Electronic Supplementary Material

Urban constructed wetlands: Assessing ecosystem services and disservices for safe, resilient, and sustainable cities

Aamir Mehmood SHAH

State Key Joint Laboratory of Environment Simulation and Pollution Control, School of Environment, Beijing Normal University, Beijing 100875, China

Gengyuan LIU (✉)

State Key Joint Laboratory of Environment Simulation and Pollution Control, School of Environment, Beijing Normal University, Beijing 100875, China; Beijing Engineering Research Center for Watershed Environmental Restoration & Integrated Ecological Regulation, Beijing 100875, China

E-mail: liugengyuan@bnu.edu.cn

Yu CHEN

State Key Joint Laboratory of Environment Simulation and Pollution Control, School of Environment, Beijing Normal University, Beijing 100875, China

Qing YANG

Advanced Interdisciplinary Institute of Environment and Ecology, Beijing Normal University, Zhuhai 519087, China

Ningyu YAN

Key Laboratory for City Environmental Safety and Green Development of the Ministry of Education, Institute of Environmental and Ecological Engineering, Guangdong University of Technology, Guangzhou 510006, China; Southern Marine Science and Engineering Guangdong Laboratory (Guangzhou), Guangzhou 511458, China

Feni AGOSTINHO, Cecilia M. V. B. ALMEIDA, Biagio F. GIANNETTI

State Key Joint Laboratory of Environment Simulation and Pollution Control, School of Environment, Beijing Normal University, Beijing 100875, China; Programa de Pós-graduação em Engenharia de Produção, Laboratório de Produção e Meio Ambiente, Universidade Paulista (UNIP), São Paulo 04026-002, Brazil

1. Growing/Maintenance of a constructed wetland system

(a) Solar energy

Area = 1 m^2

The annual solar radiation in Beijing is between 4600–5700 MJ/m^2

Average insolation used in this study = 5440 MJ/m^2 = 5.44E+09 J/m^2/yr (Zhang et al., 2020)

Albedo = 30% (Brown and Ulgiati, 2016)

Carnot efficiency = 0.93 (Brown and Ulgiati, 2016)

UEV_{solar} = 1 sej/J (by definition, Odum, 1996)

U_{sun} = (area)(avg insolation)(1−albedo)(Carnot efficiency)(UEV)

= (1 m^2)(5.44E+09 J/m^2/yr)(1–30%)(0.93)(1 sej/J) = 3.54E+09 sej/m^2/yr

(b) Geothermal energy

Area = 1 m^2

Heat flow = 2.00E+06 J/m^2/yr (International Heat Flow Database, 2010)

Carnot efficiency = 9.50% (Brown and Ulgiati, 2016)

$UEV_{\text{deep heat}}$ = 4900 sej/J (Brown and Ulgiati, 2016)

U_{geo} = (area)(heat flow)(Carnot efficiency)(UEV)

= (1 m^2)(2.0E+06 J/m^2/yr)(9.5E−2)(4900 sej/J) = 9.31E+08 sej/m^2/yr

(c) Wind energy

Land area = 1 m^2

Shelf area = 0 m^2

Density of air = 1.23 kg/m^3

Land wind velocity (V_{ref}) = 2.2 m/s (average) (Beijing Statistical Yearbook, 2011)

Ocean wind velocity (V_{ref}) = 6.64 m/s (average) (Archer and Jacobson, 2005)

Height for velocity (H) = 1000 m (Brown and Ulgiati, 2016)

Reference height (H_{ref}) = 10 m (Brown and Ulgiati, 2016)

Land drag coeff. = 1.64E−03 (Garratt, 1992)

Ocean drag coeff. = 1.26E−03 (Garratt, 1992)

Surface roughness exponent (α) = 0.25 (land) (Brown and Ulgiati, 2016)

Surface roughness exponent (α) = 0.1 (ocean) (Brown and Ulgiati, 2016)

Wind velocity absorbed (V) = $V_{\text{ref}}\left(\frac{H}{H_{\text{ref}}}\right)^{\alpha}$ (Brown and Ulgiati, 2016)

