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Development of Green Disaster Management Toolkit to Achieve Carbon Neutrality Goals in Flood Risk Management

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Abstract: Current flood risk management projects have been criticized for their high carbon emissions, raising the need for carbon emission reduction and carbon absorption efforts to mitigate environmental impacts and achieve carbon neutrality goals. The research develops a comprehensive green disaster risk management toolkit to calculate the carbon emissions and absorption quantitatively based on the unit volume of materials and processes employed in a flood risk management project. As a result of applying the developed toolkit to a about 22,300 small stream restoration projects in Korea, the total carbon emissions were estimated to be 1,158,840.7 tons of CO_2, of which 89.4% of the total carbon emissions originated from concrete-related construction activities, such as cement and ready-mixed concrete pouring. As a result of evaluating the nationwide carbon absorption results of all small stream restoration projects, total absorption by 2030 is expected to be 3.0 to 10.2 times higher than carbon emissions. The comprehensive toolkits are expected to support the selection of customized processes, materials, and methods by providing a systematic approach to calculate and minimize carbon emissions, ultimately contributing to the achievement of carbon neutrality goals in flood risk management projects.

Keywords: comprehensive green disaster risk management toolkit; carbon emission; absorption; flood risk management; carbon neutrality goals

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1. Introduction

The construction sector, including flood risk management projects, especially restoration, is known to contribute significantly to greenhouse gas emissions [1]. Notably, the Korean construction industry constitutes approximately 48% of the nation's total material consumption and 40% of its energy consumption [2,3]. Among the various administrative projects in the field of flood risk management in Korea, the small stream restoration project, the disaster prevention and recovery projects and the establishment of storm-water runoff reduction facilities are representative major projects. According to the United Nations Framework Convention on Climate Change (UNFCCC), industrialized countries must reduce their greenhouse gas (GHG) emissions [4]. Korea also announced a voluntary action plan to reduce greenhouse gas emissions by 37% from the business-as-usual level of 851 million by 2030 [5]. It is necessary to make efforts to transition to eco-friendly and low-carbon flood risk management projects to reduce carbon emissions and increase carbon absorption.

Accurate quantification of emissions and absorption is required to promote the transition to an environmentally sustainable low-carbon flood risk management project to mitigate greenhouse gas emissions. Consequently, it becomes crucial to advocate for the integration of nature-based solutions within local policies pertaining to flood risk management initiatives. This not only serves the purpose of fostering sustainable practices in the management of land, water, and biodiversity but also plays a pivotal role in diminishing vulnerability to natural disasters [6]. The establishment of a standardized framework for quantifying both emissions and absorption becomes essential for a comprehensive understanding of current greenhouse gas dynamics associated with various measures implemented for flood risk management. Additionally, careful consideration must be given to the energy footprint incurred during the transportation, construction, and maintenance of public facilities and infrastructure designed for prevention and recovery efforts. Moreover, the energy expended in the demolition and disposal of facilities and materials necessitates detailed assessment [7].

Scientific insights, policy frameworks, and pilot applications for nature-based solutions can support the effective implementation of measures for sustainable development [8]. In other words, a tool that can explain the environmental and disaster reduction effects of the installation of green and blue infrastructure can be used also as a tool to support the sustainable development of local communities. This research develops a Green Disaster Management Toolkit (GDMT) designed to assess carbon reduction efficacy, including greenhouse gas emission and the absorption status of each disaster risk management project, and supports selection of customized processes, materials, and methods suitable for carbon neutrality. The methodology for quantifying greenhouse gas emissions and absorption for each project is based on existing technologies and comprehensive literature surveys. The life cycle of a flood risk management project includes several phases, each contributing to greenhouse gas emissions, and these encompass materials production, construction, utilization, maintenance, and end-of-life considerations [9,10]. As materials production and construction phases are intricately linked to the construction process itself [11], this research focuses on the initial two phases for calculating carbon emissions, with a primary emphasis on greenhouse gas emissions stemming from primary materials and equipment.

A noteworthy feature of the GDMT is its capability to swiftly provide pertinent information on materials and components formulated during the planning phase. In the context of flood risk management, a substantial portion of carbon emissions emanates from sectors associated with small stream restoration, encompassing transportation, cement and steel manufacturing, and commercial energy consumption [12]. This research focuses on small stream restoration as a case study and utilizes the GDMT to quantify CO_2 emissions throughout the construction process of public facilities for flood risk management. This encompasses CO_2 emissions attributed to materials and the activities involved in small stream restoration projects. Furthermore, the research derives advanced low-carbon green infrastructure alternatives tailored for flood risk management projects, aligning with domestic regional and environmental conditions by drawing insights from existing case studies. The developed GDMT serves as a valuable resource for supporting the selection of adaptive flood management projects based on low-carbon green infrastructure. Additionally, it aids in identifying improvement opportunities and exploring environmentally friendly alternatives [13,14]. The devised processes and methodologies are applicable for assessing whether planned prevention and recovery projects might yield negative impacts and for devising strategies to mitigate unintended consequences.

