## CGER'S SUPERCOMPUTER MONOGRAPH REPORT Vol.30

## Development of Process-based NICE Model and Simulation of Ecosystem Dynamics in the Catchment of East Asia (Part VII)

Tadanobu Nakayama

**Center for Global Environmental Research** 



National Institute for Environmental Studies, Japan

## CGER'S SUPERCOMPUTER MONOGRAPH REPORT Vol.30

## Development of Process-based NICE Model and Simulation of Ecosystem Dynamics in the Catchment of East Asia (Part VII)

Tadanobu Nakayama





National Institute for Environmental Studies, Japan

#### CGER'S SUPERCOMPUTER MONOGRAPH REPORT Vol.30

# Development of Process-based NICE Model and Simulation of Ecosystem Dynamics in the Catchment of East Asia (Part VII)

\_\_\_\_\_Tadanobu Nakayama

#### **Edited by:**

Center for Global Environmental Research (CGER), Earth System Division (ESD) National Institute for Environmental Studies (NIES)

#### **Coordination for Resource Allocation of the Supercomputer:**

Center for Global Environmental Research (CGER), Earth System Division (ESD) National Institute for Environmental Studies (NIES)

#### Supercomputer Steering Committee (FY2023):

Masayoshi Ishii (Meteorological Research Institute, Japan Meteorological Agency) Masaki Satoh (Atmosphere and Ocean Research Institute, The University of Tokyo) Seiya Nishizawa (RIKEN Center for Computational Science) Akinori Takami (Regional Environment Conservation Division/NIES) Toshihiro Azuma (Planning Division/NIES) Hideharu Akiyoshi (Earth System Division/NIES) Tomoo Ogura (Earth System Division/NIES)

#### Maintenance of the Supercomputer System:

Environmental Information Division National Institute for Environmental Studies (NIES)

#### **Operation of the Supercomputer System:**

NEC Corporation

#### Copies of this report can be obtained from:

Center for Global Environmental Research (CGER), Earth System Division (ESD) National Institute for Environmental Studies (NIES) 16-2 Onogawa, Tsukuba, Ibaraki, 305-8506 Japan Fax: +81-29-858-2645 E-mail: www-cger@nies.go.jp

The report is also available as a PDF file. See: https://www.cger.nies.go.jp/ja/activities/supporting/publications/report/

#### Copyright 2024:

NIES: National Institute for Environmental Studies

#### Foreword

The Center for Global Environmental Research (CGER) at the National Institute for Environmental Studies (NIES) was established in October 1990, with the main objectives of contributing to the scientific understanding of global environmental change and identifying solutions to critical environmental problems. CGER conducts environmental research from an interdisciplinary, multi-agency, and international perspective, and provides an intellectual infrastructure for research activities in the form of databases and a supercomputer system. CGER also ensures that data from its long-term monitoring of the global environment is made available to the public.

CGER installed its first supercomputer system (NEC SX-3) in March 1992, and the system was upgraded to an NEC SX-4 in 1997, an NEC SX-6 in 2002, an NEC SX-8R in 2007, an NEC SX-9 in 2013, and an NEC SX-ACE in June 2015. The current system consists of an NEC SX-Aurora TSUBASA/type A511-64 and 22PB file storage to provide more computational resources and data capacity. The NIES supercomputer system is available for researchers at research institutions and universities in Japan, including NIES. The Supercomputer Steering Committee is comprised of Japan's leading scientists in climate modeling, carbon cycle, atmospheric chemistry, marine environment, and other fields related to global environmental research, and one of its functions is to evaluate research proposals that require the use of the NIES supercomputer system. To promote the dissemination of results, we publish Annual Reports and occasional Monograph Reports. Annual Reports deliver the results of all research projects that used the NIES supercomputer system each year, whereas Monograph Reports present the integrated outcomes of a particular research project.

This Monograph Report presents the results of the development process of the National Integrated Catchment-based Ecohydrology (NICE) model after the 11th (Part I), 14th (Part II), 18th (Part III), 20th (Part IV), 26th publications (Part V), and 29th publications (Part VI). This volume reviews the NICE processes developed since Part VI was published and describes how the model has been applied to evaluate plastic dynamics of various basins from regional to global scales. In order to solve this problem, NICE was extended to link it with a plastic debris (engineered materials) model for freshwater systems in this volume. This methodology is useful for quantifying the impacts of plastic waste on terrestrial and aquatic ecosystems, and developing solutions and efficient measures to reduce the plastic load on a global scale.

In future, we intend to continue our support for environmental research by using supercomputer resources and disseminating practical information based on our results.

March 2024

王段信子

Nobuko Saigusa Director Center for Global Environmental Research Earth System Division National Institute for Environmental Studies

#### Preface

This volume of the CGER's SUPERCOMPUTER MONOGRAPH REPORT series is the 30th publication on research outcomes achieved by the users of supercomputer facilities at the Center for Global Environmental Research (CGER) at the National Institute for Environmental Studies (NIES).

An advanced process-based model, known as the National Integrated Catchment-based Eco-hydrology (NICE) model, has been developed to evaluate ecosystem dynamics in catchments. NICE is a 3-D, grid-based eco-hydrology model that simulates the complex interactions between forest canopy, surface water, unsaturated zones, aquifers, lakes, and rivers. It also iteratively simulates nonlinear interactions between hydrogeomorphic and vegetation dynamics. The model can also be coupled with complex subsystems to simulate systems such as irrigation, urban water usage, stream junctions, and dams/canals; develop integrated human and natural systems; and analyze the impact of anthropogenic activity on eco-hydrologic change. Water resources are vital for human activity, but their overuse has caused serious environmental degradation, economic stagnation, and immense burdens on the surrounding environment. This is particularly evident in Asia, where finding a solution to environmental pollution is crucial.

This monograph (Part VII) succeeds the 11th (Part I), 14th (Part II), 18th (Part III), 20th (Part IV), 26th publications (Part V), and 29th publications (Part VI). This volume reviews the NICE processes developed since Part VI was published and describes how the model has been applied to evaluate plastic dynamics of various basins from regional to global scales. In order to solve this problem, NICE was extended to link it with a plastic debris model for freshwater systems, including advection, dispersion, diffusion, settling, dissolution and deterioration due to light and temperature. Establishment of complete model for the whole picture of plastic dynamics on basin scale becomes a big step forward. The results are also important for predicting and estimating the change of plastic dynamics under climate change. These results help to quantify the impacts of plastic waste on terrestrial and aquatic ecosystems, and may be useful for devising solutions and measures for reduction of plastic input to the ocean.

NICE is now being expanded to incorporate heteroaggregation, sorption, and biofouling, etc. interacting plastic with suspended matter, carbon cycle, and other media. Plastic pollution is considered to be one of today's main environmental problems, and such pollutants in streams, rivers, and oceans pose potential risks to human health and the environment. From this viewpoint, the results help develop solutions and efficient measures to reduce the plastic load on a global scale. This will be reported in the next monograph (Part VIII). I hope that this publication will help integrate knowledge and provide the understanding needed to reach sustainability by 2030 in the UN Sustainable Development Goals, which supports climate action, clean water, sustainable cities, life below water, and life on land.

March 2024

Tadanobu Nakayama

Tadanobu Nakayama Chief Senior Researcher Regional Environment Conservation Division National Institute for Environmental Studies

## Contents

Foreword	i
Preface	
Contents	
List of Figures	vi
List of Tables	ix

## Chapter 1

General Introduction	1
.1 Background	3
.2 Description of Process-Based Model NICE Applicable to Quantify Plastic Dynamics	4
.3 Objective and Methods toward Efficient Measures to Reduce Plastic Input to Ocean	6
References	8

### Chapter 2

Development of a Process-Based Eco-Hydrology Model for Evaluating Spatiotemporal
Dynamics of Macro and Microplastics for Whole of Japan
J I I
Abstract
2.1 Introduction
2.2 Methods
2.2.1 Model Description of Mass Transport Process in NICE
2.2.2 Modelling Fate and Transport of Macro and Microplastics in Land and Inland Water
by Extension of NICE-BGC
2.3 Input Data and Boundary Conditions for Simulation
2.3.1 Model Input Data
2.3.2 Plastic Generation at Point and Non-Point Sources and Removal at WWTP23
2.3.3 Running the Simulation and Verification
2.4 Results and Discussion
2.4.1 Evaluation of Hydrologic Cycle in First-Class (Class A) River Basins in Entire Japan 25
2.4.2 Analysis of Sensitivity of Microplastic Transport to Various Factors
2.4.3 Impact of Plastic Density and WWTP on Riverine Export of Plastics into Ocean29
2.5 Conclusion
References

Chapter 3	
Flux and Fate of Plastic in World's Major Rivers: Modeling Spatial and Temporal	
Variability	37
Abstract	39
3.1 Introduction	10
3.2 Methods	12
3.2.1 Coupling of NICE-BGC with Plastic Debris Model and its Application to Global	
Scale	12
3.2.2 Extension of Settling Velocity Applicable to Uncertainty Analysis	14
3.3 Input Data and Boundary Conditions for Simulation4	15
3.3.1 Model Input Data including Plastic Generation and Removal4	15
3.3.2 Boundary Conditions and Running the Simulation4	17
3.3.3 Analysis of the Influence of Various Factors on Plastic Transport4	17
3.4 Results and Discussion	18
3.4.1 Evaluation of Plastic Flux from World's Major Rivers into Ocean4	18
3.4.2 Seasonal Variation of Plastic Flux on a Global Scale4	19
3.4.3 Uncertainty and Sensitivity Analyses of Riverine Plastic Transport on Continental and	
Global Scales	51
3.5 Conclusion	52
References	53

### Chapter 4

Impact of Global Major Reservoirs and Lakes on Plastic Dynamics by Using a Process Resed Fee Hydrology Model	57
Trocess-Daseu Eco-myurology Would	••••••••••••••••••••••••••••••••
Abstract	59
4.1 Introduction	60
4.2 Methods	61
4.2.1 General Model Framework of NICE-BGC	61
4.2.2 Extension of Plastic Debris Model including Global Reservoirs and Lakes	63
4.3 Input Data and Boundary Conditions for Simulation	63
4.3.1 Model Input Data	63
4.3.2 Boundary Conditions and Running the Simulation	64
4.4 Results and Discussion	65
4.4.1 Effect of Reservoirs on Differences in Horizontal Plastic Transport	65
4.4.2 Effect of Reservoirs on Differences in Plastic Burial	66
4.4.3 Change in Global Plastic Cycle by Considering Effects of Lentic Waters	67
4.5 Conclusion	69
References	69

Chapter 5	
Plastic Trade-Off: Impact of Export and Import of Waste Plastic on Plastic Dyna	mics
in Asian Region	73
Abstract	75
5.1 Introduction	76
5.2 Methods	78
5.2.1 General Model Framework of NICE-BGC	78
5.2.2 Extension of Plastic Debris Model including Effect of Waste Plastic Trade	79
5.3 Input Data and Boundary Conditions for Simulation	80
5.3.1 Model Input Data including Effect of Waste Plastic Trade	80
5.3.2 Running the Simulation and Verification	83
5.4 Results and Discussion	84
5.4.1 Seasonal Variations of Riverine Plastic Transport	84
5.4.2 Distribution of Microplastic in Asian major rivers	85
5.4.3 Impact of Waste Plastic Trade on Change in Riverine Plastic Transport in Asian	
Region	86
5.5 Conclusion	87
References	88

### Chapter 6

Final Conclusions and Future Work	
6.1 Final Conclusions	
6.2 Future Work	
References	

### Appendix

Publications and Presentations	105
Original Papers and Reviews Related to This Monograph Conference Reports Related to This Monograph NICE Series in CGER's Supercomputer Monograph Report (Part I - VI) Contact Person	107 107 108 108

CGER'S SUPERCOMPUTER REPORT	(previously published)	)109
-----------------------------	------------------------	------

## **List of Figures**

### Chapter 1

1.1	Process-based National Integrated Catchment-based Eco-hydrology (NICE) model	6
1.2	NICE simulation for quantifying hydrologic cycle and its ecosystem assessment in various basins/catchments from regional to global scales. Previous model applications to regional continental and global scales (Part I–VI) and plastic	
	dynamics in the current monograph (Part VII)	7
1.3	Flow diagram of macro and microplastic transport in land and inland water by	
	extending NICE	8

(Some of the figures in Chapter 1 are reprinted from Nakayama, T. (under review) Impact of settling and resuspension on plastic dynamics during extreme flow and their seasonality in global major rivers. Hydrological Processes)

### Chapter 2

2.1	Location of the study area in entire Japan; (a) all the first-class of 109 river basins, (b) elevation, (c) land cover, (d) population density, (e) pumping and wastewater treatment plant (WWTP), and (f) mismanaged plastic waste (MPW)	
		18
2.2	Flow diagram of macro and microplastic transport in land and inland water by extending NICE-BGC	22
2.3	Simulated results of surface runoff in major rivers with large basin areas and long river channels among the first-class rivers during 2014–2015; (a) total surface runoff, (b) surface runoff, and (c) intermediate flow	26
2.4	Comparison of annual-averaged values in (a) discharge, (b) nitrogen transport, and (c) phosphorus transport in the first-class of river basins; red circle shows the nutrient transports simulated by the time series for the entire calculation period during 2014–2015, and blue triangle shows the values simulated only by the base flow of rivers	.27
2.5	Sensitivity analysis of various factors on micro-plastic concentration downstream of Tone River from June 1 to July 20 in 2014; (a) effect of particle diameter (diameter = 1, 10, 20 $\mu$ m with constant density = 1150 kg/m <sup>3</sup> ), (b) effect of particle density (density = 900, 1010, 1350 kg/m <sup>3</sup> with constant diameter = 10 $\mu$ m), (c) effect of particle degradation (with the effect of water temperature, UV irradiation, and both with diameter = 10 $\mu$ m and density = 1150 kg/m <sup>3</sup> )	28
2.6	Simulated plastic flux to the ocean; (a)-(b) annual fluxes in each first-class of 109 rivers, and (c) total flux in entire Japan with various scenarios; Blue and red bars show the flux of macro and microplastics.	28

(The figures in Chapter 2 are reprinted from Nakayama, T., Osako, M. [2023a] Development of a process-based eco-hydrology model for evaluating the spatio-temporal dynamics of macro- and micro-plastics for the whole of Japan. Ecological Modelling, 476, 110243, doi:10.1016/j.ecolmodel.2022.110243)

#### Chapter 3

3.1	Location of study area on the global scale; (a) elevation, (b) land cover, (c)	
	iertilizer and manure, (d) population density, (e) untreated wastewater	
	mismanaged plastic waste (MPW)	.42
3.2	Flow diagram of macro- and micro-plastics transport in land and inland water	
	by extending NICE-BGC	.44
3.3	Comparison between simulated annual plastic flux from the major global rivers	
	into the ocean and the previous material: (a) macro-plastic, (b) micro-plastic,	
	and (c) total plastic fluxes	.49
3.4	Relationships between population density and (a) macro-plastic concentration,	
	(b) micro-plastic concentration, (c) macro-plastic flux per unit area, and (d)	
	micro-plastic flux per unit area in global major rivers simulated by NICE	.50
3.5	Seasonal variations of (a) river discharge and plastic fluxes of (b) total, (c)	
	macro, and (d) micro plastics in each continent in the same cases as that in Fig.	
	3.3; 'AS', 'EU', 'OC', 'AF', 'NA', and 'SA' mean Asia, Europe, Oceania,	
	Africa, North America, and South America	.51
3.6	Uncertainty and sensitivity analyses using the Monte Carlo model simulations	
	to evaluate the influence of various factors on annual-averaged riverine plastic	
	transport in global major rivers: (a) macro-plastic, (b) micro-plastic, and (c) total	
	plastic fluxes	.52

(The figures in Chapter 3 are reprinted from Nakayama, T., Osako, M. [2023b] The flux and fate of plastic in the world's major rivers: Modeling spatial and temporal variability. Global and Planetary Change, 221, 104037, doi:10.1016/j.gloplacha.2023.104037)

### Chapter 4

4.1		Study area of the world's major rivers (153 basins, 325 river channels) with 82 major reservoirs (red circle) and 19 lakes (blue mesh) included in these basins
		to simulate the plastic dynamic: Green circle line (25 reservoirs of the total 82)
		and purple circle line (19 lakes) means the application of NICE-BGC and
		LAKE2K coupled model in this study
4.2		Flow diagram of macro- and micro-plastics transport in land and inland water
		by extending NICE-BGC coupled with LAKE2K to lotic and lentic waters
4.3		Difference of simulated horizontal plastic transport in inland waters with and without the presence of reservoirs; (a)-(c) macro-plastic and (d)-(f) micro- plastic transports without effect of settling and resuspension, with almost the same as the density of water (density = $1000.1 \text{ kg/m}^3$ ), and on averaged plastic condition of all iterations of Monte Carlo model simulations (density = $1008.8 \text{ kg/m}^3$ )
4.4		Comparison of (a)-(c) macro-plastic and (d)-(f) micro-plastic burials on floating condition (settling velocity = 0), with almost the same as the density of water (density = $1000.1 \text{ kg/m}^3$ ), and on averaged plastic condition of all iterations of Monte Carlo model simulations in global major reservoirs without the lake
		model (horizontal axis) and with it (vertical axis)
4.5		Simulated plastic deposition in the global (a) lakes and (b) reservoirs; Blue and
		red bars show the flux of macro and microplastics
(751	œ	

(The figures in Chapter 4 are reprinted from Nakayama, T. (under review) Impact of global major

reservoirs and lakes on plastic dynamics by using a process-based eco-hydrology model. Lakes and Reservoirs: Research and Management)

#### Chapter 5

5.1	Location of the study area in Japan and Asian regions; (a) land cover, (b) population density, (c) untreated wastewater calculated from wastewater treatment and wastewater production, and (d) mismanaged plastic waste (MPW)
5.2	Flow diagram of macro and microplastics transport in land and inland water by
	extending NICE-BGC to include the effect of waste plastic trade
5.3	Effect of waste plastic trade on MPW in Asian regions; (a)-(b) around Shanghai
	District in importing country (China) without and with this effect; (c)-(d) around
	Tokyo Metropolitan Area in exporting country (Japan) without and with this
	effect
5.4	Simulated results of seasonal variations of riverine plastic transport of Yangtze,
	Yellow, and Mekong Ganges Rivers; (a) plastic concentration, and (b) plastic
	transport in these rivers
5.5	Simulated results of the size distribution of microplastic in the water and
	riverbed sediment of Yangtze, Mekong, and Ganges Rivers; (a) normal
	frequency distribution in the water, (b) that in the sediment, and (c) relative
	abundance across different size categories in the water and sediment
5.6	Impact of waste plastic trade on variations of riverine plastic transport in Asian regions; (a) amount of plastic flux for each first-class of 109 rivers in Japan, (b) total flux in entire Japan, and (c) amount of plastic flux for Asian major rivers87

(The figures in Chapter 5 are reprinted from Nakayama, T., Osako, M. [2024] Plastic trade-off: Impact of export and import of waste plastic on plastic dynamics in Asian region. Ecological Modelling, 489, 110624, doi:10.1016/j.ecolmodel.2024.110624)

#### Chapter 6

6.1	Flow diagram of the original NICE regarding water resources, and recent	
	development of the eco-hydrological and biogeochemical coupling model	
	(NICE-BGC)	.98
6.2	Percentages of (a) exporting micro-plastic load stored on the riverbed and (b)	
	plastic load transported to the ocean during flood periods in some major global	
	rivers	.99
6.3	Improvement of the carbon cycle by including global estuaries; (a) CO <sub>2</sub> flux in	
	global estuaries, and (b) CO <sub>2</sub> evasion and sediment storage in each continent	100

(Some of the figures in Chapter 6 are reprinted from Nakayama, T. [2022] Impact of anthropogenic disturbances on carbon cycle changes in terrestrial-aquatic-estuarine continuum by using an advanced process-based model. Hydrological Processes, 36(2), e14471, doi:10.1002/hyp.14471, and Nakayama, T. (under review) Impact of settling and resuspension on plastic dynamics during extreme flow and their seasonality in global major rivers. Hydrological Processes)

## List of Tables

#### Chapter 2

2.1	List of input data sets for the NICE and NICE-BGC simulations	.23
2.2	Per capita emission of macroplastics and microplastics into rivers in previous	
	materials	.24

(The tables in Chapter 2 are reprinted from Nakayama, T., Osako, M. [2023a] Development of a processbased eco-hydrology model for evaluating the spatio-temporal dynamics of macro- and micro-plastics for the whole of Japan. Ecological Modelling, 476, 110243, doi:10.1016/j.ecolmodel.2022.110243)

### Chapter 3

3.1	List of input data sets for the NICE and NICE-BGC simulations	46
3.2	Per capita emission of macro-plastics and micro-plastics into rivers in previous	
	materials	46

(The tables in Chapter 3 are reprinted from Nakayama, T., Osako, M. [2023b] The flux and fate of plastic in the world's major rivers: Modeling spatial and temporal variability. Global and Planetary Change, 221, 104037, doi:10.1016/j.gloplacha.2023.104037)

### Chapter 4

4.1	List of inp	ut data set	ts fo	r the NI	CE and N	ICE	E-BG	C simul	ations			64
4.2	Weighted	average	of	plastic	budget	in	the	global	major	rivers	(153	
	basins/wat	ersheds, 3	25 1	river cha	nnels)							69

(The tables in Chapter 4 are reprinted from Nakayama, T. (under review) Impact of global major reservoirs and lakes on plastic dynamics by using a process-based eco-hydrology model. Lakes and Reservoirs: Research and Management)

### Chapter 5

5.1	List of input data for NICE and NICE-BGC simulations in Japan and Asian	
	regions	81
5.2	Effect of waste plastic trade on MPW in Asia Pacific and major economies in	
	2015	82

(The tables in Chapter 5 are reprinted from Nakayama, T., Osako, M. [2024] Plastic trade-off: Impact of export and import of waste plastic on plastic dynamics in Asian region. Ecological Modelling, 489, 110624, doi:10.1016/j.ecolmodel.2024.110624)

## Chapter 1

## **General Introduction**

Chapter 1 General Introduction

#### 1.1 Background

Plastic pollution is one of today's main environmental problems, and such pollutants in streams, rivers, and oceans pose potential risks to human health and the environment (Siegfried et al., 2017). Plastic accumulation on riverbanks, deltas, coastlines, and the ocean surface is rapidly increasing, and it is estimated that 60% of the plastics ever manufactured have been discarded in landfills or the natural environment (Meijer et al., 2021). Plastic waste can be roughly categorized as macro-plastic ( $\geq$ 5 mm) or micro-plastic ( $\leq$ 5 mm), the latter being further divided into primary and secondary micro-plastics according to origin (Siegfried et al., 2017). Once plastic is released into the environment, it is gradually degraded by physical, chemical, and biological processes, leading to further subdivision into many forms, all of which are impossible to remove and remain indefinitely in the environment (Zhang et al., 2021).

Previous studies on the origin and fate of plastic waste in freshwater systems have suggested that land-derived plastics are one of the main sources of marine plastic pollution (Thompson et al., 2004) because of either direct emission from coastal areas (Jambeck et al., 2015) or by transport via rivers (Lebreton et al., 2017; Schmidt et al., 2017). Over the last decade, there has been great progress in modeling the fate and transport of plastics. Kooi et al. (2018) classified plastic debris models for freshwater systems into four categories: emission-based mass balance, global, multimedia, and spatiotemporally explicit models. Because most of the above plastic debris models are based on an analogy with sediment models for inland waters, it is questionable whether these models are reasonably adaptable for modeling the dynamics of plastics with various sizes, densities, shapes, polymer types, and contact angles (Nizzetto et al., 2016; Waldschlager and Schüttrumpf, 2019).

As for the waste plastic trade, Japan was one of the top exporting countries after Europe and America, and some countries, such as China, imported this waste plastic (Nakayama and Osako, 2024). China has imported approximately 45% of all cumulative imports of plastic waste between 1988 and 2016 (Brooks et al., 2018; Dominish et al., 2020; EIA, 2021). This situation changed greatly after establishing the "Basel Convention" (United Nations, 2019) because some importing countries introduced import regulations mainly for environmental protection. Developing a framework for reversing global water resource degradation, especially plastic pollution, is also powerful for achieving Sustainable Development Goals (SDG) (UNESCO, 2022). The recent G20 Osaka Summit in 2019 shared the "Osaka Blue Ocean Vision" (Ministry of Foreign Affairs of Japan, 2019). A quantitative assessment of the fate and transport of plastics will be necessary to realize this vision because countries worldwide have decided on concrete future measures for dealing with plastic based on scientific results.

The author has developed a process-based model coupling eco-hydrology with the biogeochemical cycle (National Integrated Catchment-based Eco-hydrology (NICE)-BGC) (Nakayama, 2017a,b), incorporating complex terrestrial-aquatic linkages in the hydrologic-biogeochemical cycle. Recently, the authors extended to couple this process-based NICE-BGC with a plastic debris (engineered materials) model and evaluated spatiotemporal variations of plastic debris in the entire Japan of regional scale (Nakayama and Osako, 2023a) and the world's major rivers of global scale (Nakayama and Osako, 2023b). The successful application of the NICE model in existing research has enabled the detection of the spatiotemporal hotspots of plastic fluxes by quantifying the impacts of plastic waste on terrestrial and aquatic ecosystems. The results also help improve the plastic cycle and develop better solutions and efficient measures to reduce plastic load globally as much as possible.

#### **1.2 Description of Process-Based Model NICE Applicable to Quantify Plastic Dynamics**

The National Integrated Catchment-based Eco-hydrology (NICE) model, which includes surface-unsaturated-saturated water processes and assimilates land-surface processes, has been developed to describe phenology variations based on satellite data (Nakayama, 2008a-c, 2009, 2010, 2011a-d, 2012a-d, 2013, 2014a,b, 2015, 2016, 2017a-c, 2018, 2019, 2020, 2022, 2023a,b; Nakayama and Fujita, 2010; Nakayama and Hashimoto, 2011; Nakayama and Maksyutov, 2018; Nakayama and Osako, 2023a,b, 2024; Nakayama and Pelletier, 2018; Nakayama and Shankman, 2013a,b; Nakayama and Watanabe, 2004, 2005, 2006a,b, 2008a-c; Nakayama et al., 2006, 2007, 2010, 2012, 2021a,b, 2023) (Fig. 1.1). NICE has been applied to various basins/catchments from local and regional scales, such as the Tokyo Metropolitan area in Japan, Kushiro Wetland (the largest wetland in Japan), and Lake Kasumigaura catchment (a highly eutrophic lake in Japan), and to continental and global scales, such as the Changjiang and Yellow Rivers in China, Ob River in West Siberia, Mekong River in Southeast Asia, Mongolia. The results of these studies are described in the papers cited above and have been summarized in previous CGER Supercomputer Monograph Report Series Vols. 11 (Part I) (Nakayama and Watanabe, 2006b), 14 (Part II) (Nakayama, 2008c), 18 (Part III) (Nakayama, 2012d), 20 (Part IV) (Nakayama, 2014b), 26 (Part V) (Nakayama, 2019), and 29 (Part VI) (Nakayama, 2023b) (Fig. 1.2).

NICE consists of complex sub-models: a surface hydrology model, a land-surface model including urban and crop processes, a groundwater model, a regional atmospheric model, a mass transport model of sediment, nutrients, carbon, and plastics, and a vegetation succession model. NICE applies a rectangular coordinate system based on the Albers or Universal Transverse Mercator (UTM) projection (Nakayama, 2014a,b, 2015). It also incorporates surface-groundwater interactions assimilating land-surface processes to describe the satellite data-derived leaf area index (LAI) variations and a fraction of photosynthetically active radiation (FPAR). The surface hydrology model of the NICE consists of a kinematic wave theory-based hillslope hydrology model and a distributed stream network model based on both kinematic and dynamic wave theories. NICE also solves a partial differential equation describing the three-dimensional groundwater flow for unconfined and confined aquifers. The integration of sub-models considers water and heat fluxes from the ground to the surface, including the hydraulic potential gradient between the deepest unsaturated flow layer and groundwater level, effective precipitation calculated from actual precipitation, infiltration into the upper soil moisture store, evapotranspiration, and seepage between the river water and groundwater.

The model can iteratively simulate nonlinear interactions between hydrologic, geomorphic, and ecological processes and include new feedback through downscaling from regional to local simulations employing fine resolution. Since NICE includes vegetation succession and competition between invasive alder and native mire vegetation, in addition to the stochastic simulation of seedling establishment, mortality, and regeneration, the model improves previous modeling approaches to the dynamic interaction between hydrological and biotic processes (Pastor et al., 2002; Rietkerk et al., 2004; van de Koppel et al., 2005; Ridolfi et al., 2006; Saco et al., 2007). Using NICE, previous studies have attempted to extract the impacts of discharge, groundwater level change, sediment deposition, and nutrient availability on the complex pattern of alder invasion and vice versa (Nakayama, 2008a,b, 2009, 2010, 2012b, 2013, 2014a,b; Nakayama and Watanabe, 2004, 2006a,b).

To fill the current eco-hydrology gap, the author has further developed a new model in which the original NICE is coupled with various biogeochemical cycle models (NICE-BGC)

(Nakayama, 2016, 2017a, 2017b) (Fig. 1.1). Each sub-model offers iterative simulation most efficiently by combining on-line and off-line modes (on-line: data input/output through I/O memory, off-line: data input/output through file); this means that the newly developed model incorporates the connectivity of the biogeochemical cycle accompanied by the hydrologic cycle between surface water and groundwater, hillslopes and river networks, and other intermediate regions (Nakayama, 2016). Recently, the author modified NICE-BGC to include the effect of reservoirs (Nakayama and Pelletier, 2018) and two parameters (soil organic carbon and carbon emission from the intermediate soil pool) to improve the accuracy of long-term simulation (Nakayama, 2020).

Thus, NICE has been applied to analyze water, heat, sediment, nutrients, and carbon cycles in various basins at the regional, continental, and global scales. Incorporating the plastic debris model and its relations to these water and material cycles is important. Regarding the scale similarity and discontinuity of eco-hydrological processes, identifying the spatial coupling of local ecosystems, including energy, materials, and organisms, across ecosystem boundaries is heuristically important. Recent research has raised serious concerns regarding the extrapolation of small-scale experimental results to entire landscapes, suggesting that it is imperative to bridge the gap between ecosystems at various scales (Deegan et al., 2012). Therefore, the ecosystems should be re-evaluated by extrapolating the 'metabolic theory of ecology' (Brown et al., 2004) from the perspective of a meta-ecosystem analysis by considering multi-scaled aspects at the global–regional–micro level, like the 'river continuum concept' (Vannote et al., 1980); this is also related to a previous finding that geophysical and microbial capacities enhance net heterotrophy in inland waters (Battin et al., 2008). Therefore, an accurate model to quantify the fate and transport of plastics is needed to evaluate the spatiotemporal dynamics of macro- and micro-plastics in each basin.



Figure 1.1 Process-based National Integrated Catchment-based Eco-hydrology (NICE) model.

#### 1.3 Objective and Methods toward Efficient Measures to Reduce Plastic Input to Ocean

To study ecosystem dynamics in catchments in East Asia, a method that combines a gridbased numerical model, a ground-truth observation network, satellite data, and statistical analysis has been developed previously. The current monograph (Part VII) succeeds the *CGER Supercomputer Monograph Report Series* regarding the NICE model (Fig. 1.2).

(i) 11th publication (Part I), 2006: Governing Equation of NICE (Nakayama and Watanabe, 2006b)

(ii) 14th publication (Part II), 2008: For Nature Restoration and Urban Regeneration (Nakayama, 2008c)

(iii) 18th publication (Part III), 2012: Application of NICE to Urban Areas in Japan and China (Nakayama, 2012d)

(iv) 20th publication (Part IV), 2014: Continental-scale in Changjiang and Yellow River Basins (Nakayama, 2014b)

(v) 26th publication (Part V), 2019: Evaluation of Missing Role of Inland Water in Global Biogeochemical Cycle (Nakayama, 2019).

(vi) 29th publication (Part VI), 2023: Evaluation of Anthropogenic Activity on Hydrologic Alteration in Arid and Semi-Arid Regions of Mongolia (Nakayama, 2023b).

The process-oriented model should be linked with the plastic debris model to quantify the impacts of plastic waste on the biosphere and to aid the development of solutions and measures to reduce plastic input to the ocean. In addition, the relationship between the amount of carbon assimilated by plants and water availability is one of the fundamentals of eco-hydrological

models. Furthermore, the intensity of carbon cycling and distribution of dead and living organic matter are related to temperature (Zalewski, 2002). A grid-based approach to solving the onedimensional time-dependent equations for thermal energy balance in advective river systems is also powerful for estimating temperature with high accuracy (Yearsley, 2012), in addition to the empirical relationship between air and water temperatures widely applied to many models.

To fill the gap in current plastic debris models in different categories (Kooi et al., 2018), a comprehensive investigation was first conducted by surveying existing research on plastic cycles as much as possible. Based on that, the original NICE was extended to couple it with the plastic debris model for quantifying the impacts of plastic waste on terrestrial and aquatic ecosystems and devising solutions and measures for the reduction of plastic input to the ocean (Fig. 1.3). The model simulated quantified flood events have a great impact on the mobilization of plastic and lead to high interannual variability in fluxes. This methodology is powerful for detecting and predicting plastic dynamics in large rivers and for developing efficient measures to reduce plastic input to the ocean on regional, continental, and global scales. Details of this process are described in the following chapters.



Figure 1.2 NICE simulation for quantifying hydrologic cycle and its ecosystem assessment in various basins/catchments from regional to global scales. Previous model applications to regional, continental, and global scales (Part I–VI) and plastic dynamics in the current monograph (Part VII).



Figure 1.3 Flow diagram of macro and microplastic transport in land and inland water by extending NICE.