UEV_{wind} = 790 sej/J (Brown and Ulgiati, 2016)

U_{wind} = (0.5)(land area)(air density)(land drag coefficient)(wind velocity absorbed)^3(UEV) + (0.5)(shelf area)(air density)(ocean drag coefficient)(wind velocity absorbed)^3(UEV)

= (0.5)(1 m^2)(1.23 kg/m^3)(1.64E−03)(6.96 m/s)^3(3.15E+07 s/yr)(790 sej/J) + (0.5)(0 m^2)(1.23 kg/m^3)(1.26E−03)(10.52 m/s)^3(3.15E+07 s/yr)(790 sej/J)

= 7.72E+09 sej/m^2/yr

(d) Rain, chemical potential energy

Land area = 1 m^2

Rain (land) = 0.548 m/yr (Beijing Statistical Yearbook, 2011)

Evapotranspiration rate = 75% (Brown and Ulgiati, 2016)

Gibbs energy of rain = 4720 J/kg (Brown and Ulgiati, 2016)

UEV_{rain} = 7010 sej/J (Brown and Ulgiati, 2016)

$U_{rain\ chemical}$ = (land area)(rainfall)(% evapotranspired)(rain density)(Gibbs energy of rain)(UEV)

= (1 m^2)(0.548 m)(75%)(1000 kg/m^3)(4720 J/kg)(7010 sej/J) = 1.36E+10 sej/m^2/yr

(e) Rain, geopotential energy

Area = 1 m^2

Runoff = 9.66E–02 m/yr

Average elevation = 43.5 m

Density of water = 1000 kg/m^3

Gravity = 9.80 m/s^2

UEV_{rain} = 7.37E+04 sej/J (Odum, 1996)

$U_{rain.geopotential}$ = (Area)(Runoff)(average elevation)(Density)(Gravity)(UEV_{rain})

= (1 m^2)(9.66E–02 m/yr)(43.5 m)(1000 kg/m^3)(9.80 m/s^2)(7.37E+04 sej/J)

= 3.04E+09 sej/m^2/yr

(f) Gravel

Volume = 118 m^3

Density = 3000 kg/m^3

Area = 600 m^2

Lifetime = 20 yr

UEV_{gravel} = 1.27E+09 sej/g (Nelson et al., 2001)

U_{gravel} = [[(Volume)(Density)*1000/(Area)]/(lifetime)](UEV_{gravel})

= [[(118 m^3)(3000 kg/m^3)*1000/(600 m^2)]/(20 yr)](1.27E+09 sej/g) = 3.75E+13 sej/m^2/yr

(g) Soil

Volume = 300 m^3

Density = 2700 kg/m^3

Area = 600 m^2

Lifetime = 20 yr

UEV_{soil} = 9.41E+04 sej/J (Brown and Bardi, 2001)

U_{soil} = [[(Volume)(Density)*1000/(Area)]/(lifetime)](UEV_{soil})

= [[(300 m^3)(2700 kg/m^3)*1000/(600 m^2)]/(20 yr)](9.41E+04 sej/J) = 6.35E+09 sej/m^2/yr

(h) Sand

Volume = 200 m^3

Density = 2500 kg/m^3

Area = 600 m^2

Lifetime = 20 yr

UEV_{sand} = 1.42E+09 sej/g (Odum, 1996)

U_{sand} = [[(Volume)(Density)*1000/(Area)]/(lifetime)](UEV_{soil})

= [[(200 m^3)(2500 kg/m^3)*1000/(600 m^2)]/(20 yr)](1.42E+09 sej/g) = 5.93E+13 sej/m^2/yr

(i) Vegetation

Money paid for vegetation = 20.7 $/yr (Chen et al., 2009)

Area = 600 m^2

$UEV_{vegetation}$ = 1.47E+13 sej/$ (Jiang, 2007)

$UEV_{vegetation}$ = (Money paid for vegetation)/(Area) = (20.7 $/yr)/(600 m^2) = 5.09E+11 sej/m^2/yr