2. Literature Review

2.1. Toolkit for Calculating Carbon Emission

The Ministry of Land, Infrastructure and Maritime Affairs (MOLIMA), Korea, established the Carbon Emission Calculation Program for Facilities (CECPF) to assess greenhouse gas emissions by considering material usage and energy consumption according to the established guidelines for facility-specific carbon emission calculations [15]. This program has the advantage of being highly practical and adaptable due to its capability to accommodate diverse input values, including specifications, units, quantities, and materials for each intricate process. The Greenhouse Gas Emission Calculation Subsidy Program (GECSP), developed by the Korea Environment Institute (KEI), was designed to compute carbon emissions, incorporating the country's distinct emission factors and the energy calorific conversion factor [16]. However, a limitation of this program was its constrained diversity, as it did not permit the verification of energy consumption and CO_2 emissions based on specific types. The Korea Environment Corporation (KEC) developed the Waste Sector Greenhouse Gas Emission and Energy Consumption Calculation Tool (WSGEECT) to calculate greenhouse gas emissions according to energy, external supply, landfill, biological treatment, incineration, sewage, and wastewater [17]. However, it did not provide the capability to scrutinize emissions concerning specific processes and construction materials associated with construction activities.

The Eco-DM Program was conceived for facilitating environmental assessments through the Life Cycle Analysis (LCA) method, integrating both individualized calculation methods and industry-specific approaches. A notable advantage of this program lies in its ability to compute carbon emissions using fundamental data elements, such as construction name, period, location, scale, and project overview. LCA is a methodology employed to evaluate the environmental impacts associated with all stages of a product's life cycle, encompassing raw material extraction, materials processing, manufacturing, distribution, use, repair and maintenance, and disposal or recycling [3,18]. The application of LCA extends across diverse projects, ranging from construction and damming to wastewater treatment and general flood risk management [19–26]. However, in the various applications of LCA for estimating the environmental impact of engineering projects, research often focused on a specific product or a static function, which can be defined as a functional unit. These may include a static number of booths, the footprint of venues, or an entire event consisting of a specific configuration of settings [27,28]. The researchers in [29] divided the entire construction process of Prefabricated Floor Slabs (PFS) into three stages: production, transportation, and construction, and carbon emissions were calculated using the LCA method.

The Sacramento Metropolitan Air Quality Management District (SMAQMD) introduced the Road Construction Emission Model (RCEM) for estimating greenhouse gas emissions based on equipment usage. The SimaPro was developed for calculating carbon emissions through the LCA, offering a comprehensive set of results encompassing 17 modules related to buildings, serving as a decision-making tool during the design stage. Meanwhile, Building for Environmental and Economic Sustainability (BEES) facilitated the selection of cost-effective and environmentally friendly building products by assessing environmental performance, including carbon emissions, across various stages, such as materials, manufacturing, transportation, installation, and use. However, BEES had drawbacks, such as being limited to a domestic language and lacking a unique emission factor.

Existing programs were primarily dedicated to calculating carbon emissions based on facility, process and building materials. However, a common deficiency across most of these programs was the absence of visualization data corresponding to the calculated carbon emissions. Additionally, the universal listing of installed coefficients or building grades in Table 1 was lacking, introducing a notable limitation to the comprehensiveness of the available tools. This underscores the need for more advanced and inclusive solutions in the domain of carbon emissions assessment. Recognizing these gaps, a novel program was deemed essential, particularly for application in Korean flood risk management projects. In response, the research introduced the GDMT, designed to address these shortcomings and support carbon neutrality initiatives within the framework of flood risk management.

Table 1. Comparisons of the existing toolkit performance levels (O: High, △: Low).

Toolkits	Accessibility	Compatibility	Program Type	Visualization	Support Area	Since
CECPF	O	O	Excel VBA	△	Facility	2006
GECSP	O	O	Excel VBA	△	Road	2022
WSGEECT	O	△	Excel VBA	△	Energy	2011
Eco-DM	△	O	Excel VBA	O	Environmental	2012
RCEM	O	O	Excel VBA	△	Road	2007
SimaPro	△	△	Standalone	O	Building	2021
BEES	O	O	Standalone	O	Building	2020

2.2. Carbon Absorption Quantification Technology

The researchers in [30] introduced a method for quantifying carbon absorption by multiplying the amount of wood stored in forests by a coefficient. Numerous studies have indicated substantial carbon content in soils [31–34]. While there was no universally recognized methodology for precisely measuring or validating carbon storage in soil [35], several studies have undertaken calculations for this. The National Institute of Forest Sciences (NIFS) and [36] assessed soil carbon storage by categorizing it into forests, rice fields, fields, and grasslands. The U.S. Department of Agriculture (USDA) Natural Resources Conservancy (NRCS) utilized the Soil SURvey GeOgraphic (SSURGO) DB and the National Cooperative Soil Survey (NCSS) to estimate soil carbon storage up to a depth of 1 m below the surface across the entire United States. The authors of [37–39] conducted diverse studies to compute the quantity of carbon stored in soil based on land use status. It was recognized that the decomposition of carbon in soil, stored in an inhomogeneous form, occurred over a span ranging from a few days to hundreds of years [40]. While the method for assessing carbon absorption according to land use was suitable for large-scale evaluations, such as the assessment of carbon emissions or absorption, it was deemed inappropriate for evaluating carbon absorption in small-scale flood risk management projects.

