**Supporting Information**

# Eco-efficiency of end-of-pie systems: An extended environmental cost efficiency framework for wastewater treatment

**Xinyue Zhao[1], Chaofan Zhang[2] and Shunwen Bai[3,*]**

[1] College of Resources and Environment, Northeast Agricultural University, Harbin 150030, China
[2] Yuyang Water Conservancy bureau, Zhengzhou 450000, China
[3] State Key Laboratory of Urban Water Resource and Environment, School of Environment, Harbin Institute of Technology, Harbin 150090, China.
* Correspondence: baishunwen@hit.edu.cn

## Table S1

Table S1 Effluent quality of different effluent disposal levels

| Scenarios | Disposal requirement | Effluent quality (mg/L) | | | |
|---|---|---|---|---|---|
| | | COD | TN | TP | SS |
| Scenario-1 | Tertiary treatment | 29.8 | 12.8 | 0.5 | 8.2 |
| Scenario-2 | Intermediate treatment | 42.6 | 14.2 | 0.8 | 16.3 |
| Scenario-3 | Basic treatment | 80 | 22.6 | 2.2 | 24 |
| Scenario-4 | No treatment | 259.2 | 28.7 | 3.4 | 187.4 |

# Table S2

Table S2 Input and output elements of different scenarios

| | **Parameter and element** | **Scenario-1** | **Scenario-2** | **Scenario-3** | **Scenario-4** |
|---|---|---|---|---|---|
| Inputs | Electricity (kWh) | 4380 | 3420 | 3120 | 480 |
| | Inorganic Chemicals (t) | 0.858 | 0.658 | 0.508 | — |
| | Chemical transport (t.km) | 1716 | 1316 | 1016 | — |
| | PAM- acrylonitrile (kg) | 7.35 | 7.35 | 6.5 | — |
| Outputs | Tertiary and phosphorus precipitation solid waste (t, water 60%) | 0.923 | 0.113 | — | — |
| | Bio-sludge (t, water 80%) | 8.45 | 7.35 | 6.5 | — |
| | $CO_2$ (t) | 1.76 | 1.76 | 1.41 | — |
| | $N_2O$ (kg) | 1.02 | 0.68 | 0.18 | 0.22 |
| | COD (kg) | 298 | 426 | 800 | 2592 |
| | TN (kg) | 128 | 142 | 226 | 287 |
| | TP (kg) | 5 | 7.8 | 22 | 34 |
| | SST (kg) | 82 | 163 | 240 | 1874 |

# Table S3

Table S3 Parameters of one selected reach of *Ashihe* river

| | $k_{COD}$ (1/d) | $k_{TN}$ (1/d) | u (m/s) | A($m^2$) |
|---|---|---|---|---|
| Jan | 0.072 | 0.051 | 0.05 | 1035 |
| Feb | 0.072 | 0.051 | 0.04 | 1035 |
| Mar | 0.072 | 0.051 | 0.05 | 1035 |
| Apr | 0.100 | 0.091 | 0.46 | 1035 |
| May | 0.100 | 0.091 | 0.52 | 1035 |
| Jun | 0.100 | 0.091 | 0.33 | 1035 |
| Jul | 0.144 | 0.091 | 0.64 | 1035 |
| Aug | 0.144 | 0.091 | 0.35 | 1035 |
| Sep | 0.100 | 0.091 | 0.16 | 1035 |
| Oct | 0.100 | 0.091 | 0.13 | 1035 |
| Nov | 0.072 | 0.051 | 0.12 | 1035 |
| Dec | 0.072 | 0.051 | 0.18 | 1035 |