(j) Bricks and cement mass

Volume = 22 m^3

Density = 2000 kg/m^3

Area = 600 m^2

Lifetime = 20 yr

$UEV_{brick.cement}$ = 2.50E+09 sej/g (Brown and Bardi, 2001)

$U_{brick.cement}$ = [[(volume)(density)*1000/(Area)]/(lifetime)]($UEV_{brick.cement}$)

= [[(22 m^3)(2000 kg/m^3)*1000/(600 m^2)]/(20 yr)](2.50E+09 sej/g) = 9.18E+12 sej/m^2/yr

(k) Maintenance

Total maintenance cost per day = 5.2 yuan/day (Chen et al., 2009)

Exchange ratio = 8.28 yuan/$

Area = 600 m^2

Lifetime = 20 yr

$UEV_{maintenance}$ = 1.47E+13 sej/$ (Jiang, 2007)

$U_{maintenance}$ = [[(Total maintenance cost)*365/(exchange ratio)]/(Area)]/(lifetime)

= [[(5.2 yuan/day)*365/(8.28 yuan/$)]/(600 m^2)]/(20 yr) = 2.82E+11 sej/m^2/yr

(l) PE liner

Surface area = 900 m^2 (Chen et al., 2009)

Thickness = 1.00E−03 m

Density = 920 kg/m^3

Gibbs free energy = 3.00E+04 J/kg

Area = 1 m^2

Lifetime = 20 yr

$UEV_{PE\ liner}$ = 1.41E+05 sej/J (Nelson et al., 2001)

$U_{PE\ liner}$ = [((surface area)(thickness)(density)(Gibbs free energy)/(Area))/(lifetime)]($UEV_{PE\ liner}$)

= [((900 m^2)(1.00E−03 m)(920 kg/m^3)(3.00E+04 J/kg)/(1 m^2))/(20 yr)](1.41E+05 sej/J)

= 1.75E+11 sej/m^2/yr

(m) PE pipe

Intercept area = 0.165 m^2 (Chen et al., 2009)

Length = 120 m

Density = 920 kg/m^3

Gibbs free energy = 300 J/kg

Area = 1 m^2

$UEV_{PE\ pipe}$ = 1.41E+05 sej/J (Nelson et al., 2001)

Lifetime = 20 yr

$U_{PE\ pipe}$ = [((intercept area)(length)(density)(Gibbs free energy)/(Area))/(lifetime)]($UEV_{PE\ Pipe}$)

= [((0.165 m^2)(120 m)(920 kg/m^3)(300 J/kg)/(1 m^2))/(20 yr)](1.41E+05 sej/J)

= 3.86E+10 sej/m^2/yr

2. Ecosystem services

(1) Net primary productivity (NPP)

NPP is calculated based on the input's flows listed in the above.

(2) Carbon sequestration

Carbon fixation rate by CW-1 ecosystem vegetation (wild rice, cattail, and common reed)/unit area = (22+210+249)/3 = 160 gC/m^2/yr (Bernal & Mitsch, 2012; Bar et al., 2013; Gaglio et al., 2022)

UEV_{csi} = The specific emergy of carbon sequestration in extensive GR ecosystem (sej/gC)

= 5.80E+09 sej/gC (Campbell and Tilley, 2014)

$U_{cs} = \Sigma_i (C_{FR} * UEV_{csi})$ = (160 gC/m^2/yr) * (5.80E+09 sej/gC) = 9.30E+10 sej/m^2/yr

(3) Micro-climate regulation

Evapotranspiration capacity = (5.46+5.72)/2 = 3.73 mm/yr (Papaevangelou et al., 2010)

Water density = 1000 kg/m^3

$UEV_{mr} = UEV_{rain\ chem}$ * Gibbs en_{water} = (7010 sej/J) * (4720 J/kg)

= 3.31E+07 sej/kg = 3.31E+04 sej/g (Brown and Ulgiati, 2016)

U_{mr} = Emergy driving microclimate regulation $= \sum_i (E_{ci} \times \rho \times 1000) \times UEV_{mr}$