The predominant focus of research on traditional wetlands had historically centered on enhancing water quality. However, more recent studies have shifted towards investigating the role of wetlands in mitigating global warming gases [41–44]. In accordance with the National Greenhouse Gas Inventory's definition, small streams could be categorized as wetlands, with self-wetlands, encompassing small streams and periodically flooded areas like retention ponds, classified as artificial wetlands [45]. In Korea, most small streams were characterized by dry springs, or the runoff area was significantly small compared to the total width of the streams. In this case, absorption assessment was conducted by categorizing excluded areas of small streams into ground cover plants and inland areas into trees and ground cover plants. However, it was noteworthy that the amount of carbon stored in water in flood management projects, such as for small streams and reservoirs, was minimal. Flood risk management facilities often remain inadequately filled with water throughout the year, and the cultivation of algae for carbon absorption was challenging. Consequently, the research did not account for the amount of carbon absorption in the water component of these projects.

In Korea, the Rural Development Administration (RDA) conducted an evaluation of the annual carbon absorption of 30 major ground cover plants commonly used for landscape creation [46]. Consequently, the research adopted the methodology developed by the RDA to assess the amounts of carbon emissions absorbed by individual trees and surface plants, excluding consideration of carbon absorption in the soil and water surface. Within the GDMT, users had the ability to select ground cover plants for planting. In cases where the specific vegetation was unknown, the average value derived from the 30 specified species was utilized. The estimation of long-term carbon absorption post-construction was conducted by taking into account the photosynthesis of plants and aquatic microorganisms, as well as storage within green infra components, including soil, wetlands, and storage facilities.

2.3. Green Infra

The primary objective of traditional flood risk management facilities had traditionally been to mitigate peak runoff during heavy rainfall events and extend the peak discharge time. To fulfill this purpose, these facilities exhibit storage and infiltration functions, which share commonalities with Low Impact Development (LID) and Green Infra (GI) facilities, incorporating certain overlapping features. The research classified and outlined significant green infra facilities based on key functions, including vegetation filtration, infiltration, retention, rainwater utilization, and flow control based on the results of K-water [47], and conceptually explained the disaster and environmental performance level of each facility, as detailed in Table 2, which comprehensively classifies functions for determining performance levels, such as reducing runoff, protecting water resources and improving water quality, which includes all detailed items commonly used in the field of disaster risk management.

Table 2. Classification of LID and GI facilities by function, and disaster and environmental performance level of each facility such as ◎: Very High, O: High, △: Low.

Target	LID and GI Facilities	Performance Level		
		Runoff Reduction	**Water Resources Protection**	**Water Quality Enhancement**
Vegetation Filtration	Vegetation filtration zone	O	◎	◎
	Rainwater garden	O	◎	◎
	Waterside buffer zone	O	◎	◎
	Vegetation channel	O	◎	◎
	Curb vegetation area	O	◎	◎
	Roof greening	O	△	O
	Pathway flower bed	O	◎	◎
	Tree filtration box	O	◎	◎
Infiltration	Infiltration reservoir	◎	◎	O
	Permeability assurance	◎	◎	O
	Perforated pipe	◎	◎	O
	Infiltration sidewalk	◎	◎	O
	Infiltration ditch	◎	◎	O
	Infiltration barrel	◎	◎	O
	Infiltration pot	◎	O	O
	Water retention pavement	O	◎	O
Retention	Rainwater ponds	O	◎	◎
	Artificial wetlands	O	◎	◎
	Reservoirs	O	◎	◎
	Underground storage tanks	◎	O	O
Rainwater Utilization	Rainwater utilization facility	◎	◎	O
	Multi-source water supply system	◎	◎	O
Flood Control	Flow distribution device	◎	◎	O
	Large-diameter storm-water pipe	◎	O	O
	Temporary storage embankment	◎	O	◎

As a result of the analysis, the applicable carbon absorption facilities at the level of flood risk management were vegetation buffer zones, waterside buffer zones, infiltration reservoirs, rainwater ponds, pond-type reservoirs, and artificial wetlands among the 20 LID and GI facilities. Specifically, in the context of a small stream restoration project, there was potential to implement vegetation filtration zones and waterside buffer zones. Moreover, in the storm water runoff reduction project, the utilization of infiltration retention ponds and artificial wetlands was considered viable for achieving the intended goals.

3. Evaluation Method for Carbon Emissions and Absorption

In conducting the Life Cycle Assessment (LCA) for CO_2 emissions in the flood risk management project, the research delineated the life cycle into three principal phases: raw material production, raw material transportation, and on-site construction, as illustrated in Figure 1. The research focused on phase 1 and phase 2 as the scope of investigation, as these directly pertained to the construction process.

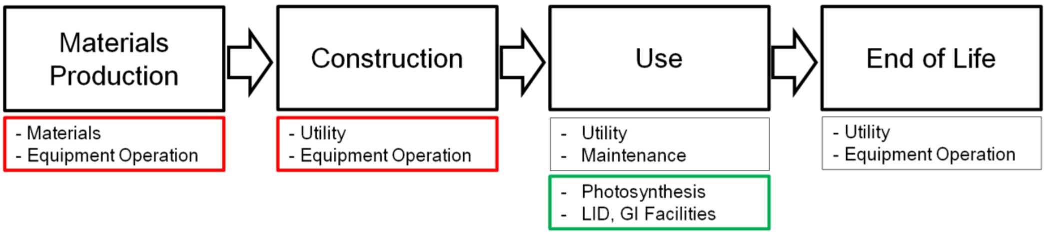

Figure 1. Four phase conceptual flowchart explaining CO_2 emissions plotted as red box and absorptions plotted as green box that may occur in flood risk management projects.

