC. Current landspreading and cattle grazing activities should be reviewed with local farmers in order to minimize the risk of impact on water quality. As the PWS pumps water that originates as both groundwater discharges and surface runoff into the Derreen stream, consideration must be taken in equal part to both, including surface catchments of streams and swallow holes.

Although the delineated ZOC of the PWS is considered to be reasonably well defined and conservatively large, additional field-based work is warranted to address technical questions that remain, specifically:

- Routine discharge (flow) measurements should be conducted at the Pollifrin spring (e.g. in the stream that flows from the spring to towards the Abbert River) – this is recommended to strengthen the estimated median discharge from the spring and, therefore, the general groundwater flow system that is associated with the Mid-Galway PWS;

- Tracer testing should be conducted from mapped dolines at Oakwood/Knockroe, to test whether or not groundwater from this largest hill in the entire study area could flow and discharge into the Derreen stream, i.e. by crossing the Abbert River and thereby testing the hydraulic function of the river as a potential hydraulic divide.

- The existing tracer test from Ballynamona should be repeated under lower flow conditions, and with a significantly large input (mass) of dye material, to verify the established positive trace to the Mid-Galway PWS. The existing positive trace, which interestingly was not detected at Pollifrin (even though it is located in direct line between Ballynamona and the PWS), raises questions about the connectivity between karst features in the southwestern part of the delineated ZOC. A new test with an expanded monitoring regime to include even the smallest of mapped springs, is recommended to verify the existing trace and provide additional information on potential other flowpaths in this part of the study area.

- Questions surrounding the swallow holes at Loch Na Lasrach as possible estavelles should be verified though additional observations and monitoring of inflows/outflows at these locations.

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APPENDIX A

Photographs

APPENDIX B

Mapped Karst Features

APPENDIX C

Subsoil Logs – window sampling (2010)

APPENDIX D

Tracer Test Results