= (0.003727 m/yr)*(1000*1000 g/m^3)*(3.31E+04 sej/g) = 3.39E+10 sej/m^2/yr

(4) Stormwater reduction

Retention volume = 14.8 m^3/yr (Thompson, 2018)

Water density = 1000 kg/m^3

Gibbs chemical energy of water = 4949 J/kg

Area of wetland = 600 m^2

$UEV_{rainwater}$ = 3.06E+04 sej/J

$UEV_{stormwater}$ = (retention volume)(water density)(Gibbs chemical energy of water)($UEV_{rainwater}$) /(Area) = (14.8 m^3/yr)(1000 kg/m^3)(4949 J/kg)(3.06E+04 sej/J)/(600 m^2) = 3.74E+09 sej/m^2/yr

(5) Water purification

Total phosphorus = 523 g/m^2/yr (Chen et al., 2009)

$UEV_{pollutant}$ = 1.64E+10 sej/g (Campbell and Ohrt, 2009) = $U_{WP} = \sum_i (P_a \times UEV_{Pollutant})$

= (523 g/m^2/yr)*(1.64E+10 sej/g) = 8.56E+12 sej/m^2/yr

Total nitrogen = 1700 g/m^2/yr (Chen et al., 2009)

UEV = 5.34E+09 sej/g (Brandt-Williams, 2002) = $U_{WP} = \sum_i (P_a \times UEV_{Pollutant})$

= (1700 g/m^2/yr)*(5.34E+09 sej/g) = 9.05E+12 sej/m^2/yr

TSS = 2480 g/m^2/yr (Chen et al., 2009)

UEV = 1.27E+09 sej/g (Campbell and Ohrt, 2009) = $U_{WP} = \sum_i (P_a \times UEV_{Pollutant})$

= (2480 g/m^2/yr)*(1.27E+09 sej/g) = 3.15E+12 sej/m^2/yr

(6) Groundwater recharge

Rainfall = 0.547 m/yr (Beijing's average annual rainfall)

Density of water = 1000 kg/m^3

Infiltration coefficient = 0.15 (Liu, 2007)

Gibbs free energy = 4.94 J/g

UEV_{gw} = 2.04E+04 sej/J (Brown and Ulgiati, 2018)

U_{gw} = (0.547 m)(1000 kg/m^3)(0.15)(4.94 J/g)(2.04E+04 sej/J)(1000) = 8.26E+09 sej/m^2/yr

Avoided cost for human health and biodiversity damage

Damages by global climate change

f_{CS} = Carbon sequestration rate by CW = 160 g/m^2/yr (Bernal and Mitsch, 2012; Brar et al., 2013; Gaglio et al., 2022)

$DALY_{CSHH}$ = 2.07E–07 person*year/kg (LCA ReCiPe Endpoint 2016 Impact Assessment Method (Ecoinvent 3.5 software))

UEV_{health} = 5.06E+15 sej/person/yr (emergy per person calculated from per capita health monetary expenditure of permanent population in Beijing in 2017, multiplied by the EMR-Emergy Money Ratio of China 2014 – both the most recent data available)

U_{CRHH} = Climate regulation = $\Sigma_i (f_{CS} * DALY_{CSHH}) * UEV_{health}$

= (160/1000 kg/m^2/yr)*(2.07E–07 person*year/kg)*(5.06E+15 sej/person/yr)

= 1.68E+08 sej/m^2/yr

Due to lack of data other greenhouse gases are not calculated in this study. In a like manner, due to the lack of PDF of species *sp* affected by greenhouse gases (PDF * m^2 * yr/kg), the U_{CRsp} is not calculated in this study.