In the material production phase, CO_2 emissions occurred during the collection and production of raw materials, including boulders and metal pieces used in the small stream restoration project. Operational time for machinery and the specifications of all engineering materials employed on-site were documented in the construction plans accessible through the Korea Online E-Procurement system (KONEPS) of the Public Procurement Service (PPS). The research scrutinized public documents for various flood risk management projects, such as the small stream restoration project, landslides protection project, and storm water runoff reduction facility installation project, within the KONEPS platform for the years 2019 to 2022. All significant equipment, such as excavators, tractors, and skidders, were rented from different vendors. The research estimated fuel consumption and the associated emissions resulting from transporting heavy machinery.

The on-site construction phase comprised five major activities: site preparation, installing off-channel features, installing block features, conducting erosion control, and re-vegetating disturbed areas. Erosion control and re-vegetation predominantly utilized hand tools and small trucks for staff and material movement around the site. Site preparation mainly employed small-engine equipment to establish access corridors for heavy equipment along riparian areas. Installing off-channel features and block features necessitated the use of various heavy equipment, including excavators, skid steers, and dump trucks.

Flood risk management projects were systematically divided into detailed processes, wherein the duration of equipment operation and the quantity of raw materials used for construction work were delineated using standardized construction work production measures. The CO_2 emissions and absorption resulting from equipment operation and material usage were computed based on standards provided by the Korea Institute of Civil Engineering and Building Technology (KICEBT). Ultimately, the research estimated the amount of CO_2 emissions and absorptions for each construction phase in the following steps. First, information on materials and the main engineering equipment used in each part of the construction process was collected from the KONEPS. Then, this collected information was inputted into the GDMT, where CO_2 emissions per unit for detailed processes, equipment operation duration, and raw material quantity were set. Utilizing the functionality of the GDMT, the research derived the quantity of each component in the flood risk management project and automatically calculated the associated CO_2 emissions (CE) using the following equation:

$$CE = \sum_{i}^{R_E} (EU_i \cdot ET_i) \quad (1)$$

in which EU_i represents the carbon emissions per unit for the detailed process, length of equipment operation and amount of raw material, ET_i denotes the total amounts for the detailed process, length of equipment operation and amount of raw material related to CO_2 emissions, i represents the number of detailed processes and R_E represents the total number of processes related to CO_2 emissions. The research also calculated the associated CO_2 absorptions (CA) using the following equation:

$$CA = \sum_{i}^{R_A} (AU_i \cdot AT_i) \tag{2}$$

in which AU_i represents the carbon absorptions per unit for the detailed process, length of equipment operation and amount of raw material, AT_i denotes the total amounts for the detailed process, length of equipment operation and amount of raw material related to CO_2 absorptions, and R_A represents the total number of processes related to CO_2 absorptions. This approach facilitated a comprehensive assessment of the carbon footprint associated with each part of the flood risk management project. Regarding the quantities derived from the GDMT and referencing the national standard estimating reference provided by the KICEBT, the research computed the fuel consumption for the primary construction equipment. This value was then multiplied by the corresponding CO_2 emission factors to determine the CO_2 emissions associated with the main equipment used in the flood risk management project. The research conducted a comprehensive analysis of CO_2 emissions throughout the flood risk management project process, encompassing emissions from materials and those produced by the primary equipment used in construction. Furthermore, using the LID and GI, the research performed an analysis of the CO_2 absorption and emission effects related to the selection and establishment of their facilities.

4. Results and Discussion

4.1. Determination of the Quantifiable Functional Unit

The GDMT developed here can evaluate quantitative CO_2 emission and absorption to improve habitat biodiversity, as higher biodiversity correlates with an enhanced ecosystem service [48]. A functional unit was established to evaluate the project results by utilizing the comparison of significance results between alternative designs. The functional unit was determined based on the carbon footprint analysis, reflecting the improvement of the function and service of the restored small stream habitat. To assess the effectiveness of implanting the vegetation shelter block and the vegetation retaining wall block and large plant structures, topographic surveys were conducted for the Ha-gok stream in Geochang-Gun, Korea. The survey results and construction information collected from the KONEPS were adapted to assess major changes in habitat types and develop an approach that integrates the LCA results for quantifying the environmental performance of a restoration project. To support the selection of customized processes, materials and methods via comparison of carbon emissions and reduction effects by alternative projects, the research made these comparisons, and analyzed carbon contents through three scenarios, S-I, S-II and S-III as shown in Table 3. In Table 3, S-I used the general small stream restoration method, S-II used an alternative method employing vegetation shelter blocks and vegetation retaining wall blocks, and S-III used the alternative method and a GI facility-like construction of waterfront green areas.

For calculating CO_2 emission, no separate materials were used for the earth works, but equipment was only used to conduct the small stream restoration project. Referring to the national standard estimating reference by the KICEBT, the research calculated the fuel consumption for excavator, Q by Equation (3):

$$Q = \frac{3600 \times q \times k \times f \times E}{\mathrm{cm}} = \frac{3600 \times q \times 0.9 \times 1 \times 0.75}{20} = 121.5q \tag{3}$$

Table 3. Summary of total quantities of used materials and equipment corresponding to the restoration project for the Ha-gok small stream located in Geochang-Gun, Korea, based on three scenarios: S-I, S-II and S-III.