#### References

- Battin, T.J., Kaplan, L.A., Findlay, S., Hopkinson, C.S., Marti, E., Packman, A.I., Newbold, J.D., Sabater, F. (2008) Biophysical controls on organic carbon fluxes in fluvial networks. Nature Geoscience, 1, 95-100, doi:10.1038/ngeo101
- Brooks, A.L., Wang, S., Jambeck, J.R. (2018) The Chinese import ban and its impact on global plastic waste trade. Scientific Advances, 4(6), eaat0131, doi:10.1126/sciadv.aat0131
- Brown, J.H., Gillooly, J.F., Allen, A.P., Savage, V.M., West, G.B. (2004) Toward a metabolic theory of ecology. Ecology, 85, 1771-1789
- Deegan, L.A., Johnson, D.S., Warren, R.S., Peterson, B.J., Fleeger, J.W., Fagherazzi, S., Wollheim, W.M. (2012) Coastal eutrophication as a driver of salt marsh loss. Nature, 490, 388-392, doi:10.1038/nature11533
- Dominish, E., Retamal, M., Wakefield-Rann, R., Florin, N. (2020) Environmentally responsible trade in waste plastics Report 1: Investigating the links between trade and marine plastic pollution. Institute for Sustainable Futures, University of Technology Sydney. https://www.dcceew.gov.au/sites/default/files/documents/ertwaste-plastics-report-1.pdf
- Environmental Investigation Agency (EIA). (2021) The Truth Behind Trash: The scale and impact of the international trade in plastic waste. https://eia-international.org/wp-content/uploads/EIA-The-Truth-Behind-Trash-FINAL.pdf
- Jambeck, J.R., Geyer, R., Wilcox, C., et al. (2015) Plastic waste inputs from land into the ocean. Science, 347, 768-771, doi:10.1126/science.1260352

- Kooi, M., Besseling, E., Kroeze, C., et al. (2018) Modelling the fate and transport of plastic decries in freshwaters: review and guidance. In: Wagner, M., Lambert, S. [Eds] Freshwater Microplastics. The Handbook of Environmental Chemistry 58, Springer, pp.125-152
- Lebreton, L, van der Zwet, J., Damsteeg, J.-W., et al. (2017) River plastic emissions to the world's oceans. Nature Communications, 8, 15611, doi:10.1038/ncomms15611
- Meijer, L.J.J., van Emmerik, T., van der Ent, R., et al. (2021) More than 1000 rivers account for 80% of global riverine plastic emissions into the ocean. Science Advances, 7, eaaz5803, doi:10.1126/sciadv.aaz5803
- Ministry of Foreign Affairs of Japan. (2019) G20 Osaka Leader's Declaration. https://www.mofa.go.jp/policy/economy/g20\_summit/osaka19/en/documents/final\_g20\_osaka\_leaders\_decl aration.html
- Nakayama, T., Watanabe, M. (2004) Simulation of drying phenomena associated with vegetation change caused by invasion of alder (Alnus japonica) in Kushiro mire. Water Resources Research, 40, W08402, doi:10.1029/2004WR003174
- Nakayama, T., Watanabe, M. (2005) Re-evaluation of groundwater dynamics about water and nutrient budgets in Lake Kasumigaura, Annual Journal of Hydroscience and Hydraulic Engineering, 49, 1231–1236 (Abst. in English)
- Nakayama, T., Watanabe, M. (2006a) Simulation of spring snowmelt runoff by considering micro-topography and phase changes in soil layer. Hydrology and Earth System Sciences Discussions, 3, 2101-2144
- Nakayama, T., Watanabe, M. (2006b) Development of process-based NICE model and simulation of ecosystem dynamics in the catchment of East Asia (Part I). CGER's supercomputer monograph report, 11, NIES, 100p., http://www.cger.nies.go.jp/publications/report/i063/I063e
- Nakayama, T., Yang, Y., Watanabe, M., Zhang, X. (2006) Simulation of groundwater dynamics in the North China Plain by coupled hydrology and agricultural models. Hydrological Processes, 20, 3441-3466, doi:10.1002/hyp.6142
- Nakayama, T., Watanabe, M., Tanji, K., Morioka, T. (2007) Effect of underground urban structures on eutrophic coastal environment. Science of the Total Environment, 373, 270-288, doi:10.1016/j.scitotenv.2006.11.033
- Nakayama, T. (2008a) Factors controlling vegetation succession in Kushiro mire. Ecological Modelling, 215, 225-236., doi:10.1016/j.ecolmodel.2008.02.017
- Nakayama, T. (2008b) Shrinkage of shrub forest and recovery of mire ecosystem by river restoration in northern Japan. Forest Ecology and Management, 256, 1927-1938, doi:10.1016/j.foreco.2008.07.017
- Nakayama, T. (2008c) Development of process-based NICE model and simulation of ecosystem dynamics in the catchment of East Asia (Part II). CGER's supercomputer monograph report, 14. NIES, 91p., http://www.cger.nies.go.jp/publications/report/i083/i083\_e
- Nakayama, T., Watanabe, M. (2008a) Missing role of groundwater in water and nutrient cycles in the shallow eutrophic Lake Kasumigaura, Japan. Hydrological Processes, 22, 1150-1172, doi:10.1002/hyp.6684
- Nakayama, T., Watanabe, M. (2008b) Role of flood storage ability of lakes in the Changjiang River catchment. Global and Planetary Change, 63, 9-22, doi:10.1016/j.gloplacha.2008.04.002
- Nakayama, T., Watanabe, M. (2008c) Modelling the hydrologic cycle in a shallow eutrophic lake. SIL Proceedings, 1922-2010, 30, 345-348
- Nakayama, T. (2009) (Chapter 1) Simulation of ecosystem degradation and its application for effective policymaking in regional scale. In: Mattia N. Gallo, Ferrari, Marco H. (Eds) River Pollution Research Progress. Nova Science Pub., Inc., New York, pp. 1-89
- Nakayama, T. (2010) Simulation of hydrologic and geomorphic changes affecting a shrinking mire. River Research and Applications, 26, 305-321, doi:10.1002/rra.1253
- Nakayama, T., Fujita, T. (2010) Cooling effect of water-holding pavements made of new materials on water and heat budgets in urban areas. Landscape and Urban Planning, 96, 57-67, doi:10.1016/j.landurbplan.2010.02.003
- Nakayama, T., Sun, Y., Geng, Y. (2010) Simulation of water resource and its relation to urban activity in Dalian City, Northern China. Global and Planetary Change, 73, 172-185, doi:10.1016/j.gloplacha.2010.06.001
- Nakayama, T. (2011a) Simulation of complicated and diverse water system accompanied by human intervention in the North China Plain. Hydrological Processes, 25, 2679-2693, doi:10.1002/hyp.8009
- Nakayama, T. (2011b) Simulation of the effect of irrigation on the hydrologic cycle in the highly cultivated Yellow River Basin. Agricultural and Forest Meteorology, 151, 314-327, doi:10.1016/j.agrformet.2010.11.006
- Nakayama, T. (2011c) Feedback mechanism and complexity in ecosystem-development of integrated assessment system towards eco-conscious society-, Chemical Engineering of Japan, 75, 789-791 (in Japanese)
- Nakayama, T. (2011d) Construction of integrated assessment system for win-win solution of hydrothermal degradations in urban area towards eco-conscious society, Chemical Information and Computer Sciences, 29, 63-65 (in Japanese)

- Nakayama, T., Hashimoto, S. (2011) Analysis of the ability of water resources to reduce the urban heat island in the Tokyo megalopolis. Environmental Pollution, 159, 2164-2173, doi:10.1016/j.envpol.2010.11.016
- Nakayama, T. (2012a) Visualization of the missing role of hydrothermal interactions in a Japanese megalopolis for a win-win solution. Water Science and Technology, 66, 409-414, doi:10.2166/wst.2012.205
- Nakayama, T. (2012b) Feedback and regime shift of mire ecosystem in northern Japan. Hydrological Processes, 26, 2455-2469, doi:10.1002/hyp.9347
- Nakayama, T. (2012c) Impact of anthropogenic activity on eco-hydrological process in continental scales. Procedia Environmental Sciences, 13, 87-94, doi:10.1016/j.proenv.2012.01.008
- Nakayama, T. (2012d) Development of process-based NICE model and simulation of ecosystem dynamics in the catchment of East Asia (Part III). CGER's supercomputer monograph report, 18. NIES, 98p., http://www.cger.nies.go.jp/publications/report/i103/en/
- Nakayama, T., Hashimoto, S., Hamano, H. (2012) Multiscaled analysis of hydrothermal dynamics in Japanese megalopolis by using integrated approach. Hydrological Processes, 26, 2431-2444, doi:10.1002/hyp.9290
- Nakayama, T. (2013) For improvement in understanding eco-hydrological processes in mire. Ecohydrology and Hydrobiology, 13, 62-72, doi:10.1016/j.ecohyd.2013.03.004
- Nakayama, T., Shankman, D. (2013a) Impact of the Three-Gorges Dam and water transfer project on Changjiang floods. Global and Planetary Change, 100, 38-50, doi:10.1016/j.gloplacha.2012.10.004
- Nakayama, T., Shankman, D. (2013b) Evaluation of uneven water resource and relation between anthropogenic water withdrawal and ecosystem degradation in Changjiang and Yellow River Basins. Hydrological Processes, 27(23), 3350-3362, doi:10.1002/hyp.9835
- Nakayama, T. (2014a) (Chapter 16) Hydrology–ecology interactions. In: Saeid Eslamian (Ed.) Handbook of Engineering Hydrology, 1: Fundamentals and Applications. Taylor & Francis, pp. 329-344
- Nakayama, T. (2014b) Development of process-based NICE model and simulation of ecosystem dynamics in the catchment of East Asia (Part IV). CGER's supercomputer monograph report, 20. NIES, 102p., http://www.cger.nies.go.jp/publications/report/i114/en/
- Nakayama, T. (2014) (Chapter 33) Integrated assessment system using process-based eco-hydrology model for adaptation strategy and effective water resources management. In: Venkat Lakshmi (Ed.) Remote Sensing of the Terrestrial Water Cycle (Geophysical Monograph Series 206), pp. 521-535, doi:10.1002/9781118872086.ch33
- Nakayama, T. (2016) New perspective for eco-hydrology model to constrain missing role of inland waters on boundless biogeochemical cycle in terrestrial-aquatic continuum. Ecohydrology and Hydrobiology, 16, 138-148, doi:10.1016/j.ecohyd.2016.07.002
- Nakayama, T. (2017a) Development of an advanced eco-hydrologic and biogeochemical coupling model aimed at clarifying the missing role of inland water in the global biogeochemical cycle. Journal of Geophysical Research: Biogeosciences, 122, 966-988, doi:10.1002/2016JG003743
- Nakayama, T. (2017b) Scaled-dependence and seasonal variations of carbon cycle through development of an advanced eco-hydrologic and biogeochemical coupling model. Ecological Modelling, 356, 151-161, doi:10.1016/j.ecolmodel.2017.04.014
- Nakayama, T. (2017c) Biogeochemical contrast between different latitudes and the effect of human activity on spatiotemporal carbon cycle change in Asian river systems. Biogeosciences Discussions, doi:10.5194/bg-2017-447
- Nakayama, T. (2018) Interaction between surface water and groundwater and its effect on ecosystem and biogeochemical cycle. Journal of Groundwater Hydrology, 60, 143-156, doi:10.5917/jagh.60.143 (in Japanese)
- Nakayama, T., Maksyutov, S. (2018) Application of process-based eco-hydrological model to broader northern Eurasia wetlands through coordinate transformation. Ecohydrology and Hydrobiology, 18, 269-277, doi:10.1016/j.ecohyd.2017.11.002
- Nakayama, T., Pelletier, G.J. (2018) Impact of global major reservoirs on carbon cycle changes by using an advanced eco-hydrologic and biogeochemical coupling model. Ecological Modelling, 387, 172-186, doi:10.1016/j.ecolmodel.2018.09.007
- Nakayama, T. (2019) Development of process-based NICE model and simulation of ecosystem dynamics in the catchment of East Asia (Part V). CGER's supercomputer monograph report, 26. NIES, 122p., http://www.cger.nies.go.jp/publications/report/i148/en/
- Nakayama, T. (2020) Inter-annual simulation of global carbon cycle variations in a terrestrial-aquatic continuum. Hydrological Processes, 34, 662-678, doi:10.1002/hyp.13616
- Nakayama, T., Wang, Q., Okadera, T. (2021a) Evaluation of spatio-temporal variations in water availability using a process-based eco-hydrology model in arid and semi-arid regions of Mongolia. Ecological Modelling, 440, 109404, doi:10.1016/j.ecolmodel.2020.109404

- Nakayama, T., Wang, Q., Okadera, T. (2021b) Sensitivity analysis and parameter estimation of anthropogenic water uses for quantifying relation between groundwater overuse and water stress in Mongolia. Ecohydrology and Hydrobiology, 21, 490-500, doi:10.1016/j.ecohyd.2021.07.006
- Nakayama, T. (2022) Impact of anthropogenic disturbances on carbon cycle changes in terrestrial-aquaticestuarine continuum by using an advanced process-based model. Hydrological Processes, 36, e14471, doi:10.1002/hyp.14471
- Nakayama, T. (2023a) Evaluation of global biogeochemical cycle in lotic and lentic waters by developing an advanced eco-hydrologic and biogeochemical coupling model. Ecohydrology, e2555, doi:10.1002/eco.2555
- Nakayama, T. (2023b) Development of process-based NICE model and simulation of ecosystem dynamics in the catchment of East Asia (Part VI). CGER's supercomputer monograph report, 29. NIES, 95p., http://www.cger.nies.go.jp/publications/report/i164/en/
- Nakayama, T., Okadera, T., Wang, Q. (2023) Impact of various anthropogenic disturbances on water availability in the entire Mongolian basins towards effective utilization of water resources. Ecohydrology and Hydrobiology, 23(4), doi:10.1016/j.ecohyd.2023.04.006
- Nakayama, T., Osako, M. (2023a) Development of a process-based eco-hydrology model for evaluating the spatiotemporal dynamics of macro- and micro-plastics for the whole of Japan. Ecological Modelling, 476, 110243, doi:10.1016/j.ecolmodel.2022.110243
- Nakayama, T., Osako, M. (2023b) The flux and fate of plastic in the world's major rivers: Modelling spatial and temporal variability. Global and Planetary Change, 221, 104037, doi:10.1016/j.gloplacha.2023.104037
- Nakayama, T., Osako, M. (2024) Plastic trade-off: Impact of export and import of waste plastic on plastic dynamics in Asian region. Ecological Modelling, 489, 110624, doi:10.1016/j.ecolmodel.2024.110624
- Nizzetto, L., Bussi, G., Futter, M.N., et al. (2016) A theoretical assessment of microplastic transport in river catchments and their retention by soils and river sediments. Environmental Science: Processes & Impacts, 18, 1050-1059, doi:10.1039/c6em00206d
- Pastor, J., Peckham, B., Bridgham, S., Weltzin, J., Chen, J. (2002) Plant community dynamics, nutrient cycling, and alternative stable equilibria in peatlands. American Naturalist, 160, 553-568
- Ridolfi, L., D'Odorico, P., Laio, F. (2006) Effect of vegetation-water table feedbacks on the stability and resilience of plant ecosystems. Water Resources Research, 42, W01201, doi:10.1029/2005WR004444
- Rietkerk, M., Dekker, S.C., Wassen, M.J., Verkroost, A.W.M., Bierkens, M.F.P. (2004) A putative mechanism for bog patterning. American Naturalist, 163, 699-708
- Saco, P.M., Willgoose, G.R., Hancock, G.R. (2007) Eco-geomorphology of banded vegetation patterns in arid and semi-arid regions. Hydrology and Earth System Sciences, 11, 1717-1730
- Schmidt, C., Krauth, T., Wagner, S. (2017) Export of plastic debris by rivers into the sea. Environmental Science & Technology, 51, 12246-12253, doi:10.1021/acs.est.7b02368
- Siegfried, M., Koelmans, A.A., Besseling, E., Kroeze, C. (2017) Export of microplastics from land to sea. A modelling approach. Water Research, 127, 249-257, doi:10.1016/j.watres.2017.10.011
- Thompson, R.C., Olsen, Y., Mitchell, R.P., et al. (2004) Lost at sea: Where is all the Plastic? Science, 304, 838, doi: 10.1126/science.1094559
- UNESCO. (2022) IHP-IX: Strategic Plan of the Intergovernmental Hydrological Programme: Science for a Water Secure World in a Changing Environment, ninth phase 2022-2029. https://unesdoc.unesco.org/ark:/48223/pf0000381318.locale=en
- United Nations. (2019) Basel Convention: Controlling transboundary movements of hazardous wastes and their disposal.

http://www.basel.int/Implementation/MarinePlasticLitterandMicroplastics/Overview/tabid/6068/Default.asp x

- van de Koppel, J., van der Wal, D., Bakker, J.P., Herman, P.M.J. (2005) Self-organization and vegetation collapse in salt marsh ecosystems. American Naturalist, 165, E1-E12
- Vannote, R.L., Minshall, G.W., Cummins, K.W., Sedell, J.R., Cushing, C.E. (1980) The river continuum concept. Canadian Journal of Fisheries and Aquatic Sciences, 37, 130-137
- Waldschläger, K., Schüttrumpf, H. (2019) Erosion behavior of different microplastic particles in comparison to natural sediments. Environmental Science & Technology, 53, 13219-13227, doi:10.1021/acs.est.9b05394
- Yearsley, J. (2012) A grid-based approach for simulating stream temperature. Water Resources Research, 48, W03506, doi:10.1029/2011WR011515
- Zalewski, M. (2002) Ecohydrology—The use of ecological and hydrological processes for sustainable management of water resources / Ecohydrologie—la prise en compte de processus écologiques et hydrologiques pour la gestion durable des ressources en eau. Hydrological Sciences Journal, 47, 823-832
- Zhang, K., Hamidian, A.H., Tubic, A., et al. (2021) Understanding plastic degradation and microplastic formation in the environment: A review. Environmental Pollution, 274, 116554, doi:10.1016/j.envpol.2021.116554

Chapter 1 General Introduction

## Chapter 2

Development of a Process-Based Eco-Hydrology Model for Evaluating Spatiotemporal Dynamics of Macro and Microplastics for Whole of Japan Chapter 2 Development of a Process-Based Eco-Hydrology Model for Evaluating Spatiotemporal Dynamics of Macro and Microplastics for Whole of Japan

#### Abstract

Plastic contamination has been receiving considerable attention during the last few decades. Although some models could simulate the transport and fate of plastic debris in freshwater systems, a complete model for plastic dynamics on a basin scale has yet to be established. In the present study, the authors extended process-based eco-hydrology models, NICE (National Integrated Catchment-based Eco-hydrology) and NICE-BGC (BioGeochemical Cycle), to link them with plastic debris models, and applied them to all the 109 first-class (class A) river basins throughout Japan. The new model included advection, dispersion, diffusion, settling, dissolution, and deterioration due to light and temperature. These processes could help evaluate the effect of mismanaged plastic waste (MPW) and point sources (tires, personal care products, dust, and laundry) on the spatiotemporal dynamics of macro and microplastics there. The model showed that the simulated hydrologic cycle generally agreed with the observed one. In contrast, the simulated value of annual-averaged nutrient transports was overestimated compared to the observed value averaged over non-flood periods. Sensitivity analysis of microplastic transport to various factors also implied degradation effects would not be negligible under some conditions. Generally, large amounts of plastic flowed out of some limited rivers (Tone, Kiso, Yodo, and Ara Rivers) with a large proportion of macroplastic flux compared to microplastic flux. Further, scenario analysis quantified the total plastic flux varied according to the efficiency of microplastic removal in wastewater treatment plants (WWTP) and density of plastic and was estimated as within the range of 1,100-3,500 tons/yr, relatively like that of existing values. It was also clarified that only a limited proportion of plastics discharged onto land flowed out into the ocean intensively during rainfall seasons. These results help quantify the impacts of plastic waste on the biosphere and may aid the development of solutions and measures to reduce plastic input to the ocean.

#### Keywords: Eco-hydrology model; mismanaged plastic waste; plastic debris; river basin

Chapter 2 Development of a Process-Based Eco-Hydrology Model for Evaluating Spatiotemporal Dynamics of Macro and Microplastics for Whole of Japan

#### **2.1 Introduction**

Plastic pollution is considered one of today's main environmental problems, and such pollutants in streams, rivers, and oceans pose potential risks to human health and the environment (Siegfried et al., 2017). Plastic accumulation on riverbanks, deltas, coastlines, and the ocean surface is rapidly increasing, and it is estimated that 60% of the plastics ever manufactured have been discarded in landfills, or the natural environment (Meijer et al., 2021). Based on size, plastic waste can be roughly categorized as macroplastic ( $\geq$ 5 mm) or microplastic (<5 mm), and the latter is sometimes further categorized partially as nanoplastic (<100 nm). Microplastic is also divided into primary (intentionally manufactured as small) and secondary (arising through decomposition, fragmentation, and degradation of larger pieces) microplastics according to origin (Siegfried et al., 2017). Once plastic is released into the environment, it is impossible to remove and remains indefinitely.

Previous studies on the origin and fate of plastic waste in freshwater systems have suggested that land-derived plastics are one of the main sources of marine plastic pollution (Thompson et al., 2004) because of either direct emission from coastal areas (Jambeck et al., 2015) or by transport via rivers (Lebreton et al., 2017; Schmidt et al., 2017). Although Jambeck et al. (2015) were the first to estimate the mass of land-based plastic waste entering the global ocean, they did not consider plastic waste from inland water or its size class. Subsequent studies (Lebreton et al., 2017; Schmidt et al., 2017) estimated the distribution of global riverine emissions of plastic into the ocean by using empirical indicators representative of waste generation (mismanaged plastic waste: MPW) inside a river basin. Using a probabilistic approach, Meijer et al. (2021) proposed a more accurate analysis to account for the spatial distribution plastic waste generation (Lebreton and Andrady, of 2019) and climatological/geographical differences within river basins. They estimated that more than 1,000 rivers account for 80% of global riverine plastic emissions into the ocean, which range between 0.8 and 2.7 million metric tons per year. On a regional scale, only a few studies have evaluated the concentration and riverine flux of plastics in Japan (Kataoka et al., 2019; Nihei et al., 2020). Such assessment of the fate and transport of plastics would also be necessary to realize the "Osaka Blue Ocean Vision" shared at the G20 Osaka Summit 2019 (Ministry of Foreign Affairs of Japan, 2019).

Over the last decade, there has been great progress in modeling the fate and transport of plastics. Kooi et al. (2018) classified plastic debris models for freshwater systems into four categories: emission-based mass balance, global, multimedia, and spatiotemporally explicit models. Boucher et al. (2020) have summarized the previous development of science-based metrics to measure the leakage and circularity of plastics. In particular, the global and spatially explicit model is powerful for estimating the riverine export of plastics to coastal seas (Praetorius et al., 2012; Quik et al., 2015; Nizzetto et al., 2016; Besseling et al., 2017; Siegfried et al., 2017; van Wijnen et al., 2019; Whitehead et al., 2021). Some of these studies (Siegfried et al., 2017; van Wijnen et al., 2019; Strokal et al., 2021) adapted a process-oriented model to continental and global scales by extending an existing non-dynamic nutrient export model. However, the fate of microplastics is also dependent on their size, density, shape, and polymer type: factors that were not included in these previous global analyses of generic material (Jambeck et al., 2015; Lebreton et al., 2017; Schmidt et al., 2017; Meijer et al., 2021). Nizzetto et al. (2016) incorporated the settling and resuspension of microplastics to estimate their retention in rivers by extending the in-stream sediment model used in a previous study (Lazar et al., 2010). They conducted a sensitivity analysis of the size and density of microplastics in fluxes using this spatially explicit model of INCA-Contaminants. Whitehead et al. (2021) also

used the same model to simulate the microplastic mass loads of four particle size classes in various reaches of the Thames River. It is expected that the accuracy of global or regional emissions estimated using the above probabilistic approach (Meijer et al., 2021) would be improved by using the spatially explicit model (Unice et al., 2019). These models will help to identify the hotspots and sinks of plastic pollution and resolve the source-flux-sink nexus within river basins (Windsor et al., 2019).

Because most of the above plastic debris models are based on an analogy with sediment models for inland waters, it is questionable whether these models are reasonably adaptable for modeling the dynamics of plastics with various sizes, densities, shapes, polymer types, and contact angles (Nizzetto et al., 2016; Waldschlager and Schüttrumpf, 2019). The transport of microplastics in river ecosystems is either gravity-driven (vertical transport) or occurs through settling (horizontal transport) (Kumar et al., 2021). Cowger et al. (2021) modified the Rouse profile of vertical concentration to include all traditional domains of transport (bed load, settling suspended load, and wash load) as well as additional domains specific to low-density materials with increasing velocities in water (rising suspended load and surface load); this revealed that the vertical profile of low-density plastics such as polyethylene (PE), polypropylene (PP), and polystyrene (PS) under the predominance of wind shear differs considerably from the original Rouse profile of natural sediment (Liu et al., 2021). Particle size generally appears to be a more sensitive parameter influencing microplastic transport and retention efficiency because of its wide range across several orders of magnitude. However, there is a sharp change in parameter sensitivity when the density approaches that of water (Nizzetto et al., 2016). It is also important to model the transport of plastics in air, water, and soil (Koutnik et al., 2021). These factors must be considered when assessing the fate and transport of plastics in various basins over scales ranging from local/regional to continental/global.

One of the authors has developed a process-based model coupling eco-hydrology with the biogeochemical cycle (National Integrated Catchment-based Eco-hydrology (NICE)-BGC) (Nakayama, 2016, 2017a, 2017b), incorporating complex terrestrial-aquatic linkages in the hydrologic-biogeochemical cycle. NICE-BGC can simulate nonlinear interactions between hydrologic, geomorphic, and ecological processes (water, heat, sediment, nutrient, and carbon cycles, etc.). In this chapter, the process-based NICE-BGC was extended to link it with a plastic debris (engineered materials) model for freshwater systems and applied to all 109 first-class (class A) river basins in the whole of Japan (Nakayama and Osako, 2023a) (Fig. 2.1a). The new model included advection, dispersion, diffusion, settling, dissolution, and deterioration due to light and temperature but assumed no interaction with suspended matter (hetero-aggregation), resuspension, biofouling, or wind effects. For model simplification, the authors also assumed microplastics to be pure, inert polymers with spherical particles of constant size and density. Based on this background, two basic issues were addressed: (i) How does emission change relative to differences in the size and density of mismanaged plastic waste (MPW)? (ii) How do hydraulic structures and water treatment plants affect riverine emissions of plastic into the ocean? To clarify these issues, NICE-BGC simulated how about 36,000 tons/yr of MPW (Meijer et al., 2021) and point sources such as tires, personal care products (PCPs), dust, and laundry in the entire country are transported from land to river, and finally to the ocean. Establishing a complete model for plastic dynamics on a basin scale becomes a big step forward. The results are also important for predicting and estimating the change of plastic dynamics under climate change in the future. These results help quantify the impacts of plastic waste on terrestrial and aquatic ecosystems. They may be useful for devising solutions and measures to reduce plastic input to the ocean.

Chapter 2 Development of a Process-Based Eco-Hydrology Model for Evaluating Spatiotemporal Dynamics of Macro and Microplastics for Whole of Japan



Figure 2.1 Location of the study area in entire Japan; (a) all the first-class of 109 river basins, (b) elevation, (c) land cover, (d) population density, (e) pumping and wastewater treatment plant (WWTP), and (f) mismanaged plastic waste (MPW)

#### 2.2 Methods

#### 2.2.1 Model Description of Mass Transport Process in NICE-BGC

The NICE series of process-based catchment models have been developed for application to natural, agricultural, and urban regions in various catchments and basins (Nakayama, 2008a– c, 2009, 2010, 2011a–d, 2012a–d, 2013, 2014a,b, 2015, 2016, 2017a–c, 2018, 2019, 2020, 2022, 2023a,b; Nakayama and Fujita, 2010; Nakayama and Hashimoto, 2011; Nakayama and Maksyutov, 2018; Nakayama and Osako, 2023a,b, 2024; Nakayama and Pelletier, 2018; Nakayama and Shankman, 2013a,b; Nakayama and Watanabe, 2004, 2005, 2006a,b, 2008a–c; Nakayama et al., 2006, 2007, 2010, 2012, 2021a,b, 2023) (Fig. 1.1). The NICE model consists of complex sub-models: a surface hydrology model; a land-surface model including urban and crop processes; a groundwater model; a regional atmospheric model; a mass transport model of sediment, nutrients, carbon, and plastics; and a vegetation succession model.

The two-dimensional diffusion model, including sedimentation (here corresponding to plastic in this study) in NICE (Fig. 1.1) simulates the mass transport in a hillslope after simulation of the hillslope runoff model including snowmelt runoff (Nakayama and Watanabe, 2004; Nakayama, 2010).

$$\frac{\partial}{\partial t} \{ D \cdot C \} + \frac{\partial (M \cdot C)}{\partial x} + \frac{\partial (N \cdot C)}{\partial y}$$

$$= \frac{\partial}{\partial x} \{ Kx \cdot D \cdot \frac{\partial C}{\partial x} \} + \frac{\partial}{\partial y} \{ Ky \cdot D \cdot \frac{\partial C}{\partial y} \} + D \cdot L(C) + q_{su} - w_f \cdot c_b$$
(2.1)

where *M* and *N* are discharges per unit width along the *x* and *y* coordinate axes; *H* (m) is the elevation of the hillslope bottom; *S* (m) is the hydraulic head; *D* (m) is the flow depth (=*S*-*H*); *C* (mg/l) is the mass concentration;  $K_x$  and  $K_y$  (m/s) are the kinematic eddy diffusivities along the *x* and *y* coordinate axes; *L*(*C*) is the concentration of MPW in this study;  $q_{su}$  (m/s) is the rate of resuspension from the hillslope bed;  $w_f$  (m/s) is the settling velocity of macro and microplastics; and  $c_b$  (mg/l) is the standard concentration.

The suspended load per unit width in two-dimensional uniform flow is expressed by the following equation (Itakura, 1984):

$$qs = \int_{b}^{h} c(z)u(z)dz \tag{2.2}$$

where *h* (m) is flow depth; c(z) is the concentration at z above the riverbed; u(z) is the flow velocity at z above the riverbed; and *b* (m) is the riverbed elevation. Although the concentration would greatly depend on the value of *b*, the author used the semi-empirical relation (*b*=0.05*h*) in the following sections. When the riverbed is at equilibrium conditions, and the particle size distribution is uniform, the resuspension rate from the riverbed is equal to the sedimentation volume.  $c_b$  and  $q_{su}$  are expressed by using a theory based on an energy equation of solid-liquid two-phase flow and the Monin-Obukhov length in the following equations (2.3)-(2.7) (Itakura, 1984):

$$c_b = K[\alpha_* \frac{\rho_s - \rho}{\rho_s} \cdot \frac{gd}{u_* w_f} \cdot \Omega - 1]$$
(2.3)

$$\frac{q_{su}}{\sqrt{s'gd}} = K[\alpha_* \frac{\rho}{\rho_s} \cdot \frac{\Omega}{\sqrt{\tau_*}} - \frac{w_f}{\sqrt{s'gd}}]$$
(2.4)

$$\Omega = \frac{\tau_*}{B_*} \cdot \frac{\int_{a'} \frac{\xi_{\sqrt{\pi}} \exp[-\xi^2] d\xi}{\int_{a'} \frac{1}{\sqrt{\pi}} \exp[-\xi^2] d\xi} + \frac{\tau_*}{B_* \eta_0} - 1$$
(2.5)

$$\int_{a'}^{\infty} \xi \frac{1}{\sqrt{\pi}} \exp[-\xi^2] d\xi = \frac{1}{\sqrt{2\pi}} \exp(-a'^2)$$
(2.6)

$$\int_{a'}^{\infty} \xi \frac{1}{\sqrt{\pi}} \exp[-\xi^2] d\xi \cong \frac{1}{\sqrt{2\pi}} \exp(-a'^2) \cdot (\alpha_1 T + \alpha_2 T^2 + \alpha_3 T^3)$$
(2.7)

where  $a'(=B*/\tau^* - 1/\eta_0)$ ,  $T (= 1/(1+0.33267 \sqrt{2}a'))$ ,  $\eta_0 = 0.5$ ,  $B^* = 0.143$ ,  $\alpha^* = 0.14$ , K = 0.008,  $\alpha_1 = 0.4361836$ ,  $\alpha_2 = -0.1201676$ , and  $\alpha_3 = 0.937298$  are constants;  $\rho$  (kg/m<sup>3</sup>) and  $\rho_s$  (kg/m<sup>3</sup>) are the density of water and fine sand, respectively; g (m/s<sup>2</sup>) is the gravitational acceleration; s' $(=\rho_s/\rho-1)$  is the relative gravity of fine sand in water; and d (m) is particle size. The Chapter 2 Development of a Process-Based Eco-Hydrology Model for Evaluating Spatiotemporal Dynamics of Macro and Microplastics for Whole of Japan

concentration c is expressed in equation (2.8) (Shimizu and Arai, 1988), and the settling velocity  $w_f$  uses Rubey's formula (Rubey, 1933) in equation (2.9):

$$c = \frac{c_b}{\beta} (1 - e^{-\beta}) , \ \beta = \frac{w_f h}{\varepsilon}$$
(2.8)

$$w_f = \sqrt{\frac{2}{3}(s-1)gd + \alpha^2} - \alpha , \ \alpha = \frac{6\nu}{d} , \ \varepsilon = \frac{\rho_s}{\rho}$$
(2.9)

A recent study has shown that the velocity of microplastic deposition follows patterns for naturally occurring allochthonous particles (Hoellein et al., 2019). A one-dimensional diffusion model including sedimentation (here corresponding to plastic in this study) in the following equation (2.10) simulates the mass transport in a river channel after simulation of the stream network model (Nakayama and Watanabe, 2004; Nakayama, 2010):

$$\frac{\partial}{\partial t}(A \cdot C) + \frac{\partial(A \cdot U \cdot C)}{\partial x} = \frac{\partial}{\partial x} \{A \cdot Kx \cdot \frac{\partial C}{\partial x}\} + S + q_{su} - w_f \cdot c_b$$
(2.10)

where A (m<sup>2</sup>) is the cross-sectional area of the river channel, and S is the sources and sinks of the constituent due to reactions and mass transfer mechanisms. The above equation (2.10) equals equation (2.1) when the cross-section is rectangular. The simulated lateral inflow of mass was input to equation (2.10) if the lateral inflow simulated by a hillslope model enters along the side of the river channel.

The bed material load is expressed in Einstein's formula (Einstein, 1950) in equation (2.11):

$$q_{B*} = \frac{q_B}{\sqrt{(\rho_s/\rho - 1)gd^3}}, q_B = (8\tau_* - 0.047)^{3/2}, \tau_* = \frac{u_*^2}{(\rho_s/\rho - 1)gd} (2.11)$$

where d (m) is the particle diameter of the bed material load,  $\tau^*$  is the non-dimensional tractive force, and  $u^*$  (m/s) is friction velocity, respectively. The continuity equation of riverbed sediment is expressed by using the suspended load  $q_{su}$  and the bed material load  $q_B$  in the following:

$$\frac{\partial z_B}{\partial t} = -\frac{1}{1-\lambda} (q_{su} - w_f c_b + \frac{\partial q_B}{\partial x})$$
(2.12)

where  $z_B$  (m) is the bed elevation; and  $\lambda$  is the porosity of the bed material (void ratio). It was assumed that a little water would remain in the grid to keep dissolving the mass flux, even in cases where the flow depth is almost zero, which is necessary to simulate flush-out of the mass process at higher precipitation. Furthermore, it was assumed that all the water and mass would mix completely in a vertical direction when the flow depth rose to the upper grid in the next time step. This model applies to the surface runoff comprising surface and intermediate flows.

# 2.2.2 Modelling Fate and Transport of Macro and Microplastics in Land and Inland Water by Extension of NICE

In this study, NICE-BGC (Nakayama, 2016, 2017a, 2017b) was extended to model the fate and transport of macro and microplastics in land and water (Nakayama and Osako, 2023a) (Fig. 2.2). The new model included advection, dispersion, diffusion, settling, dissolution and

deterioration due to light and temperature, but assumed no interaction with suspended matter (heteroaggregation) (Praetorius et al., 2012), resuspension (Waldschlager and Schüttrumpf, 2019), biofouling (Kooi et al., 2017), or wind effects. Thus, the model can simulate the hydrograph for plastic transport with various shear stresses during storm events, as proposed by Kumar et al. (2021). The authors also assumed that microplastics are pure, inert polymers with spherical particles of constant size and density for model simplification.

The transport of plastic on a hillslope was simulated in the above equations (2.1)-(2.9), except (2.4). Because equation (2.4) assumes the resuspension rate when a riverbed is under equilibrium conditions, and the particle size distribution is uniform, applying this formula directly to plastic is difficult. It is difficult to grasp the heterogeneous distribution of settled and deposited plastic on hillslopes, although some studies have evaluated the erosion behavior of microplastic particles compared to sediments (Waldschlager and Schüttrumpf, 2019). For model simplification, we also assume that this plastic is negligible compared to discharged plastic and that resuspension is zero on hillslopes. After the simulation of plastic transport on a hillslope, the authors used the estimated rate of conversion of macroplastics to microplastics (3%/yr) in the same way as van Wijnen et al. (2019), with the extension of the conversion rate employed by Jambeck et al. (2015) (Fig. 2.2).

NICE-BGC simulates plastic transport in a river channel by extending QUAL2Kw (Pelletier et al., 2006). Macro and microplastics become buried through settling, dissolution, and deterioration due to light, temperature, advection, dispersion, and diffusion. The terms of sources and sinks for the constituent S due to reactions and mass transfer mechanisms can be added to the above equation (2.10):

$$S_{Pmac} = -\frac{v_{Pmac}}{h} P_{mac} - k_{Pmac}(T) P_{mac} - \alpha_{Pmac} \frac{I(0)/24}{k_e h} (1 - e^{-k_e h}) P_{mac}$$
(2.13)  

$$S_{Pmic} = -\frac{v_{Pmic}}{h} P_{mic} - k_{Pmic}(T) P_{mic} - \alpha_{Pmic} \frac{I(0)/24}{k_e h} (1 - e^{-k_e h}) P_{mic}$$
$$+ k_{Pmac}(T) P_{mac} + \alpha_{Pmac} \frac{I(0)/24}{k_e h} (1 - e^{-k_e h}) P_{mac}$$
(2.14)

where  $P_{mac}$  (µg/l) and  $P_{mic}$  (µg/l) are the macro and microplastic concentrations; *T* is the water temperature;  $v_{Pmac}$  and  $v_{Pmic}$  are the settling velocities of macro and microplastics (m/d);  $k_{Pmac}(T)$ and  $k_{Pmic}(T)$  are the temperature-dependent plastic dissolution rates (/d); and  $\alpha_{Pmac}$  and  $\alpha_{Pmic}$  are the light efficiency factors (-), respectively. We assume that the deterioration due to light can be modeled as a first-order temperature-dependent decay, and the deterioration rate  $k_e$  due to light is based on the Beer-Lambert law. We also assume that there is no interaction with suspended matter (hetero-aggregation), resuspension, biofouling, or the effects of wind. Furthermore, we assume that the deterioration of macroplastics due to light and temperature shows the transition to microplastics, and this disappearance term in equation (2.13) was added to equation (2.14). Chapter 2 Development of a Process-Based Eco-Hydrology Model for Evaluating Spatiotemporal Dynamics of Macro and Microplastics for Whole of Japan



Figure 2.2 Flow diagram of macro and microplastic transport in land and inland water by extending NICE-BGC

#### 2.3 Input Data and Boundary Conditions for Simulation

#### 2.3.1 Model Input Data

The input data at various spatial resolutions were prepared and arranged to calculate a spatially averaged 0.1° x 0.1° grid (about 9-11 km resolution) using the Spatial Analyst Tools in ArcGIS v10.3 software for a simulation of Japan as a whole (Fig. 2.1 and Table 2.1); elevation, land cover, soil texture, vegetation type, river networks, lakes and wetlands, reservoirs and dams, and geological structures were categorized based on the global and Japanese datasets. To create the grid data from point, polyline, and polygon data for different sources with different spatial resolutions in a reasonable way, overlay analysis was conducted using GIS tools (intersect, union, and identity) (ESRI, 2019).