# Table S4

Table S4 Parameters of one selected reach of *Songhua* river

| | $k_{COD}$ (1/d) | $k_{TN}$ (1/d) | u (m/s) | $M_y$ ($m^2$/s) | H (m) | B (m) |
|---|---|---|---|---|---|---|
| Jan | 0.15 | 0.142 | 2.39 | 0.38 | 2.3 | 450 |
| Feb | 0.15 | 0.142 | 2.00 | 0.38 | 2.3 | 450 |
| Mar | 0.15 | 0.142 | 1.67 | 0.38 | 2.3 | 450 |
| Apr | 0.15 | 0.172 | 2.04 | 0.38 | 2.3 | 450 |
| May | 0.15 | 0.142 | 2.97 | 0.38 | 2.3 | 450 |
| Jun | 0.15 | 0.172 | 2.54 | 0.38 | 2.3 | 450 |
| Jul | 0.15 | 0.231 | 1.60 | 0.38 | 2.3 | 450 |
| Aug | 0.15 | 0.231 | 3.23 | 0.38 | 2.3 | 450 |
| Sep | 0.15 | 0.172 | 3.21 | 0.38 | 2.3 | 450 |
| Oct | 0.15 | 0.142 | 2.71 | 0.38 | 2.3 | 450 |

# Table S5

Table S5 Normalized results for each impact category of each scenario

| Impact category | Normalized scores | | | |
|---|---|---|---|---|
| | Scenario-1 | Scenario-2 | Scenario-3 | Scenario-4 |
| ADE | 72.1 | 52.3 | 33.7 | 1.86 |
| ADF | 308 | 227 | 202 | 23.3 |
| GW | 376 | 291 | 251 | 18.8 |
| OD | 3.94 | 2.93 | 1.73 | 0.02 |
| HT | 78.8 | 57.5 | 47.9 | 12.2 |
| FAET | 616 | 442 | 376 | 213 |
| PO | 105 | 77.7 | 69.1 | 6.77 |
| A | 352 | 253 | 227 | 29.9 |

# Table S6

Table S6 The calculated characterization factors for COD and TN

| Empirical formula | Environmental condition | $v_{\mathrm{COD}}$ | $v_{TN}$ | $WP_{COD}$ | $WP_{TN}$ |
|---|---|---|---|---|---|
| $C_5H_7O_2N$ | Aerobic | 0.2 | 1 | 0.3875 | 4.4286 |
| $C_7H_{12}O_4N$ | Aerobic | 0.14 | 1 | 0.2672 | 4.4286 |
| $C_9H_{15}O_5N$ | Aerobic | 0.10 | 1 | 0.2039 | 4.4286 |
| $C_9H_{16}O_5N$ | Aerobic | 0.10 | 1 | 0.1987 | 4.4286 |

# Table S7

Table S7 Changing BDO normalization results along the longitudinal orientation (*Ashihe* river)

| X (m) | Scenario-4 | Scenario-3 | Scenario-2 | Scenario-1 |
|---|---|---|---|---|
| 0.00E+00 | 1942.46 | 1206.92 | 738.40 | 643.24 |
| 2.00E+04 | 1863.26 | 1161.52 | 710.92 | 619.65 |
| 4.00E+04 | 1787.44 | 1117.89 | 684.50 | 596.94 |
| 8.00E+04 | 1645.31 | 1035.63 | 634.65 | 554.06 |
| 1.00E+05 | 1578.73 | 996.87 | 611.14 | 533.82 |
| 1.20E+05 | 1514.97 | 959.61 | 588.53 | 514.33 |
| 1.40E+05 | 1453.89 | 923.78 | 566.77 | 495.58 |
| 1.60E+05 | 1395.39 | 889.34 | 545.85 | 477.52 |
| 2.00E+05 | 1285.64 | 824.36 | 506.35 | 443.40 |
| 4.00E+05 | 857.38 | 565.60 | 348.61 | 306.65 |
| 6.00E+05 | 575.79 | 389.58 | 240.84 | 212.67 |
| 8.00E+05 | 389.15 | 269.24 | 166.87 | 147.84 |
| 1.00E+06 | 264.51 | 186.62 | 115.92 | 102.99 |
| 1.20E+06 | 180.71 | 129.67 | 80.70 | 71.87 |
| 1.40E+06 | 124.01 | 90.29 | 56.28 | 50.22 |
| 1.60E+06 | 85.43 | 62.99 | 39.31 | 35.14 |
| 1.80E+06 | 59.05 | 44.00 | 27.49 | 24.61 |
| 2.00E+06 | 40.94 | 30.78 | 19.25 | 17.25 |
| 2.20E+06 | 28.45 | 21.55 | 13.49 | 12.10 |
| 2.40E+06 | 19.81 | 15.11 | 9.46 | 8.49 |