Work Type	**Processes**	**Unit**	**Total Quantity**		
			S-I	**S-II**	**S-III**
Earth Works	Cutting Soil	m^3	412	412	412
	Digging Soil	m^3	120	120	120
	Backfilling (Soil)	m^3	118	118	136
	Cleaning up Soil	m^3	354	354	354
	Breaking Groundless Concrete	m^3	9.8	9.8	9.8
	Loading Waste	m^3	9.8	9.8	9.8
Embankment Works	Installing Retaining Wall Block	m^2	300	300	300
	Block Stuffing (Soil)	m^3	42	75	75
	Block Stuffing (Stone)	m^3	18	36	36
	Nonwoven Fabric	m^2	300	300	300
	Backfilling (Stone)	m^3	114	90	90
	Concrete treated base	m^3	66.1	60	60
	Euro form	m^2	183.2	180	180
	Vegetation shelter block	m^2	-	120	120
Drainage Works Structure Works	Waterproofing Sheet (PE)	m	9	9	9
	Concrete treated base	m^3	9.1	9.1	9.1
	Euro form	m^2	32.4	32.4	32.4
	Reinforcement Assembling	ton	0.324	0.324	0.324
Transportation Works	Heavy Machinery	Number	1	1	1
	Retaining Wall Block	Number	936	936	936
	Stone	m^3	137	137	137
	Ready-mixed Concrete	m^3	72	72	72
	Rebar	ton	0.324	0.324	0.324
	Polyethylene (PE) Pipe	m	9	9	9
	Grass	m^2	-	120	120
Planting Works	Tulip Tree	Tree	-	-	150
	Cherry	Tree	-	-	150
	Ginkgo	Tree	-	-	150
	Sheep's principal Tree	Tree	-	-	2700
	Zoysia Tenifolia	m^2	-	-	265

The values of the coefficients, such as k and f, and factor and efficiency, E, were determined by using the national standard estimating reference from KICEBT. The equipment CO_2 emission of mixer-trucks and dump trucks for the small stream restoration project was calculated by using the national standard estimating reference from KICEBT. Table 4 shows the CO_2 emission and absorption factor per unit results for detailed equipment operation and materials used. The research calculated the related CO_2 emission and absorption automatically by using the GDMT.

The calculation results showed that the small stream restoration project could lead to CO_2 emissions ranging from 59.6 to 86.7 tonCO_2. In the case of the Ha-gok stream baseline scenario (S-I), the small stream restoration emitted 86.7 tons CO_2 to restore a total of 42 m of stream. In the case of alternative (S-II), the amount of CO_2 emission was 85.3 tonCO_2 and in the case of S-III the amount of CO_2 emission was 59.6 tonCO_2. As a result of the analysis of carbon contents by scenarios, since only absorption was considered for vegetation shelter block and green infra, the amount of carbon generated in all scenarios immediately after the project was the same. In terms of absorption, when the vegetation shelter block was used as an alternative method for embankment work in S-II, about 12.66% of carbon emissions could be absorbed. As can be seen in Figure 2, the S-III scenario absorbed 52.85% of carbon emissions, showing that the carbon absorption rate was higher than that of S-I and S-II. In terms of sustainable development, green infra facilities are believed to be able to support carbon neutrality.

Table 4. Summary of the CO_2 emission and absorption factors per unit results for detailed equipment operation and materials used corresponding to the restoration project for the Ha-gok small stream located in Geochang-Gun, Republic of Korea, based on three scenarios: S-I, S-II and S-III.

Work Type	Processes	CO_2 Emission Factor		CO_2 Absorption Factor	
		Materials ($kgCO_2$/Unit)	Equipment ($kgCO_2$/Unit)	Tree ($kgCO_2/m^2/yr$)	Plants ($kgCO_2/m^2/yr$)
Earth Works	Cutting Soil		0.36		
	Digging Soil		0.36		
	Backfilling (Soil)		0.36		
	Cleaning up Soil		0.36		
	Breaking Groundless Concrete		26.56		
	Loading Waste		0.36		
Embankment Works	Installing Retaining Wall Block	346.00	13.41		
	Block Stuffing (Soil)		0.82		
	Block Stuffing (Stone)		0.91		
	Nonwoven Fabric	346.00	13.41		
	Backfilling (Stone)		0.91		
	Concrete treated base	346.00	1.83		
	Euro form		183.2		
	Vegetation shelter block		6.64		
Drainage Works	Waterproofing Sheet (PE)	2.37	9.06		
Structure Works	Concrete treated base	346.00	1.83		
	Euro form		183.2		
	Reinforcement Assembling	2340.00	0.324		
Planting Works	Tulip Tree			101.9	
	Cherry			26.9	
	Ginkgo			35.4	
	Sheep's principal Tree			55.6	
	Zoysia Tenifolia				1.80

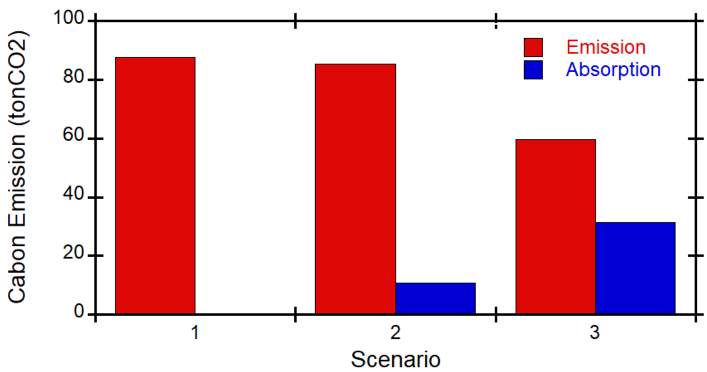

Figure 2. Comparison results of carbon emissions and absorptions results by scenario.