The authors also subdivided the agricultural regions of GLC2000 into major crops in MIRCA2000 (Portmann et al., 2010) and the FAO crop definition (Leff et al., 2004) (Table 1). The irrigation type (surface water, groundwater, and other) and irrigation water use derived using the global datasets were also defined in the same way as in the author's previous study (Nakayama, 2020). The total nutrient nitrogen and phosphorus consumptions for each crop were calculated to obtain the totals for N and P fertilizer, N and P manure, and N deposition
using ArcGIS software to merge the data with MIRCA2000 in each 5 arc-minute grid ( $\approx 10$  km); this confirmed that the calculated total consumption of each nutrient was within the range of the previous data (Bouwman et al., 2009). Therefore, for the NICE-BGC simulation, the authors used the spatially distributed data for fertilizer and manure application for each crop after that.

Although data for plastics are scarce, the authors used some data to simulate the plastic debris for Japan as a whole; population data at 250 m resolution was obtained from the Japanese Census in 2015 (Japanese Government Statistics, 2021), wastewater treatment plants (WWTP) at 2,185 locations (Ministry of Land, Infrastructure, Transport and Tourism, 2013) as point sources, and MPW at 1 km resolution (Lebreton and Andrady, 2019) as a diffuse source (Table 2.1).

Data set	Original resolution	Year	Source and reference			
Climatology	1.0 °	1998-2015	ERA-interim; ECMWF (2019)			
Elevation	1.0 km	around 1996	GTOPO30; U.S. Geological Survey (1996)			
Land cover	1.0 km	around 2000	GLC2000; European Commission (2015)			
Soil texture	1.0 km	around 1970-2000	HWSD; European Commission (2012)			
Vegetation type	0.25 °	around 2000	GLDAS Vegetation Class; NASA (2013)			
River networks	line	around 2000	MLIT (2012)			
Lakes and wetlands	0.5 min	around 1990-2000	GLWD; Lehner and Döll (2004)			
Geological structures	0.5 °	around 1970-2000	GLiM; Hartmann and Moosdorf (2012)			
Crop type	5 min	around 2000	MIRCA2000; Portmann et al. (2010)			
Irrigation type	5 min	2000-2008	GMIA; FAO (2016)			
Irrigation water use	5 min	1998-2002	GCWM; Siebert and Döll (2010)			
Basin boundary	50 m	around 2010	MLIT (2011)			
Reservoirs and dams	point	2014	MLIT (2016)			
Fertilizer use	5 min	around 2000	Earth Stat; Mueller et al. (2012)			
Manure use	5 min	1998-2014	Zhang et al. (2017)			
Population	250 m	2015	Japanese Government Statistics (2021)			
Wastewater treatment plants	point	2010	MLIT (2013)			
Mismanaged plastic waste	1.0 km	2015	Lebreton and Andrady (2019)			

Table 2.1 List of input data sets for the NICE and NICE-BGC simulations

# 2.3.2 Plastic Generation at Point and Non-Point Sources and Removal at WWTP

Some previous studies of plastic dynamics on a global scale (Lebreton and Andrady, 2019; Strokal et al., 2021). Lebreton and Andrady (2019) have predicted future plastic waste generation by considering population and GDP growth rates per country. These proposed three scenarios: (A) business as usual, (B) improvement of waste management, and (C) reduction of plastic use and improvement of waste management. This approach effectively evaluates future MPW production on a regional scale. Strokal et al. (2021) developed five scenarios with different levels of urbanization and wastewater treatment rates by considering different levels of socioeconomic challenge for mitigation and adaptation as five Shared Socioeconomic Pathways (SSPs). This approach is also useful for assessing the impact of urbanization on future river pollution by adopting a multi-pollutant approach. In the UK, Whitehead et al. (2021) also considered three scenarios for wastewater effluent, sewage sludge application, and mitigation in the basin of the Thames River.

Table 2.2 summarizes the per capita emission of macroplastics and microplastics into rivers determined in previous studies (Siegfried et al., 2017; van Wijnen et al., 2019; Boucher et al., 2020; Strokal et al., 2021). Generally, microplastics at point sources originate from four

sources: personal care products (PCPs), laundry fibers, car tire wear, and fragmentation of macroplastics. We estimated microplastic fluxes by multiplying these per capita emissions and their population distribution for each catchment flow into WWTP in the NICE-BGC simulation (Table 2.1). For estimating the variations of total flux in Japan as a whole, we used the removal efficiency of microplastic in WWTP (99, 97, and 95%) (higher removal efficiency for almost all secondary and tertiary treatments in Japan) and the density of the plastic (1010.0, 1001.0, and 1000.5 kg/m<sup>3</sup>) (the lower-density plastics, PE, PP, and PS, are overwhelmingly present in Japanese rivers) in the model based on previous studies for Japan (Kataoka et al., 2019; Nihei et al., 2020) and other developed countries (Siegfried et al., 2017; van Wijnen et al., 2019; Strokal et al., 2021).

Plastic sources	Quantitative estimate (kg/capita/year)	OECD Countries	Africa	Middle East & North Africa	East Asia & Pacific (incl. Japan)	Eastern & Central Asia	Latin America	South Asia	Re fe re nce	
Personal care products (PCPs)	0.0071									
Household dust (HD)	0.08								Siegfried et al.(2017)	
Laundry inputs or fibres (LD)	0.12									
Tyre wear (TRWP)	0.18									
Personal care products (PCPs)	0.0071									
Household dust (HD)	0.08									
Laundry inputs or fibres (LD)	0.12								Strokal et al.(2021)	
Tyre wear (TRWP); HDI<0.785	0.018									
Tyre wear (TRWP); HDI>0.785	0.18									
Macroplastics (non-point sources)	17.3	8.8	27	16	23	15	23	8.5		
Personal care products (PCPs)	0.0028	0.0055	0.0007	0.0007	0.0049	0.0049	0.0025	0.0007	van Wiinen et al (2010)	
Laundry inputs or fibres (LD)	0.0451	0.11	0.007	0.047	0.041	0.047	0.028	0.036	van wijnen et al.(2019)	
Tyre wear (TRWP)	0.0662	0.18	0.0072	0.068	0.018	0.077	0.041	0.072		
Personal care products (PCPs)	0.005									
Laundry inputs or fibres (LD)	0.015								Powebor at al (2020)	
Tyres (car)	0.43									
Tyres (truck)	0.43								Boucher et al. (2020)	
Tyres (plane)	0.01									
Plastic production (pellet loss)	0.005									

Table 2.2 Per capita emission of macroplastics and microplastics into rivers in previous materials

# 2.3.3 Running the Simulation and Verification

The simulation area in all the 109 first-class river basins throughout Japan was 26.0° wide by 22.0° long in longitude-latitude coordinates (Nakayama and Osako, 2023a) (Fig. 2.1). The NICE simulation of eco-hydrological processes was performed at 0.1° x 0.1° resolution in the horizontal direction and 20 layers in the vertical direction. Simulations were performed with a time step of  $\Delta t = 1$  h for two years during 2014-2015 after a 6-month warm-up period until a time-varying equilibrium. The periods of some input data, such as vegetation type and land cover, do not cover the simulation period (Table 2.1).

Subsequently, NICE-BGC simulation for terrestrial ecosystems was conducted at the same spatial resolution with a time step of  $\Delta t = 1$  day for the same period by inputting some of the results simulated by NICE iteratively after calculating the daily-averaged data from 1-hourly data. The authors used previous data (Ministry of Land, Infrastructure, Transport and Tourism, 2013) for per capita emission of microplastics into rivers (PCPs, dust, laundries, and tires) and removal efficiency in WWTP (Siegfried et al., 2017) as a point source (Fig. 2.2 and Table 2.2). The model also simulated the outflow of macroplastics originating from MPW (Lebreton and Andrady, 2019) as a diffuse source (Fig. 2.1f).

Then, NICE-BGC simulation for aquatic ecosystems was conducted by inputting the simulated results for land to a stream network model with a time step of  $\Delta t = 0.70$  min to ensure the stability of the model. The simulation was conducted for the whole of Japan in the same way as the author's previous study on the global scale (Nakayama, 2017a), where the hydrologic and nutrient cycles in the world's major rivers were simulated and verified within

the range of previous datasets and materials as far as possible. The results yielded quantitative measures of model performance in reproducing the seasonality and inter-annual variability in nutrient and carbon fluxes, as described previously by Nakayama (2020, 2022). These mean the extension of NICE-BGC coupled with the plastic debris model in the present study would be a better choice for simulating the fate and transport of plastic waste on a basin scale, as described below (Nakayama and Osako, 2023a).

# 2.4 Results and Discussion

# 2.4.1 Evaluation of Hydrologic Cycle in First-Class (Class A) River Basins in Entire Japan

The authors evaluated the hydrologic cycle in first-class river basins in Japan. Fig. 2.3 shows the simulated results for surface runoff in major rivers with large basin areas and long river channels among the first-class rivers (No. 28; Tone River, No. 36; Shinano River, No. 54; Kiso River, and No. 62; Yodo River in Fig. 2.1a) during 2014–2015. The results show that the intermediate flow was almost constant (Fig. 2.3c) compared to the surface runoff (Fig. 2.3b), implying that surface runoff is intensive during rainfall events and greatly contributes to the outflow of plastic. It is also apparent that surface runoff is limited in small river basins but cannot be ignored. Because it is difficult to validate the hillslope runoff with almost no observation data, the authors compared the simulated annual-averaged values for discharge, nitrogen, and phosphorus transport with the previous observation data (Kataoka et al., 2019; Ministry of Land, Infrastructure, Transport, and Tourism, 2021a) for first-class river basins (Fig. 2.4). Although the simulated discharges are slightly underestimated relative to the observed values, particularly in rivers with snow areas (No. 3; Ishikari River, and No. 17; Kitakami River, No. 35; Agano River, No. 36; Shinano River in Fig. 2.1a), the simulated results are generally in good agreement with observed ones (Fig. 2.4a). Transports of nutrients simulated by the time series for the entire calculation period during 2014-2015 (red circle in the figures) are overestimated in comparison with the observed values (Figs 2.4b-c) because observation of concentrations was conducted only in the non-flood periods (Kataoka et al., 2019). The simulated values averaged only for the base flow of rivers are within the range of those in the observed values (blue triangle in the figures). The hydrologic regimes of baseflow and stormflow events are important for remobilizing plastic particles in inland waters (Drummond et al., 2020).



Figure 2.3 Simulated results of surface runoff in major rivers with large basin areas and long river channels among the first-class rivers during 2014–2015; (a) total surface runoff, (b) surface runoff, and (c) intermediate flow



Figure 2.4 Comparison of annual-averaged values in (a) discharge, (b) nitrogen transport, and (c) phosphorus transport in the first-class of river basins; red circle shows the nutrient transports simulated by the time series for the entire calculation period during 2014–2015, and blue triangle shows the values simulated only by the base flow of rivers.

#### 2.4.2 Analysis of Sensitivity of Microplastic Transport to Various Factors

The authors analyzed the sensitivity of microplastic concentration to various factors in the downstream stretch of the Tone River in summer (June 1 to July 20, 2014) (Fig. 2.5). It was found that the concentration of microplastics was greatly affected by their particle size and density, which determine the settling velocity (Nizzetto et al., 2016). Almost all plastic particles with a density lower than water (polypropylene; PP) are more buoyant than those with a higher density (polystyrene; PS and polyethylene terephthalate; PET) (Fig. 2.5b). The simulated value was generally within the range of previous observations for limited, non-flood periods in the same river (microplastic concentration between 0.03 and 2.36  $\mu$ g/L) (Kataoka et al., 2019; Nihei et al., 2020). The simulated result also agreed with previous work showing that microplastics smaller than 0.2 mm would be poorly retained in the Thames River, UK, and would eventually be conveyed to the marine environment (Nizzetto et al., 2016; Whitehead et al., 2021). The simulation also showed that the effects of degradation (i.e., a decrease in concentration) resulting from both water temperature and UV irradiation (in Fig. 2.5c) would not be negligible because there is a great variation with these two values. This effect is particularly predominant

under some conditions, for example, in hot and cold water and with stronger UV irradiation in summer.



Figure 2.5 Sensitivity analysis of various factors on microplastic concentration downstream of Tone River from June 1 to July 20 in 2014; (a) effect of particle diameter (diameter = 1, 10, 20  $\mu$ m with constant density = 1150 kg/m3), (b) effect of particle density (density = 900, 1010, 1350 kg/m<sup>3</sup> with constant diameter = 10  $\mu$ m), (c) effect of particle degradation (with the effect of water temperature, UV irradiation, and both with diameter = 10  $\mu$ m and density = 1150 kg/m<sup>3</sup>).

## 2.4.3 Impact of Plastic Density and WWTP on Riverine Export of Plastics into Ocean

The model simulated the total plastic flux to the ocean for Japan as a whole (Fig. 2.6). Generally, large amounts of plastic flow out of some limited rivers such as the Tone (No. 28), Kiso (No. 54), Yodo (No. 62), and Ara Rivers (No. 29), where there is a large proportion of macroplastic flux in comparison with microplastic flux (Fig. 2.6b). However, the modeled results for microplastic flux are a little overestimated compared to previous observations (Kataoka et al., 2019) in some rivers (Fig. 2.6a). The analysis of this scenario also shows that the total flux for Japan varies according to the removal efficiency of microplastics in WWTP (99, 97, and 95%) and the density of the plastic (1010.0, 1001.0, and 1000.5 kg/m3) (Fig. 2.6c). The simulated flux is within the range of 1,100–3,500 tons/yr, with 1,395 tons/yr in case-Ab (removal efficiency = 99% and density of plastic =  $1001.0 \text{ kg/m}^3$ ). This result is relatively within the range of previously determined values, i.e., 1,835 tons/yr (Meijer et al., 2021) and 210-4,976 tons/yr (Nihei et al., 2020); this shows that only limited plastics are discharged intensively to land out into the ocean during rainfall seasons, in agreement with a previous study indicating that nearly 99% of microplastics are deposited during their transport to coastal regions (Koutnik et al., 2021). It will be necessary to improve the accuracy of the modeled results further by validating observations.



Figure 2.6 Simulated plastic flux to the ocean; (a)-(b) annual fluxes in each first-class of 109 rivers, and (c) total flux in entire Japan with various scenarios; Blue and red bars show the flux of macro and microplastics.

# **2.5** Conclusion

This chapter describes the extension of the process-based eco-hydrology model NICE to couple with the plastic debris (engineered materials) model for freshwater systems and apply it to all the first-class (class A) river basins in the entire Japan (109 river basins). The new model was constructed to include as many processes related to plastic dynamics in the biosphere, applicable to regional and basin scales, advection, dispersion, diffusion, settling, dissolution, and deterioration due to light and temperature. NICE-BGC simulated how mismanaged plastic waste (MPW) of about 36,000 tons/yr and point sources such as tires, personal care products (PCPs), dust, and laundry in the entire country are transported from land to river and finally to

the ocean. The simulated result quantified large amounts of plastic flowing out of some limited rivers intensively during rainfall seasons and that macroplastic flux accounts for a larger proportion than there. Although scenario analysis quantified the total flux varied according to some factors and was estimated as within the range of existing studies, it is further necessary to minimize errors and uncertainties by using more accurate, more long-term, and more observations. These results help quantify the impacts of plastic waste on terrestrial and aquatic ecosystems and find solutions and measures to reduce plastic input to the ocean.

#### References

- Besseling, E., Quik, J.T.K., Sun, M., Koelmans, A.A. (2017) Fate and nano- and microplastic in freshwater systems: A modelling study. Environmental Pollution, 220, 540-548, doi:10.1016/j.envpol.2016.10.001
- Boucher, J., Billard, G., Simeone, E., Sousa, J. (2020) The marine plastic footprint. Global Marine and Polar Programme. IUCN. Switzerland. 69 pp., doi:10.2305/IUCN.CH.2020.01.en
- Cowger, W., Gray, A.B., Guilinger, J.J., et al. (2021) Concentration depth profiles of microplastic particles in river flow and implications for surface sampling. Environmental Science & Technology, 55, 6032-6041, doi:10.1021/acs.est.1c01768
- Drummond, J.D., Nel, H.A., Packman, A.I., Krause, S. (2020) Significance of Hyporheic Exchange for Predicting Microplastic Fate in Rivers. Environmental Science & Technology Letters, 7, 10, 727-732, doi:10.1021/acs.estlett.0c00595
- Einstein, H.A. (1950) The bed load function for sediment transportation in open channel flows. Technical Bulletin 1026, USDA, Soil Conservation Service
- ESRI. (2019) Overlay Layers. Portal for ArcGIS. https://gislab.depaul.edu/portal/portalhelp/en/portal/latest/use/geoanalytics-overlay-layers.htm

European Commission. (2015) Global Land Cover 2000. https://forobs.jrc.ec.europa.eu/products/glc2000/glc2000.php

- Hoellein, T.J., Shogren, A.J., Tank, J.L., et al. (2019) Microplastic deposition velocity in streams follows patterns for naturally occurring allochthonous particles. Scientific Reports, 9, 3740, doi:10.1038/s41598-019-40126-3
- Itakura, T. (1984) Investigations of some turbulent diffusion phenomena in rivers. Research Report of Civil Engineering Research Institute of Hokkaido, 83, 1-91 (in Japanese, with English Abstr.)
- Jambeck, J.R., Geyer, R., Wilcox, C., et al. (2015) Plastic waste inputs from land into the ocean. Science, 347, 768-771, doi:10.1126/science.1260352
- Japanese Government Statistics. (2021) E-Stat: Statistics of Japan. https://www.e-stat.go.jp/en
- Kataoka, T., Nihei, Y., Kudou, K., Hinata, H. 2019. Assessment of the sources and inflow processes of microplastics in the river environments of Japan. Environmental Pollution, 244, 958–965, doi:10.1016/j.envpol.2018.10.111
- Kooi, M., van Nes, E.H., Scheffer, M., Koelmans, A.A. (2017) Ups and downs in the ocean: Effects of biofouling on vertical transport of microplastics. Environmental Science & Technology, 51, 7963-7971, doi:10.1021/acs.est.6b04702
- Kooi, M., Besseling, E., Kroeze, C., et al. (2018) Modelling the fate and transport of plastic decries in freshwaters: review and guidance. In: Wagner, M., Lambert, S. [Eds] Freshwater Microplastics. The Handbook of Environmental Chemistry 58, Springer, pp.125-152
- Kooi, M., Koelmans, A.A. (2019) Simplifying microplastic via continuous probability distributions for size, shape, and density. Environmental Science & Technology Letters, 6, 551-557, doi:10.1021/acs.est.9b00379
- Koutnik, V.S., Leonard, J., Alkidim, S., et al. (2021) Distribution of microplastics in soil and freshwater environments: global analysis and framework for transport modelling. Environmental Pollution, 224, 116552, doi:10.1016/j.envpol.2021.116552
- Kumar, R., Sharma, P., Verma, A., et al. (2021) Effect of physical characteristics and hydrodynamic conditions on transport and deposition of microplastics in riverine ecosystem. Water, 13, 2710, doi:10.3390/w13192710
- Lazar, A.N., Butterfield, D., Futter, M.N., et al. (2010) An assessment of the fine sediment dynamics in an upland river system: INCA-Sed modifications and implications for fisheries. Science of the Total Environment, 408, 2555-2566, doi:10.1016/j.scitotenv.2010.02.030
- Lebreton, L., Andrady, A. (2019) Future scenarios of global plastic waste generation and disposal. Palgrave Communications, 5, 6, doi:10.1057/s41599-018-0212-7

- Lebreton, L, van der Zwet, J., Damsteeg, J.-W., et al. (2017) River plastic emissions to the world's oceans. Nature Communications, 8, 15611, doi:10.1038/ncomms15611
- Liu, Y., You, J., Li, Y., et al. (2021) Insights into the horizontal and vertical profiles of microplastics in a river emptying into the sea affected by intensive anthropogenic activities in Northern China. Science of the Total Environment, 779, 146589, doi:10.1016/j.scitotenv.2021.146589
- Mai, L., Sun, X.-F., Xia, L.-L., Bao, L.-J., Liu, L.-Y., Zeng, E.Y. (2020) Global riverine plastic outflows. Environmental Science & Technology, 54, 10049-10056, Doi:10.1021/acs.est.0c02273
- Meijer, L.J.J., van Emmerik, T., van der Ent, R., et al. (2021) More than 1000 rivers account for 80% of global riverine plastic emissions into the ocean. Science Advances, 7, eaaz5803, doi:10.1126/sciadv.aaz5803
- Ministry of Foreign Affairs of Japan. (2019) G20 Osaka Leader's Declaration. https://www.mofa.go.jp/policy/economy/g20\_summit/osaka19/en/documents/final\_g20\_osaka\_leaders\_decl aration.html
- Ministry of Land, Infrastructure, Transport and Tourism (MLIT). (2013) Digital national land information: Sewerage system related facility. https://nlftp.mlit.go.jp/ksj/gml/datalist/KsjTmplt-P22.html
- Ministry of Land, Infrastructure, Transport and Tourism (MLIT). 2021a.Water information system. http://www1.river.go.jp/
- Ministry of Land, Infrastructure, Transport and Tourism (MLIT). (2021b) Latest situation of the spread of sewage treatment population in Japan. Press Release. https://www.mlit.go.jp/report/press/content/001421074.pdf (in Japanese)
- Nakayama, T., Watanabe, M. (2004) Simulation of drying phenomena associated with vegetation change caused by invasion of alder (Alnus japonica) in Kushiro Mire. Water Resources Research, 40, W08402, doi:10.1029/2004WR003174
- Nakayama, T., Watanabe, M. (2005) Re-evaluation of groundwater dynamics about water and nutrient budgets in Lake Kasumigaura, Annual Journal of Hydroscience and Hydraulic Engineering, 49, 1231-1236 (Abst. in English)
- Nakayama, T., Watanabe, M. (2006a) Simulation of spring snowmelt runoff by considering micro-topography and phase changes in soil layer. Hydrology and Earth System Sciences Discussions, 3, 2101-2144
- Nakayama, T., Watanabe, M. (2006b) Development of process-based NICE model and simulation of ecosystem dynamics in the catchment of East Asia (Part I). CGER's Supercomputer Monograph Report, 11, NIES, 100p., http://www.cger.nies.go.jp/publications/report/i063/I063e
- Nakayama, T., Yang, Y., Watanabe, M., Zhang, X. (2006) Simulation of groundwater dynamics in North China Plain by coupled hydrology and agricultural models. Hydrological Processes, 20(16), 3441-3466, doi:10.1002/hyp.6142
- Nakayama, T., Watanabe, M., Tanji, K., Morioka, T. (2007) Effect of underground urban structures on eutrophic coastal environment. Science of the Total Environment, 373(1), 270-288, doi:10.1016/j.scitotenv.2006.11.033
- Nakayama, T. (2008a) Factors controlling vegetation succession in Kushiro Mire. Ecological Modelling, 215, 225-236, doi:10.1016/j.ecolmodel.2008.02.017
- Nakayama, T. (2008b) Shrinkage of shrub forest and recovery of mire ecosystem by river restoration in northern Japan. Forest Ecology and Management, 256, 1927-1938, doi:10.1016/j.foreco.2008.07.017
- Nakayama, T. (2008c) Development of process-based NICE model and simulation of ecosystem dynamics in the catchment of East Asia (Part II). CGER's Supercomputer Monograph Report, 14, NIES, 91p., http://www.cger.nies.go.jp/publications/report/i083/i083 e
- Nakayama, T., Watanabe, M. (2008a) Missing role of groundwater in water and nutrient cycles in the shallow eutrophic Lake Kasumigaura, Japan. Hydrological Processes, 22, 1150-1172, doi:10.1002/hyp.6684
- Nakayama, T., Watanabe, M. (2008b) Role of flood storage ability of lakes in the Changjiang River catchment. Global and Planetary Change, 63, 9-22, doi:10.1016/j.gloplacha.2008.04.002
- Nakayama, T., Watanabe, M. (2008c) Modelling the hydrologic cycle in a shallow eutrophic lake. Verh International Verein Limnology (International Association of Theoretical and Applied Limnology), 30(3), 345-348
- Nakayama, T. (2009) Simulation of ecosystem degradation and its application for effective policy-making in regional scale. In: Gallo, M.N., Ferrari M.H. [Eds], River pollution research progress (Chapter 1), Nova Science Pub., Inc., New York, 1-89
- Nakayama, T. (2010) Simulation of hydrologic and geomorphic changes affecting a shrinking mire. River Research and Applications, 26(3), 305-321, doi:10.1002/rra.1253
- Nakayama, T., Fujita, T. (2010) Cooling effect of water-holding pavements made of new materials on water and heat budgets in urban areas. Landscape and Urban Planning, 96, 57-67, doi:10.1016/j.landurbplan.2010.02.003

- Nakayama, T., Sun, Y., Geng, Y. (2010) Simulation of water resource and its relation to urban activity in Dalian City, Northern China. Global and Planetary Change, 73, 172-185, doi:10.1016/j.gloplacha.2010.06.001
- Nakayama, T. (2011a) Simulation of complicated and diverse water system accompanied by human intervention in the North China Plain. Hydrological Processes, 25, 2679-2693, doi:10.1002/hyp.8009
- Nakayama, T. (2011b) Simulation of the effect of irrigation on the hydrologic cycle in the highly cultivated Yellow River Basin. Agricultural and Forest Meteorology, 151, 314-327, doi:10.1016/j.agrformet.2010.11.006
- Nakayama, T. (2011c) Feedback mechanism and complexity in ecosystem—development of integrated assessment system towards eco-conscious society—, Chemical Engineering of Japan, 75, 789-791 (in Japanese)
- Nakayama, T. (2011d) Construction of integrated assessment system for win-win solution of hydrothermal degradations in urban area towards eco-conscious society, Chemical Information and Computer Sciences, 29(4), 63-65 (in Japanese)
- Nakayama, T., Hashimoto, S. (2011) Analysis of the ability of water resources to reduce the urban heat island in the Tokyo megalopolis. Environmental Pollution, 159, 2164-2173, doi:10.1016/j.envpol.2010.11.016
- Nakayama, T. (2012a) Visualization of missing role of hydrothermal interactions in Japanese megalopolis for winwin solution. Water Science and Technology, 66(2), 409-414, doi:10.2166/wst.2012.205
- Nakayama, T. (2012b) Feedback and regime shift of mire ecosystem in northern Japan. Hydrological Processes, 26(16), 2455-2469, doi:10.1002/hyp.9347
- Nakayama, T. (2012c) Impact of anthropogenic activity on eco-hydrological process in continental scales. Procedia Environmental Sciences, 13, 87-94, doi:10.1016/j.proenv.2012.01.008
- Nakayama, T. (2012d) Development of process-based NICE model and simulation of ecosystem dynamics in the catchment of East Asia (Part III). CGER's Supercomputer Monograph Report, 18, NIES, 98p., http://www.cger.nies.go.jp/publications/report/i103/en/
- Nakayama, T., Hashimoto, S., Hamano, H. (2012) Multi-scaled analysis of hydrothermal dynamics in Japanese megalopolis by using integrated approach. Hydrological Processes, 26(16), 2431-2444, doi:10.1002/hyp.9290
- Nakayama, T. (2013) For improvement in understanding eco-hydrological processes in mire. Ecohydrology and Hydrobiology, 13, 62-72, doi:10.1016/j.ecohyd.2013.03.004
- Nakayama, T., Shankman, D. (2013a) Impact of the Three-Gorges Dam and water transfer project on Changjiang floods. Global and Planetary Change, 100, 38-50, doi:10.1016/j.gloplacha.2012.10.004
- Nakayama, T., Shankman, D. (2013b) Evaluation of uneven water resource and relation between anthropogenic water withdrawal and ecosystem degradation in Changjiang and Yellow River basins. Hydrological Processes, 27(23), 3350-3362, doi:10.1002/hyp.9835
- Nakayama, T. (2014a) Hydrology–ecology interactions. In: Eslamian, S. [Ed] Handbook of Engineering Hydrology Vol. 1: Fundamentals and Applications (Chapter 16), Taylor and Francis, 329-344
- Nakayama, T. (2014b) Development of process-based NICE model and simulation of ecosystem dynamics in the catchment of East Asia (Part IV). CGER's Supercomputer Monograph Report, 20, NIES, 102p., http://www.cger.nies.go.jp/publications/report/i114/en/
- Nakayama, T. (2015) Integrated assessment system using process-based eco-hydrology model for adaptation strategy and effective water resources management. In: Lakshmi V. [Ed] Remote Sensing of the Terrestrial Water Cycle (Geophysical Monograph Series 206) (Chapter 33), AGU, 521-535 doi:10.1002/9781118872086.ch33
- Nakayama, T. (2016) New perspective for eco-hydrology model to constrain missing role of inland waters on boundless biogeochemical cycle in terrestrial-aquatic continuum. Ecohydrology and Hydrobiology, 16, 138-148, doi:10.1016/j.ecohyd.2016.07.002
- Nakayama, T. (2017a) Development of an advanced eco-hydrologic and biogeochemical coupling model aimed at clarifying the missing role of inland water in the global biogeochemical cycle. Journal of Geophysical Research Biogeosciences, 122, 966-988, doi:10.1002/2016JG003743
- Nakayama, T. (2017b) Scaled-dependence and seasonal variations of carbon cycle through development of an advanced eco-hydrologic and biogeochemical coupling model. Ecological Modelling, 356, 151-161, doi:10.1016/j.ecolmodel.2017.04.014
- Nakayama, T. (2017c) Biogeochemical contrast between different latitudes and the effect of human activity on spatio-temporal carbon cycle change in Asian river systems. Biogeosciences Discussions, doi:10.5194/bg-2017-447
- Nakayama, T. (2018) Interaction between surface water and groundwater and its effect on ecosystem and biogeochemical cycle. Journal of Groundwater Hydrology, 60(2), 143-156, doi:10.5917/jagh.60.143 (in Japanese)

- Nakayama, T., Maksyutov, S. (2018) Application of process-based eco-hydrological model to broader northern Eurasia wetlands through coordinate transformation. Ecohydrology and Hydrobiology, 18, 269-277, doi:10.1016/j.ecohyd.2017.11.002
- Nakayama, T., Pelletier, G.J. (2018) Impact of global major reservoirs on carbon cycle changes by using an advanced eco-hydrologic and biogeochemical coupling model. Ecological Modelling, 387, 172-186, doi:10.1016/j.ecolmodel.2018.09.007
- Nakayama, T. (2019) Development of process-based NICE model and simulation of ecosystem dynamics in the catchment of East Asia (Part V). CGER's Supercomputer Monograph Report, 26, NIES, 122p., http://www.cger.nies.go.jp/publications/report/i148/en/
- Nakayama, T. (2020) Inter-annual simulation of global carbon cycle variations in a terrestrial-aquatic continuum. Hydrological Processes, 34(3), 662-678, doi:10.1002/hyp.13616
- Nakayama, T., Wang, Q., Okadera, T. (2021a) Evaluation of spatio-temporal variations in water availability using a process-based eco-hydrology model in arid and semi-arid regions of Mongolia. Ecological Modelling, 440, 109404, doi:10.1016/j.ecolmodel.2020.109404
- Nakayama, T., Wang, Q., Okadera, T. (2021b) Sensitivity analysis and parameter estimation of anthropogenic water uses for quantifying relation between groundwater overuse and water stress in Mongolia. Ecohydrology and Hydrobiology, 21(3), 490-500, doi:10.1016/j.ecohyd.2021.07.006
- Nakayama, T. (2022) Impact of anthropogenic disturbances on carbon cycle changes in terrestrial-aquaticestuarine continuum by using an advanced process-based model. Hydrological Processes, 36(2), e14471, doi:10.1002/hyp.14471
- Nakayama, T. (2023a) Evaluation of global biogeochemical cycle in lotic and lentic waters by developing an advanced eco-hydrologic and biogeochemical coupling model. Ecohydrology, e2555, doi:10.1002/eco.2555
- Nakayama, T. (2023b) Development of process-based NICE model and simulation of ecosystem dynamics in the catchment of East Asia (Part VI). CGER's supercomputer monograph report, 29. NIES, 95p., http://www.cger.nies.go.jp/publications/report/i164/en/
- Nakayama, T., Okadera, T., Wang, Q. (2023) Impact of various anthropogenic disturbances on water availability in the entire Mongolian basins towards effective utilization of water resources. Ecohydrology and Hydrobiology, 23(4), doi:10.1016/ j.ecohyd.2023.04.006
- Nakayama, T., Osako, M. (2023a) Development of a process-based eco-hydrology model for evaluating the spatiotemporal dynamics of macro- and micro-plastics for the whole of Japan. Ecological Modelling, 476, 110243, doi:10.1016/j.ecolmodel.2022.110243
- Nakayama, T., Osako, M. (2023b) The flux and fate of plastic in the world's major rivers: Modeling spatial and temporal variability. Global and Planetary Change, 221, 104037, doi:10.1016/j.gloplacha.2023.104037
- Nakayama, T., Osako, M. (2024) Plastic trade-off: Impact of export and import of waste plastic on plastic dynamics in Asian region. Ecological Modelling, 489, 110624, doi:10.1016/j.ecolmodel.2024.110624
- Nihei, Y., Yoshida, T., Kataoka, T., Ogata, R. (2020) High-resolution mapping of Japanese microplastic and microplastic emissions from the land into the sea. Water, 12, 951, doi:10.3390/w12040951
- Nizzetto, L., Bussi, G., Futter, M.N., et al. (2016) A theoretical assessment of microplastic transport in river catchments and their retention by soils and river sediments. Environmental Science: Processes & Impacts, 18, 1050-1059, doi:10.1039/c6em00206d
- Pelletier, G.J., Chapra, S.C., Tao, H. (2006) QUAL2Kw A framework for modeling water quality in streams and rivers using a genetic algorithm for calibration. Environmental Modelling and Software, 21, 419-425, doi:10.1016/j.envsoft.2005.07.002
- Praetorius, A., Scheringer, M., Hungerbühler, K. (2012) Development of environmental fate models for engineered nanoparticles A case study of TiO2 nanoparticles in the Rhine River. Environmental Science & Technology, 46, 6705-6713, doi:10.1021/es204530n
- Quik, J.T.K., de Klein, J.J.M., Koelmans, A.A. (2015) Spatially explicit fate modelling of nanomaterials in natural waters. Water Research, 80, 200-208, doi:10.1016/j.watres.2015.05.025
- Rubey, W. (1933) Settling velocities of gravel, sand and silt particles. American Journal of Science, 5, 325–338, doi:10.2475/ajs.s5-25.148.325
- Schmidt, C., Krauth, T., Wagner, S. (2017) Export of plastic debris by rivers into the sea. Environmental Science & Technology, 51, 12246-12253, doi:10.1021/acs.est.7b02368
- Shimizu, Y, Arai, N. (1988) Numerical simulation of flow and bed variations in the river mouth region. Research Report of Civil Engineering Research Institute of Hokkaido, 419, 5-36
- Siegfried, M., Koelmans, A.A., Besseling, E., Kroeze, C. (2017) Export of microplastics from land to sea. A modelling approach. Water Research, 127, 249-257, doi:10.1016/j.watres.2017.10.011
- Strokal, M., Bai, Z., Franssen, W., et al. (2021) Urbanization: an increasing source of multiple pollutants to rivers in the 21st century. Urban Sustainability, 1, 24, doi:10.1038/s42949-021-00026-w

- Thompson, R.C., Olsen, Y., Mitchell, R.P., et al. (2004) Lost at sea: Where is all the Plastic? Science, 304, 838, Doi:10.1126/science.1094559
- UNESCO. (2022) IHP-IX: Strategic Plan of the Intergovernmental Hydrological Programme: Science for a Water Secure World in a Changing Environment, ninth phase 2022-2029. https://unesdoc.unesco.org/ark:/48223/pf0000381318.locale=en
- Unice, K.M., Weeber, M.P., Abramson, M.M., et al. (2019) Characterizing export of land-based microplastics to the estuary - part I: Application of integrated geospatial microplastic transport models to assess tire and road wear particles in the Seine watershed. Science of the total Environmental, 646, 1639-1649, Doi:10.1016/j.scitotenv.2018.07.368
- United Nations. (2019) Basel Convention: Controlling transboundary movements of hazardous wastes and their disposal.

http://www.basel.int/Implementation/MarinePlasticLitterandMicroplastics/Overview/tabid/6068/Default.asp x

- U.S. Geological Survey (USGS). (1996) Global 30 Arc-Second Elevation (GTOPO30). USGS. doi:10.5066/F7DF6PQS
- Van Wijnen, J., Ragas, A.M.J., Kroeze, C. (2019) Modelling global river export of microplastics to the marine environment: Sources and future trends. Science of the Total Environment, 673, 392-401, doi:10.1016/j.scitotenv.2019.04.078
- Waldschlager, K., Schüttrumpf, H. (2019) Erosion behavior of different microplastic particles in comparison to natural sediments. Environmental Science & Technology, 53, 13219-13227, doi:10.1021/acs.est.9b05394
- Whitehead, P.G., Bussi, G., Hughes, J.M.R., et al. (2021) Modelling microplastics in the River Thames: sources, sinks and policy implications. Water, 13, 861, doi:10.3390/w13060861
- Windsor, F.M., Durance, I., Horton, A.A., et al. (2019) A catchment-scale perspective of plastic pollution. Global Change Biology, 25, 1207-1221, doi:10.1111/gcb.14572

This article was published in Ecological Modelling, 476, Nakayama, T., Osako, M., Development of a processbased eco-hydrology model for evaluating the spatio-temporal dynamics of macro- and micro-plastics for the

whole of Japan, 110243, Copyright Elsevier (2023a).