3. Ecosystem disservices

(1) Greenhouse gases emission

CH_4 amount emitted = 2.9 mg/m^2/hr (Mander et al., 2014)

Conversion (mg/hr to kg/yr) = 8.76E−03 kg/m^2/yr

DALY= 4.40E−06 person*year/kg

t_H = 5.06E+15 sej/person/yr

U_{CH4} = (CH_4 amount emitted)(8.76E−03 kg/m^2/yr)(DALYs)(t_H)

= (2.9 mg/m^2/hr)(8.76E−03 kg/m^2/yr)(4.40E−06 person*year/kg)(5.06E+15 sej/person/yr)

= 5.66E+08 sej/m^2/yr

N_2O amount emitted = 0.14 mg/m^2/hr (Mander et al., 2014)

DALY = 8.87E−05 person*year/kg

t_H = 5.06E+15 sej/person/yr

U_{N2O} = (N_2O amount emitted)(8.76E−03 kg/m^2/yr)(DALYs)(t_H)

= (0.14 mg/m^2/hr)(8.76E−03 kg/m^2/yr)(8.87E−05 person*year/kg)(5.06E+15 sej/person/yr)

= 5.50E+08 sej/m^2/yr

CO_2 amount emitted =184.7 mg/m^2/hr (Mander et al., 2014)

DALY = 2.07E−07 person*year/kg

t_H = 5.06E+15 sej/person/yr

U_{CO2} = (CO_2 amount emitted)(8.76E−03 kg/m^2/yr)(DALYs)(t_H)

= (184.7 mg/m^2/hr)(8.76E−03 kg/m^2/yr)(2.07E−07person*year/kg)(5.06E+15 sej/person/yr)

= 1.69E+09 sej/m^2/yr

(2) Mosquitoes problem

Amount of organophosphate = 2.44 g/m^2/yr (available at: archive.epa.gov/pesticides/reregistration/web/html/temephos_red.html)

UEV = 2.47E+13 sej/kg (Lyu et al., 2021)

$U_{mosq} = O_{amount} \times UEV_{pest}$ = (2.44 g/m^2/yr)*(2.47E+13 sej/kg) = 6.03E+10 sej/m^2/yr

(3) Green waste

There are different disposal options for green roofs waste. Materials can be landfilled, reused, or recycled and burned. However, many cities do not have the necessary facilities for the recycling process. Landfill costs depend on many factors such as technology, location, size of the facility, and available landfill capacity in a municipality. Therefore, we assume green waste is dump into the landfill via the help of labor.

Green waste harvesting and disposal cost = 6 $\$/m^2$ (El Hawary and Shaban, 2018)

Assume 2.00 times CW plants is clipped in a year in Beijing = 6*2 = 12 $\$/m^2/yr$

EMR = 1.59E+12 sej/$ (Odum, 1996)

U_{GW} = (12 $\$/m^2/yr$)*(1.59E+12 sej/$) = 1.91E+13 $sej/m^2/yr$

4. Input (raw data) or construction cost data of 8-CWs

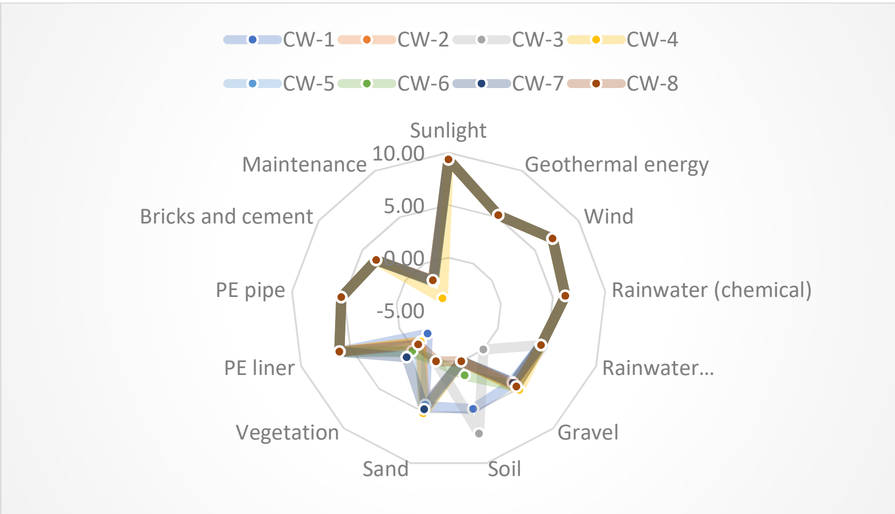
Table A1 Input (raw data) or construction cost data of 8-CWs