# Table S8

Table S8 Changing BDO normalization results of scenario-4 (*Songhua* river)

| X (m) | Y=0 (m) | Y=50 (m) | Y=100 (m) | Y=150 (m) |
|---|---|---|---|---|
| 1000 | 1.93E+03 | 1.39E+02 | 5.18E-02 | 9.99E-08 |
| 2000 | 1.36E+03 | 3.66E+02 | 7.06E+00 | 9.81E-03 |
| 3000 | 1.11E+03 | 4.62E+02 | 3.33E+01 | 4.14E-01 |
| 4000 | 9.61E+02 | 4.98E+02 | 6.91E+01 | 2.58E+00 |
| 5000 | 8.58E+02 | 5.07E+02 | 1.05E+02 | 7.52E+00 |
| 6000 | 7.82E+02 | 5.04E+02 | 1.35E+02 | 1.51E+01 |
| 7000 | 7.23E+02 | 4.97E+02 | 1.61E+02 | 2.45E+01 |
| 8000 | 6.75E+02 | 4.86E+02 | 1.81E+02 | 3.50E+01 |
| 9000 | 6.36E+02 | 4.75E+02 | 1.97E+02 | 4.58E+01 |
| 10000 | 6.02E+02 | 4.63E+02 | 2.10E+02 | 5.64E+01 |
| 11000 | 5.73E+02 | 4.51E+02 | 2.20E+02 | 6.66E+01 |
| 12000 | 5.48E+02 | 4.40E+02 | 2.28E+02 | 7.62E+01 |
| 13000 | 5.26E+02 | 4.30E+02 | 2.34E+02 | 8.51E+01 |
| 14000 | 5.06E+02 | 4.19E+02 | 2.39E+02 | 9.32E+01 |
| 15000 | 4.88E+02 | 4.10E+02 | 2.42E+02 | 1.01E+02 |
| 16000 | 4.72E+02 | 4.00E+02 | 2.44E+02 | 1.07E+02 |

# Table S9

Table S9 Changing BDO normalization results of scenario-3 (*Songhua* river)

| X (m) | Y=0 (m) | Y=50 (m) | Y=100 (m) | Y=150 (m) |
|---|---|---|---|---|
| 1000 | 1.20E+03 | 8.63E+01 | 3.22E-02 | 6.21E-08 |
| 2000 | 8.47E+02 | 2.27E+02 | 4.38E+00 | 6.09E-03 |
| 3000 | 6.90E+02 | 2.87E+02 | 2.07E+01 | 2.57E-01 |
| 4000 | 5.97E+02 | 3.09E+02 | 4.29E+01 | 1.60E+00 |
| 5000 | 5.33E+02 | 3.15E+02 | 6.49E+01 | 4.67E+00 |
| 6000 | 4.86E+02 | 3.13E+02 | 8.40E+01 | 9.38E+00 |
| 7000 | 4.49E+02 | 3.08E+02 | 9.98E+01 | 1.52E+01 |
| 8000 | 4.19E+02 | 3.02E+02 | 1.12E+02 | 2.17E+01 |
| 9000 | 3.95E+02 | 2.95E+02 | 1.23E+02 | 2.84E+01 |
| 10000 | 3.74E+02 | 2.87E+02 | 1.30E+02 | 3.50E+01 |
| 11000 | 3.56E+02 | 2.80E+02 | 1.37E+02 | 4.13E+01 |
| 12000 | 3.40E+02 | 2.73E+02 | 1.42E+02 | 4.73E+01 |
| 13000 | 3.26E+02 | 2.67E+02 | 1.45E+02 | 5.28E+01 |
| 14000 | 3.14E+02 | 2.60E+02 | 1.48E+02 | 5.78E+01 |
| 15000 | 3.03E+02 | 2.54E+02 | 1.50E+02 | 6.25E+01 |
| 16000 | 2.93E+02 | 2.48E+02 | 1.52E+02 | 6.66E+01 |