4.2. Evaluation of Effectiveness of Small Stream Restoration Projects

In order to calculate the carbon generated by the implementation of the small stream restoration project, the GDMT was employed to assess CO_2 emissions from a total of 63 small streams located in Yong-in City, Korea. The average CO_2 emissions for small streams restoration projects in Yong-in were determined to be 242.1 tons of CO_2. Among these streams, the Suyouk stream had the highest carbon emissions at 1965 tons of CO_2, while the Jinae stream had the least at 33.4 tons of CO_2. It was reported that 48 small streams, which account for 38.7% of all small streams, emitted 93.9% of all CO_2 emissions, and the top 11 small streams emitted 50.8% of all emissions.

By work type, the weir and drop structure works exhibited the highest carbon emissions, releasing 28,034,976 tons of CO_2 and representing 94.89% of the total emissions, as shown in Table 5. Following closely was the erosion control and re-vegetation, contributing the second-highest carbon emissions at 904,235 tons of CO_2, accounting for 3.1% of the total emissions. Subsequently, earth works generated 547,332 tons of CO_2, ranking as the third-largest contributor and constituting 1.9% of the total emissions. As a result, it was found that most of the carbon was generated in the use of concrete, and not much carbon was generated in the soil. To estimate the total carbon emission amount of small stream restoration projects nationwide, the research analyzed the correlation between the carbon emissions and characteristic information such as mean slope, mean height, watershed area, watershed width, channel length and channel sinuosity of the small stream in the project, as shown in Figure 3.

Table 5. Comparison of carbon emissions by work type for a small stream restoration project.

Work Type	Total Carbon Emission ($tonCO_2$)	Mean Carbon Emission per Small Stream ($tonCO_2$/Stream)	Ratio (%)
Soil Removal	147,592	1180.7	0.5
Embankment	56,773	454.2	0.2
Backfilling (Soil)	40,026	320.2	0.1
Cleaning up Soil	359,714	2877.7	1.2
Erosion control and re-vegetation	904,235	7233.9	3.1
Weir and Drop Structure	28,034,976	224,279.8	94.9

In order to quantitatively compare the correlation between characteristic information and the predicted CO_2 emission, the research calculated the correlation coefficient and compared the results. The results show that the value of the correlation coefficient of the channel length was the largest at 0.453, followed by the watershed area, the channel sinuosity, the watershed width, the mean height and the mean slope, and each of these correlation coefficient values was calculated as 0.220, 0.164, 0.144, −0.129, and 0.010. The longer the length of the small stream restoration project, the higher the carbon emissions from the restoration project as shown in Figure 3e. However, it was difficult to find an appropriate correlation and homogeneity of variance due to the large variation in carbon emissions by small stream restoration project, as all small streams across the country have different watershed characteristics and project conditions, such as the amount of materials and equipment required for each.

The research developed a non-linear multi-regression equation for predicting the carbon emission equation as a function of the length of small stream restoration project, derived by using the robust minimum covariance determinant regression method [49,50]. The data sets used in the development of the new carbon emission equation were collected from 63 small streams located in Yong-in City, Korea in which the CO_2 emission amount for each small stream restoration project was determined by using the GDMT. The new regression equation derived by using the robust minimum covariance determinant regression method was given as

$$C_P = 291.15 + 56.64L^{1.74} \tag{4}$$

in which C_P represents the predicted carbon emission and L represents the length of the small stream restoration project. Sixty-three measured data sets were used to verify the proposed equation for predicting carbon emission, in which the determinant coefficient was 0.546. For the verification of the proposed equation, carbon emissions predicted by the proposed equation were compared with determined carbon emission amounts. The comparisons of predicted carbon emissions by Equation (4), with determined data using the GDMT, are shown in Figure 4. This figure shows that the proposed equation predicted well the represented determined data. The research conducted a comprehensive analysis of the environmental impact of entire small stream restoration projects, focusing on CO_2 emissions and absorption. Assuming that small stream restoration projects would be completed, the derived regression equation was applied to 22,093 small stream restoration projects nationwide to predict carbon emissions. Predicted results showed that a total of 1,158,840.7 tonCO_2 would be emitted during the entire small stream restoration projects. As of 2022, about 40% of all stream restoration projects have been completed, and it would be expected that an additional 695,304.4 tonCO_2 would be emitted when the small stream restoration projects are completed in the future.