# Chapter 3

# Flux and Fate of Plastic in World's Major Rivers: Modeling Spatial and Temporal Variability

Chapter 3 Flux and Fate of Plastic in World's Major Rivers: Modeling Spatial and Temporal Variability

# Abstract

Over the past few decades, environmental contamination from plastics has received considerable attention from scientists, policymakers, and the public. Although some models successfully simulated the transport and fate of plastic debris in freshwater systems, a complete model of the dynamics of plastics in rivers on a global scale has yet to be elucidated. Recently, two process-based eco-hydrology models, NICE and NICE-BGC, were applied to evaluate biogeochemical cycling in various river basins on local/regional to continental/global scales. This effort provided insights into quantifying the role of inland waters on global biogeochemical cycles but was limited in its treatment of plastic dynamics. Here, we linked NICE-BGC to a plastic debris model that accounts for the transport and fate of plastic debris (advection, dispersion, diffusion, settling, dissolution, and biochemical degradation by light and temperature). We evaluated spatiotemporal variations of plastic debris in the world's major rivers (325 rivers) by simulating the amount of plastic that flows from land into rivers and finally into the ocean. Our NICE-BGC simulations show how diffuse sources of mismanaged plastic waste (MPW) and point sources of tires, personal care products (PCPs), dust, and laundry in these 325 rivers are transported from land to rivers and finally to the ocean. We compare continental-scale simulated plastic transport from agricultural and urban land uses to previous studies. Our model results confirm previous assessments that flood events greatly impact the mobilization of plastic and lead to high interannual variability in fluxes. Using "untreated wastewater" and a two-dimensional diffusion model simulation for macro-plastic transport helped decrease the model's uncertainty beyond previous studies that included only sewerage connectivity, removal efficiency, and transport probability. Uncertainty and sensitivity analyses using Monte Carlo model simulations also clarified that most plastic fluxes originate in 20 global rivers, largely in Asia, and are greatly influenced by the effects of the summer monsoon. The new model presented here may be valuable for detecting and predicting plastic dynamics in large rivers and developing efficient measures to reduce plastic input to the ocean on a global scale.

## Keywords: Eco-hydrology model; global river basins; plastic debris; untreated wastewater

# **3.1 Introduction**

Plastic pollution is considered one of today's main environmental problems, and such pollutants in streams, rivers, and oceans pose potential risks to human health and the environment (Siegfried et al., 2017). Plastic waste can be roughly categorized as macroplastic ( $\geq 5$  mm) or microplastic ( $\leq 5$  mm), the latter being further divided into primary and secondary microplastics according to origin (Siegfried et al., 2017). Once plastic is released into the environment, it is gradually degraded by physical, chemical, and biological processes, leading to further subdivision into many forms, all of which are impossible to remove and remain indefinitely in the environment (Zhang et al., 2021; Nakayama and Osako, 2023a).

Previous studies on the origin and fate of plastic waste in freshwater systems have suggested that land-derived plastics are one of the main sources of marine plastic pollution (Thompson et al., 2004). Although Jambeck et al. (2015) were the first to estimate the mass of land-based plastic entering the global ocean, they did not consider plastic waste from inland water. They did not classify the plastic according to particle size. Subsequent studies (Lebreton et al., 2017; Schmidt et al., 2017) estimated the distribution of global riverine emissions of plastic into the ocean using empirical indicators representative of waste generation (mismanaged plastic waste: MPW) inside a river basin. Using a probabilistic approach, Meijer et al. (2021) proposed a more accurate analysis to account for the spatial distribution of plastic waste generation (Lebreton and Andrady, 2019) and climatological/geographical differences within river basins. Other studies evaluated the impact of flood events on plastic mobilization and suggested its high inter-annual variability (van Emmerik et al., 2019; Roebroek et al., 2021), which had been previously ignored in global plastic transport models. Larger plastic debris from low-density polymers such as polyethylene (PE), polypropylene (PP), and polystyrene (PS) are predominantly transported in normal flat water.

In contrast, the relatively larger fraction of plastic litter retained in the bottom sediment, for example, high-density polymer such as polyvinyl chloride (PVC), is transported as bedload and efficiently flushed from riverbeds during flooding (Hurley et al., 2018; Schwarz et al., 2019). It is also expected that extreme events such as floods and droughts will increase further with climate change. The recent G20 Osaka Summit in 2019 shared the "Osaka Blue Ocean Vision" (Ministry of Foreign Affairs of Japan, 2019), which is positioned alongside COP (Conference of the Parties) as part of global warming countermeasures. A quantitative assessment of the fate and transport of plastics will be necessary to realize this vision because countries worldwide have decided on concrete future measures for dealing with plastic based on scientific results.

Over the last decade, there has been great progress in modeling the fate and transport of plastics. Kooi et al. (2018) classified plastic debris models for freshwater systems into four categories: an emission-based mass balance model, a global model, a multimedia model, and a spatiotemporally explicit model. Some studies (Siegfried et al., 2017; van Wijnen et al., 2019; Strokal et al., 2021) adapted a process-oriented model to continental and global scales by extending an existing non-dynamic nutrient export model. However, the fate of microplastics is also dependent on their size, density, shape, and polymer type: factors that were not included in the previous global analyses (Jambeck et al., 2015; Lebreton et al., 2017; Schmidt et al., 2017; Meijer et al., 2021). Some studies also quantified plastic pathways in a hypothetical catchment (Mellink et al., 2022) and incorporated the settling and resuspension of microplastics to estimate their retention in rivers and conducted a sensitivity analysis of the size and density of microplastics in fluxes (Nizzetto et al., 2016; Whitehead et al., 2021). Further, Cowger et al. (2021) modified the Rouse profile of vertical concentration (depth profile of suspended load concentration assuming a steady and uniform flow and equilibrium between upward turbulence

CGER-I169-2024, CGER/NIES

and settling velocity) to include all traditional domains of transport (bed load, settling suspended load, and wash load) as well as additional domains specific to low-density materials such as PE, PP, and PS (rising suspended load and surface load). These factors must be considered when assessing the fate and transport of plastics in various basins over scales ranging from local/regional to continental/global.

Recently, a process-based model coupling eco-hydrology with the biogeochemical cycle (National Integrated Catchment-based Eco-hydrology (NICE)-BGC) was developed to incorporate complex terrestrial-aquatic linkages in the hydrologic-biogeochemical cycle (Nakayama, 2017a, 2017b). This model was applied to evaluate the biogeochemical cycle in various basins on scales ranging from local/regional to continental/global. This effort gave insights into the quantification of the role of inland water on the biogeochemical cycle but has been limited in evaluating plastic dynamics there. In the present study, the process-based NICE-BGC was extended to link it with a plastic debris (engineered materials) model and evaluated spatiotemporal variations of plastic debris in the world's major rivers (325 rivers) by simulating the amount of plastic that flows from land into rivers and finally into the ocean (Nakayama and Osako, 2023b) (Fig. 3.1). The new model included both transport and fate of plastic debris (advection, dispersion, diffusion, settling, dissolution and biochemical degradation by light and temperature), unlike the case in previous studies. For model simplification, it was also assumed that plastics are pure and inert polymers with a continuous probability distribution of size, shape, and density (Kooi and Koelmans, 2019). In this chapter, we developed a new model to address these gaps. Specifically, we quantified: (i) How does plastic flux change spatiotemporally in major global rivers? (ii) how do floods alter this? (iii) How much uncertainty and sensitivity do plastic flux simulated by the model have? To clarify these issues, NICE-BGC simulated how among 81.8 Tg/yr of global MPW across the globe (Meijer et al., 2021) - about 39.2 Tg/yr, and point sources such as tires, personal care products (PCPs), dust, and laundry in these 325 rivers are transported from land to rivers, and finally to the ocean. The model showed that hydrometeorological change, particularly during flood periods, affected the seasonal variations of plastic transport. Using "untreated wastewater" and the simulation using a two-dimensional diffusion model for macroplastic transport helped decrease the model's uncertainty beyond previous studies only with sewerage connectivity, removal efficiency, and transport probability. The new model developed in this study might detect the spatiotemporal hotspots of plastic fluxes by quantifying the impacts of plastic waste on terrestrial and aquatic ecosystems. The results also help improve the plastic cycle and develop better solutions and efficient measures to reduce plastic load on a global scale as much as possible.



Figure 3.1 Location of study area on the global scale; (a) elevation, (b) land cover, (c) fertilizer and manure, (d) population density, (e) untreated wastewater calculated from wastewater treatment and wastewater production, and (f) mismanaged plastic waste (MPW)

# 3.2 Methods

#### 3.2.1 Coupling of NICE-BGC with Plastic Debris Model and its Application to Global Scale

The original NICE (National Integrated Catchment-based Eco-hydrology) comprises complex sub-compartments such as the surface hydrology of hillslope and stream flows, a land-surface model including urban and crop processes, a groundwater model, a regional atmospheric model, a sediment and nutrient mass transport model, and a vegetation succession model (Nakayama and Watanabe, 2004). To fill the current eco-hydrology gap, one of the authors has further developed a new model in which the original NICE is coupled with various biogeochemical cycle models (NICE-BGC) (Nakayama, 2017a, 2017b, 2022) (Fig. 1.1). Each sub-model offers iterative simulation most efficiently by combining on-line and off-line modes (on-line: data input/output through I/O memory, off-line: data input/output through file); this means that the newly developed model incorporates the connectivity of the biogeochemical cycle accompanied by the hydrologic cycle between surface water and groundwater, hillslopes and river networks, and other intermediate regions (Nakayama, 2016). Recently, one of the authors modified NICE-BGC to include the effect of reservoirs (Nakayama and Pelletier, 2018),

improve the accuracy of long-term simulation (Nakayama, 2020), and extend it to the terrestrial-aquatic-estuarine continuum (Nakayama, 2022).

In this study, NICE-BGC (Nakayama, 2017a, 2017b) was extended to model the fate and transport of macro and microplastic in land and water (Nakayama and Osako, 2023b) (Fig. 3.2). The authors also conducted uncertainty and sensitivity analyses using Monte Carlo model simulations by extending the concept from spherical particles to a continuous probability distribution of size, shape, and density (Kooi and Koelmans, 2019) to evaluate plastic dynamics on the continental and global scales. The new model also included advection, dispersion, diffusion, settling, dissolution, and biochemical degradation by light and temperature but assumed no interaction with suspended matter (hetero-aggregation) (Praetorius et al., 2012), resuspension (Waldschläger and Schüttrumpf, 2019), biofouling (Kooi et al., 2017), physical abrasion, or wind effects. The previous model of Meijer et al. (2021) used the probabilistic approach of plastic transport and did not explicitly include overland transport and accumulation processes. The model of Mellink et al. (2022) quantified plastic pathways within a river catchment but in a hypothetical local area under simpler conditions. In contrast, the present new model, by extending NICE-BGC, explicitly simulated overland transport and accumulation processes globally and simulated the fate and transport of both macro and microplastics there. Thus, the model could simulate the hydrograph for plastic transport with various shear stresses during storm events, as proposed by Kumar et al. (2021). For model simplification, it was also assumed that microplastics are pure and inert polymers with a continuous probability distribution of size, shape, and density (Kooi and Koelmans, 2019).

The transport of plastic on a hillslope was simulated in equations (2.1)-(2.9), except (2.4), in Chapter 2. Because equation (2.4) assumes the resuspension rate when a riverbed is under equilibrium conditions, and the particle size distribution is uniform, applying this formula directly to plastic is difficult. It is difficult to grasp the heterogeneous distribution of settled and deposited plastic on hillslopes, although some studies have evaluated the erosion behavior of microplastic particles compared to sediments (Waldschläger and Schüttrumpf, 2019). For model simplification, we also assumed that this plastic is negligible compared to discharged plastic and that resuspension is zero on hillslopes. After the simulation of plastic transport on a hillslope, the authors used the estimated rate of conversion of macroplastics to microplastics (3%/yr) in the same way as van Wijnen et al. (2019), with the extension of the conversion rate employed by Jambeck et al. (2015) (Fig. 3.2).

NICE-BGC simulates plastic transport in a river channel by extending QUAL2Kw (Pelletier et al., 2006). Macro and microplastics become buried through settling, dissolution, and deterioration due to light, temperature, advection, dispersion, and diffusion. The terms of sources and sinks for the constituent S due to reactions and mass transfer mechanisms can be added to equation (2.10) in Chapter 2:

$$S_{Pmac} = -\frac{v_{Pmac}}{h} P_{mac} - k_{Pmac}(T) P_{mac} - \alpha_{Pmac} \frac{I(0)/24}{k_e h} (1 - e^{-k_e h}) P_{mac}$$
(3.1)

$$S_{Pmic} = -\frac{v_{Pmic}}{h} P_{mic} - k_{Pmic}(T) P_{mic} - \alpha_{Pmic} \frac{I(0)/24}{k_e h} (1 - e^{-k_e h}) P_{mic} + k_{Pmac}(T) P_{mac} + \alpha_{Pmac} \frac{I(0)/24}{k_e h} (1 - e^{-k_e h}) P_{mac}$$
(3.2)

where  $P_{mac}$  (µg/l) and  $P_{mic}$  (µg/l) are the macro and microplastic concentrations; T is the water temperature;  $v_{Pmac}$  and  $v_{Pmic}$  are the settling velocities of macro and microplastics (m/d);  $k_{Pmac}(T)$ and  $k_{Pmic}(T)$  are the temperature-dependent plastic dissolution rates (/d); and  $\alpha_{Pmac}$  and  $\alpha_{Pmic}$  are the light efficiency factors (-), respectively. We assume that the deterioration due to light can be modeled as a first-order temperature-dependent decay, and the deterioration rate  $k_e$  due to light is based on the Beer-Lambert law. We also assume that there is no interaction with suspended matter (hetero-aggregation), resuspension, biofouling, or the effects of wind. Furthermore, if the deterioration of macroplastics due to light and temperature shows the transition to microplastics, this disappearance term in equation (3.1) was added to equation (3.2).





#### 3.2.2 Extension of Settling Velocity Applicable to Uncertainty Analysis

For the calculation of settling velocity, the authors extended Rubey's formula (Rubey, 1933) for spherical particles in equation (2.9) in Chapter 2 to Stokes' formula for different shapes by applying the equivalent sphere diameter  $d_{equi}$  (Waldschläger et al., 2020):

$$w_f = \sqrt{\frac{4}{3} \frac{d_{equi}}{c_D} |\frac{\rho_s}{\rho} - 1|g}$$
(3.3)

$$CSF = \frac{H}{\sqrt{LW}}$$
(3.4)

$$d_{equi} = (LWH)^{1/3} \approx L(CSF)^{1/3} \qquad \text{where } L \approx W \tag{3.5}$$

where CSF is the dimensionless Corey Shape factor determined by length:width:height (L:W:H) ratios for different shapes of the plastic particle (shortest H, middle W, and longest L side lengths);  $C_D$  is the drag coefficient at a constant value (= 0.44) for turbulent flow at a high Reynolds number in actual rivers (Re > 1000).

# 3.3 Input Data and Boundary Conditions for Simulation

#### 3.3.1 Model Input Data including Plastic Generation and Removal

The input data at various spatial resolutions were prepared and arranged to calculate a spatially averaged 1°x1° grid using the Spatial Analyst Tools in ArcGIS v10.3 software for the global simulation (Fig. 3.1 and Table 3.1); elevation, land cover, soil texture, vegetation type, river networks, lakes and wetlands, reservoirs and dams, geological structures, crop type, irrigation type, irrigation water use, fertilizer use, manure use, and atmospheric N deposition were categorized based on global datasets. Although data for plastics are scarce, the authors used some data to simulate global plastic debris, gridded population data at 1 km resolution in 2015 (NASA, 2018) (Fig. 3.1d), wastewater production, collection, treatment and reuse data at 5 arcmin (about 10 km) resolution (Jones et al., 2021) (Fig. 3.1e), and MPW at 1 km resolution (Lebreton and Andrady, 2019) (Fig. 3.1f) as a diffuse source (Table 3.1). To create the grid data from point, polyline, and polygon data for different sources with different spatial resolutions in a reasonable way, overlay analysis was conducted using GIS tools (intersect, union, and identity) (ESRI, 2019).

Table 3.2 summarizes the per capita emission of macroplastics and microplastics into rivers determined in previous studies (Siegfried et al., 2017; van Wijnen et al., 2019; Boucher et al., 2020; Strokal et al., 2021). Generally, microplastics at point sources originate from four sources: personal care products (PCPs), laundry fibers, car tire wear, and fragmentation of macro-plastics. We estimated the potential microplastic fluxes by multiplying these per capita emissions and their population distribution for each catchment flow into WWTPs (Waste Water Treatment Plants) in the NICE-BGC simulation (Fig. 3.1d and Table 3.1). We also applied "untreated wastewater" and converted it to the removal efficiency of microplastic, the former of which was calculated by subtracting the ratio of wastewater treatment and wastewater production from 1 at 5 arcmin resolution (Jones et al., 2021). This method differs from those used in most previous studies (Siegfried et al., 2017; van Wijnen et al., 2019; Meijer et al., 2021; Strokal et al., 2021), which considered only sewerage connectivity (0-1), microplastic removal efficiency, and transport probability of plastics (did not include overland transport and accumulation processes) with relatively large uncertainty. It was also assumed that microplastic concentration on hillslopes was constant (Wagner et al., 2019), and the time series proportional to hillslope runoff was calculated at each time step.

Data set	Original resolution	Year	Source and reference			
Climatology	1.0°	1998-2015	ERA-interim; ECMWF (2013)			
	1.0°	1998-2015	CRU TS3.24; CRU (2017)			
Elevation	1.0km	around 1996	GTOPO30; U.S. Geological Survey (1996a)			
		around 2018	SRTM; U.S. Geological Survey (2018)			
Land cover	1.0km	around 2000	GLC2000; European Commission (2015)			
Soil texture	1.0km	around 1970-2000	HWSD; European Commission (2012)			
Vegetation type	0.25°	around 2000	GLDAS Vegetation Class; NASA (2013)			
River networks	1.0km	around 1996	HYDRO1K; U.S. Geological Survey (1996b)			
Lakes and wetlands	0.5 min	around 1990-2000	GLWD; Lehner and Döll (2004)			
Reservoirs and Dams	point	around 2010	GRanD; Lehner et al. (2011)			
Geological structures	0.5°	around 1970-2000	GLiM; Hartmann and Moosdorf (2012)			
Crop type	5 min	around 2000	MIRCA2000; Portmann et al. (2010)			
Irrigation type	5 min	2000-2008	GMIA; FAO (2016)			
Irrigation water use	5 min	1998-2002	GCWM; Siebert and Döll (2010)			
Fertilizer use	5 min	around 2000	Earth Stat; Mueller et al. (2012)			
Manure use	5 min	1998-2014	Zhang et al. (2017)			
Atmospheric N deposition	0.5°	1998-2015	ISIMIP2a; Tian et al. (2018)			
Population	1.0km	2015	NASA (2018)			
Wastewater production and treatment	5 min	2015	Jones et al. (2021)			
Mismanaged plastic waste	1.0 km	2015	Lebreton and Andrady (2019)			

# Table 3.1 List of input data sets for the NICE and NICE-BGC simulations

# Table 3.2 Per capita emission of macroplastics and microplastics into rivers in previous materials

Plastic sources	World ave. (kg/cap./yr)	OECD Countries (kg/cap./yr)	Africa (kg/cap./yr)	Mid. East & North Africa (kg/cap./yr)	East Asia & Pacific incl. Japan (kg/cap./yr)	Eastern & Central Asia (kg/cap./yr)	Latin America (kg/cap./yr)	South Asia (kg/cap./yr)	Reference
Personal care products (PCPs)	0.0071								
Household dust (HD)	0.08								Siegfried et al.
Laundry inputs or fibres (LD)	0.12								(2017)
Tyre wear (TRWP)	0.18								
Personal care products (PCPs)	0.0071								
Household dust (HD)	0.08								Strokal et al
Laundry inputs or fibres (LD)	0.12								(2021)
Tyre wear (TRWP); HDI<0.785	0.018								(2021)
Tyre wear (TRWP); HDI>0.785	0.18								
Macroplastics (non-point sources)	17.3	8.8	27	16	23	15	23	8.5	
Personal care products (PCPs)	0.0028	0.0055	0.0007	0.0007	0.0049	0.0049	0.0025	0.0007	van Wijnen et al.
Laundry inputs or fibres (LD)	0.0451	0.11	0.007	0.047	0.041	0.047	0.028	0.036	(2019)
Tyre wear (TRWP)	0.0662	0.18	0.0072	0.068	0.018	0.077	0.041	0.072	
Personal care products (PCPs)	0.005								
Laundry inputs or fibres (LD)	0.015								
Tyres (car)	0.43								Boucher et al.
Tyres (truck)	0.43								(2020)
Tyres (plane)	0.01								
Plastic production (pellet loss)	0.005								

## 3.3.2 Boundary Conditions and Running the Simulation

After the NICE simulation of eco-hydrological processes at 1°x1° resolution in the horizontal direction and in 20 layers in the vertical direction, NICE-BGC simulation for terrestrial ecosystems was conducted at the same spatial resolution with a time step of  $\Delta t = 1$ day for the same period by inputting some of the results (soil temperature, surface runoff, and groundwater level) simulated by NICE iteratively after calculating the daily-averaged data from 1-hourly data. The authors used previous data for per capita emission of microplastics into rivers (PCPs, dusts, laundries, and tires) (Table 3.2) and the revised removal efficiency in WWTPs (as described in section 3.3.1) as a point source (Fig. 3.2). The model also simulated the outflow of macro-plastics originating from MPW (Lebreton and Andrady, 2019) as a diffuse source. Then, NICE-BGC simulation for aquatic ecosystems was conducted by inputting the simulated results for land to a stream network model with a time step of  $\Delta t = 0.70$  min to ensure model stability. The hydrologic and carbon cycles were simulated and verified using the previous datasets and materials as far as possible. Though the present study assumed no interaction with suspended matter (hetero-aggregation), resuspension, biofouling, and wind effects in the model, these processes are also important to improve the accuracy of the plastic cycle in the future. The simulated values were generally within the range of previous data for 27 different rivers, although the model simulated only the world's major rivers (325 rivers), as described by Nakayama (2017a). The continental values were estimated by compilation of the world's major river basins (153 basins), which occupy about 65.9% of the total continental area (Nakayama and Osako, 2023b). A basin-scale comparison for representative rivers between the model results and previous results in the GloRiCh database (Hartman et al., 2014) was also conducted. The results yielded quantitative measures of model performance in terms of reproducing the seasonality and inter-annual variability in carbon fluxes, as described by Nakayama (2020).

# 3.3.3 Analysis of the Influence of Various Factors on Plastic Transport

Because there is insufficient data on the characteristics of plastics on the continental and global scales, it is important to evaluate the uncertainty of plastic transport and its sensitivity to various factors (Nakayama and Osako, 2023b). The authors also assumed plastics to be pure and inert polymers with a continuous probability distribution, a power law probability distribution for plastic size (*L*: length of plastic particle), a universal bimodal shape probability distribution for *CSF* in equation (3.4), and a normal-inverse Gaussian shape probability distribution for density ( $\rho_s$ ) (Kooi and Koelmans, 2019):

$$\mathbf{P}_{size}(x) = \frac{1-\alpha}{UL^{1-\alpha} - LL^{1-\alpha}} x^{-\alpha}$$
(3.6)

$$\mathbf{P}_{shape}(x) = \frac{\lambda_1}{\sqrt{2\pi\sigma_1^2}} e^{-(x-\mu_1)^2/2\sigma_1^2} + \frac{\lambda_2}{\sqrt{2\pi\sigma_2^2}} e^{-(x-\mu_2)^2/2\sigma_2^2}$$
(3.7)

$$\mathbf{P}_{density}(x) = \frac{\theta \delta K_1[\theta \sqrt{\delta^2 + (x-\omega)^2}]}{\pi \sqrt{\delta^2 + (x-\omega)^2}} e^{\delta \sqrt{\theta^2 - \varphi^2} + \varphi(x-\omega)}$$
(3.8)

where *LL* and *UL* are the lower and upper limits of plastic size;  $\alpha$  is the exponent (= 1.5 ~ 2.5);  $\lambda_i$ ,  $\mu_i$ ,  $\sigma_i$  are the relative contribution, mean, and standard deviation of a two normal distribution ( $\lambda_1 = 0.059$ ,  $\lambda_2 = 0.941$ ,  $\mu_1 = 0.076$ ,  $\mu_2 = 0.441$ ,  $\sigma_1 = 0.030$ ,  $\sigma_2 = 0.189$ ); *K*<sub>1</sub> is a modified Bessel

function of the third kind with order 1;  $\omega$ ,  $\delta$ ,  $\theta$ ,  $\varphi$  are the location, scale, trail heaviness, and asymmetry of the distribution ( $\omega = 0.839$ ,  $\delta = 0.097$ ,  $\theta = 75.13$ ,  $\varphi = 71.30$ ), respectively.

For uncertainty and sensitivity analyses, the authors first calculated the cumulative probability distribution of size, shape, and density and their inverse functions. It was assumed that these probability distributions of size, shape, and density would also apply to macroplastics by extension from microplastics in the previous study (Kooi and Koelmans, 2019). Secondly, Monte Carlo model simulations (10 iterations) were conducted to generate a uniform random number between 0 and 1, and the size, shape, and density were determined under the fixed random number. Thirdly, the equivalent sphere diameter (equation (3.5)) and settling velocity (equation (3.3)) were calculated to determine plastic transport on the continental and global scales in each case. Finally, uncertainty and sensitivity analyses were conducted to evaluate the effect of various factors on plastic transport by ranking the model parameters according to their contribution to prediction uncertainty (Nakayama and Osako, 2023b).

#### **3.4 Results and Discussion**

#### 3.4.1 Evaluation of Plastic Flux from World's Major Rivers into Ocean

The authors compared the simulated annual plastic flux into the ocean with data for previous materials in global major rivers (Lebreton et al., 2017; Schmidt et al., 2017; Best, 2018; Mai et al., 2020; Meijer et al., 2021; Roebroek et al., 2021) (Fig. 3.3). Simulation for hillslope runoff was conducted in three cases for microplastics; case-A and case-B used the same value of per capita emission of microplastics for the whole world (Siegfried et al., 2017) and a different value of per capita emission for the whole world (Boucher et al., 2020). In contrast, case-C used different values for each region (van Wijnen et al., 2019) (Table 3.2). The simulation of hillslope runoff was also conducted for macroplastics with three different densities: case-a, case-b, and case-c (1001.0, 1000.001, and 1000.0001 kg/m<sup>3</sup>). The simulated macroplastics with values exceeding 1001.0 kg/m<sup>3</sup> were similar for case-a, and those with values of less than 1000.0001 kg/m<sup>3</sup> were similar for case-c because almost all were deposited in shallower hillslope runoff in the former and flowed into inland water in the latter. The simulated plastic flux generally agreed with the values estimated in previous studies. However, the former value underestimated the latter in the Yangtze River. It overestimated it in the Ganges River due to the high uncertainty of the estimated flux, particularly in South and Southeast Asia. In particular, the simulated microplastics in case-A and case-B were relatively similar to the results reported by Schmidt et al. (2017). Though the value in case-C was underestimated, the result was reasonable considering another previous study in which the MPW-based models generally overestimated the reported field measurements (Mai et al., 2020). Interestingly, the simulated total fluxes were within the range of the results reported by Roebroek et al. (2021), representing potential plastic mobilization between non-flood conditions and the undefended 10-year return period. This result suggests that it is important to consider the effect of inter-annual variability to improve the accuracy of plastic flux estimation.



Figure 3.3 Comparison between simulated annual plastic flux from the major global rivers into the ocean and the previous material: (a) macroplastic, (b) microplastic, and (c) total plastic fluxes

#### 3.4.2 Seasonal Variation of Plastic Flux on a Global Scale

The authors estimated the relationships between population density, plastic concentrations, and plastic fluxes per unit area in global major rivers (Fig. 3.4). This revealed a relatively linear relationship between population density and plastic fluxes in global basins (Figs 3.4c-d). While there was a positive relationship for macroplastic flux ( $R^2 = 0.33$  and PCC = 0.53) (Fig. 3.4c), the correlations were relatively high for microplastic flux ( $R^2 = 0.82$  and PCC = 0.91) (Fig. 3.4d). In contrast, there was no clear relationship between population density and concentration for macro and microplastics (Figs 3.4a-b). Because the concentration was often almost zero despite the significant population density, this suggests a certain threshold at which the concentration has a non-zero value. The result also implies that there is not necessarily a tendency for a positive relationship between concentration and water discharge in river basins (such as the Ganges, Mississippi, St. Lawrence, and the Yangtze); this may be because of a large shear stress causing resuspension during flood periods, or a relatively large urban area ratio. It will be further necessary to prove that the positive relationship results from plastic concentration from the riverbed and banks

as well as activation of additional inputs from stormwater drains and combined sewer overflows during flood periods (Wagner et al., 2019).

NICE-BGC also simulated seasonal variations of river discharge and plastic fluxes in each continent in the same way as that shown in Fig. 3.3 (Fig. 3.5). The simulated result showed that the seasonal variations of plastic fluxes depend largely on per capita emission and density. In particular, the simulated values for microplastics in case-A and case-B were larger than that in case-C (Fig. 3.5d), and the simulated value for macroplastics in case-b was intermediate between the other two (Fig. 3.5c). The author's previous study had shown that river discharge had a seasonal pattern, with a peak flow typically occurring during the spring snowmelt season and the summer/autumn high rainfall seasons and a low flow during winter (Nakayama, 2017b) (Fig. 3.5a). The simulation indicated that the total plastic flux ranged between 0.8 and 1.5 Tg/yr in major global rivers (Fig. 3.5b), in reasonably good agreement with previous studies (Jambeck et al., 2015; Lebreton et al., 2017; Schmidt et al., 2017; Meijer et al., 2021). The simulated result showed that changes in plastic fluxes (Figs 3.5b-d) are greatly affected by those of discharge in major global rivers. However, the simulated value showed a dominant contribution of the summer monsoon in Asia and differed from the magnitude of river discharge, where South America following Asia contributed the most. This characteristic is related to agricultural and urban land ratio on a continental scale and agrees reasonably with previous studies indicating that more than 74% of waste is delivered between May and October from limited large rivers in Asia (Lebreton et al., 2017; Best, 2018).



Figure 3.4 Relationships between population density and (a) macroplastic concentration, (b) microplastic concentration, (c) macro-plastic flux per unit area, and (d) microplastic flux per unit area in global major rivers simulated by NICE



Figure 3.5 Seasonal variations of (a) river discharge and plastic fluxes of (b) total, (c) macro, and (d) microplastics in each continent in the same cases as that in Fig. 3.3; 'AS', 'EU', 'OC', 'AF', 'NA', and 'SA' mean Asia, Europe, Oceania, Africa, North America, and South America

# 3.4.3 Uncertainty and Sensitivity Analyses of Riverine Plastic Transport on Continental and Global Scales

The authors simulated annual-averaged riverine plastic transport by conducting uncertainty and sensitivity analyses coupled with Monte Carlo model simulations to evaluate the influence of various factors on plastic transport (Fig. 3.6). For the simulation, we also assumed that lowerdensity plastics such as PE, PP, and PS, which make up the majority of plastics in most rivers (Siegfried et al., 2017; van Wijnen et al., 2019; Strokal et al., 2021), are also affected by biofouling and show a 4% increase in their densities, regarding previous studies (Kaiser et al., 2017; Kooi et al., 2017). The simulated result showed that some rivers, such as the Ganges, Yangtze, Yellow, Nile, and Indus, dominate plastic transport on both the continental and global scales. It was also interesting that the flux of microplastic (Fig. 3.6b) showed greater uncertainty than macroplastic (Fig. 3.6a) in rivers, making larger contributions, mainly because of the wider range of microplastic particle size. Meijer et al. (2021) did not include the effect of microplastic transport in their model (Fig. 3.6c). Although there was some scattering of plastic fluxes in each iteration, the averaged values for both macro and microplastics from all iterations were within the previous data range (Schmidt et al., 2017; Meijer et al., 2021). Most plastic fluxes flowed out of approximately 20 global rivers, in general agreement with the plastic outflow from a limited river pointed out by previous studies (Lebreton et al., 2017; Schmidt et al., 2017; Meijer et al., 2021). This result also indicates that the application of the microplastic probability distribution in equations (3.6)-(3.8) (Kooi and Koelmans, 2019) to macroplastic is not a bad assumption for major global rivers.



Figure 3.6 Uncertainty and sensitivity analyses using the Monte Carlo model simulations to evaluate the influence of various factors on annual-averaged riverine plastic transport in global major rivers: (a) macroplastic, (b) microplastic, and (c) total plastic fluxes.

# **3.5 Conclusion**

This chapter describes the extension of NICE to incorporate a plastic debris (engineered materials) model for freshwater systems and applied to the world's major rivers (325 rivers).

Unlike previous research, the new model included a comprehensive process of plastic dynamics to simulate the fate and transport of plastics on a global scale. NICE-BGC simulated how among 81.8 Tg/yr of global mismanaged plastic waste (MPW) across the globe – approximately 39.2 Tg/yr and point sources such as tires, PCPs, dust, and laundry in these 325 rivers are transported from land to rivers, and finally to the ocean. Using untreated wastewater, simulation with a two-dimensional diffusion model for macroplastic transport, and the connection between hillslope and stream network models helped decrease the model's uncertainty beyond previous studies. A relatively linear relationship between population density and plastic fluxes in the global basins was demonstrated. The model also revealed a seasonal variation of plastic flux in Asia and its large contribution that was affected by the summer monsoon; this differed in magnitude from river discharge and was related to the ratio of agricultural to urban land on a continental scale. Uncertainty and sensitivity analyses using Monte Carlo model simulations assuming a continuous probability distribution of size, shape, and density also clarified the effects of various factors on plastic transport. Most of the plastic fluxes were shown to flow out of about 20 global rivers, reflecting that flood events greatly impact plastic mobilization and high inter-annual variability. The new model developed in this study might contribute significantly to detecting these spatiotemporal hotspots of plastic fluxes and to develop better solutions and efficient measures to reduce plastic load on a global scale as much as possible.