# Table S10

Table S10 Changing BDO normalization results of scenario-2 (*Songhua* river)

| X (m) | Y=0 (m) | Y=50 (m) | Y=100 (m) | Y=150 (m) |
|---|---|---|---|---|
| 1000 | 7.34E+02 | 5.28E+01 | 1.97E-02 | 3.80E-08 |
| 2000 | 5.18E+02 | 1.39E+02 | 2.68E+00 | 3.73E-03 |
| 3000 | 4.22E+02 | 1.76E+02 | 1.26E+01 | 1.57E-01 |
| 4000 | 3.65E+02 | 1.89E+02 | 2.63E+01 | 9.79E-01 |
| 5000 | 3.26E+02 | 1.93E+02 | 3.97E+01 | 2.86E+00 |
| 6000 | 2.97E+02 | 1.92E+02 | 5.14E+01 | 5.74E+00 |
| 7000 | 2.75E+02 | 1.89E+02 | 6.11E+01 | 9.32E+00 |
| 8000 | 2.57E+02 | 1.85E+02 | 6.88E+01 | 1.33E+01 |
| 9000 | 2.41E+02 | 1.80E+02 | 7.50E+01 | 1.74E+01 |
| 10000 | 2.29E+02 | 1.76E+02 | 7.98E+01 | 2.14E+01 |
| 11000 | 2.18E+02 | 1.71E+02 | 8.36E+01 | 2.53E+01 |
| 12000 | 2.08E+02 | 1.67E+02 | 8.66E+01 | 2.89E+01 |
| 13000 | 2.00E+02 | 1.63E+02 | 8.88E+01 | 3.23E+01 |
| 14000 | 1.92E+02 | 1.59E+02 | 9.06E+01 | 3.54E+01 |
| 15000 | 1.85E+02 | 1.55E+02 | 9.18E+01 | 3.82E+01 |
| 16000 | 1.79E+02 | 1.52E+02 | 9.28E+01 | 4.08E+01 |

# Table S11

Table S11 Changing BDO normalization results of scenario-1 (*Songhua* river)

| X (m) | Y=0 (m) | Y=50 (m) | Y=100 (m) | Y=150 (m) |
|---|---|---|---|---|
| 1000 | 6.39E+02 | 4.60E+01 | 1.71E-02 | 3.31E-08 |
| 2000 | 4.51E+02 | 1.21E+02 | 2.34E+00 | 3.25E-03 |
| 3000 | 3.68E+02 | 1.53E+02 | 1.10E+01 | 1.37E-01 |
| 4000 | 3.18E+02 | 1.65E+02 | 2.29E+01 | 8.53E-01 |
| 5000 | 2.84E+02 | 1.68E+02 | 3.46E+01 | 2.49E+00 |
| 6000 | 2.59E+02 | 1.67E+02 | 4.48E+01 | 5.00E+00 |
| 7000 | 2.39E+02 | 1.64E+02 | 5.32E+01 | 8.12E+00 |
| 8000 | 2.23E+02 | 1.61E+02 | 5.99E+01 | 1.16E+01 |
| 9000 | 2.10E+02 | 1.57E+02 | 6.53E+01 | 1.51E+01 |
| 10000 | 1.99E+02 | 1.53E+02 | 6.95E+01 | 1.87E+01 |
| 11000 | 1.90E+02 | 1.49E+02 | 7.28E+01 | 2.20E+01 |
| 12000 | 1.81E+02 | 1.46E+02 | 7.54E+01 | 2.52E+01 |
| 13000 | 1.74E+02 | 1.42E+02 | 7.74E+01 | 2.81E+01 |
| 14000 | 1.67E+02 | 1.39E+02 | 7.89E+01 | 3.08E+01 |
| 15000 | 1.61E+02 | 1.35E+02 | 8.00E+01 | 3.33E+01 |
| 16000 | 1.56E+02 | 1.32E+02 | 8.08E+01 | 3.55E+01 |