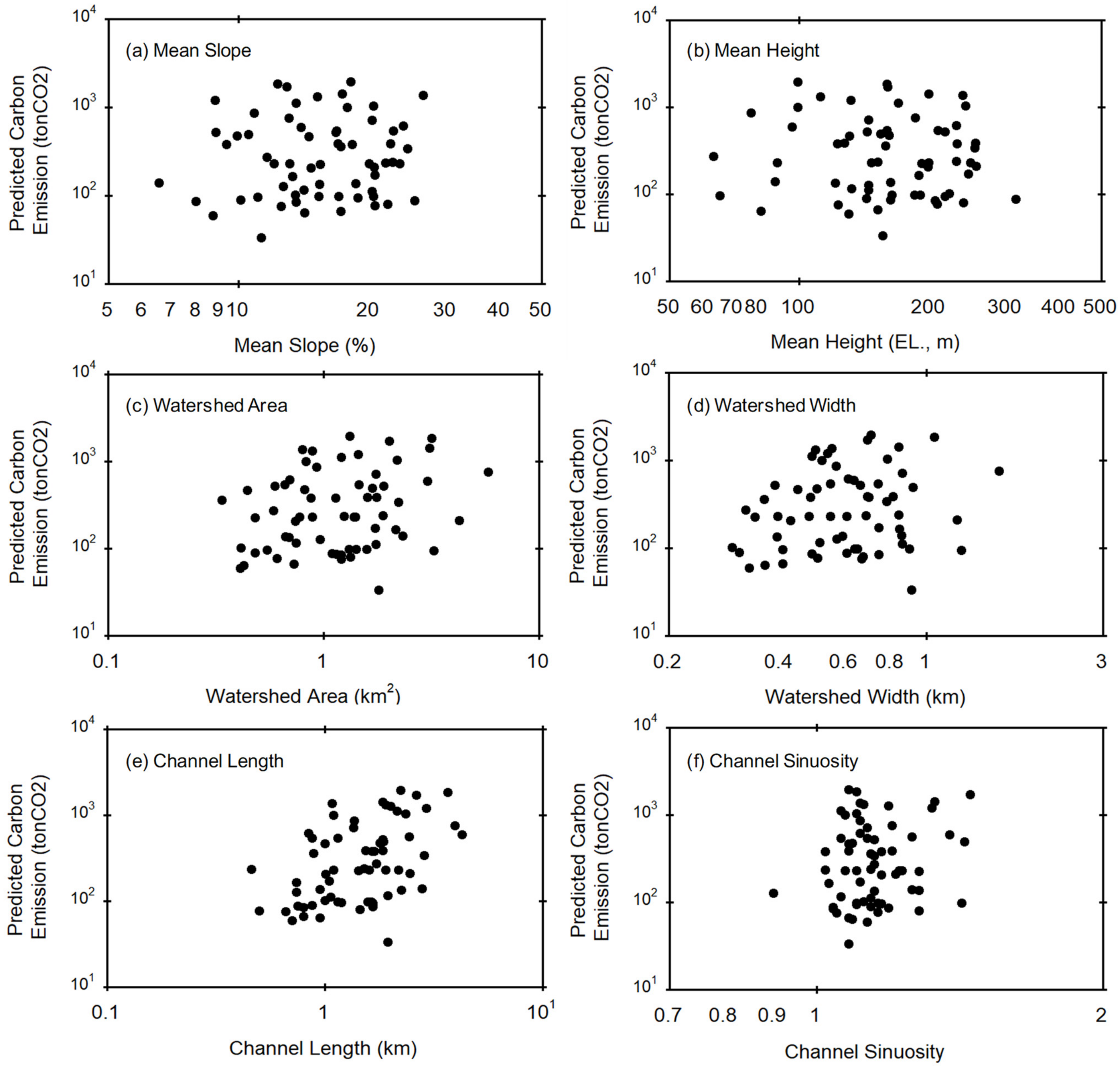

Figure 3. Comparisons of the correlation between carbon emissions and characteristic information, such as mean slope, mean height, watershed area, watershed width, channel length and channel sinuosity of the small stream restoration project performed in Young-in City, Republic of Korea.

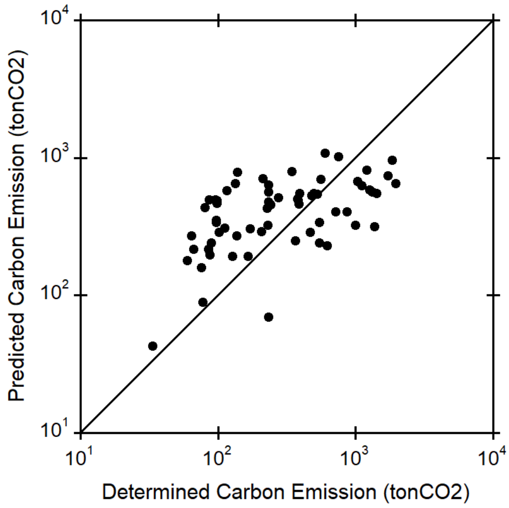

Figure 4. Comparisons of predicted CO_2 emissions by regression equation developed here with determined values using the GDMT for small stream restoration projects performed in Young-in City, Republic of Korea.

To evaluate the overall environmental consequences, the research predicted the total carbon absorption resulting from small stream restoration projects nationwide. The prediction revealed a promising trend, indicating that, by the year 2030, carbon absorption is expected to be approximately 3.0 to 10.2 times higher than the total carbon emissions of 1,158,840.7 tonCO_2 from the entire small stream restoration projects. Looking further into the future, by 2050, vegetation is anticipated to absorb up to 32 times the amount of carbon emissions attributable to the projects. These findings emphasize the significant carbon mitigation benefits associated with stream restoration projects. The results suggested positive effects in CO_2 absorption that substantially outweighs emissions, highlighting the environmental sustainability of these initiatives over the long term. As progress towards the future, it would be expected that these insights provide valuable information for policymakers and stakeholders to enhance the effectiveness and ecological impact of stream restoration projects.