	Input raw data							
	CW-1	**CW-2**	**CW-3**	**CW-4**	**CW-5**	**CW-6**	**CW-7**	**CW-8**
Sunlight	3.54E+09	3.54E+09	3.54E+09	3.54E+09	3.54E+09	3.54E+09	3.54E+09	3.54E+09
Geothermal energy	1.90E+05	1.90E+05	1.90E+05	1.90E+05	1.90E+05	1.90E+05	1.90E+05	1.90E+05
Wind	9.77E+06	9.77E+06	9.77E+06	9.77E+06	9.77E+06	9.77E+06	9.77E+06	9.77E+06
Rainwater (chemical)	1.94E+06	1.94E+06	1.94E+06	1.94E+06	1.94E+06	1.94E+06	1.94E+06	1.94E+06
Rainwater (geopotential)	4.12E+04	4.12E+04	4.12E+04	4.12E+04	4.12E+04	4.12E+04	4.12E+04	4.12E+04
	CW-1	**CW-2**	**CW-3**	**CW-4**	**CW-5**	**CW-6**	**CW-7**	**CW-8**
Gravel	2.95E+04	3.15E+04	0.00E+00	1.30E+05	1.26E+04	6.70E+04	2.52E+04	7.10E+04
Soil	6.75E+04	0.00E+00	1.06E+07	0.00E+00		3.90E+01		
Sand	4.17E+04	2.80E+04	0.00E+00	1.25E+05	2.80E+04		7.20E+04	
Vegetation	3.45E–02	4.40E–01	3.48E+00	3.62E–01	2.70E–01	1.90E+00	1.00E–01	3.62E–01
PE liner	1.24E+06	1.24E+06	1.24E+06	1.24E+06	1.24E+06	1.24E+06	1.24E+06	1.24E+06
PE pipe	2.73E+05	2.73E+05	2.73E+05	2.73E+05	2.73E+05	2.73E+05	2.73E+05	2.73E+05
Bricks and cement	3.67E+03	3.67E+03	3.67E+03	3.67E+03	3.67E+03	3.67E+03	3.67E+03	3.67E+03
Maintenance	1.91E–02	2.04E–02	1.00E–02	2.55E–04	2.04E–02	1.91E–02	1.91E–02	2.04E–02

Table A2. Input (raw data) or construction cost data of 8-CWs

	Input raw data							
	CW-1	**CW-2**	**CW-3**	**CW-4**	**CW-5**	**CW-6**	**CW-7**	**CW-8**
Sunlight	9.35	9.35	9.35	9.35	9.35	9.35	9.35	9.35
Geothermal energy	5.19	5.19	5.19	5.19	5.19	5.19	5.19	5.19
Wind	7.00	7.00	7.00	7.00	7.00	7.00	7.00	7.00
Rainwater (chemical)	6.19	6.19	6.19	6.19	6.19	6.19	6.19	6.19
Rainwater (geopotential)	4.41	4.41	4.41	4.41	4.41	4.41	4.41	4.41
Gravel	4.25	4.31	0.00	5.13	4.12	4.67	4.25	4.71
Soil	4.67	0.00	7.10	0.00	0.00	1.39	0.00	0.00
Sand	4.41	4.28	0.00	5.12	4.28	0.00	4.72	0.00
Vegetation	–2.00	–1.00	0.34	–1.00	–0.50	0.19	1.00	–0.64
PE liner	6.12	6.12	6.12	6.12	6.12	6.12	6.12	6.12
PE pipe	5.27	5.27	5.27	5.27	5.27	5.27	5.27	5.27
Bricks and cement	3.36	3.36	3.36	3.36	3.36	3.36	3.36	3.36
Maintenance	–1.90	–1.80	–2.00	–3.75	–1.80	–1.90	–1.90	–1.80

Note: Consider sunlight value (3.54E+09 = 9.35), geothermal energy (1.90E+05 = 5.19), wind (9.77E+06 = 6.97 around 7.00), rainwater chemical (1.94E+06 = 6.19), etc.



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