#### References

- Best, J. (2018) Anthropogenic stresses on the world's big rivers. Nature Geoscience, 12, 7–21, doi:10.1038/s41561-018-0262-x
- Boucher, J., Billard, G., Simeone, E., Sousa, J. (2020) The marine plastic footprint. Global Marine and Polar Programme. IUCN. Switzerland. 69 pp., doi:10.2305/IUCN.CH.2020.01.en
- Climatic Research Unit (CRU). (2017) CRU TS3.24 of High Resolution Gridded Data of Month-by-month Variation in Climate. http://catalogue.ceda.ac.uk/
- Cowger, W., Gray, A.B., Guilinger, J.J., et al. (2021) Concentration depth profiles of microplastic particles in river flow and implications for surface sampling. Environmental Science & Technology, 55, 6032-6041, Doi:10.1021/acs.est.1c01768
- Dottori, F., Salamon, P., Bianchi, A., Alfieri, L., Hirpa, F.A., Feyen, L. (2016) Development and evaluation of a framework for global flood hazard mapping. Advances in Water Resources, 94, 87-102, doi:10.1016/j.advwatres.2016.05.002
- Drummond, J.D., Nel, H.A., Packman, A.I., Krause, S. (2020) Significance of Hyporheic Exchange for Predicting Microplastic Fate in Rivers. Environmental Science & Technology Letters, 7, 10, 727-732, doi:10.1021/acs.estlett.0c00595
- ESRI. (2019) Overlay Layers. Portal for ArcGIS. https://gislab.depaul.edu/portal/portalhelp/en/portal/latest/use/geoanalytics-overlay-layers.htm
- European Centre for Medium-Range Weather Forecasts (ECMWF). (2013) ERA-Interim. http://data-portal.ecmwf.int/data/d/interim daily/
- European Commission. (2012) Harmonized World Soil Database. http://eusoils.jrc.ec.europa.eu/ESDB\_Archive/soil\_data/global.htm
- European Commission. (2015) Global Land Cover 2000. https://forobs.jrc.ec.europa.eu/products/glc2000/glc2000.php
- Food and Agriculture Organization of the United Nations (FAO). (2016) Global Map of Irrigation Areas (GMIA). http://www.fao.org/nr/water/aquastat/irrigationmap/index.stm
- Hartmann, J., Moosdorf, N. (2012) The new global lithological map database GLiM: A representation of rock properties at the Earth surface. Geochemistry, Geophysics, Geosystems, 13, Q12004, doi:10.1029/2012GC004370
- Hartman, J, Lauerwald, R, Moosdorf, N. (2014) A Brief Overview of the GLObal RIver Chemistry Database, GLORICH. Procedia Earth and Planetary Science, 10, 23-27, doi:10.1016/j.proeps.2014.08.005

- Hurley, E., Woodward, J., Rothwell, J.J. (2018) Microplastic contamination of river beds significantly reduced by catchment-wide flooding. Nature Geoscience, 11, 251-257, doi:10.1038/s41561-018-0080-1
- Jambeck, J.R., Geyer, R., Wilcox, C., et al. (2015) Plastic waste inputs from land into the ocean. Science, 347, 768-771, doi:10.1126/science.1260352
- Jones, E.R., van Vliet, M.T.H., Qadir, M., Bierkens, M.F.P. (2021) Country-level and gridded estimates of wastewater production, collection, treatment and reuse. Earth System Science Data, 13, 237-254, doi:10.5194/essd-13-237-2021
- Kaiser, D., Kowalski, N., Waniek, J.J. (2017) Effects of biofouling on the sinking behavior of microplastics. Environmental Research Letters, 12, 124003, Doi:10.1088/1748-9326/aa8e8b
- Kataoka, T., Nihei, Y., Kudou, K., Hinata, H. (2019) Assessment of the sources and inflow processes of microplastics in the river environments of Japan. Environmental Pollution, 244, 958–965, doi:10.1016/j.envpol.2018.10.111
- Kooi, M., van Nes, E.H., Scheffer, M., Koelmans, A.A. (2017) Ups and downs in the ocean: Effects of biofouling on vertical transport of microplastics. Environmental Science & Technology, 51, 7963-7971, doi:10.1021/acs.est.6b04702
- Kooi, M., Besseling, E., Kroeze, C., et al. (2018) Modelling the fate and transport of plastic decries in freshwaters: review and guidance. In: Wagner, M., Lambert, S. [Eds] Freshwater Microplastics. The Handbook of Environmental Chemistry 58, Springer, pp.125-152
- Kooi, M., Koelmans, A.A. (2019) Simplifying microplastic via continuous probability distributions for size, shape, and density. Environmental Science & Technology Letters, 6, 551-557, doi:10.1021/acs.est.9b00379
- Koutnik, V.S., Leonard, J., Alkidim, S., et al. (2021) Distribution of microplastics in soil and freshwater environments: global analysis and framework for transport modelling. Environmental Pollution, 224, 116552, doi:10.1016/j.envpol.2021.116552
- Kumar, R., Sharma, P., Verma, A., et al. (2021) Effect of physical characteristics and hydrodynamic conditions on transport and deposition of microplastics in riverine ecosystem. Water, 13, 2710, doi:10.3390/w13192710
- Lazar, A.N., Butterfield, D., Futter, M.N., et al. (2010) An assessment of the fine sediment dynamics in an upland river system: INCA-Sed modifications and implications for fisheries. Science of the Total Environment, 408, 2555-2566, doi:10.1016/j.scitotenv.2010.02.030
- Lebreton, L., Andrady, A. (2019) Future scenarios of global plastic waste generation and disposal. Palgrave Communications, 5, 6, doi:10.1057/s41599-018-0212-7
- Lebreton, L, van der Zwet, J., Damsteeg, J.-W., et al. (2017) River plastic emissions to the world's oceans. Nature Communications, 8, 15611, doi:10.1038/ncomms15611
- Lehner, B., Döll, P. (2004) Development and validation of a global database of lakes, reservoirs and wetlands. Journal of Hydrology, 296, 1-22, doi:10.1016/j.jhydrol.2004.03.028
- Lehner, B., Reidy Liermann, C., Revenga, C., et al. (2011) High-resolution mapping of the world's reservoirs and dams for sustainable river-flow management. Frontiers in Ecology and the Environment, 9, 494-502, doi:10.1890/100125
- Liu, Y., You, J., Li, Y., et al. (2021) Insights into the horizontal and vertical profiles of microplastics in a river emptying into the sea affected by intensive anthropogenic activities in Northern China. Science of the Total Environment, 779, 146589, doi:10.1016/j.scitotenv.2021.146589
- Mai, L., Sun, X.-F., Xia, L.-L., Bao, L.-J., Liu, L.-Y., Zeng, E.Y. (2020) Global riverine plastic outflows. Environmental Science & Technology, 54, 10049-10056, doi:10.1021/acs.est.0c02273
- Meijer, L.J.J., van Emmerik, T., van der Ent, R., et al. (2021) More than 1000 rivers account for 80% of global riverine plastic emissions into the ocean. Science Advances, 7, eaaz5803, doi:10.1126/sciadv.aaz5803
- Mellink, Y., van Emmerik, T., Kooi, M., Laufkötter, C., Niemann, H. (2022) The Plastic Pathfinder: A macroplastic transport and fate model for terrestrial environments. Frontiers in Environmental Science, 10, 979685, doi:10.3389/fenvs.2022.979685
- Ministry of Foreign Affairs of Japan. (2019) G20 Osaka Leader's Declaration. https://www.mofa.go.jp/policy/economy/g20\_summit/osaka19/en/documents/final\_g20\_osaka\_leaders\_decl aration.html
- Mueller, N.D., Gerber, J.S., Johnston, M., et al. (2012) Closing yield gaps through nutrient and water management. Nature, 490, 254-257, doi:10.1038/nature11420
- Nakayama, T., Watanabe, M. (2004) Simulation of drying phenomena associated with vegetation change caused by invasion of alder (Alnus japonica) in Kushiro Mire. Water Resources Research, 40(8), W08402, Doi:10.1029/2004WR003174
- Nakayama, T. (2013) For improvement in understanding eco-hydrological processes in mire. Ecohydrology & Hydrobiology, 13, 62-72, doi:10.1016/j.ecohyd.2013.03.004

- Nakayama, T. (2016) New perspective for eco-hydrology model to constrain missing role of inland waters on boundless biogeochemical cycle in terrestrial-aquatic continuum. Ecohydrology and Hydrobiology, 16, 138-148, Doi:10.1016/j.ecohyd.2016.07.002
- Nakayama, T. (2017a) Development of an advanced eco-hydrologic and biogeochemical coupling model aimed at clarifying the missing role of inland water in the global biogeochemical cycle. Journal of Geophysical Research: Biogeosciences, 122, 966-988, doi:10.1002/2016JG003743
- Nakayama, T. (2017b) Scaled-dependence and seasonal variations of carbon cycle through development of an advanced eco-hydrologic and biogeochemical coupling model. Ecological Modelling, 356, 151-161, Doi:10.1016/j.ecolmodel.2017.04.014
- Nakayama, T., Pelletier, G. (2018) Impact of global major reservoirs on carbon cycle changes by using an advanced eco-hydrologic and biogeochemical coupling model. Ecological Modelling, 387, 172-186, doi:10.1016/j.ecolmodel.2018.09.007
- Nakayama, T. (2020) Inter-annual simulation of global carbon cycle variations in a terrestrial-aquatic continuum. Hydrological Processes, 34(3), 662-678, doi:10.1002/hyp.13616
- Nakayama, T. (2022) Impact of anthropogenic disturbances on carbon cycle changes in terrestrial-aquaticestuarine continuum by using an advanced process-based model. Hydrological Processes, 36(2), e14471, doi:10.1002/hyp.14471
- Nakayama, T., Osako, M. (2023a) Development of a process-based eco-hydrology model for evaluating the spatiotemporal dynamics of macro- and micro-plastics for the whole of Japan. Ecological Modelling, 476, 110243, doi:10.1016/j.ecolmodel.2022.110243
- Nakayama, T., Osako, M. (2023b) The flux and fate of plastic in the world's major rivers: Modeling spatial and temporal variability. Global and Planetary Change, 221, 104037, doi:10.1016/j.gloplacha.2023.104037
- NASA. (2018) Gridded Population of the World, Version 4 (GPWv4). https://sedac.ciesin.columbia.edu/data/set/gpw-v4-population-count-adjusted-to-2015-unwpp-countrytotals-rev11
- Nizzetto, L., Bussi, G., Futter, M.N., et al. (2016) A theoretical assessment of microplastic transport in river catchments and their retention by soils and river sediments. Environmental Science: Processes & Impacts, 18, 1050-1059, doi:10.1039/c6em00206d
- OECD. (2022) Global Plastics Outlook: Economic Drivers, Environmental Impacts and Policy Options, OECD Publishing, Paris. https://doi.org/10.1787/de747aef-en
- Pelletier, G.J., Chapra, S.C., Tao, H. (2006) QUAL2Kw A framework for modeling water quality in streams and rivers using a genetic algorithm for calibration. Environmental Modelling and Software, 21, 419-425, doi:10.1016/j.envsoft.2005.07.002
- Peng, Y., Wu, P., Schartup, A.T., Zhang, Y. (2021) Plastic waste release caused by COVID-19 and its fate in the global ocean. Proceedings of the National Academy of Sciences of the United States of America, 118(47), e2111530118, doi:10.1073/pnas.2111530118
- Portmann, F.T., Siebert, S., Döll, P. (2010) MIRCA2000 Global monthly irrigated and rainfed crop areas around the year 2000: A new high-resolution data set for agricultural and hydrological modelling. Global Biogeochemical Cycles, 24, GB 1011, doi:10.1029/2008GB003435
- Praetorius, A., Scheringer, M., Hungerbühler, K. (2012) Development of environmental fate models for engineered nanoparticles - A case study of TiO2 nanoparticles in the Rhine River. Environmental Science & Technology, 46, 6705-6713, doi:10.1021/es204530n
- Roebroek, C.T.J., Harrigan, S., van Emmerik, T.H.M., et al. (2021) Plastic in global rivers: are floods making it worse? Environmental Research Letters, 16, 025003, doi:10.1088/1748-9326/abd5df
- Rubey, W. (1933) Settling velocities of gravel, sand and silt particles. American Journal of Science, 5, 325–338, doi:10.2475/ajs.s5-25.148.325
- Schmidt, C., Krauth, T., Wagner, S. (2017) Export of plastic debris by rivers into the sea. Environmental Science & Technology, 51, 12246-12253, doi:10.1021/acs.est.7b02368
- Schwarz, A.E., Ligthart, T.N., Boukris, E., van Harmelen, T. (2019) Sources, transport, and accumulation of different types of plastic litter in aquatic environments: A review study. Marine Pollution Bulletin, 143, 92-100, doi:10.1016/j.marpolbul.2019.04.029
- Seeley, M., Song, B., Passie, R., Hale, R.C. (2020) Microplastics affect sedimentary microbial communities and nitrogen cycling. Nature Communications, 11, 2372, doi:10.1038/s41467-020-16235-3
- Siebert, S., Döll, P. (2010) Quantifying blue and green virtual water contents in global crop production as well as potential production losses without irrigation. Journal of Hydrology, 384, 198–217
- Siegfried, M., Koelmans, A.A., Besseling, E., Kroeze, C. (2017) Export of microplastics from land to sea. A modelling approach. Water Research, 127, 249-257, doi:10.1016/j.watres.2017.10.011

- Strokal, M., Bai, Z., Franssen, W., et al. (2021) Urbanization: an increasing source of multiple pollutants to rivers in the 21st century. Urban Sustainability, 1, 24, doi:10.1038/s42949-021-00026-w
- Thompson, R.C., Olsen, Y., Mitchell, R.P., et al. (2004) Lost at sea: Where is all the Plastic? Science, 304, 838, doi:10.1126/science.1094559
- Tian, H., Yang, J., Lu, C., et al. (2018) The global N2O model intercomparison project. Bulletin of the American Meteorological Society, 99(6), 1231-1251, doi:10.1175/bams-d-17-0212.1
- U.S. Geological Survey (USGS). (1996a) GTOPO30 Global 30 Arc Second Elevation Data Set. USGS. http://www1.gsi.go.jp/geowww/globalmap-gsi/gtopo30/gtopo30.html
- U.S. Geological Survey (USGS). (1996b) HYDRO1K. USGS. https://lta.cr.usgs.gov/HYDRO1K
- U.S. Geological Survey (USGS). (2018) Shuttle Radar Topography Mission (SRTM) 1 Arc-Second Global. USGS. doi:10.5066/F7PR7TFT
- van Emmerik, T., Strady, E., Kieu-Le, T.-C., Nguyen, L., Gratiot, N. (2019) Seasonality of riverine macroplastic transport. Scientific Reports, 9, 13549, doi:10.1038/s41598-019-50096-1
- van Wijnen, J., Ragas, A.M.J., Kroeze, C. (2019) Modelling global river export of microplastics to the marine environment: Sources and future trends. Science of the Total Environment, 673, 392-401, doi:10.1016/j.scitotenv.2019.04.078
- Wagner, S., Klöckner, P., Stier, B., Römer, M., Seiwert, B., Reemtsma, T., Schmidt, C. (2019) Relationship between discharge and river plastic concentrations in a rural and an urban catchment. Environmental Science & Technology, 53, 10082-10091, doi:10.1021/acs.est.9b03048
- Waldschläger, K., Schüttrumpf, H. (2019) Erosion behavior of different microplastic particles in comparison to natural sediments. Environmental Science & Technology, 53, 13219-13227, doi:10.1021/acs.est.9b05394
- Waldschläger, K., Born, M., Cowger, W., Gray, A., Schüttrumpf, H. (2020) Settling and rising velocities of environmentally weathered micro- and macroplastic particles. Environmental Research, 191, 110192, doi:10.1016/j.envres.2020.110192
- Whitehead, P.G., Bussi, G., Hughes, J.M.R., et al. (2021) Modelling microplastics in the River Thames: sources, sinks and policy implications. Water, 13, 861, doi:10.3390/w13060861
- Zhang, B., Tian, H., Lu, C., et al. (2017) Global manure nitrogen production and application in cropland during 1860-2014; a 5 arcmin gridded global dataset for Earth system modelling. Earth System Science Data, 9, 667-678, doi:10.5194/essd-9-667-2017
- Zhang, K., Hamidian, A.H., Tubic, A., et al. (2021) Understanding plastic degradation and microplastic formation in the environment: A review. Environmental Pollution, 274, 116554, doi:10.1016/j.envpol.2021.116554

This article was published in Global and Planetary Change, 221, Nakayama, T., Osako, M., The flux and fate of plastic in the world's major rivers: Modeling spatial and temporal variability, 104037, Copyright Elsevier (2023b).

# Chapter 4

Impact of Global Major Reservoirs and Lakes on Plastic Dynamics by Using a Process-Based Eco-Hydrology Model Chapter 4 Impact of Global Major Reservoirs and Lakes on Plastic Dynamics by Using a Process-Based Eco-Hydrology Model
## Abstract

Environmental contamination by plastics has received considerable attention from scientists, policymakers, and the public. In this study, the process-based model NICE-BGC was extended to couple with LAKE2K in a stratified water quality model to evaluate the global plastic dynamics in both lotic and lentic waters. The new model could simulate riverine plastic transport in inland waters with and without the presence of major global reservoirs and lakes. The result showed the simulated plastic transport with the presence of reservoirs becomes slightly smaller than that without the presence of reservoirs. In particular, the plastic burial simulated by the model became different with and without the lake model when the density of plastic was higher than that of water. This result showed there are limits to applying the same partial differential equations as inorganic carbon for the derivatives either with or without the reservoirs, as assumed by the author's previous study, especially when the plastic density is higher than that of water. The model also simulated plastic sedimentation in the global lakes and reservoirs together and showed that there were more plastic deposits in the reservoirs than the lakes except for the Caspian Sea, and most lentic waters are found to deposit more microplastics than macro-plastics as pointed out by the previous study. Finally, the author quantified the weighted average of plastic budget in the major global rivers with the effect of anthropogenic factors such as the construction of artificial dams and global lakes in lentic water. The simulated result also showed that incorporating the lake model in NICE-BGC led to improved estimates of plastic dynamics in inland waters and may aid the development of solutions and measures to reduce plastic input to the ocean.

# Keywords: Eco-hydrology model; lake model; lotic and lentic waters; regulated rivers; riverine plastic transport

## 4.1 Introduction

Plastic pollution is considered one of today's main environmental problems, and such pollutants in streams, rivers, and oceans pose potential risks to human health and the environment (Siegfried et al., 2017). Once plastic is released into the environment, it is gradually degraded by physical, chemical, and biological processes, leading to further subdivision into an enormous number of forms, all of which are impossible to remove and remain indefinitely in the environment. Previous studies on the origin and fate of plastic waste in freshwater systems have suggested that land-derived plastics are one of the main sources of marine plastic pollution (Thompson et al., 2004). Some studies (Jambeck et al., 2015; Lebreton et al., 2017; Schmidt et al., 2017) estimated the distribution of global riverine emissions of plastic into the ocean using empirical indicators representative of waste generation (mismanaged plastic waste: MPW) inside a river basin. Using a probabilistic approach, Meijer et al. (2021) proposed a more accurate form of analysis to account for the spatial distribution of plastic waste generation (Lebreton and Andrady, 2019) and climatological/geographical differences within river basins. Other studies (Siegfried et al., 2017; van Wijnen et al., 2019; Strokal et al., 2021) adapted a process-oriented model to continental and global scales by extending an existing non-dynamic nutrient export model. There is no doubt that these studies are valuable for quantifying the plastic dynamics, though they didn't explicitly address the effects of reservoirs and lakes in lentic waters.

In contrast, regulated rivers have increased year by year, and other previous studies have evaluated the effect of damming on microplastic transport in rivers (Watkins et al., 2019; Leiser et al., 2020; Dhivert et al., 2022; Wu et al., 2022; Shen et al., 2023). Within global freshwater, hydraulic structures such as dams and weirs intercept 65% of plastic waste before it reaches the ocean (Lebreton et al., 2017). It is important that the dams intercepted a large amount of microplastics in sediment but did not trap floating microplastics in water (Shen et al., 2023); this is also related to the fact that microplastics settled out of the water column and into the sediment in the slower moving waters of the impoundment where sediment microplastic concentrations were an order of magnitude higher than those in water samples (Watkins et al., 2019) and where there is a reservoir-dominated transition from riverine zone to lacustrine-like zone towards the downstream by hydro-sedimentary processes (Dhivert et al., 2022). On a basin scale, the previous study also showed that local gross domestic product (GDP) and basin area were the key factors controlling microplastic distribution and that population density might not be the decisive factor (Wu et al., 2022). Further, another study evaluated that sinking velocities of microplastics are related to biofouling, metal sorption, and aggregation in the reservoirs (Leiser et al., 2020). It is necessary to incorporate these effects in modeling plastic dynamics in lotic and lentic waters. Quantitative assessment of the fate and transport of plastics in these waters is also important for achieving the Sustainable Development Goals (SDG) (UNESCO, 2022) because countries worldwide have decided on concrete future measures for dealing with plastic based on scientific results.

The author has developed a process-based model coupling eco-hydrology with the biogeochemical cycle (National Integrated Catchment-based Eco-hydrology (NICE)-BGC) (Nakayama, 2017a, 2017b), incorporating complex terrestrial-aquatic linkages in the hydrologic-biogeochemical cycle. Recently, the author extended to couple this process-based NICE-BGC with a plastic debris (engineered materials) model and evaluated spatiotemporal variations of plastic debris in the entire Japan of regional scale (Nakayama and Osako, 2023a) and the world's major rivers of global scale (Nakayama and Osako, 2023b) without the effect of major reservoirs and great lakes. Based on this background, there are two basic science

questions: (i) How many plastics are trapped in major global reservoirs and lakes? (ii) How do these global lentic waters influence macro and microplastic dynamics in inland waters? To clarify these issues, in this chapter, the author extended NICE-BGC with a plastic debris model from inland water to regulated rivers and lakes and included changes in the plastic dynamic of the biosphere (terrestrial and aquatic ecosystems) resulting from anthropogenic activities such as construction of artificial dams (Nakayama, under review) (Fig. 4.1). The present study is also an important step not only for qualification of processes, but identification of hierarchy of drivers in various river catchments affected by anthropogenic activities.



Figure 4.1 Study area of the world's major rivers (153 basins, 325 river channels) with 82 major reservoirs (red circle) and 19 lakes (blue mesh) included in these basins to simulate the plastic dynamic; Green circle line (25 reservoirs of the total 82) and purple circle line (19 lakes) means the application of NICE-BGC and LAKE2K coupled model in this study

## 4.2 Methods

## 4.2.1 General Model Framework of NICE-BGC

The author has so far developed an advanced process-based model derived by coupling a process-based National Integrated Catchment-based Eco-hydrology (NICE) model with various biogeochemical cycle models (NICE-BGC) (Nakayama, 2017a, 2017b, 2022). This model incorporates the connectivity of the biogeochemical cycle accompanied by the hydrologic cycle between surface water and groundwater, hillslopes and river networks, and other intermediate regions. Recently, the author extended to couple this process-based NICE-BGC with a plastic debris (engineered materials) model and evaluated spatiotemporal variations of plastic debris in the entire Japan of regional scale (Nakayama and Osako, 2023b) (Fig. 4.1). The new model also included advection, dispersion, diffusion, settling, dissolution and deterioration due to light and

temperature, but assumed no interaction with suspended matter (hetero-aggregation) (Praetorius et al., 2012), resuspension (Waldschläger and Schüttrumpf, 2019), biofouling (Kooi et al., 2017, 2018), or wind effects.

In the above previous study, the author incorporated resuspension and settling by extending the author's previous studies (Nakayama and Osako, 2023a, 2023b, 2024). The original model assumed the resuspension rate when a riverbed is under equilibrium conditions, and the particle size distribution is uniform; it was difficult to apply this formula directly to plastic. It is difficult to grasp the heterogeneous distribution of settled and deposited plastic on hillslopes, although some studies have evaluated the erosion behavior of microplastic particles compared to sediments (Waldschläger and Schüttrumpf, 2019). The new model included the plastic budget in the water and the bed sediment of any given reach in the same way as the previous studies (Nizzetto et al., 2016; Koutnik et al., 2021). Thus, the model could simulate the concentration of plastics in the water and the bed sediment and evaluate the hydrograph for plastics transport with various shear stresses during storm events, as proposed by Kumar et al. (2021). For model simplification, it was also assumed that microplastics are pure and inert polymers with a continuous probability distribution of size, shape, and density (Kooi and Koelmans, 2019). After the simulation of plastic transport on a hillslope, the author used the estimated rate of conversion of macroplastics to microplastics (3%/yr) in the same way as van Wijnen et al. (2019), with the extension of the conversion rate employed by Jambeck et al. (2015) (Fig. 4.2).



Figure 4.2 Flow diagram of macro and microplastics transport in land and inland water by extending NICE-BGC coupled with LAKE2K to lotic and lentic waters

## 4.2.2 Extension of Plastic Debris Model including Global Reservoirs and Lakes

The author's previous study (Nakayama and Pelletier, 2018) applied the deficit ratio depending on the water level difference above and below the dam to calculate the inorganic carbon mass balance. About the rationale for the influence of reservoirs on organic carbon (DOC, POC), nutrients, etc., it is difficult to generalize whether reservoirs would either increase or decrease POC or DOC because each reservoir would be different in the balance of factors that would change the DOC and POC concentrations. So, this previous study assumed the same partial differential equations for the derivatives either with or without the reservoirs except for the extra reaeration effect of the dams after solving DIC concentration (as mass balance). To solve this problem and to evaluate the effect of lotic and lentic waters on carbon cycle changes, the author recently coupled NICE-BGC with LAKE2K in stratified water quality model (Chapra and Martin, 2012) in his study (Nakayama, 2023). LAKE2K simulates the lake as a one-dimensional system consisting of three vertical layers (epilimnion, metalimnion, and hypolimnion). So, this coupled model enables the simulation of the hydrologic and biogeochemical cycles in global reservoirs and lakes of lentic water. It is possible to simulate implicitly the effect of reservoirs and lakes on organic carbon (DOC, POC) and nutrient fluxes without assuming the deficit ratio (Nakayama and Pelletier, 2018). In the present study, the author further extended this coupled model to simulate the plastic dynamic in both lotic and lentic waters (Nakayama, under review), extending the author's previous studies (Nakayama and Osako, 2023a, 2023b, 2024). This model was applied to the world's major rivers (153 basins, 325 river channels), with 25 global reservoirs and 19 lakes included in these basins (Fig. 4.1).

## 4.3 Input Data and Boundary Conditions for Simulation

## 4.3.1 Model Input Data

The input data at hybrid spatial resolutions were prepared and arranged to calculate spatially averaged 1°x1° grid in global scale using the Spatial Analyst Tools in ArcGIS v10.3 software for the simulation (Fig. 4.1 and Table 4.1); elevation, land cover, soil texture, vegetation type, river networks, lakes and wetlands, reservoirs and dams, geological structures, crop type, irrigation type, irrigation water use, fertilizer use, and manure use were categorized based on the global and Japanese datasets. Although data for plastics are scarce, the author used some data to simulate the plastic debris in the major global rivers, gridded population data at 1 km resolution from global data in 2015 (NASA, 2018), wastewater production, collection, treatment and reuse data at 5 arcmin (about 10 km) resolution (Jones et al., 2021), and MPW at 1 km resolution (Lebreton and Andrady, 2019) as a diffuse source (Table 4.1). To create the grid data from point, polyline, and polygon data for different sources with different spatial resolutions in a reasonable way, overlay analysis was conducted using GIS tools (intersect, union, and identity) (ESRI, 2019). MPW was input to the model as a diffuse source of plastics in the two-dimensional hillslope runoff model of NICE-BGC (Fig. 4.2). In particular, the author used the estimated rate of conversion of macro-plastics to microplastics (3%) in the same way as van Wijnen et al. (2019).

The author also used the per capita emission of microplastics in each economic region determined in a previous study (van Wijnen et al., 2019). Generally, microplastics at point sources originate from four sources: personal care products (PCPs), laundry fibers, car tire wear,

and fragmentation of macroplastics. We estimated the potential fluxes of microplastics by multiplying these per capita emissions and their population distribution for each catchment flow into WWTPs (Waste Water Treatment Plants) in the NICE-BGC simulation (Fig. 4.2). We also applied "untreated wastewater" and converted to removal efficiency of microplastic, the former of which was calculated by subtracting the ratio of wastewater treatment and wastewater production at 5 arcmin resolution (Jones et al., 2021). The result shows that the removal efficiency of microplastic in the developed countries was much higher than in the other developing countries. It was also assumed that microplastic concentration on hillslopes was constant (Wagner et al., 2019), and the time series proportional to hillslope runoff was and Osako, 2023a, 2023b).

Data set	Original resolution	Year	Source and reference			
Climatology	1.0°	2014-2015	ERA-interim; ECMWF (2019)			
Elevation	1.0km	around 1996	GTOPO30; U.S. Geological Survey (1996a)			
Land cover	1.0km	around 2000	GLC2000; European Commission (2015)			
Soil texture	1.0km	around 1970-2000	HWSD; European Commission (2012)			
Vegetation type	0.25°	around 2000	GLDAS Vegetation Class; NASA (2013)			
River networks	1.0km	around 1996	HYDRO1K; U.S. Geological Survey (1996b)			
Lakes and wetlands	0.5 min	around 1990-2000	GLWD; Lehner and Döll (2004)			
Reservoirs and Dams	point	around 2010	GRanD; Lehner et al. (2011)			
Geological structures	0.5°	around 1970-2000	GLiM; Hartmann and Moosdorf (2012)			
Crop type	5 min	around 2000	MIRCA2000; Portmann et al. (2010)			
Irrigation type	5 min	2000-2008	GMIA; FAO (2016)			
Irrigation water use	rrigation water use 5 min 1998-2002		GCWM; Siebert and Döll (2010)			
Fertilizer use	5 min	around 2000	Earth Stat; Mueller et al. (2012)			
Manure use	5 min	1998-2014	Zhang et al. (2017)			
Atmospheric N deposition	0.5°	1998-2015	ISIMIP2a; Tian et al. (2018)			
Estuary	polygon	around 2000	Global Estuary Database; Alder (2003)			
Estuary type	0.5°	around 2000	Global Coastal Typology; Dürr et al. (2011)			
Coastal line	0.5°	around 2000	MARCATS; Laruelle et al. (2013)			
Water level	point	1992-2021	G-REALM; USDA (2022)			
Population	1.0km	2015	NASA (2018)			
Wastewater production and treatment	5 min	2015	Jones et al. (2021)			
Mismanaged plastic waste	1.0 km	2015	Lebreton and Andrady (2019)			

Table 4.1 List of ir	put data sets for f	the NICE and NICE	<b>2-BGC simulations</b>
----------------------	---------------------	-------------------	--------------------------

## 4.3.2 Boundary Conditions and Running the Simulation

After the NICE simulation of eco-hydrological processes at  $1^{\circ}x1^{\circ}$  resolution in the horizontal direction and in 20 layers in the vertical direction, NICE-BGC simulation for terrestrial ecosystems was conducted at the same spatial resolution with a time step of  $\Delta t = 1$  day for two years during 2014–2015 by inputting some values simulated by NICE iteratively after calculating the daily-averaged data from 1-hourly data (Fig. 4.2). The author used previous data for per capita emission of microplastics into rivers (PCPs, dusts, laundries, and tires) and removal efficiency in WWTPs as a point source. The model also simulated the outflow of macroplastics originating from MPW (Lebreton and Andrady, 2019) as a diffuse source. Then, NICE-BGC simulation for aquatic ecosystems was conducted by inputting the simulated results for land to a stream network model with a time step of  $\Delta t = 0.70$  min and to a lake model with

a time step of  $\Delta t = 6$  hours to ensure model stability. The hydrologic cycle and plastic transport in the world's major river basins (153 basins) were simulated and verified using the previous datasets and materials as far as possible in the continental scale in the author's previous study (Nakayama and Osako, 2023b).

For the simulation of plastic flux, the author calculated the weighted average value by multiplying each probability with each flux and their summation; this assumes that both micro and macroplastics are pure and inert polymers with a continuous probability distribution of size, shape, and density (Kooi and Koelmans, 2019) in the same way as the author's previous study (Nakayama and Osako, 2023b). Uncertainty and sensitivity analyses were conducted by using Monte Carlo model simulations to rank the model parameters according to their contribution to prediction uncertainty. The results yielded quantitative measures of model performance in reproducing the seasonality and intra-annual variability in the hydrologic cycle and plastic transport there.

## 4.4 Results and Discussion

## 4.4.1 Effect of Reservoirs on Differences in Horizontal Plastic Transport

The author simulated riverine plastic transport in inland waters with and without reservoirs (Fig. 4.3). The simulated results are shown with and without the effect of settling and resuspension. It can be seen that the simulated plastic transport with the presence of reservoirs becomes slightly smaller than that without the presence of reservoirs on floating condition, i.e., settling velocity = 0 (Figs 4.3a and 4.3d), with almost the same as the density of water (density = 1000.1 kg/m<sup>3</sup>) (Figs 4.3b and 4.3e), and on averaged plastic condition of all iterations of Monte Carlo model simulations (density = 1008.8 kg/m<sup>3</sup>) (Nakayama and Osako, 2023b) (Figs 4.3c and 4.3f). In particular, the simulated microplastic transport (Figs 4.3a-c). This result also shows that the dams trap some amounts of floating microplastics in water (22%), contrary to the more trapped (65%) in the previous study (Lebreton et al., 2017).



Figure 4.3 Difference of simulated horizontal plastic transport in inland waters with and without the presence of reservoirs; (a)-(c) macroplastic and (d)-(f) microplastic transports without effect of settling and resuspension, with almost the same as the density of water (density = 1000.1 kg/m<sup>3</sup>), and on averaged plastic condition of all iterations of Monte Carlo model simulations (density = 1008.8 kg/m<sup>3</sup>)

## 4.4.2 Effect of Reservoirs on Differences in Plastic Burial

Fig. 4.4 compares plastic burial in major global reservoirs with and without the lake model. The simulated burial with the lake model is similar to that without the lake model on floating conditions, i.e., settling velocity = 0 (Figs 4.4 and 4.4d). In contrast, the results become different with and without the lake model with almost the same as the density of water (density = 1000.1 kg/m<sup>3</sup>) (Figs 4.4b and 4.4e) and on averaged plastic condition of all iterations of Monte Carlo model simulations (Nakayama and Osako, 2023b) (Figs 4.4c and 4.4f). This result showed there are limits to the application of the same partial differential equations as in inorganic carbon for the derivatives either with or without the reservoirs as assumed by the author's previous study (Nakayama and Pelletier, 2018) especially when the plastic density is slightly higher than that of water; this is also related to the improvement of retention time and the accuracy of the reservoir's hypsographic information in the form of an elevation-area curve inputted into the lake model (Chapra and Martin, 2012) (Fig. 4.2) and the associated plastic dynamics of horizontal and vertical transports there.



Figure 4.4 Comparison of (a)-(c) macro-plastic and (d)-(f) microplastic burials on floating condition (settling velocity = 0), with almost the same as the density of water (density = 1000.1 kg/m<sup>3</sup>), and on averaged plastic condition of all iterations of Monte Carlo model simulations in global major reservoirs without the lake model (horizontal axis) and with it (vertical axis)

## 4.4.3 Change in Global Plastic Cycle by Considering Effects of Lentic Waters

Fig. 4.5 compares plastic sedimentation in the global lakes and reservoirs (Hoffman and Hittinger, 2017; Ghayebzadeh et al., 2020; Gao et al., 2023). Most plastics are deposited in the global river basins, such as the Caspian Sea, the Three Gorges Dam (Yangtze River), and the Tarbela Dam (Indus River). Though the observed data are limited, the simulated results reproduce reasonably the observed values. The result also shows that there are more plastic deposits in the reservoirs than the lakes, except for a significant amount of plastic deposits in the Caspian Sea, which agrees reasonably that lotic systems have higher densities of plastic accumulation than lentic systems (D'Avignon et al., 2022). In addition, except for some rivers, such as the Yangtze and Yellow Rivers, most lentic waters deposit more microplastics than macroplastics, as pointed out by the previous study (Chen et al., 2022).

Table 4.2 shows the weighted average of plastic budget in major global rivers. The simulated result shows that the plastic deposition in the global major lakes  $(0.110\pm0.079 \text{ Tg/yr})$  is smaller than that in the global major reservoirs  $(0.386\pm0.103 \text{ Tg/yr})$ , which is the opposite of the carbon cycle estimated by the previous author's study (Nakayama, 2023). The result also shows that it is difficult to ignore the plastics sinking into lakes and reservoirs beds. However, the amount of deposited plastics simulated by the model there (0.496 Tg/yr) is smaller than that

in the previous material (3.1 Tg/yr) (OECD, 2022). In addition, the simulated result showed that artificial structures such as dams and lakes intercept some amounts of plastics before they reach the ocean (22%; reservoir + 6%; lakes = 28%; total), though the amount trapped is not as great as 65% in the previous study (Lebreton et al., 2017). The result also showed that microplastics are more retained (38%) by the lakes and reservoirs than macroplastics (22%), which agreed with the previous study (Chen et al., 2022) that the hydraulic sorting preferentially retains higher proportions of small-sized plastics and that the fluvial flooding more easily evacuates large-sized plastics. The riverine plastic transport to the ocean is  $1.253\pm0.393$  Tg/yr, with a macroplastic flux of  $0.815\pm0.305$  Tg/yr and a microplastic flux of  $0.439\pm0.248$  Tg/yr, which is in the range of previous values 0.41-4.0 Tg/yr (Meijer et al., 2021).