5. Conclusions

Most disaster risk management measures, such as construction projects and small stream restoration projects, were mostly focused on material production and equipment use, which was expected to contribute significantly to CO_2 emissions. Therefore, efforts were needed to convert disaster risk management measures into eco-friendly and low-carbon projects to achieve the carbon neutrality goal for climate change mitigation and adaptation. To support this conversion, the research developed GDMT, a novel toolkit that could calculate CO_2 emissions and absorption by using only the generalized project plan information provided by KONEPS. In the GDMT, the user could easily change the work type, such as processes, materials, and methods, by simply selecting from already established measures, and could directly compare the CO_2 emissions and absorption of each small stream restoration project by using the visualized results function, so it would be possible to establish customized measures, including LID and GI, at the planning stage to achieve the carbon neutrality goal and reduce disaster risk.

To efficiently provide calculation results, the study evaluated existing CO_2 emissions and absorption calculation programs and toolkits to identify and improve the limitations of diversity and visualization capabilities. The biggest difference between the GDMT developed in the research and the existing toolkit was that CO_2 emissions and absorption could be quantified in the GDMT. The standardized framework established to quantify both emissions and absorption was essential for a comprehensive understanding of greenhouse gas dynamics related to various disaster risk management measures. The research developed a comprehensive calculation analysis of CO_2 emissions, considering factors such as energy utilization and project scale by focusing on the initial stages of materials production and construction. The research also developed a CO_2 absorption calculation method for certain green-based elements, such as surface plants and artificial wetlands, which are mainly used in disaster risk management projects to quantify CO_2 absorption for vegetation, land, and water surface area, major factors affecting CO_2 absorption.

The development of toolkits was also important for sustainable disaster risk management, but it was also very important to select measures to support the achievement of carbon neutrality goals. The research attempted to help select appropriate measures to reduce CO_2 emissions and increase CO_2 absorption by introducing LID and GI-related measures through literature reviews. The research quantified CO_2 emissions and absorption by alternatives, applying GDMT to find alternative low-carbon green infrastructure solutions that fit local and environmental conditions during the construction process through case studies related to small stream restoration projects. Carbon emissions and absorption for small stream restoration projects in three scenarios, S-I, S-II, and S-III, using methods such as vegetation shelter blocks, retaining wall blocks, and green infrastructure, constructed in Ha-gok small stream located in Geochang-Gun, Korea were evaluated. The evaluation results indicated that the CO_2 emissions by small stream restoration project ranged from 59.6 to 86.7 tons of CO_2. The alternative scenarios, such as S-II and S-III, showed varying levels of CO_2 emissions, and the S-III scenario demonstrated the lowest emissions with 59.6 tons of CO_2. The comparative analysis results revealed that the vegetation shelter blocks and green infrastructure contributed to carbon absorption and the S-III scenario absorbed 52.85% of the emitted CO_2.

The research aimed to show that it was difficult to achieve the carbon neutrality goal when the small stream restoration project was completed with the current work type. To calculate the total CO_2 emissions of the small river maintenance project, CO_2 emissions by project scales and work types were first calculated and analyzed for 63 small stream restoration projects in Yong-in City, Korea. The results demonstrated that the weir and drop structure works contributed significantly to CO_2 emissions by accounting for 93.41% of total CO_2 emissions, followed by erosion control and re-vegetation work accounting for 3.01% of total CO_2 emissions, and earthwork accounting for 2.01% of total CO_2 emissions. As a result of analyzing the amount of carbon emissions generated by the small stream restoration projects and the amount of carbon emissions by work type, it was found that the amount of carbon emissions was significantly related to the scale of the small stream restoration project.

A non-linear multiple regression equation was developed to predict CO_2 emissions based on the length of the small stream restoration project by analyzing the correlation coefficients between the amounts of CO_2 emissions obtained in the research and the characteristic information of 63 small rivers in Yong-in City, Korea. The regression method presented in the research was not perfect, but it could be used to predict future carbon emissions when the entire nationwide small stream restoration project proceeds in the current work types. The results showed that approximately 1,158,840.7 tons of CO_2 were emitted from previous small stream restoration projects, and an additional 695,304.4 tons of CO_2 would be emitted when all small stream restoration projects distributed nationwide were completed. In addition, the research also highlighted that CO_2 absorption could increase by 3.0 to 10.2 times of total emissions by 2030. If the small stream restoration project proceeds in the direction of considering sustainability and carbon reduction effects from a long-term perspective, vegetation is expected to absorb up to 32 times carbon emissions by 2050.

These findings provided valuable insights for policymakers and stakeholders into the potential positive environmental effects of small stream restoration initiatives by suggesting the possibility that the ecological impact of the project could lead to significant CO_2 uptake benefits in the long term beyond the initial CO_2 emissions. The GDMT, a practice tool developed in the research, might be used to help decision makers choose environmentally sustainable small stream restoration measures at the planning stage by comparing the calculated CO_2 emissions and absorption results for each alternative. The GDMT, a practice tool developed in the research, is expected to be used by decision makers to calculate CO_2 emissions and absorption for each alternative at the planning stage and compare the results in order to select environmentally sustainable disaster risk management measures.

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