Figure 4.5 Simulated plastic deposition in the global (a) lakes and (b) reservoirs; Blue and red bars show the flux of macro and microplastics

River	Macro P flux (Tg/yr)	Micro P flux (Tg/yr)	Total P flux (Tg/yr)
Riverine Transport to Ocean	1.056±0.294	0.693±0.227	1.749±0.371
Reservoir Storage	0.206±0.065	$0.180 \pm 0.080$	0.386±0.103
Lake Storage	0.035±0.049	$0.075 \pm 0.061$	0.110±0.079
Net Transport to Ocean	0.815±0.305	$0.439 \pm 0.248$	$1.253 \pm 0.393$

## Table 4.2 Weighted average of plastic budget in the global major rivers (153 basins/watersheds,<br/>325 river channels)

## 4.5 Conclusion

The process-based model NICE-BGC was extended to a couple with LAKE2K in a stratified water quality model to evaluate the global plastic dynamics in both lotic and lentic waters. The new model could simulate riverine plastic transport and burial in inland waters with and without the presence of major global reservoirs and lakes. In particular, the plastic burial simulated by the model became different with and without the lake model when the density of plastic was higher than that of water. This result showed there are limits to applying the same partial differential equations as inorganic carbon for the derivatives either with or without the reservoirs, as assumed by the author's previous study. The model also simulated plastic sedimentation in both lakes and reservoirs and showed that there were more plastic deposits in the reservoirs than the lakes except for the Caspian Sea, and most lentic waters are found to deposit more microplastics than macroplastics as pointed out by the previous study. Finally, the author evaluated global changes in plastic dynamics due to anthropogenic factors such as the construction of artificial dams and natural lakes in lentic water. The simulated result also showed that incorporating the lake model in NICE-BGC led to improved estimates of plastic dynamics in inland waters and may aid the development of solutions and measures to reduce plastic input to the ocean.

#### References

- Alder, J. (2003) Putting the coast in the "Sea Around Us". The Sea Around Us Newsletter, 15, 1-2. http://data.unepwcmc.org/datasets/23
- Best, J. (2018) Anthropogenic stresses on the world's big rivers. Nature Geoscience, 12, 7–21, doi:10.1038/s41561-018-0262-x
- Chapra, S.C., Martin, J.L. (2012) LAKE2K: A modelling framework for simulating lake water quality (Version 1.4): Documentation and users manual. Civil and Environmental Engineering Dept., Tufts University, Medford, MA
- Chen, Y., Gao, B., Xu, D., et al. (2022) Catchment-wide flooding significantly altered microplastics organization in the hydro-fluctuation belt of the reservoir. iScience, 25, 104401, doi:10.1016/j.isci.2022.104401
- D'Avignon, G., Gregory-Eaves, I., Ricciardi, A. (2022) Microplastics in lakes and rivers: an issue of emerging significance to limnology. Environmental Review, 30, 228–244, Doi:10.1139/er-2021-0048
- Dhivert, E., Phuong, N.N., Mourier, B., et al. (2022) Microplastic trapping in dam reservoirs driven by complex hydrosedimentary processes (Villerest Reservoir, Loire River, France). Water Research, 225, 119187, doi:10.1016/j.watres.2022.119187

- Dürr, H.H., Laruelle, G.G., van Kempen, C.M., et al. (2011) Worldwide typology of nearshore coastal systems: Defining the estuarine filter of river inputs to the oceans. Estuaries and Coasts, 34(3), 441-458, doi:10.1007/s12237-011-9381-y
- Elagami, H., Ahmadi, P., Fleckenstein, J.H., et al. (2022) Measurement of microplastic settling velocities and implications for residence times in thermally stratified lakes. Limnology and Oceanography, 67, 934–945, doi:10.1002/lno.12046
- ESRI. (2019) Overlay Layers. Portal for ArcGIS. https://gislab.depaul.edu/portal/portalhelp/en/portal/latest/use/geoanalytics-overlay-layers.htm
- European Centre for Medium-Range Weather Forecasts (ECMWF). (2019) ERA-Interium. https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era-interim/
- European Commission. (2012) Harmonized World Soil Database. http://eusoils.jrc.ec.europa.eu/ESDB\_Archive/soil\_data/global.htm
- European Commission. (2015) Global Land Cover 2000. https://forobs.jrc.ec.europa.eu/products/glc2000/glc2000.php
- Food and Agriculture Organization of the United Nations (FAO). (2016) Global Map of Irrigation Areas (GMIA). http://www.fao.org/nr/water/aquastat/irrigationmap/index.stm
- Gao, B., Chen, Y., Xu, D., et al. (2023) Substantial burial of terrestrial microplastics in the Three Gorges Reservoir, China. Communications Earth & Environment, 4, 32, doi:10.1038/s43247-023-00701-z
- Geyer, R., Jambeck, J.R., Law, K.L. (2017) Production, use, and fate of all plastics ever made. Science Advances, 3, e1700782, doi:10.1126/sciadv.1700782
- Ghayebzadeh, M., Aslani, H., Taghipour, H., Mousavi, S. (2020) Estimation of plastic waste inputs from land into the Caspian Sea: A significant unseen marine pollution. Marine Pollution Bulletin, 151, 110871, doi:10.1016/j.marpolbul.2019.110871
- Grumbine, R. E., Dore, J., Xu, J. (2012) Mekong hydropower: drivers of change and governance challenges. Frontiers in Ecology and the Environment, 10, 91-98, doi:10.1890/110146
- Haberstroh, C.J., Arias, M.E., Yin, Z., et al. (2021) Plastic transport in a complex confluence of the Mekong River in Cambodia. Environmental Research Letters, 16, 095009, doi:10.1088/1748-9326/ac2198
- Hartmann, J., Moosdorf, N. (2012) The new global lithological map database GLiM: A representation of rock properties at the Earth surface. Geochemistry, Geophysics, Geosystems, 13, Q12004, doi:10.1029/2012GC004370
- Hoffman, M., Hittinger, E. (2017) Inventory and transport of plastic debris in the Laurentian Great Lakes. Marine Pollution Bulletin, 115, 237-281, doi:10.1016/j.marpolbul.2016.11.061
- Hurley, E., Woodward, J., Rothwell, J.J. (2018) Microplastic contamination of river beds significantly reduced by catchment-wide flooding. Nature Geoscience, 11, 251-257, doi:10.1038/s41561-018-0080-1
- Jambeck, J.R., Geyer, R., Wilcox, C., et al. (2015) Plastic waste inputs from land into the ocean. Science, 347, 768-771, doi:10.1126/science.1260352
- Jones, E.R., van Vliet, M.T.H., Qadir, M., Bierkens, M.F.P. (2021) Country-level and gridded estimates of wastewater production, collection, treatment and reuse. Earth System Science Data, 13, 237-254, doi:10.5194/essd-13-237-2021
- Kooi, M., van Nes, E.H., Scheffer, M., Koelmans, A.A. (2017) Ups and downs in the ocean: Effects of biofouling on vertical transport of microplastics. Environmental Science & Technology, 51, 7963-7971, doi:10.1021/acs.est.6b04702
- Kooi, M., Besseling, E., Kroeze, C., et al. (2018) Modelling the fate and transport of plastic decries in freshwaters: review and guidance. In: Wagner, M., Lambert, S. [Eds] Freshwater Microplastics. The Handbook of Environmental Chemistry 58, Springer, pp.125-152
- Kooi, M., Koelmans, A.A. (2019) Simplifying microplastic via continuous probability distributions for size, shape, and density. Environmental Science & Technology Letters, 6, 551-557, doi:10.1021/acs.est.9b00379
- Koutnik, V.S., Leonard, J., Alkidim, S., et al. (2021) Distribution of microplastics in soil and freshwater environments: global analysis and framework for transport modelling. Environmental Pollution, 224, 116552, doi:10.1016/j.envpol.2021.116552
- Kumar, R., Sharma, P., Verma, A., et al. (2021) Effect of physical characteristics and hydrodynamic conditions on transport and deposition of microplastics in riverine ecosystem. Water, 13, 2710, doi:10.3390/w13192710
- Laruelle, G. G., Dürr, H. H., Lauerwald, R., Hartmann, J., Slomp, C. P., Goossens, N., & Regnier, P. A. G. (2013) Global multi-scale segmentation of continental and coastal waters from the watersheds to the continental margins. Hydrology and Earth System Sciences, 17, 2029–2051, doi:10.5194/hess-17-2029-2013
- Lebreton, L., Andrady, A. (2019) Future scenarios of global plastic waste generation and disposal. Palgrave Communications, 5, 6, doi:10.1057/s41599-018-0212-7

- Lebreton, L, van der Zwet, J., Damsteeg, J.-W., et al. (2017) River plastic emissions to the world's oceans. Nature Communications, 8, 15611, doi:10.1038/ncomms15611
- Lehner, B., Döll, P. (2004) Development and validation of a global database of lakes, reservoirs and wetlands. Journal of Hydrology, 296, 1-22, doi:10.1016/j.jhydrol.2004.03.028
- Lehner, B., Reidy Liermann, C., Revenga, C., et al. (2011) High-resolution mapping of the world's reservoirs and dams for sustainable river-flow management. Frontiers in Ecology and the Environment, 9, 494-502, doi:10.1890/100125
- Leiser, R., Wu, G.-M., Neu T.R., Wendt-Potthoff, K. (2020) Biofouling, metal sorption and aggregation are related to sinking of microplastics in a stratified reservoir. Water Research, 176, 115748, doi:10.1016/j.watres.2020.115748
- Li, Y., Lu, Z., Zheng, H., et al. (2020) Microplastics in surface water and sediments of Chongming Island in the Yangtze Estuary, China. Environmental Sciences Europe, 32, 15, Doi:10.1186/s12302-020-0297-7
- Liu, Y., You, J., Li, Y., et al. (2021) Insights into the horizontal and vertical profiles of microplastics in a river emptying into the sea affected by intensive anthropogenic activities in Northern China. Science of the Total Environment, 779, 146589, doi:10.1016/j.scitotenv.2021.146589
- Meijer, L.J.J., van Emmerik, T., van der Ent, R., et al. (2021) More than 1000 rivers account for 80% of global riverine plastic emissions into the ocean. Science Advances, 7, eaaz5803, doi:10.1126/sciadv.aaz5803
- Ministry of Land, Infrastructure, Transport and Tourism (MLIT). (2012) Digital national land information: River networks ver.3.1. https://nlftp.mlit.go.jp/ksj/gml/datalist/KsjTmplt-W05.html
- Ministry of Land, Infrastructure, Transport and Tourism (MLIT). (2013) Digital national land information: Sewerage system related facility ver.1.1. https://nlftp.mlit.go.jp/ksj/gml/datalist/KsjTmplt-P22.html
- Ministry of Land, Infrastructure, Transport and Tourism (MLIT). (2016) Digital national land information: Reservoirs and dams ver.3.0. https://nlftp.mlit.go.jp/ksj/gml/datalist/KsjTmplt-W01.html
- Mueller, N.D., Gerber, J.S., Johnston, M., et al. (2012) Closing yield gaps through nutrient and water management. Nature, 490, 254-257, doi:10.1038/nature11420
- Nakayama, T. (2017a) Development of an advanced eco-hydrologic and biogeochemical coupling model aimed at clarifying the missing role of inland water in the global biogeochemical cycle. Journal of Geophysical Research: Biogeosciences, 122, 966-988, Doi:10.1002/2016JG003743
- Nakayama, T. (2017b) Scaled-dependence and seasonal variations of carbon cycle through development of an advanced eco-hydrologic and biogeochemical coupling model. Ecological Modelling, 356, 151-161, doi:10.1016/j.ecolmodel.2017.04.014
- Nakayama, T. (2022) Impact of anthropogenic disturbances on carbon cycle changes in terrestrial-aquaticestuarine continuum by using an advanced process-based model. Hydrological Processes, 36(2), e14471, doi:10.1002/hyp.14471
- Nakayama, T. (2023) Evaluation of global biogeochemical cycle in lotic and lentic waters by developing an advanced eco-hydrologic and biogeochemical coupling model. Ecohydrology, e2555, doi:10.1002/eco.2555
- Nakayama, T., Pelletier, G. (2018) Impact of global major reservoirs on carbon cycle changes by using an advanced eco-hydrologic and biogeochemical coupling model. Ecological Modelling, 387, 172-186, doi:10.1016/j.ecolmodel.2018.09.007
- Nakayama, T., Osako, M. (2023a) Development of a process-based eco-hydrology model for evaluating the spatiotemporal dynamics of macro- and micro-plastics for the whole of Japan. Ecological Modelling, 476, 110243, doi:10.1016/j.ecolmodel.2022.110243
- Nakayama, T., Osako, M. (2023b) The flux and fate of plastic in the world's major rivers: Modeling spatial and temporal variability. Global and Planetary Change, 221, 104037, doi:10.1016/j.gloplacha.2023.104037
- Nakayama, T., Osako, M. (2024) Plastic trade-off: Impact of export and import of waste plastic on plastic dynamics in Asian region. Ecological Modelling, 489, 110624, doi:10.1016/j.ecolmodel.2024.110624
- Nakayama, T. (under review) Impact of global major reservoirs and lakes on plastic dynamics by using a processbased eco-hydrology model. Lakes and Reservoirs: Research and Management
- NASA. (2013) GLDAS vegetation class. http://ldas.gsfc.nasa.gov/gldas/GLDASvegetation.php
- NASA. (2018) Gridded Population of the World, Version 4 (GPWv4). https://sedac.ciesin.columbia.edu/data/set/gpw-v4-population-count-adjusted-to-2015-unwpp-countrytotals-rev11
- Nizzetto, L., Bussi, G., Futter, M.N., et al. (2016) A theoretical assessment of microplastic transport in river catchments and their retention by soils and river sediments. Environmental Science: Processes & Impacts, 18, 1050-1059, doi:10.1039/c6em00206d
- OECD. (2022) Global Plastics Outlook: Economic Drivers, Environmental Impacts and Policy Options, OECD Publishing, Paris. https://doi.org/10.1787/de747aef-en

- Portmann, F.T., Siebert, S., Döll, P. (2010) MIRCA2000 Global monthly irrigated and rainfed crop areas around the year 2000: A new high-resolution data set for agricultural and hydrological modelling. Global Biogeochemical Cycles, 24, GB 1011, doi:10.1029/2008GB003435
- Praetorius, A., Scheringer, M., Hungerbühler, K. (2012) Development of environmental fate models for engineered nanoparticles - A case study of TiO2 nanoparticles in the Rhine River. Environmental Science & Technology, 46, 6705-6713, doi:10.1021/es204530n
- Schmidt, C., Krauth, T., Wagner, S. (2017) Export of plastic debris by rivers into the sea. Environmental Science & Technology, 51, 12246-12253, doi:10.1021/acs.est.7b02368
- Shen, J., Gu, X., Liu, R., et al. (2023) Damming has changed the migration process of microplastics and increased the pollution risk in the reservoirs in the Shaying River Basin. Journal of Hazardous Materials, 443, 130067, doi:10.1016/j.jhazmat.2022.130067
- Siebert, S., Döll, P. (2010) Quantifying blue and green virtual water contents in global crop production as well as potential production losses without irrigation. Journal of Hydrology, 384, 198–217, doi:10.1016/j.jhydrol.2009.07.031
- Siegfried, M., Koelmans, A.A., Besseling, E., Kroeze, C. (2017) Export of microplastics from land to sea. A modelling approach. Water Research, 127, 249-257, doi:10.1016/j.watres.2017.10.011
- Singh, N., Mondal, A., Bagri, A., et al. (2021) Characteristics and spatial distribution of microplastics in the lower Ganga River water and sediment. Marine Pollution Bulletin, 163, 111960, doi:10.1016/j.marpolbul.2020.111960
- Strokal, M., Bai, Z., Franssen, W., et al. (2021) Urbanization: an increasing source of multiple pollutants to rivers in the 21st century. Urban Sustainability, 1, 24, doi:10.1038/s42949-021-00026-w
- Thompson, R.C., Olsen, Y., Mitchell, R.P., et al. (2004) Lost at sea: Where is all the Plastic? Science, 304, 838, doi:10.1126/science.1094559
- Tian, H., Yang, J., Lu, C., et al. (2018) The global N2O model intercomparison project. Bulletin of the American Meteorological Society, 99(6), 1231-1251, doi:10.1175/bams-d-17-0212.1
- UNESCO. (2022) IHP-IX: Strategic Plan of the Intergovernmental Hydrological Programme: Science for a Water Secure World in a Changing Environment, ninth phase 2022-2029. https://unesdoc.unesco.org/ark:/48223/pf0000381318.locale=en
- United Nations. (2019) Basel Convention: Controlling transboundary movements of hazardous wastes and their disposal.

http://www.basel.int/Implementation/MarinePlasticLitterandMicroplastics/Overview/tabid/6068/Default.asp x

- U.S. Geological Survey (USGS). (1996a) Global 30 Arc-Second Elevation (GTOPO30). USGS. https://doi.org/10.5066/F7DF6PQS
- U.S. Geological Survey (USGS). (1996b) HYDRO1K. USGS. https://doi.org/10.5066/F77P8WN0
- U. S. Department of Agriculture (USDA). (2022) Global Reservoirs and Lakes Monitor (G-REALM). https://ipad.fas.usda.gov/cropexplorer/global\_reservoir/
- van Emmerik, T., Strady, E., Kieu-Le, T.-C., Nguyen, L., Gratiot, N. (2019) Seasonality of riverine macroplastic transport. Scientific Reports, 9, 13549, doi:10.1038/s41598-019-50096-1
- van Emmerik, T., Mellink, Y., Hauk, R., et al. (2022) Rivers as plastic reservoirs. Frontiers in Water, 3, 786936, doi:10.3389/frwa.2021.786936
- van Wijnen, J., Ragas, A.M.J., Kroeze, C. (2019) Modelling global river export of microplastics to the marine environment: Sources and future trends. Science of the Total Environment, 673, 392-401, doi:10.1016/j.scitotenv.2019.04.078
- Wagner, S., Klöckner, P., Stier, B., Römer, M., Seiwert, B., Reemtsma, T., Schmidt, C. (2019) Relationship between discharge and river plastic concentrations in a rural and an urban catchment. Environmental Science & Technology, 53, 10082-10091, doi:10.1021/acs.est.9b03048
- Waldschläger, K., Schüttrumpf, H. (2019) Erosion behavior of different microplastic particles in comparison to natural sediments. Environmental Science & Technology, 53, 13219-13227, doi:10.1021/acs.est.9b05394
- Watkins, L., McGrattan, S., Sullivan, P.J., Walter M.T. (2019) The effect of dams on river transport of microplastic pollution. Science of the Total Environment, 664, 834-840, doi:10.1016/j.scitotenv.2019.02.028
- Wu, F., Wang, J., Jiang, S., et al. (2022) Effect of cascade damming on microplastics transport in rivers: A largescale investigation in Wujiang River, Southwest China. Chemosphere, 299, 134455, doi:10.1016/j.chemosphere.2022.134455
- Zhang, B., Tian, H., Lu, C., et al. (2017) Global manure nitrogen production and application in cropland during 1860-2014; a 5 arcmin gridded global dataset for Earth system modelling. Earth System Science Data, 9, 667-678, doi:10.5194/essd-9-667-2017

## Chapter 5

## Plastic Trade-Off: Impact of Export and Import of Waste Plastic on Plastic Dynamics in Asian Region

Chapter 5 Plastic Trade-Off: Impact of Export and Import of Waste Plastic on Plastic Dynamics in Asian Region

## Abstract

Environmental contamination by plastics has received considerable attention from scientists, policymakers, and the public. In this study, the authors applied the eco-hydrology model coupled with the plastic debris model in Asian regions by including the effect of waste plastic trade. Results showed that settling and resuspension of plastic particles greatly impact the mobilization of plastic and its high intra-annual variability and that plastic transport becomes drastically higher during the flood periods, accounting for most of the annual flux. In particular, the model simulated the size distribution of plastics in the water and riverbed sediment of the major global rivers and showed that the coarser particles are more distributed in the riverbed than those in the water. Further, the authors evaluated the impact of waste plastic trade on changes in riverine plastic transport by including the effect of plastic trade on Mismanaged Plastic Waste (MPW) in the extension of previous studies. They modified the calculation of municipal plastic waste by including these effects of plastic trade and disposal. They revised MPW, assuming that the import of plastics is treated the same as the export of plastics as the first approximation. The modified MPW became smaller than the original one in the exporting countries and vice versa in the importing countries. Further, this analysis clarified waste plastic trade has promoted a decrease in riverine plastic transport in Japanese rivers, its slight increase in the Yangtze, Yellow, and Ganges Rivers, and almost constant in the Mekong, Indus, Irrawaddy, and Brahmaputra Rivers. The present results help quantify plastic trade-off about the impact of the export and import of waste plastic on plastic dynamics at a regional scale.

# Keywords: Eco-hydrology model; flux; plastics; regional scale; riverine plastic transport; waste disposal; waste plastic trade

## **5.1 Introduction**

Plastic pollution is a serious environmental problem, and such pollutants from lands to rivers and finally to oceans severely affect human health and the environment (Siegfried et al., 2017). The difference between plastic and natural particles such as sand and sediment is that the plastic is gradually degraded by physical, chemical, and biological processes and leads to further subdivision into an enormous number of forms once released into the environment. Previous studies on the origin and fate of plastic waste in freshwater systems have suggested that land-derived plastics are the dominant sources of marine plastic pollution (Thompson et al., 2004). Some studies (Jambeck et al., 2015; Lebreton et al., 2017; Schmidt et al., 2017) estimated the distribution of global riverine emissions of plastic into the ocean using empirical indicators representative of waste generation (mismanaged plastic waste: MPW) inside a river basin. In contrast to these studies, Meijer et al. (2021) recently proposed a more accurate form of analysis to account for the spatial distribution of plastic waste generation (Lebreton and Andrady, 2019) and climatological/geographical differences within river basins by using a probabilistic approach. Other studies (Siegfried et al., 2017; van Wijnen et al., 2019; Strokal et al., 2021) adapted a process-oriented model to continental and global scales by extending an existing non-dynamic nutrient export model. However, these global plastic transport models ignored the impact of flood events on plastic mobilization and its high inter-annual variability, where the plastic transport increases up to a factor of five to ten at the floods (van Emmerik et al., 2019; Roebroek et al., 2021). Larger plastic debris from low-density polymers such as polyethylene (PE), polypropylene (PP), and polystyrene (PS) are predominantly transported in normal flat water.

In contrast, the relatively larger fraction of plastic litter retained in the bottom sediment is efficiently flushed from riverbeds during flooding (Nizzetto et al., 2016; Hurley et al., 2018; Schwarz et al., 2019), which should be modeled and clarified from the viewpoint of seasonal variations of plastic riverine plastic transport; this is also related to the fact that the larger plastic particles are efficiently distributed in the bed sediment than those in the water column because the aggregation of micro-plastics mixed with organic minerals is one of the mechanisms for the micro-plastic sedimentation (Kooi et al., 2018; Koutnik et al., 2021; Liu et al., 2021). Because extreme events such as floods and droughts are expected to increase further with climate change, it is important to evaluate the impact of flood events on plastic mobilization and its high variability using the process-oriented model.

In contrast, recent study shows that previous studies about riverine plastic outflows based on the concept of MPW were substantially greater than reported field data and advocates the need for robust model using the Human Development Index (HDI) as the main predictor (Mai et al., 2020; Strokal et al., 2021). From another point of view, MPW (Lebreton and Andrady, 2019) used in the authors' previous study (Nakayama and Osako, 2023a, 2023b) did not include the effect of waste plastic trade flow between Japan and abroad (Fig. 5.1). Japan was some of top exporting countries of waste plastic after Europe and America, and some countries such as China imported this waste plastic. China has imported approximately 45% of all cumulative imports of plastic waste between 1988 and 2016 (Brooks et al., 2018; Dominish et al., 2020; EIA, 2021). This situation changed greatly after establishing the "Basel Convention" (United Nations, 2019) because some importing countries introduced import regulations mainly for environmental protection. China also attempted to reduce the import of low-value plastic via the "Green Fence" policy in 2015 (Dominish et al., 2020). Combining the fate and transport model with social system methods such as material flow analysis is important to assess environmental emissions under climate change. Developing a framework for reversing global water resource degradation, especially plastic pollution, is also powerful for achieving Sustainable Development Goals (SDG) (UNESCO, 2022). The recent G20 Osaka Summit in 2019 shared the "Osaka Blue Ocean Vision" (Ministry of Foreign Affairs of Japan, 2019), which is positioned alongside COP (Conference of the Parties) as part of global warming countermeasures. A quantitative assessment of the fate and transport of plastics will be necessary to realize this vision because countries worldwide have decided on concrete future measures for dealing with plastic based on scientific results. In particular, the previous studies clarified a dominant contribution of the summer monsoon in Asia and that more than 74% of waste is delivered between May and October from limited large rivers in Asia (Lebreton et al., 2017; Best, 2018; Nakayama and Osako, 2023b).

One of the authors has developed a process-based model coupling eco-hydrology with the biogeochemical cycle (National Integrated Catchment-based Eco-hydrology (NICE)-BGC) (Nakayama, 2017a, 2017b), incorporating complex terrestrial-aquatic linkages in the hydrologic-biogeochemical cycle. Recently, the authors extended to couple this process-based NICE-BGC with a plastic debris (engineered materials) model and evaluated spatiotemporal variations of plastic debris in the entire Japan of regional scale (Nakayama and Osako, 2023a) and the world's major rivers of global scale (Nakayama and Osako, 2023b). Based on this background, three basic issues were addressed (Nakayama and Osako, 2024): (i) How does the movement of plastic particles between water and riverbed sediment affect the mobilization of plastic and its high intra-annual variability? (ii) How does the waste plastic trade affect mismanaged plastic waste? (iii) How does the waste plastic trade affect riverine plastic transport in Asia? To clarify these issues, NICE-BGC simulated the seasonal variations of riverine plastic transport during 2014-2015. In particular, the model could include the effect of waste plastic trade flow between Japan and abroad. The authors evaluated the impact of waste plastic trade on change in riverine plastic transport in Asian regions by including the effect of waste plastic trade on Mismanaged Plastic Waste (MPW) in the extension of the previous studies (Lebreton and Andrady, 2019; Meijer et al., 2021). This analysis also clarified whether the waste plastic trade has promoted a decrease or an increase in riverine plastic transport in Asian rivers. The present study is also an important step not only for the qualification of processes but also for identifying the hierarchy of drivers in various river catchments.



Figure 5.1 Location of the study area in Japan and Asian regions; (a) land cover, (b) population density, (c) untreated wastewater calculated from wastewater treatment and wastewater production, and (d) mismanaged plastic waste (MPW)

## 5.2 Methods

## 5.2.1 General Model Framework of NICE-BGC

One of the authors has so far developed an advanced process-based model derived by coupling a process-based National Integrated Catchment-based Eco-hydrology (NICE) model with various biogeochemical cycle models (NICE-BGC) (Nakayama, 2017a, 2017b, 2022). This model incorporates the connectivity of the biogeochemical cycle accompanied by the hydrologic cycle between surface water and groundwater, hillslopes and river networks, and other intermediate regions. Recently, the authors extended to couple this process-based NICE-BGC with a plastic debris (engineered materials) model and evaluated spatiotemporal variations of plastic debris in the entire Japan of regional scale (Nakayama and Osako, 2023a) and the world's major rivers of global scale (Nakayama and Osako, 2023b) (Fig. 5.1). The new model also included advection, dispersion, diffusion, settling, dissolution and deterioration due to light and temperature, but assumed no interaction with suspended matter (hetero-aggregation) (Praetorius et al., 2012), resuspension (Waldschläger and Schüttrumpf, 2019), biofouling (Kooi et al., 2017, 2018), or wind effects.

## 5.2.2 Extension of Plastic Debris Model including Effect of Waste Plastic Trade

In this chapter, the authors newly incorporated resuspension in addition to settling by extending the authors' previous studies (Nakayama and Osako, 2023a, 2023b, 2024). The original model assumed the resuspension rate when a riverbed is under equilibrium conditions and the particle size distribution is uniform; applying this formula directly to plastic was difficult. It is difficult to grasp the heterogeneous distribution of settled and deposited plastic on hillslopes. However, some studies have evaluated the erosion behavior of microplastic particles compared to sediments (Waldschläger and Schüttrumpf, 2019). The new model included the mass budget in the water and the bed sediment of any given reach in the same way as the previous studies (Nizzetto et al., 2016; Koutnik et al., 2021). Thus, the model could simulate the concentration of plastics in the water and the bed sediment and evaluate the hydrograph for plastics transport with various shear stresses during storm events, as proposed by Kumar et al. (2021). For model simplification, it was also assumed that microplastics are pure and inert polymers with a continuous probability distribution of size, shape, and density (Kooi and Koelmans, 2019). After simulation of plastic transport on a hillslope, the authors used the estimated rate of conversion of macroplastics to microplastics (3%/yr) in the same way as van Wijnen et al. (2019), with extension of the conversion rate employed by Jambeck et al. (2015) (Fig. 5.2). MPW is the most important variable for the diffuse input of macroplastics and secondary microplastics into rivers.



Figure 5.2 Flow diagram of macro and microplastics transport in land and inland water by extending NICE-BGC to include the effect of waste plastic trade

## 5.3 Input Data and Boundary Conditions for Simulation

## 5.3.1 Model Input Data including Effect of Waste Plastic Trade

The input data at hybrid spatial resolutions were prepared and arranged to calculate spatially averaged 0.1°x0.1° grid in Japan and 1°x1° grid in Asian regions using the Spatial Analyst Tools in ArcGIS v10.3 software for the simulation (Fig. 5.1 and Table 5.1); elevation, land cover, soil texture, vegetation type, river networks, lakes and wetlands, reservoirs and dams, geological structures, crop type, irrigation type, irrigation water use, fertilizer use, and manure use were categorized based on the global and Japanese datasets. Although data for plastics are scarce, the authors used some data to simulate the plastic debris in the entire Japan and Asian regions: gridded population data at 250 m resolution from the Japanese Census in 2015 (Japanese Government Statistics, 2021) and 1 km resolution from global data in 2015 (NASA, 2018), wastewater production, collection, treatment and reuse data at 5 arcmin (about 10 km) resolution (Jones et al., 2021), and MPW at 1 km resolution (Lebreton and Andrady, 2019) as a diffuse source (Table 5.1). To create the grid data from point, polyline, and polygon data for different sources with different spatial resolutions in a reasonable way, overlay analysis was conducted using GIS tools (intersect, union, and identity) (ESRI, 2019).

In this chapter, the authors added the effect of waste plastic trade on MPW in the Asian Pacific and major economies in 2015 (Nakayama and Osako, 2024) in the reference of the previous studies (United Nations, 2015; Brooks et al., 2018; Lebreton and Andrady, 2019) (Table 5.2). In Asia, Japan was the top exporter of waste plastic in 2015 (1.60 million MT of plastic), and most Southeast Asian countries exported more than they imported. China was the top importer of plastic (7.35 million MT), but approximately 1.3 million to 3.5 million MT of plastic was estimated to enter the ocean annually from the coastline (Brooks et al., 2018). The authors modified the calculation of municipal plastic waste by including these effects of plastic trade and disposal. They revised MPW, assuming that the ratio between MPW and municipal plastic waste was constant in each country. While it is reasonable to assume that the export of plastics is treated as a diffuse source of variations in MPW, the same treatment in importing plastics is likely to have great uncertainty; this is because the geographical distribution of plastic imports cannot be assumed equal to that of the population density grid used to estimate the geographical distribution of MPW. In this study, the authors assumed that the import of plastics is treated as the same as the export of plastics as the first approximation. The result shows that the modified MPW was smaller than the original one in the exporting countries and vice versa in the importing countries (Fig. 5.3). These data were input to the model as a diffuse source of plastics in two-dimensional hillslope runoff model of NICE-BGC including mobilization (Fig. 5.2).

The authors also used the per capita emission of micro-plastics in each economic region determined in a previous study (van Wijnen et al., 2019). Generally, microplastics at point sources are considered to originate from four sources: personal care products (PCPs) (0.0007–0.0049 kg/cap./yr), laundry fibers (0.036–0.041 kg/cap./yr), and car tire wear (0.018–0.077 kg/cap./yr) in Asian regions (Nakayama and Osako, 2023a, 2023b). We estimated the potential fluxes of microplastics by multiplying these per capita emissions and their population distribution for each catchment flow into WWTPs (Waste Water Treatment Plants) in the NICE-BGC simulation (Fig. 5.2). We also applied "untreated wastewater" and converted to removal efficiency of microplastic, the former of which was calculated by subtracting the ratio of wastewater treatment and wastewater production at 5 arcmin resolution (Jones et al., 2021). This method differs from those used in most previous studies (Siegfried et al., 2017; van Wijnen

et al., 2019; Meijer et al., 2021; Strokal et al., 2021) because these studies considered only sewerage connectivity (0–1) microplastic removal efficiency, and transport probability of plastics with relatively large uncertainty. The removal efficiency of microplastic in the Japanese WWTPs was much higher than in the other Asian regions (Fig. 5.1c), which was caused by almost all secondary and tertiary treatments in Japan (Nakayama and Osako, 2023a). It was also assumed that micro-plastic concentration on hillslopes was constant (Wagner et al., 2019), and the time series proportional to hillslope runoff was calculated at each time step. Details are described in the authors' previous study (Nakayama and Osako, 2023a, 2023b).

Data set	Original resolution	Year	Source and reference			
Climatology	1.0°	1998-2015	ERA-interim; ECMWF (2019)			
Elevation	1.0km	around 1996	GTOPO30; U.S. Geological Survey (1996a)			
Land cover	1.0km	around 2000	GLC2000; European Commission (2015)			
Soil texture	1.0km	around 1970-2000	HWSD; European Commission (2012)			
Vegetation type	0.25°	around 2000	GLDAS Vegetation Class; NASA (2013)			
River networks	line	around 1996 around 2000	HYDRO1K; U.S. Geological Survey (1996b) MLIT (2012)			
Lakes and wetlands	0.5 min	around 1990-2000	GLWD; Lehner and Döll (2004)			
Reservoirs and Dams	point	around 2010 2014	GRanD; Lehner et al. (2011) MLIT (2016)			
Geological structures	0.5°	around 1970-2000	GLiM; Hartmann and Moosdorf (2012)			
Crop type	5 min	around 2000	MIRCA2000; Portmann et al. (2010)			
Irrigation type	5 min	2000-2008	GMIA; FAO (2016)			
Irrigation water use	5 min	1998-2002	GCWM; Siebert and Döll (2010)			
Fertilizer use	5 min	around 2000	Earth Stat; Mueller et al. (2012)			
Manure use	5 min	1998-2014	Zhang et al. (2017)			
Population	1.0km	2015 2015	NASA (2018) Japanese Government Statistics (2021)			
Wastewater production and treatment	5 min	2015	Jones et al. (2021)			
Wastewater treatment plants	point	2010	MLIT (2013)			
Mismanaged plastic waste	1.0 km	2015	Lebreton and Andrady (2019)			

Table	5.1	List	of input	data	for	NICE	and	NI	CE	-BGC	simu	lations	in	Japan	and	Asian	regions
-------	-----	------	----------	------	-----	------	-----	----	----	------	------	---------	----	-------	-----	-------	---------

Country	Municipal platic waste (ton/yr)	MPW (ton/yr)	Plastic export (ton/yr)	Plastic import (ton/yr)	Direct disposal to sea	Revised municipal platic waste (ton/yr)	Revised MPW (ton/yr)	
Japan	$4.75 \times 10^{6}$	7.16×10 <sup>4</sup>	$1.60 \times 10^{6}$	$2.11 \times 10^4$		$3.17 \times 10^{6}$	$4.78 \times 10^{4}$	
China	$2.49 \times 10^{7}$	$1.74 \times 10^{7}$	$3.04 \times 10^{4}$	$7.35 \times 10^{6}$	$1.30 - 3.50 \times 10^{6}$	$2.98 \times 10^{7}$	$2.08 \times 10^{7}$	
Hong Kong	$5.88 \times 10^{5}$	$1.18 \times 10^{4}$	$2.82 \times 10^{6}$	$2.87 \times 10^{6}$		6.38×10 <sup>5</sup>	$1.28 \times 10^{5}$	
Malaysia	$1.32 \times 10^{6}$	$1.12 \times 10^{6}$	$1.82 \times 10^{5}$	$2.50 \times 10^{5}$		$1.39 \times 10^{6}$	$1.17 \times 10^{6}$	
Thailand	$2.98 \times 10^{6}$	$1.79 \times 10^{6}$	$2.66 \times 10^5$	$5.62 \times 10^4$		$2.77 \times 10^{6}$	$1.66 \times 10^{6}$	
Rep. of Korea	$1.21 \times 10^{6}$	2.42×10 <sup>4</sup>	$1.88 \times 10^{5}$	$6.80 \times 10^4$		$1.09 \times 10^{6}$	2.18×10 <sup>4</sup>	
Indonesia	$6.57 \times 10^{6}$	$1.64 \times 10^{6}$	$1.49 \times 10^{5}$	9.71×10 <sup>4</sup>		$6.52 \times 10^{6}$	$1.62 \times 10^{6}$	
Vietnam	$1.47 \times 10^{6}$	$1.23 \times 10^{6}$	$1.19 \times 10^{5}$	$8.84 \times 10^4$		$1.43 \times 10^{6}$	$1.20 \times 10^{6}$	
Philippines	$5.37 \times 10^{6}$	$4.56 \times 10^{6}$	$1.17 \times 10^{5}$	$1.94 \times 10^{3}$		$5.25 \times 10^{6}$	$4.46 \times 10^{6}$	
Singapore	$2.45 \times 10^{5}$	$4.90 \times 10^{3}$	6.23×10 <sup>4</sup>	$4.80 \times 10^{3}$		$1.88 \times 10^{5}$	$3.75 \times 10^{3}$	
Bangladesh	$1.08 \times 10^{6}$	$1.08 \times 10^{6}$	$3.90 \times 10^4$	$1.28 \times 10^4$		$1.05 \times 10^{6}$	$1.05 \times 10^{6}$	
Cambodia	$2.83 \times 10^{5}$	$2.61 \times 10^{5}$	$1.43 \times 10^{4}$	$5.75 \times 10^{2}$		$2.69 \times 10^{5}$	$2.48 \times 10^{5}$	
Lao PDR	$1.48 \times 10^{5}$	$1.48 \times 10^{5}$	$8.62 \times 10^2$	$1.26 \times 10^{3}$		$1.48 \times 10^{5}$	$1.48 \times 10^{5}$	
Myanmar	$1.07 \times 10^{6}$	$1.07 \times 10^{6}$	$3.74 \times 10^{2}$	$9.87 \times 10^{2}$		$1.07 \times 10^{6}$	$1.07 \times 10^{6}$	
India	$1.71 \times 10^{7}$	$1.45 \times 10^{7}$	$5.61 \times 10^{3}$	$1.86 \times 10^{5}$		$1.73 \times 10^{7}$	$1.47 \times 10^{7}$	
Pakistan	$1.42 \times 10^{6}$	$1.35 \times 10^{6}$	$3.02 \times 10^4$	3.39×10 <sup>4</sup>		$1.42 \times 10^{6}$	$1.35 \times 10^{6}$	
Russia	$3.97 \times 10^{6}$	$8.84 \times 10^{5}$	$1.01 \times 10^{4}$	$2.01 \times 10^4$		$3.98 \times 10^{6}$	$8.86 \times 10^{5}$	
Mongolia	6.22×10 <sup>4</sup>	4.10×10 <sup>4</sup>	$7.01 \times 10^{3}$	8.30×10 <sup>1</sup>		5.53×10 <sup>4</sup>	$3.64 \times 10^4$	
USA	$2.68 \times 10^{7}$	5.36×10 <sup>5</sup>	$2.05 \times 10^{6}$	3.93×10 <sup>5</sup>		$2.51 \times 10^{7}$	$5.03 \times 10^{5}$	
EU	$3.14 \times 10^{7}$	$3.55 \times 10^{6}$	$3.08 \times 10^{6}$	$4.12 \times 10^5$		$2.87 \times 10^{7}$	$3.24 \times 10^{6}$	
UK	$3.02 \times 10^{6}$	6.04×10 <sup>4</sup>	$7.92 \times 10^{5}$	8.73×10 <sup>4</sup>		$2.32 \times 10^{6}$	4.63×10 <sup>4</sup>	
Canada	$2.38 \times 10^{6}$	4.76×10 <sup>4</sup>	$2.11 \times 10^{5}$	$2.49 \times 10^{5}$		$2.42 \times 10^{6}$	$4.84 \times 10^{4}$	
Australia	5.33×10 <sup>5</sup>	$1.07 \times 10^{4}$	$2.06 \times 10^{5}$	$1.40 \times 10^4$		3.41×10 <sup>5</sup>	$6.85 \times 10^{3}$	
New Zealand	$1.75 \times 10^{5}$	$3.50 \times 10^{3}$	$4.72 \times 10^4$	$6.42 \times 10^{3}$		$1.34 \times 10^{5}$	$2.68 \times 10^{3}$	
World	$1.81 \times 10^{8}$	8.18×10 <sup>7</sup>	$1.46 \times 10^{7}$	$1.53 \times 10^{7}$		$1.82 \times 10^{8}$	$8.21 \times 10^{7}$	
Reference	Lebreton and Andrady (2019)	Lebreton and Andrady (2019)	United Nations (2015)	United Nations (2015)	Brooks et al. (2018)			

Table 5.2 Effect of waste plastic trade on MPW in Asia Pacific and major economies in 2015



Figure 5.3 Effect of waste plastic trade on MPW in Asian regions; (a)-(b) around Shanghai District in importing country (China) without and with this effect; (c)-(d) around Tokyo Metropolitan Area in exporting country (Japan) without and with this effect

## 5.3.2 Running the Simulation and Verification

The authors used a hybrid model with different spatial resolutions between Japan and Asian regions (Fig. 5.1). The simulation in all of the 109 first-class (class A) river basins throughout Japan (MLIT, 2012) was performed at 0.1° x 0.1° resolution in the horizontal direction and 20 layers in the vertical direction (Nakayama and Osako, 2023a). The simulation in Asian regions was conducted at 1°x1° resolution in the horizontal direction and in the same layers in the vertical direction (Nakayama and Osako, 2023b). NICE-BGC simulation for terrestrial ecosystems was conducted at the same spatial resolution with a time step of  $\Delta t = 1$  day for two years during 2014-2015 by inputting some values simulated by NICE iteratively after calculating the daily-averaged data from 1-hourly data (Fig. 5.2). The authors used previous data for per capita emission of micro-plastics into rivers (PCPs, dust, laundries, and tires) and removal efficiency in WWTPs as a point source. The model also simulated the outflow of macroplastics originating from MPW (Lebreton and Andrady, 2019), including the effect of waste plastic trade flow between Japan and abroad as a diffuse source (Nakayama and Osako, 2024). Then, NICE-BGC simulation for aquatic ecosystems was conducted by inputting the simulated results for land to a stream network model with a time step of  $\Delta t = 0.70$  min to ensure model stability. The hydrologic cycle and river plastic transport were simulated and verified using the previous datasets and materials as far as possible in Japan (Nakayama and Osako, 2023a) and continental scale (Nakayama and Osako, 2023b).

For uncertainty and sensitivity analyses, the authors first calculated the cumulative probability distribution of size, shape, and density and their inverse functions in the assumption that these probability distributions of size, shape, and density would also apply to macroplastics by extension from micro-plastics in the previous study (Kooi and Koelmans, 2019). Shape categories were considered the dimensionless Corey Shape factor determined by length:width:height ratios for different shapes of plastic particles (Nakayama and Osako, 2023b). Secondly, Monte Carlo model simulations (10 iterations) were conducted to generate a uniform random number between 0 and 1, and the size, shape, and density were determined under the fixed random number. Thirdly, the equivalent sphere diameter and settling velocity were calculated to determine plastic transport in each case on the continental and global scales. Finally, uncertainty and sensitivity analyses were conducted by ranking the model parameters according to their contribution to prediction uncertainty. Details are described in the authors' previous study (Nakayama and Osako, 2023b). The results yielded quantitative measures of model performance in reproducing the seasonality and intra-annual variability in the hydrologic cycle and plastic transport there.

## 5.4 Results and Discussion

### 5.4.1 Seasonal Variations of Riverine Plastic Transport

The authors simulated riverine plastic transport with the effect of settling and resuspension of plastic particles in the extension of the authors' previous studies (Nakayama and Osako, 2023a, 2023b). The model simulated seasonal variations of riverine plastic transport in Asian Rivers (Fig. 5.4) in comparison to the previous studies in the Yangtze (Zhao et al., 2019; Han et al., 2023), Yellow (Han et al., 2020; Qian et al., 2023), and Mekong Rivers (Haberstroh et al., 2021; van Emmerik et al., 2023), respectively. The simulated plastic concentrations were higher from summer to fall and linearly corresponded to the observed concentrations of plastics, though the units are different. The simulated plastic transport in the Yangtze River was much higher than that in the previous data (Zhao et al., 2019) because this data accounted only for the surface layer (around 30 cm depth) and might be underestimated (their estimated flux was 537.6–905.9 tons/yr, and much smaller than other previous studies). The simulated plastic transports in these rivers were generally in the range of previous materials (Jambeck et al., 2015; Lebreton et al., 2017; Schmidt et al., 2017) and showed that the plastic transport became drastically higher during these periods, accounting for most of the annual flux.



Figure 5.4 Simulated results of seasonal variations of riverine plastic transport of Yangtze, Yellow, and Mekong Ganges Rivers; (a) plastic concentration, and (b) plastic transport in these rivers

## 5.4.2 Distribution of Microplastic in Asian major rivers

The model also simulated the size distribution of micro-plastic in the water and sediment of the Yangtze, Mekong, and Ganges Rivers (Fig. 5.5). Generally, the coarser particles are more distributed in the riverbed than those in the water in the same way as the previous studies (Kooi et al., 2018; Liu et al., 2021) (Fig. 5.5c); this is also related to the fact that the micro-plastic sedimentation is promoted by the aggregation of micro-plastic mixed with organic minerals and sediments (Liu et al., 2021). However, the simulated result (Figs 5.5a-b) showed the opposite trend to some field observations in the Yangtze (Li et al., 2020), Mekong (Haberstroh et al., 2021), and Ganges Rivers (Singh et al., 2021), respectively; this is related to the fact that PP tends to be most prevalent in the water and PE is more prevalent in the sediment (Koutnik et al., 2021). In contrast, the model accounted for the different polymer types via the density of the particles. Other studies also showed that most plastics in most rivers are affected by biofouling and an increase in their densities (Kaiser et al., 2017; Kooi et al., 2017). It is a great step to model this process in the present study because few previous studies evaluated the model of the fate and transport of plastics, including settling and resuspension in the global river basins. Interestingly, the simulated total fluxes were within the range of the results reported by Roebroek et al. (2021), representing potential plastic mobilization between non-flood conditions and the undefended 10-year return period. This result suggests that it is important to consider the effect of inter-annual variability to improve the accuracy of plastic flux estimation.



Figure 5.5 Simulated results of the size distribution of microplastic in the water and riverbed sediment of Yangtze, Mekong, and Ganges Rivers; (a) normal frequency distribution in the water, (b) that in the sediment, and (c) relative abundance across different size categories in the water and sediment

# 5.4.3 Impact of Waste Plastic Trade on Change in Riverine Plastic Transport in Asian Region

The authors simulated to evaluate the impact of waste plastic trade on variations of riverine plastic transport in Asian regions (Fig. 5.6). The result reveals that the waste plastic trade causes large differences in plastic transport between exporting and importing countries. The riverine plastic transport decreased greatly in the river basin of the exporting country (Japan) (Figs 5.6a-b), where the plastic in case-c (its density is 1000.5 kg/m<sup>3</sup>) is most sensitive to the plastic trade. In contrast, the transport increases slightly in the Yangtze, Yellow, and Ganges Rivers. It is almost constant in the Mekong, Indus, Irrawaddy, and Brahmaputra Rivers (Fig. 5.6c) by the effect of plastic trade. In particular, the macroplastic flux is mainly affected by the plastic trade because MPW is the important variable for the diffuse input of macroplastics and secondary micro-plastics into rivers in NICE-BGC in the same way as the previous study (van Wijnen et al., 2019) (Fig. 5.2). The result is also related to the dynamic of plastic movement between water and riverbed sediment, which might affect the mobilization of plastic and its high intra-annual variability in each river (Fig. 5.4). Anyway, this result shows that it is necessary to assess

the trade-off of riverine plastic transports between exporting and importing countries in more detail.



Figure 5.6 Impact of waste plastic trade on variations of riverine plastic transport in Asian regions; (a) amount of plastic flux for each first-class of 109 rivers in Japan, (b) total flux in entire Japan, and (c) amount of plastic flux for Asian major rivers

### **5.5** Conclusion

This chapter applied process-based NICE-BGC to Asian regions during the past two years by including the effect of waste plastic trade flow between Japan and abroad. The model was able to simulate the seasonal variations of riverine plastic transport. The result showed that the settling and resuspension of plastic particles greatly impact plastic mobilization and its high intra-annual variability. Further, the authors evaluated the impact of the waste plastic trade on changes in riverine plastic transport in Asian regions by including the effect of waste plastic trade on Mismanaged Plastic Waste (MPW) in the extension of the previous studies. This analysis clarified the waste plastic trade has promoted the decrease of riverine plastic transport in Japanese rivers, its slight increase in the Yangtze, Yellow, and Ganges Rivers, and almost constant in the Mekong, Indus, Irrawaddy, and Brahmaputra Rivers. The present results help to quantify the plastic trade-off about the impact of the export and import of waste plastic on plastic dynamics on a regional scale. They may aid the development of solutions and measures to reduce plastic input to the ocean.

#### References

- Best, J. (2018) Anthropogenic stresses on the world's big rivers. Nature Geoscience, 12, 7–21, doi:10.1038/s41561-018-0262-x
- Brooks, A.L., Wang, S., Jambeck, J.R. (2018) The Chinese import ban and its impact on global plastic waste trade. Scientific Advances, 4(6), eaat0131, doi:10.1126/sciadv.aat0131
- Climatic Research Unit (CRU). (2017) CRU TS3.24 of High Resolution Gridded Data of Month-by-month Variation in Climate. http://catalogue.ceda.ac.uk/
- Dominish, E., Retamal, M., Wakefield-Rann, R., Florin, N. (2020) Environmentally responsible trade in waste plastics Report 1: Investigating the links between trade and marine plastic pollution. Institute for Sustainable Futures, University of Technology Sydney. https://www.dcceew.gov.au/sites/default/files/documents/ertwaste-plastics-report-1.pdf
- Environmental Investigation Agency (EIA). (2021) The Truth Behind Trash: The scale and impact of the international trade in plastic waste. https://eia-international.org/wp-content/uploads/EIA-The-Truth-Behind-Trash-FINAL.pdf
- ESRI. (2019) Overlay Layers. Portal for ArcGIS. https://gislab.depaul.edu/portal/portalhelp/en/portal/latest/use/geoanalytics-overlay-layers.htm
- European Centre for Medium-Range Weather Forecasts (ECMWF). (2019) ERA-Interim. http://data-portal.ecmwf.int/data/d/interim\_daily/
- European Commission. (2012) Harmonized World Soil Database. http://eusoils.jrc.ec.europa.eu/ESDB\_Archive/soil\_data/global.htm
- European Commission. (2015) Global Land Cover 2000. https://forobs.jrc.ec.europa.eu/products/glc2000/glc2000.php
- Food and Agriculture Organization of the United Nations (FAO). (2016) Global Map of Irrigation Areas (GMIA). http://www.fao.org/nr/water/aquastat/irrigationmap/index.stm
- Haberstroh, C.J., Arias, M.E., Yin, Z., et al. (2021) Plastic transport in a complex confluence of the Mekong River in Cambodia. Environmental Research Letters, 16, 095009, doi:10.1088/1748-9326/ac2198
- Han, M., Niu, X., Tang, M., et al. (2020) Distribution of microplastics in surface water of the lower Yellow River near estuary. Science of the Total Environment, 707, 135601, doi:10.1016/j.scitotenv.2019.135601
- Han, N., Ao, H., Zhao, Mai, Z., et al. (2023) Characteristics of (micro)plastic transport in the upper reaches of the Yangtze River. Science of the Total Environment, 855, 158887, doi:10.1016/j.scitotenv.2022.158887
- Hartmann, J., Moosdorf, N. (2012) The new global lithological map database GLiM: A representation of rock properties at the Earth surface. Geochemistry, Geophysics, Geosystems, 13, Q12004, doi:10.1029/2012GC004370
- Hurley, E., Woodward, J., Rothwell, J.J. (2018) Microplastic contamination of river beds significantly reduced by catchment-wide flooding. Nature Geoscience, 11, 251-257, Doi:10.1038/s41561-018-0080-1
- Jambeck, J.R., Geyer, R., Wilcox, C., et al. (2015) Plastic waste inputs from land into the ocean. Science, 347, 768-771, doi:10.1126/science.1260352
- Japanese Government Statistics. (2021) E-Stat: Statistics of Japan. https://www.e-stat.go.jp/en
- Jones, E.R., van Vliet, M.T.H., Qadir, M., Bierkens, M.F.P. (2021) Country-level and gridded estimates of wastewater production, collection, treatment and reuse. Earth System Science Data, 13, 237-254, doi:10.5194/essd-13-237-2021
- Kaiser, D., Kowalski, N., Waniek, J.J. (2017) Effects of biofouling on the sinking behavior of microplastics. Environmental Research Letters, 12, 124003, doi:10.1088/1748-9326/aa8e8b

- Kooi, M., van Nes, E.H., Scheffer, M., Koelmans, A.A. (2017) Ups and downs in the ocean: Effects of biofouling on vertical transport of microplastics. Environmental Science & Technology, 51, 7963-7971, doi:10.1021/acs.est.6b04702
- Kooi, M., Besseling, E., Kroeze, C., et al. (2018) Modelling the fate and transport of plastic decries in freshwaters: review and guidance. In: Wagner, M., Lambert, S. [Eds] Freshwater Microplastics. The Handbook of Environmental Chemistry 58, Springer, pp.125-152
- Kooi, M., Koelmans, A.A. (2019) Simplifying microplastic via continuous probability distributions for size, shape, and density. Environmental Science & Technology Letters, 6, 551-557, doi:10.1021/acs.est.9b00379
- Koutnik, V.S., Leonard, J., Alkidim, S., et al. (2021) Distribution of microplastics in soil and freshwater environments: global analysis and framework for transport modelling. Environmental Pollution, 224, 116552, doi:10.1016/j.envpol.2021.116552
- Kumar, R., Sharma, P., Verma, A., et al. (2021) Effect of physical characteristics and hydrodynamic conditions on transport and deposition of microplastics in riverine ecosystem. Water, 13, 2710. doi:10.3390/w13192710
- Lebreton, L., Andrady, A. 2019. Future scenarios of global plastic waste generation and disposal. Palgrave Communications, 5, 6, doi:10.1057/s41599-018-0212-7
- Lebreton, L, van der Zwet, J., Damsteeg, J.-W., et al. (2017) River plastic emissions to the world's oceans. Nature Communications, 8, 15611, doi:10.1038/ncomms15611
- Lehner, B., Döll, P. (2004) Development and validation of a global database of lakes, reservoirs and wetlands. Journal of Hydrology, 296, 1-22, doi:10.1016/j.jhydrol.2004.03.028
- Lehner, B., Reidy Liermann, C., Revenga, C., et al. (2011) High-resolution mapping of the world's reservoirs and dams for sustainable river-flow management. Frontiers in Ecology and the Environment, 9, 494-502, doi:10.1890/100125
- Li, Y., Lu, Z., Zheng, H., et al. (2020) Microplastics in surface water and sediments of Chongming Island in the Yangtze Estuary, China. Environmental Sciences Europe, 32, 15, doi:10.1186/s12302-020-0297-7
- Liu, Y., You, J., Li, Y., et al. (2021) Insights into the horizontal and vertical profiles of microplastics in a river emptying into the sea affected by intensive anthropogenic activities in Northern China. Science of the Total Environment, 779, 146589, doi:10.1016/j.scitotenv.2021.146589
- Mai, L., Sun, X.-F., Xia, L.-L., Bao, L.-J., Liu, L.-Y., Zeng, E.Y. (2020) Global riverine plastic outflows. Environmental Science & Technology, 54, 10049-10056, doi:10.1021/acs.est.0c02273
- Meijer, L.J.J., van Emmerik, T., van der Ent, R., et al. (2021) More than 1000 rivers account for 80% of global riverine plastic emissions into the ocean. Science Advances, 7, eaaz5803, doi:10.1126/sciadv.aaz5803
- Ministry of Foreign Affairs of Japan. (2019) G20 Osaka Leader's Declaration. https://www.mofa.go.jp/policy/economy/g20\_summit/osaka19/en/documents/final\_g20\_osaka\_leaders\_decl aration.html
- Ministry of Land, Infrastructure, Transport and Tourism (MLIT). (2012) Digital national land information: River networks ver.3.1. https://nlftp.mlit.go.jp/ksj/gml/datalist/KsjTmplt-W05.html
- Ministry of Land, Infrastructure, Transport and Tourism (MLIT). (2013) Digital national land information: Sewerage system related facility ver.1.1. https://nlftp.mlit.go.jp/ksj/gml/datalist/KsjTmplt-P22.html
- Ministry of Land, Infrastructure, Transport and Tourism (MLIT). (2016) Digital national land information: Reservoirs and dams ver.3.0. https://nlftp.mlit.go.jp/ksj/gml/datalist/KsjTmplt-W01.html
- Mueller, N.D., Gerber, J.S., Johnston, M., et al. (2012) Closing yield gaps through nutrient and water management. Nature, 490, 254-257, doi:10.1038/nature11420
- Nakayama, T. (2017a) Development of an advanced eco-hydrologic and biogeochemical coupling model aimed at clarifying the missing role of inland water in the global biogeochemical cycle. Journal of Geophysical Research: Biogeosciences, 122, 966-988, doi:10.1002/2016JG003743
- Nakayama, T. (2017b) Scaled-dependence and seasonal variations of carbon cycle through development of an advanced eco-hydrologic and biogeochemical coupling model. Ecological Modelling, 356, 151-161, doi:10.1016/j.ecolmodel.2017.04.014
- Nakayama, T. (2022) Impact of anthropogenic disturbances on carbon cycle changes in terrestrial-aquaticestuarine continuum by using an advanced process-based model. Hydrological Processes, 36(2), e14471, doi:10.1002/hyp.14471
- Nakayama, T., Osako, M. (2023a) Development of a process-based eco-hydrology model for evaluating the spatiotemporal dynamics of macro- and micro-plastics for the whole of Japan. Ecological Modelling, 476, 110243, doi:10.1016/j.ecolmodel.2022.110243
- Nakayama, T., Osako, M. (2023b) The flux and fate of plastic in the world's major rivers: Modeling spatial and temporal variability. Global and Planetary Change, 221, 104037, doi:10.1016/j.gloplacha.2023.104037
- Nakayama, T., Osako, M. (2024) Plastic trade-off: Impact of export and import of waste plastic on plastic dynamics in Asian region. Ecological Modelling, 489, 110624, doi:10.1016/j.ecolmodel.2024.110624

NASA. (2013) GLDAS vegetation class. http://ldas.gsfc.nasa.gov/gldas/GLDASvegetation.php

- NASA. (2018) Gridded Population of the World, Version 4 (GPWv4). https://sedac.ciesin.columbia.edu/data/set/gpw-v4-population-count-adjusted-to-2015-unwpp-country-totals-rev11
- Nizzetto, L., Bussi, G., Futter, M.N., et al. (2016) A theoretical assessment of microplastic transport in river catchments and their retention by soils and river sediments. Environmental Science: Processes & Impacts, 18, 1050-1059, doi:10.1039/c6em00206d
- OECD. (2022) Global Plastics Outlook: Economic Drivers, Environmental Impacts and Policy Options, OECD Publishing, Paris. https://doi.org/10.1787/de747aef-en
- Our World in Data. (2022) Ocean plastics: How much do rich countries contribute by shipping their waste overseas? https://ourworldindata.org/plastic-waste-trade
- Portmann, F.T., Siebert, S., Döll, P. (2010) MIRCA2000 Global monthly irrigated and rainfed crop areas around the year 2000: A new high-resolution data set for agricultural and hydrological modelling. Global Biogeochemical Cycles, 24, GB 1011, Doi:10.1029/2008GB003435
- Praetorius, A., Scheringer, M., Hungerbühler, K. (2012) Development of environmental fate models for engineered nanoparticles - A case study of TiO2 nanoparticles in the Rhine River. Environmental Science & Technology, 46, 6705-6713, doi:10.1021/es204530n
- Qian, Y., Shang, Y., Zheng, Y., et al. (2023) Temporal and spatial variation of microplastics in Baotou section of Yellow River, China. Journal of Environmental Management, 338, 117803, doi:10.1016/j.jenvman.2023.117803
- Roebroek, C.T.J., Harrigan, S., van Emmerik, T.H.M., et al. (2021) Plastic in global rivers: are floods making it worse? Environmental Research Letters, 16, 025003, doi:10.1088/1748-9326/abd5df
- Schmidt, C., Krauth, T., Wagner, S. (2017) Export of plastic debris by rivers into the sea. Environmental Science & Technology, 51, 12246-12253, doi:10.1021/acs.est.7b02368
- Schwarz, A.E., Ligthart, T.N., Boukris, E., van Harmelen, T. (2019) Sources, transport, and accumulation of different types of plastic litter in aquatic environments: A review study. Marine Pollution Bulletin, 143, 92-100, doi:10.1016/j.marpolbul.2019.04.029
- Siebert, S., Döll, P. (2010) Quantifying blue and green virtual water contents in global crop production as well as potential production losses without irrigation. Journal of Hydrology, 384, 198–217
- Siegfried, M., Koelmans, A.A., Besseling, E., Kroeze, C. (2017) Export of microplastics from land to sea. A modelling approach. Water Research, 127, 249-257, doi:10.1016/j.watres.2017.10.011
- Singh, N., Mondal, A., Bagri, A., et al. (2021) Characteristics and spatial distribution of microplastics in the lower Ganga River water and sediment. Marine Pollution Bulletin, 163, 111960, doi:10.1016/j.marpolbul.2020.111960
- Strokal, M., Bai, Z., Franssen, W., et al. (2021) Urbanization: an increasing source of multiple pollutants to rivers in the 21st century. Urban Sustainability, 1, 24, doi:10.1038/s42949-021-00026-w
- Thompson, R.C., Olsen, Y., Mitchell, R.P., et al. (2004) Lost at sea: Where is all the Plastic? Science, 304, 838, doi:10.1126/science.1094559
- Tian, H., Yang, J., Lu, C., et al. (2018) The global N2O model intercomparison project. Bulletin of the American Meteorological Society, 99(6), 1231-1251, doi:10.1175/bams-d-17-0212.1
- UNESCO. (2022) IHP-IX: Strategic Plan of the Intergovernmental Hydrological Programme: Science for a Water Secure World in a Changing Environment, ninth phase 2022-2029. https://unesdoc.unesco.org/ark:/48223/pf0000381318.locale=en.
- United Nations. (2015) UN Comtrade Database in 2015. https://comtrade.un.org/data/
- United Nations. (2019) Basel Convention: Controlling transboundary movements of hazardous wastes and their disposal.

http://www.basel.int/Implementation/MarinePlasticLitterandMicroplastics/Overview/tabid/6068/Default.asp x

- U.S. Geological Survey (USGS). (1996a) GTOPO30 Global 30 Arc Second Elevation Data Set. USGS. http://www1.gsi.go.jp/geowww/globalmap-gsi/gtopo30/gtopo30.html
- U.S. Geological Survey (USGS). (1996b) HYDRO1K. USGS. https://lta.cr.usgs.gov/HYDRO1K
- U.S. Geological Survey (USGS). (2018) Shuttle Radar Topography Mission (SRTM) 1 Arc-Second Global. USGS. doi:10.5066/F7PR7TFT
- van Emmerik, T., Strady, E., Kieu-Le, T.-C., Nguyen, L., Gratiot, N. (2019) Seasonality of riverine macroplastic transport. Scientific Reports, 9, 13549, doi:10.1038/s41598-019-50096-1
- van Emmerik, T., Schreyers, L.J., Mellink, Y., et al. (2023) Large variation in Mekong river plastic transport between wet and dry season. Frontiers, doi:10.31223/X5HW82

- van Wijnen, J., Ragas, A.M.J., Kroeze, C. (2019) Modelling global river export of microplastics to the marine environment: Sources and future trends. Science of the Total Environment, 673, 392-401, doi:10.1016/j.scitotenv.2019.04.078
- Wagner, S., Klöckner, P., Stier, B., Römer, M., Seiwert, B., Reemtsma, T., Schmidt, C. (2019) Relationship between discharge and river plastic concentrations in a rural and an urban catchment. Environmental Science & Technology, 53, 10082-10091, doi:10.1021/acs.est.9b03048
- Waldschläger, K., Schüttrumpf, H. (2019) Erosion behavior of different microplastic particles in comparison to natural sediments. Environmental Science & Technology, 53, 13219-13227, doi:10.1021/acs.est.9b05394
- Zhang, B., Tian, H., Lu, C., et al. (2017) Global manure nitrogen production and application in cropland during 1860-2014; a 5 arcmin gridded global dataset for Earth system modelling. Earth System Science Data, 9, 667-678, doi:10.5194/essd-9-667-2017
- Zhao, S., Wang, T., Zhu, L., et al. (2019) Analysis of suspended microplastics in the Chagjiang Estuary: Implications for riverine plastic load to the ocean. Water Research, 161, 560-569, doi:10.1016/j.watres.2019.06.019

This article was published in Ecological Modelling, 489, Nakayama, T., Osako, M., Plastic trade-off: Impact of

export and import of waste plastic on plastic dynamics in Asian region, 110624, Copyright Elsevier (2024).

Chapter 5 Plastic Trade-Off: Impact of Export and Import of Waste Plastic on Plastic Dynamics in Asian Region

Chapter 6

## **Final Conclusions and Future Work**

Chapter 6 Final Conclusions and Future Work
## **6.1 Final Conclusions**

In a previous work, the National Integrated Catchment-based Eco-hydrology (NICE) model, which includes surface-groundwater interactions and assimilates land-surface processes, was developed to describe phenology variations based on satellite data (Nakayama, 2008a-c, 2009, 2010, 2011a-d, 2012a-d, 2013, 2014a,b, 2015, 2016, 2017a-c, 2018, 2019, 2020, 2022, 2023a,b; Nakayama and Fujita, 2010; Nakayama and Hashimoto, 2011; Nakayama and Maksyutov, 2018; Nakayama and Osako, 2023a,b, 2024; Nakayama and Pelletier, 2018; Nakayama and Shankman, 2013a,b; Nakayama and Watanabe, 2004, 2005, 2006a,b, 2008a-c; Nakayama et al., 2006, 2007, 2010, 2012, 2021a,b, 2023) (Fig. 1.1). NICE has been applied to various basins/catchments from local and regional scales, such as the Tokyo Metropolitan area in Japan, Kushiro Wetland (the largest wetland in Japan), and Lake Kasumigaura catchment (a highly eutrophic lake in Japan), and to continental and global scales, such as the Changjiang and Yellow Rivers in China, Ob River in West Siberia, Mekong River in Southeast Asia, and Mongolia. The results of these studies have been summarized in previous monograph series: the 11th (Part I), 14th (Part II), 18th (Part III), 20th (Part IV), 26th publications (Part V), and 29th publications (Part VI) (Fig. 1.2). In this monograph (Part VII), NICE was further extended to couple it with the plastic debris model for quantifying the spatiotemporal dynamics of both macro- and micro-plastics and the impacts of plastic waste on terrestrial and aquatic ecosystems and devising solutions and measures for reduction of plastic input to the ocean (Fig. 1.3).

Chapter 2 reports the extension of NICE-BGC to couple with the plastic debris model for freshwater systems and applied it to all the first-class (class A) river basins in Japan (109 river basins). The result showed that large amounts of plastic flowed out of some limited rivers intensively during rainfall seasons. Scenario analysis also quantified the total plastic flux varied according to the efficiency of micro-plastic removal in WWTP and the density of plastic. It was estimated to be within the range of 1,100–3,500 tons/yr (Nakayama and Osako, 2023a).

Chapter 3 reports the application of NICE-BGC coupled with the plastic debris model to the world's major rivers (325 rivers) to simulate the fate and transport of plastics on a global scale. The model revealed a seasonal variation of plastic flux in Asia and its large contribution that was affected by the summer monsoon. Monte Carlo model simulations assuming a continuous probability distribution of size, shape, and density also clarified the effects of various factors on plastic transport. Most plastic fluxes were shown to flow out of about 20 global rivers, reflecting that flood events greatly impact plastic mobilization and high inter-annual variability (Nakayama and Osako, 2023b).

Chapter 4 reports the extension of NICE-BGC to couple with LAKE2K in a stratified water quality model to evaluate the global plastic dynamics in both lotic and lentic waters. The model simulated plastic sedimentation in both lakes and reservoirs and showed more plastic deposits than in the lakes except for the Caspian Sea. Most lentic waters deposit more micro-plastics than macro-plastics (Nakayama, under review).

Chapter 5 reports the application of the above model to Asian regions during the past two years by including the effect of waste plastic trade flow between Japan and abroad. The model evaluated the impact of the waste plastic trade on changes in riverine plastic transport in Asian regions by including the effect of the waste plastic trade on MPW in the extension of the previous studies (Nakayama and Osako, 2024).

In this monograph, the new model simulated the spatiotemporal dynamics of the plastic cycle in various basins, both on regional and global scales. In particular, they simulated the retention and degradation of plastics in inland water by including advection, dispersion, diffusion, settling, dissolution and deterioration due to light and temperature (Figs. 2.5 and 2.6);

this is a great improvement from previous studies that did not account for remobilization or burial of microplastic particles (Siegfried et al., 2017; Meijer et al., 2021), and assumed a constant retention factor and transport of a constant fraction of MPW to rivers (van Wijnen et al., 2019). Using untreated wastewater with a reasonable spatial distribution (Jones et al., 2021) and simulation of a two-dimensional diffusion model for macro-plastic transport (Fig. 3.3) represented an extension of previous studies on a global scale. The result showed that the process-based model is powerful enough to quantify the detailed processes of the plastic cycle, some of which were simulated in black boxes by most previous models. In contrast, more spatiotemporal input data on MPW in various sectors is required. However, the new model is useful for evaluating the spatiotemporal dynamics of plastic cycles in basin scales. The use of more ground data, GPS tracking, image analysis of drones, and aerial photographs, and the application of a learning algorithm, such as random forest, to improve census data downscaling (Nicolas et al., 2016) are necessary to improve the accuracy of the heterogeneous distribution of plastic dynamics and their seasonal variations on various basins.

The model also clarified that the horizontal transport and vertical burial of plastic litter might be greatly affected by reservoirs and lakes in the major global rivers (Fig. 4.5) and that the application of the same partial differential equations as in inorganic carbon for the derivatives as assumed by the author's previous study (Nakayama and Pelletier, 2018) is limited when the plastic density is higher than that of water (Figs 4.3 and 4.4). However, many small and medium rivers and their reservoirs and lakes are also not yet included, though the model includes the world's major river basins (153 basins), which occupy about 65.9% of the total continental area (Nakayama, 2017a, 2017b, 2022). Further, the model showed that the transport of plastic litter might be affected by urbanization and waste plastic trade on a regional scale (Brooks et al., 2018; Strokal et al., 2021) (Fig. 5.6). However, the authors assumed that the ratio between MPW and municipal plastic waste was constant both with and without the effects of plastic trade and disposal in each country (Fig. 5.3 and Table 5.2). From this viewpoint, it is necessary to understand the relevance of the plastic waste trade and verify the value of this revised MPW, considering the plastic waste trade in more detail in the future. From another point of view, it is also valuable to combine NICE with social system methods such as material flow analysis for assessing loss and emissions into the aquatic environment (OECD, 2022) instead of inputting the given value of MPW (Fig. 5.2).

NICE is a useful tool for predicting and resolving future problems about plastic pollution in various basins. This methodology is also useful for evaluating spatiotemporal variations in plastic dynamics with limited inventory data, particularly in developing countries. The future effects of extensive plastic disposal have not been clarified yet. Therefore, it is also a useful tool to quantify plastic trade-offs about the impact of the export and import of waste plastic on plastic dynamics on a regional scale and may aid the development of solutions and measures to reduce plastic input to the ocean.

## 6.2 Future Work

This monograph (Part VII) indicates the new development, coupled with eco-hydrology and plastic debris model, and its application to various basins from regional to global scales for quantifying the fate and transport of plastic dynamics there. The result about regional scale made clear that more detailed data about size, shape, and density is needed (Fig. 2.6). Future advances in the uncertainty model would greatly contribute to the elucidation of the transport and the retention of macro- and micro-plastics in rivers together with further field surveys and laboratory experiments about plastic degradation through photodegradation, temperature, physical abrasion, biodegradation, and weathering. The result on a global scale showed that flood events have a great impact on plastic mobilization and its high inter-annual variability (Fig. 3.5). In addition, the concrete composition of artificial structures and their operations might have different effects on the variations of the plastic cycle and should be evaluated more accurately (Fig. 4.5). Evaluating efficient spatiotemporal extrapolation methods from limited data, particularly in developing countries, is becoming extremely important. Further, the result showed that the transport of plastic litter might be affected by urbanization and waste plastic trade on a regional scale (Fig. 5.6). It is further necessary to improve the accuracy to resolve the impact of plastic trade-off on the plastic cycle in the basin scale, so-called, the transboundary pollution problem of the plastic cycle, which has become increasingly serious in recent years.

To solve the above plastic problems, now the model is being further extended to include another process to incorporate various datasets and to improve the accuracy of simulated results on both regional and global scales concerning the following:

(i) The interaction with suspended matter (hetero-aggregation), resuspension, biofouling, and wind effects should be included in the model (Praetorius et al., 2012; Kooi et al., 2017; Waldschläger and Schüttrumpf, 2019). NICE was further developed by coupling it with biogeochemical cycle models (NICE-BGC), thus incorporating hydrological, nutrient, and carbon cycles in terrestrial–aquatic linkages, including aquatic metabolism and terrestrially derived carbon (Nakayama, 2017a,b, 2020, 2022, 2023) (Fig. 6.1). In the future, NICE-BGC should be expanded to include hetero-aggregation, resuspension, biofouling, and wind effects to improve the accuracy of the plastic cycle.

(ii) Most models ignored the impact of flood events on plastic mobilization and suggested its high inter-annual variability where the plastic transport increases up to a factor of five to ten at the floods (van Emmerik et al., 2019; Roebroek et al., 2021). Because it is expected that extreme events such as floods and droughts will increase further with climate change, it is important to evaluate the impact of flood events on plastic mobilization and its high variability by using the process-oriented model (Nakayama, under review) (Fig. 6.2). This is also effective to clarify the dominant contribution of the summer monsoon in Asia and that more than 74% waste is delivered between May and October from few large rivers in Asia (Lebreton et al., 2017; Best, 2019) (Fig. 3.5).

(iii) The author's previous study showed that estuarine carbon cycle was sensitive to intense anthropogenic disturbances reflected by nutrient load, seawater temperature, sea level rise, and ocean acidification (Nakayama, 2022) (Fig. 6.3). Because the plastic dynamics are closely related to the carbon cycles, such as flocculation, heteroaggregation, and biofouling, it is important to extended NICE-BGC to evaluate biogeochemical and plastic dynamics in terrestrial-aquatic-estuarine continuum (Nakayama, in prep.).

(iv) In more detail, the model should include the effects of waste plastic trade and disposal between exporting and importing countries (Brooks et al., 2018). Therefore, the fate and transport models should be combined with social system methods such as material flow analysis for assessing loss and emissions into the aquatic environment (OECD, 2022) instead of inputting the given value of MPW (Fig. 5.2) under climate change conditions.

Plastic pollution has recently been considered a serious environmental problem, and pollutants from land to rivers and finally to oceans severely affect human health and the environment (Siegfried et al., 2017). Previous studies on the origin and fate of plastic waste in freshwater systems suggested that land-derived plastics are the dominant source of marine plastic pollution (Thompson et al., 2004). It is necessary to identify plastic pollution hotspots

and sinks and resolve the source–flux–sink nexus within river basins (Windsor et al., 2019). From another point of view, developing a framework to reverse the degradation of global water resources, particularly plastic pollution, is crucial for achieving the Sustainable Development Goals (SDG) (UNESCO, 2022). The recent G20 Osaka Summit in 2019 shared the "Osaka Blue Ocean Vision" (Ministry of Foreign Affairs of Japan, 2019), which is positioned alongside the Conference of the Parties (COP) as a part of global warming countermeasures. A quantitative assessment of plastic fate and transport will be necessary to realize this vision because countries worldwide have decided on concrete future measures for dealing with plastics based on scientific results.

The ongoing studies (i)–(iv) are expected to be reported in the next monograph (Part VIII) in the future.



Figure 6.1 Flow diagram of the original NICE regarding water resources and recent development of the eco-hydrological and biogeochemical coupling model (NICE-BGC)



Figure 6.2 Percentages of (a) exporting micro-plastic load stored on the riverbed and (b) plastic load transported to the ocean during flood periods in some major global rivers.



Figure 6.3 Improvement of the carbon cycle by including global estuaries; (a) CO<sub>2</sub> flux in global estuaries, and (b) CO<sub>2</sub> evasion and sediment storage in each continent

#### References

- Best, J. (2019) Anthropogenic stresses on the world's big rivers. Nature Geoscience, 12, 7-21, doi:10.1038/s41561-018-0262-x
- Brooks, A.L., Wang, S., Jambeck, J.R. (2018) The Chinese import ban and its impact on global plastic waste trade. Scientific Advances, 4(6), eaat0131, doi:10.1126/sciadv.aat0131
- Jones, E.R., van Vliet, M.T.H., Qadir, M., Bierkens, M.F.P. (2021) Country-level and gridded wastewater production, collection, treatment, and reuse estimates. Earth System Science Data, 13, 237-254, doi:10.5194/essd-13-237-2021.
- Kooi, M., van Nes, E.H.V., Scheffer, M., Koelmans, A.A. (2017) Ups and downs in the ocean: Effects of biofouling on vertical transport of microplastics. Environmental Science and Technology, 51, 7963-7971, doi: 10.1021/acs.est.6b04702
- Lebreton, L.C.M., van der Zwet, J., Damsteeg, J.W. et al. (2017) River plastic emissions to the world's oceans. Nature Communications, 8, 15611, doi: 10.1038/ncomms15611
- Meijer, L.J.J., van Emmerik, T., van dr Ent, R., et al. (2021) More than 1000 rivers account for 80% of global riverine plastic emissions into the ocean. Science Advances, 7, eaaz5803, doi:10.1126/sciadv.aaz5803
- Ministry of Foreign Affairs of Japan. (2019) G20 Osaka Leader's declaration. https://www.mofa.go.jp/policy/economy/g20\_summit/osaka19/en/documents/final\_g20\_osaka\_leaders\_decl aration.html

- Nakayama, T., Watanabe, M. (2004) Simulation of drying phenomena associated with vegetation change caused by invasion of alder (*Alnus japonica*) in Kushiro Mire. Water Resources Research, 40, W08402, doi:10.1029/2004WR003174
- Nakayama, T., Watanabe, M. (2005) Re-evaluation of groundwater dynamics about water and nutrient budgets in Lake Kasumigaura, Annual. Journal of Hydroscience and Hydraulic Engineering, 49, 1231-1236 (Abst. in English)
- Nakayama, T., Watanabe, M. (2006a) Simulation of spring snowmelt runoff by considering micro-topography and phase changes in soil layer. Hydrology and Earth System Sciences Discussions, 3, 2101-2144
- Nakayama, T., Watanabe, M. (2006b) Development of process-based NICE model and simulation of ecosystem dynamics in the catchment of East Asia (Part I). CGER's supercomputer monograph report, 11. NIES, 100p., http://www.cger.nies.go.jp/publications/report/i063/I063e
- Nakayama, T., Yang, Y., Watanabe, M., Zhang, X. (2006) Simulation of groundwater dynamics in the North China Plain by coupled hydrology and agricultural models. Hydrological Processes, 20, 3441-3466, doi:10.1002/hyp.6142
- Nakayama, T., Watanabe, M., Tanji, K., Morioka, T. (2007) Effect of underground urban structures on eutrophic coastal environment. Science of the Total Environment, 373, 270-288, doi: 10.1016/j.scitotenv.2006.11.033
- Nakayama, T. (2008a) Factors controlling vegetation succession in Kushiro Mire. Ecological Modelling, 215, 225-236., doi:10.1016/j.ecolmodel.2008.02.017
- Nakayama, T. (2008b) Shrinkage of shrub forest and recovery of mire ecosystem by river restoration in northern Japan. Forest Ecology and Management, 256, 1927-1938, doi:10.1016/j.foreco.2008.07.017
- Nakayama, T. (2008c) Development of process-based NICE model and simulation of ecosystem dynamics in the catchment of East Asia (Part II). CGER's supercomputer monograph report, 14. NIES, 91p., http://www.cger.nies.go.jp/publications/report/i083/i083e
- Nakayama, T., Watanabe, M. (2008a) Missing role of groundwater in water and nutrient cycles in the shallow eutrophic Lake Kasumigaura, Japan. Hydrological Processes, 22, 1150-1172, doi:10.1002/hyp.6684
- Nakayama, T., Watanabe, M. (2008b) Role of flood storage ability of lakes in the Changjiang River catchment. Global and Planetary Change, 63, 9-22, doi:10.1016/j.gloplacha.2008.04.002
- Nakayama, T., Watanabe, M. (2008c) Modelling the hydrologic cycle in a shallow eutrophic lake. SIL Proceedings, 1922-2010 (International Association of Theoretical and Applied Limnology), 30, 345-348
- Nakayama, T. (2009) Simulation of ecosystem degradation and its application for effective policy-making in regional scale. In: Gallo, M. N. M., Ferrari, H. (Eds) River Pollution Research Progress (Chapter 1), Nova Science Pub., Inc., New York, pp. 1-89
- Nakayama, T. (2010) Simulation of hydrologic and geomorphic changes affecting a shrinking mire. River Research and Applications, 26, 305-321, doi:10.1002/rra.1253
- Nakayama, T., Fujita, T. (2010) Cooling effect of water-holding pavements made of new materials on water and heat budgets in urban areas. Landscape and Urban Planning, 96, 57-67, doi:10.1016/j.landurbplan.2010.02.003
- Nakayama, T., Sun, Y., Geng, Y. (2010) Simulation of water resource and its relation to urban activity in Dalian City, Northern China. Global and Planetary Change, 73, 172-185, doi:10.1016/j.gloplacha.2010.06.001
- Nakayama, T. (2011a) Simulation of complicated and diverse water system accompanied by human intervention in the North China Plain. Hydrological Processes, 25, 2679-2693, doi:10.1002/hyp.8009
- Nakayama, T. (2011b) Simulation of the effect of irrigation on the hydrologic cycle in the highly cultivated Yellow River Basin. Agricultural and Forest Meteorology, 151, 314-327, doi:10.1016/j.agrformet.2010.11.006
- Nakayama, T. (2011c) Feedback mechanism and complexity in ecosystem–development of integrated assessment system towards eco-conscious society-, Chemical Engineering of Japan, 75, 789-791 (in Japanese)
- Nakayama, T. (2011d) Construction of integrated assessment system for win-win solution of hydrothermal degradations in urban area towards eco-conscious society, Chemical Information and Computer Sciences, 29, 63-65 (in Japanese)
- Nakayama, T., Hashimoto, S. (2011) Analysis of the ability of water resources to reduce the urban heat island in the Tokyo megalopolis. Environmental Pollution, 159, 2164-2173, doi:10.1016/j.envpol.2010.11.016
- Nakayama, T. (2012a) Visualization of the missing role of hydrothermal interactions in a Japanese megalopolis for a win-win solution. Water Science and Technology, 66, 409-414, doi:10.2166/wst.2012.205
- Nakayama, T. (2012b) Feedback and regime shift of mire ecosystem in northern Japan. Hydrological Processes, 26, 2455-2469, doi:10.1002/hyp.9347
- Nakayama, T. (2012c) Impact of anthropogenic activity on eco-hydrological process in continental scales. Procedia Environmental Sciences, 13, 87-94, doi:10.1016/j.proenv.2012.01.008

- Nakayama, T. (2012d) Development of process-based NICE model and simulation of ecosystem dynamics in the catchment of East Asia (Part III). CGER's supercomputer monograph report, 18. NIES, 98p., http://www.cger.nies.go.jp/publications/report/i103/en/
- Nakayama, T., Hashimoto, S., Hamano, H. (2012) Multiscaled analysis of hydrothermal dynamics in Japanese megalopolis by using integrated approach. Hydrological Processes, 26, 2431-2444, doi:10.1002/hyp.9290
- Nakayama, T. (2013) For improvement in understanding eco-hydrological processes in mire. Ecohydrology and Hydrobiology, 13, 62-72, doi:10.1016/j.ecohyd.2013.03.004
- Nakayama, T., Shankman, D. (2013a) Impact of the Three-Gorges Dam and water transfer project on Changjiang floods. Global and Planetary Change, 100, 38-50, doi:10.1016/j.gloplacha.2012.10.004
- Nakayama, T., Shankman, D. (2013b) Evaluation of uneven water resource and relation between anthropogenic water withdrawal and ecosystem degradation in Changjiang and Yellow River Basins. Hydrological Processes, 27(23), 3350-3362, doi:10.1002/hyp.9835
- Nakayama, T. (2014a) Hydrology–ecology interactions. In: Eslamian, S. (Ed.) Handbook of Engineering Hydrology, 1: Fundamentals and Applications (Chapter 16), Taylor & Francis, pp. 329-344
- Nakayama, T. (2014b) Development of process-based NICE model and simulation of ecosystem dynamics in the catchment of East Asia (Part IV). CGER's supercomputer monograph report, 20. NIES, 102p., http://www.cger.nies.go.jp/publications/report/i114/en/
- Nakayama, T. (2014) Integrated assessment system using process-based eco-hydrology model for adaptation strategy and effective water resources management. In: Lakshmi, V. (Ed.) Remote Sensing of the Terrestrial Water Cycle (Geophysical Monograph Series 206) (Chapter 33), AGU, pp. 521-535, doi:10.1002/9781118872086.ch33
- Nakayama, T. (2016) New perspective for eco-hydrology model to constrain missing role of inland waters on boundless biogeochemical cycle in terrestrial-aquatic continuum. Ecohydrology and Hydrobiology, 16, 138-148, doi:10.1016/j.ecohyd.2016.07.002
- Nakayama, T. (2017a) Development of an advanced eco-hydrologic and biogeochemical coupling model aimed at clarifying the missing role of inland water in the global biogeochemical cycle. Journal of Geophysical Research: Biogeosciences, 122, 966-988, doi:10.1002/2016JG003743
- Nakayama, T. (2017b) Scaled-dependence and seasonal variations of carbon cycle through development of an advanced eco-hydrologic and biogeochemical coupling model. Ecological Modelling, 356, 151-161, doi:10.1016/j.ecolmodel.2017.04.014
- Nakayama, T. (2017c) Biogeochemical contrast between different latitudes and the effect of human activity on spatiotemporal carbon cycle change in Asian river systems. Biogeosciences Discussions, doi:10.5194/bg-2017-447
- Nakayama, T. (2018) Interaction between surface water and groundwater and its effect on ecosystem and biogeochemical cycle. Journal of Groundwater Hydrology, 60, 143-156, doi:10.5917/jagh.60.143 (in Japanese)
- Nakayama, T., Maksyutov, S. (2018) Application of process-based eco-hydrological model to broader northern Eurasia wetlands through coordinate transformation. Ecohydrology and Hydrobiology, 18, 269-277, doi:10.1016/j.ecohyd.2017.11.002
- Nakayama, T., Pelletier, G.J. (2018) Impact of global major reservoirs on carbon cycle changes by using an advanced eco-hydrologic and biogeochemical coupling model. Ecological Modelling, 387, 172-186, doi:10.1016/j.ecolmodel.2018.09.007
- Nakayama, T. (2019) Development of process-based NICE model and simulation of ecosystem dynamics in the catchment of East Asia (Part V). CGER's supercomputer monograph report, 26. NIES, 122p., http://www.cger.nies.go.jp/publications/report/i148/en/
- Nakayama, T. (2020) Inter-annual simulation of global carbon cycle variations in a terrestrial-aquatic continuum. Hydrological Processes, 34, 662-678, doi:10.1002/hyp.13616
- Nakayama, T., Wang, Q., Okadera, T. (2021a) Evaluation of spatio-temporal variations in water availability using a process-based eco-hydrology model in arid and semi-arid regions of Mongolia. Ecological Modelling, 440, 109404, doi:10.1016/j.ecolmodel.2020.109404
- Nakayama, T., Wang, Q., Okadera, T. (2021b) Sensitivity analysis and parameter estimation of anthropogenic water uses for quantifying relation between groundwater overuse and water stress in Mongolia. Ecohydrology and Hydrobiology, 21, 490-500, doi:10.1016/j.ecohyd.2021.07.006
- Nakayama, T. (2022) Impact of anthropogenic disturbances on carbon cycle changes in terrestrial-aquaticestuarine continuum by using an advanced process-based model. Hydrological Processes, 36, e14471, doi:10.1002/hyp.14471
- Nakayama, T. (2023a) Evaluation of global biogeochemical cycle in lotic and lentic waters by developing an advanced eco-hydrologic and biogeochemical coupling model. Ecohydrology, e2555, doi:10.1002/eco.2555

- Nakayama, T. (2023b) Development of process-based NICE model and simulation of ecosystem dynamics in the catchment of East Asia (Part VI). CGER's supercomputer monograph report, 29. NIES, 95p., http://www.cger.nies.go.jp/publications/report/i164/en/
- Nakayama, T., Okadera, T., Wang, Q. (2023) Impact of various anthropogenic disturbances on water availability in the entire Mongolian basins towards effective utilization of water resources. Ecohydrology and Hydrobiology, 23(4), doi:10.1016/j.ecohyd.2023.04.006
- Nakayama, T., Osako, M. (2023a) Development of a process-based eco-hydrology model for evaluating the spatiotemporal dynamics of macro- and micro-plastics for the whole of Japan. Ecological Modelling, 476, 110243, doi:10.1016/j.ecolmodel.2022.110243
- Nakayama, T., Osako, M. (2023b) The flux and fate of plastic in the world's major rivers: Modelling spatial and temporal variability. Global and Planetary Change, 221, 104037, doi:10.1016/j.gloplacha.2023.104037
- Nakayama, T., Osako, M. (2024) Plastic trade-off: Impact of export and import of waste plastic on plastic dynamics in Asian region. Ecological Modelling, 489, 110624, doi:10.1016/j.ecolmodel.2024.110624
- Nakayama, T. (under review) Impact of global major reservoirs and lakes on plastic dynamics by using a processbased eco-hydrology model. Lakes and Reservoirs: Research and Management
- Nakayama, T. (under review) Impact of settling and resuspension on plastic dynamics during extreme flow and their seasonality in global major rivers. Hydrological Processes
- Nakayama, T. (under review) Evaluation of flux and fate of plastic in terrestrial-aquatic-estuarine continuum by using an advanced process-based model. Ecohydrology
- Nicolas, G., Robinson, T.P., Wint, G.R., et al. (2016) Using random forest to improve the downscaling of global livestock census data. PLOS ONE, 11, e0150424, doi:10.1371/journal.pone.0150424
- OECD. (2022) Global Plastics Outlook: Economic Drivers, Environmental Impacts and Policy Options, OECD Publishing, Paris. https://doi.org/10.1787/de747aef-en
- Praetorius, A., Scheringer, M., Hungerbühler, K. (2012) Development of environmental fate models for engineered nanoparticles - A case study of TiO2 nanoparticles in the Rhine River. Environmental Science and Technology, 46, 6705-6713, doi:10.1021/es204530n
- Roebroek, C.T.J., Harrigan, S., van Emmerik, T.H.M., et al. (2021) Plastic in global rivers: are floods making it worse? Environmental Research Letters, 16, 025003, doi:10.1088/1748-9326/abd5df
- Siegfried, M., Koelmans, A.A., Besseling, E., Kroeze, C. (2017) Export of microplastics from land to sea. A modelling approach. Water Research, 127, 249-257, doi:10.1016/j.watres.2017.10.011
- Strokal, M., Bai, Z., Franssen, W., et al. (2021) Urbanization: an increasing source of multiple pollutants to rivers in the 21st century. Urban Sustainability, 1, 24, doi:10.1038/s42949-021-00026-w
- Thompson, R.C., Olsen, Y., Mitchell, R.P., et al. (2004) Lost at sea: Where is all the Plastic? Science, 304, 838, doi:10.1126/science.1094559
- UNESCO (2022) IHP-IX: Strategic Plan of the intergovernmental hydrological programme: Science for a water secure world in a changing environment, ninth phase 2022-2029. https://unesdoc.unesco.org/ark:/48223/pf0000381318.locale=en
- van Emmerik, T., Strady, E., Kieu-Le, T.-C., Nguyen, L., Gratiot, N. (2019) Seasonality of riverine macroplastic transport. Scientific Reports, 9, 13549, doi:10.1038/s41598-019-50096-1
- van Wijnen, J., Ragas, A.M.J., Kroeze, C. (2019) Modelling global river export of microplastics to the marine environment: Sources and future trends. Science of the Total Environment, 673, 392-401, doi:10.1016/j.scitotenv.2019.04.078
- Waldschläger, K., Schüttrumpf, H. (2019) Erosion behavior of different microplastic particles in comparison to natural sediments. Environmental Science and Technology, 53, 13219-13227, doi:10.1021/acs.est.9b05394
- Windsor, F.M., Durance, I., Horton, A.A., et al. (2019) A catchment-scale perspective of plastic pollution. Global Change Biology, 25, 1207-1221, doi:10.1111/gcb.14572

Chapter 6 Final Conclusions and Future Work

# Appendix

# **Publications and Presentations**

Appendix Publications and Presentations

### **Publications and Presentations**

#### **Original Papers and Reviews Related to This Monograph:**

- Nakayama, T., Osako, M. (2023a) Development of a process-based eco-hydrology model for evaluating the spatiotemporal dynamics of macro- and micro-plastics for the whole of Japan. Ecological Modelling, 476, 110243, doi:10.1016/j.ecolmodel.2022.110243
- Nakayama, T., Osako, M. (2023b) The flux and fate of plastic in the world's major rivers: Modeling spatial and temporal variability. Global and Planetary Change, 221, 104037, doi:10.1016/j.gloplacha.2023.104037
- Nakayama, T., Osako, M. (2024) Plastic trade-off: Impact of export and import of waste plastic on plastic dynamics in Asian region. Ecological Modelling, 489, 110624, doi:10.1016/j.ecolmodel.2024.110624
- Nakayama, T. (under review) Impact of global major reservoirs and lakes on plastic dynamics by using a processbased eco-hydrology model. Lakes and Reservoirs: Research and Management
- Nakayama, T. (under review) Impact of settling and resuspension on plastic dynamics during extreme flow and their seasonality in global major rivers. Hydrological Processes
- Nakayama, T. (under review) Evaluation of flux and fate of plastic in terrestrial-aquatic-estuarine continuum by using an advanced process-based model. Ecohydrology

#### **Conference Reports Related to This Monograph:**

- Nakayama, T., Imaizumi, Y., Ishigaki, T., Osako, M. (2021) Evaluation of spatio-temporal dynamics of microplastics developing a process-based eco-hydrology model in Japan. paper number VPA-062, Waste Management and Valorisation for a Sustainable Future, Seoul, South Korea (Virtual Conference), 26–28 October (Website)
- Nakayama, T., Imaizumi, Y., Ishigaki, T., Osako, M. (2022) Simulation of plastic pathways from land to ocean using spatio-temporally explicit eco-hydrology model in entire Japan. paper number IN01A, Ocean Sciences Meeting 2022, Honolulu, USA (Virtual Conference), 27 February 4 March (Website)
- Nakayama, T., Osako, M. (2022) Evaluation of fate and transport of macro- and micro-plastics in terrestrial-aquatic continuum of entire Japan by developing a spatio-temporally explicit eco-hydrology model. paper number EGU22-1566, EGU General Assembly 2022, Vienna, Austria (Virtual Conference), 23– 27 May (Website), doi: 10.5194/egusphere-egu22-1566
- Nakayama, T., Osako, M. (2022) Seasonal variations of fate and transport of plastic debris in global scale. session number TS-2.2, 7th International Marine Debris Conference, Busan, Korea (Virtual Conference), 18–23 September (Website)
- Nakayama, T., Osako, M. (2022) Spatio-temporal dynamics of riverine plastic transport in continental and global scales by developing an advanced process-based model. paper number H54G-07, AGU Fall Meeting 2022, Chicago, USA (Virtual Conference), 12–16 December (Website)
- Nakayama, T., Osako, M. (2023) Seasonal variations of plastic transport in global major rivers. session number 12dO1, Goldschmidt2023, Lyon, France (Virtual Conference), 9-14 July (Website)
- Nakayama, T. (2023) Impact of extreme flow and seasonality on plastic dynamics in global river basins. paper number H52F-06, AGU23, San Francisco, USA (Virtual Conference), 11–15 December (Website)
- Nakayama, T. (2024) Evaluation of biogeochemical cycles and their relation to plastic dynamics in terrestrialaquatic-estuarine continuum by using an advanced process-based model. paper number OP31F-07, Ocean Sciences Meeting 2024, New Orleans, USA (Virtual Conference), 18-23 February (Website)

## NICE Series in CGER's Supercomputer Monograph Report (Part I - VI):

- Nakayama, T., Watanabe, M. (2006) Development of process-based NICE model and simulation of ecosystem dynamics in the catchment of East Asia (Part I). CGER's Supercomputer Monograph Report, 11, NIES, 100p., http://www.cger.nies.go.jp/publications/report/i063/I063e
- Nakayama, T. (2008) Development of process-based NICE model and simulation of ecosystem dynamics in the catchment of East Asia (Part II). CGER's Supercomputer Monograph Report, 14, NIES, 91p., http://www.cger.nies.go.jp/publications/report/i083/i083\_e
- Nakayama, T. (2012) Development of process-based NICE model and simulation of ecosystem dynamics in the catchment of East Asia (Part III). CGER's Supercomputer Monograph Report, 18, NIES, 98p., http://www.cger.nies.go.jp/publications/report/i103/en/
- Nakayama, T. (2014) Development of process-based NICE model and simulation of ecosystem dynamics in the catchment of East Asia (Part IV). CGER's Supercomputer Monograph Report, 20, NIES, 102p., http://www.cger.nies.go.jp/publications/report/i114/en/
- Nakayama, T. (2019) Development of process-based NICE model and simulation of ecosystem dynamics in the catchment of East Asia (Part V). CGER's Supercomputer Monograph Report, 26, NIES, 122p., http://www.cger.nies.go.jp/publications/report/i148/en/
- Nakayama, T. (2023) Development of process-based NICE model and simulation of ecosystem dynamics in the catchment of East Asia (Part VI). CGER's Supercomputer Monograph Report, 29, NIES, 95p., http://www.cger.nies.go.jp/publications/report/i167/en/

## **Contact Person**

Tadanobu Nakayama

Regional Environment Conservation Division National Institute for Environmental Studies (NIES) 16-2 Onogawa, Tsukuba, Ibaraki 305-8506, Japan Phone: +81-29-850-2564 E-mail: nakat@nies.go.jp

Profile: https://www.nies.go.jp/researchers-e/100190.html ORCID: https://orcid.org/0000-0002-8233-034X Web of Science: https://www.webofscience.com/wos/author/record/938567 ResearchGate: https://www.researchgate.net/profile/Tadanobu\_Nakayama

## CGER'S SUPERCOMPUTER ACTIVITY REPORT (Out of stock)

Vol. 1-1992 (CGER-I010-1994) Vol. 2-1993 (CGER-I016-1994) Vol. 3-1994 (CGER-I020-1995) Vol. 4-1995 (CGER-I024-1996) Vol. 5-1996 (CGER-I030-1997) Vol. 6-1997 (CGER-I034-1999) Vol. 7-1998 (CGER-I039-2000) Vol. 8-1999 (CGER-I043-2000) Vol. 9-2000 (CGER-I050-2002) Vol.10-2001 (CGER-I054-2002) Vol.11-2002 (CGER-I058-2004) Vol.12-2003 (CGER-I061-2005) Vol.13-2004 (CGER-I064-2006) Vol.14-2005 (CGER-I070-2007)

## 国立環境研究所スーパーコンピュータ利用研究年報 NIES Supercomputer Annual Report

平成 18 年度 2006 (CGER-I078-2008) Out of stock 平成 19 年度 2007 (CGER-I086-2008) Out of stock 平成 20 年度 2008 (CGER-I090-2009) Out of stock 平成 21 年度 2009 (CGER-I095-2010) Out of stock 平成 22 年度 2010 (CGER-I099-2011) Out of stock 平成 23 年度 2011 (CGER-I106-2012) Out of stock 平成 24 年度 2012 (CGER-I113-2013) Out of stock 平成 25 年度 2013 (CGER-I119-2014) Out of stock 平成 26 年度 2014 (CGER-I125-2015) 平成 27 年度 2015 (CGER-I130-2016) 平成 28 年度 2016 (CGER-I136-2017) 平成 29 年度 2017 (CGER-I141-2018) 平成 30 年度 2018 (CGER-I146-2019) 令和元年度 2019 (CGER-I151-2020) 令和2年度2020 (CGER-I156-2021) 令和3年度2021(CGER-I161-2022) 令和4年度2022(CGER-I168-2024)

## **CGER'S SUPERCOMPUTER MONOGRAPH REPORT**

- Vol. 1 CGER-I021-'96 (Out of stock) KOMORI S.: Turbulence Structure and CO<sub>2</sub> Transfer at the Air-Sea Interface and Turbulent Diffusion in Thermally-Stratified Flows
- Vol. 2 CGER-I022-'96 (Out of stock) TOKIOKA T., NODA A., KITOH A., NIKAIDOU Y., NAKAGAWA S., MOTOI T., YUKIMOTO S., TAKATA K.: A Transient CO<sub>2</sub> Experiment with the MRI CGCM -Annual Mean Response-
- Vol. 3 CGER-I025-'97 (Out of stock) NUMAGUTI A., SUGATA S., TAKAHASHI M., NAKAJIMA T., SUMI A.: Study on the Climate System and Mass Transport by a Climate Model
- Vol. 4 CGER-I028-'97 (Out of stock)
  AKIYOSHI H.: Development of a Global 1-D Chemically Radiatively Coupled Model and an Introduction to the Development of a Chemically Coupled General Circulation Model

- Vol. 5 CGER-I035-'99 (Out of stock)
  WATANABE M., AMANO K., KOHATA K.: Three-Dimensional Circulation Model Driven by Wind, Density, and Tidal Force for Ecosystem Analysis of Coastal Seas
- Vol. 6 CGER-I040-2000 (Out of stock) HAYASHI Y.Y., TOYODA E., HOSAKA M., TAKEHIRO S., NAKAJIMA K., ISHIWATARI M.: Tropical Precipitation Patterns in Response to a Local Warm SST Area Placed at the Equator of an Aqua Planet
- Vol. 7 CGER-I045-2001 (Out of stock) NODA A., YUKIMOTO S., MAEDA S., UCHIYAMA T., SHIBATA K., YAMAKI S.: A New Meteorological Research Institute Coupled GCM (MRI-CGCM2) -Transient Response to Greenhouse Gas and Aerosol Scenarios-
- Vol. 8 CGER-I055-2003 (Out of stock)
  NOZAWA T., EMORI S., NUMAGUTI A., TSUSHIMA Y., TAKEMURA T., NAKAJIMA T., ABE-OUCHI A., KIMOTO M.: Transient Climate Change Simulations in the 21st Century with the CCSR/NIES CGCM under a New Set of IPCC Scenarios
- Vol. 9 CGER-I057-2004 (Out of stock) MIYAZAKI T., FUJISHIMA S., YAMAMOTO M., WEI Q., HANAZAKI H.: Vortices, Waves and Turbulence in a Rotating Stratified Fluid
- Vol. 10 CGER-I060-2005 (Out of stock) HAYASHI S., MURAKAMI S., XU K., WATANABE M.: Modeling of Daily Runoff in the Changjiang (Yangtze) River Basin and Its Application to Evaluating the Flood Control Effect of the Three Gorges Project
- Vol. 11 CGER-I063-2006 (Out of stock) NAKAYAMA T., WATANABE M.: Development of Process-based NICE Model and Simulation of Ecosystem Dynamics in the Catchment of East Asia (Part I)
- Vol. 12 CGER-I073-2007 (Out of stock) NOZAWA T., NAGASHIMA T., OGURA T., YOKOHATA T., OKADA N., SHIOGAMA H.: Climate Change Simulations with a Coupled Ocean-Atmosphere GCM Called the Model for Interdisciplinary Research on Climate: MIROC
- Vol. 13 CGER-I080-2008 (Out of stock) SHIBATA K., DEUSHI M.: Simulations of the Stratospheric Circulation and Ozone during the Recent Past (1980-2004) with the MRI Chemistry-Climate Model
- Vol. 14 CGER-I083-2008 (Out of stock) NAKAYAMA T.: Development of Process-based NICE Model and Simulation of Ecosystem Dynamics in the Catchment of East Asia (Part II)
- Vol. 15 CGER-I092-2010 (Out of stock) MAKSYUTOV, S., NAKATSUKA Y., VALSALA V., SAITO M., KADYGROV N., AOKI T., EGUCHI N., HIRATA R., IKEDA M., INOUE G., NAKAZAWA T., ONISHI R., PATRA P.K., RICHARDSON A.D., SAEKI T., YOKOTA T.: Algorithms for Carbon Flux Estimation Using GOSAT Observational Data
- Vol. 16 CGER-I097-2011 (Out of stock) NAKAJIMA K.: Idealized Numerical Experiments on the Space-time Structure of Cumulus Convection Using a Large-domain Two-dimensional Cumulus-Resolving Model
- Vol. 17 CGER-I098-2011 (Out of stock) UEDA H.: Atmospheric Motion and Air Quality in East Asia
- Vol. 18 CGER-I103-2012 (Out of stock) NAKAYAMA T.: Development of Process-based NICE Model and Simulation of Ecosystem Dynamics in the Catchment of East Asia (Part III)
- Vol. 19 CGER-I108-2013 (Out of stock) KOMORI S.: Numerical Simulations of Turbulence Structure and Scalar Transfer across the Air-Water Interfaces

- Vol. 20 CGER-I114-2014 (Out of stock) NAKAYAMA T.: Development of Process-based NICE Model and Simulation of Ecosystem Dynamics in the Catchment of East Asia (Part IV)
- Vol. 21 CGER-I120-2015 SHIOGAMA H.: Influence of Anthropogenic Aerosol Emissions on Pattern Scaling Projections
- Vol. 22 CGER-I127-2016 SATOH M., ROH, W., HASHINO, T.: Evaluations of Clouds and Precipitations in NICAM Using the Joint Simulator for Satellite Sensors
- Vol. 23 CGER-I132-2017 GOTO, D., SCHUTGENS, N.A.J., OIKAWA, E., TAKEMURA, T., NAKAJIMA, T.: Improvement of a global aerosol transport model through validation and implementation of a data assimilation system
- Vol. 24 CGER-I138-2018 TAKEMURA, T., AND SPRINTARS DEVELOPER TEAM : Development of a global aerosol climate model SPRINTARS
- Vol. 25 CGER-I143-2019 MAKSYUTOV, S., ODA, T., SAITO, M., TAKAGI, H., BELIKOV, D., VALSALA, V.: Transport modeling algorithms for application of the GOSAT observations to the global carbon cycle modeling
- Vol. 26 CGER-I148-2019 NAKAYAMA T.: Development of Process-based NICE Model and Simulation of Ecosystem Dynamics in the Catchment of East Asia (Part V)
- Vol. 27 CGER-I153-2021

ISHIWATARI M., NAKAJIMA K., TAKEHIRO, S., KAWAI Y., TAKAHASHI Y. O., HASHIMOTO G. L., SASAKI Y., and HAYASHI Y.-Y.: Numerical studies on the variety of climates of exoplanets using idealistic configurations

- Vol. 28 CGER-I158-2022 YOKOHATA T.: Development of an integrated land surface model with ecosystems, human water management, crop growth, and land-use change: MIROC-INTEG-LAND
- Vol. 29 CGER-I167-2023 NAKAYAMA T.: Development of Process-based NICE Model and Simulation of Ecosystem Dynamics in the Catchment of East Asia (Part VI)
- Vol. 30 CGER-I169-2024 NAKAYAMA T.: Development of Process-based NICE Model and Simulation of Ecosystem Dynamics in the Catchment of East Asia (Part VII)

レポートの多くは、地球環境研究センターのウェブサイトから PDF 形式で閲覧可能です。 https://www.cger.nies.go.jp/ja/activities/supporting/publications/report/

Many of the reports are also available as PDF files. See: https://www.cger.nies.go.jp/ja/activities/supporting/publications/report/