Article

Lifecycle Assessment of Two Urban Water Treatment Plants of Pakistan

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Supplementary Materials

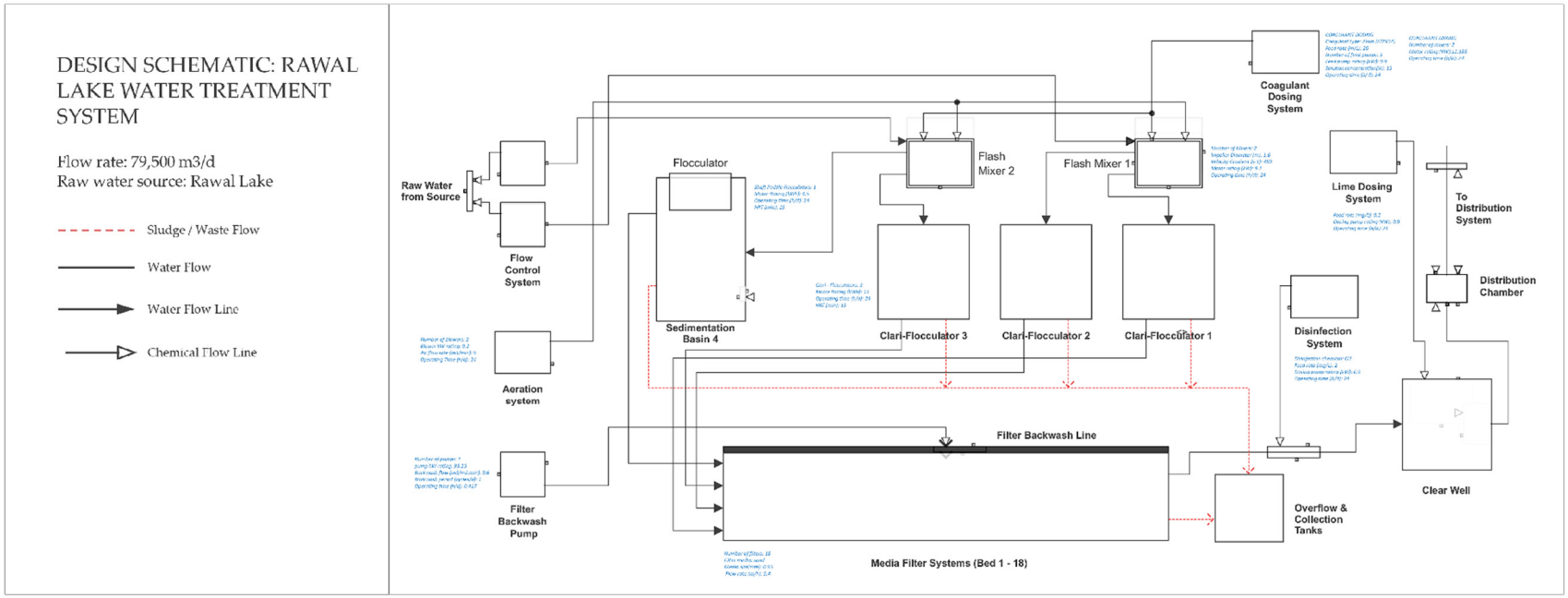


Figure S1. Process design and treatment schematic of Rawal Lake Water Treatment System. The treatment process train with unit process details are listed in notes adjacent to each process. Red dashed lines represent sludge and waste flows while black solid lines represent water flows.

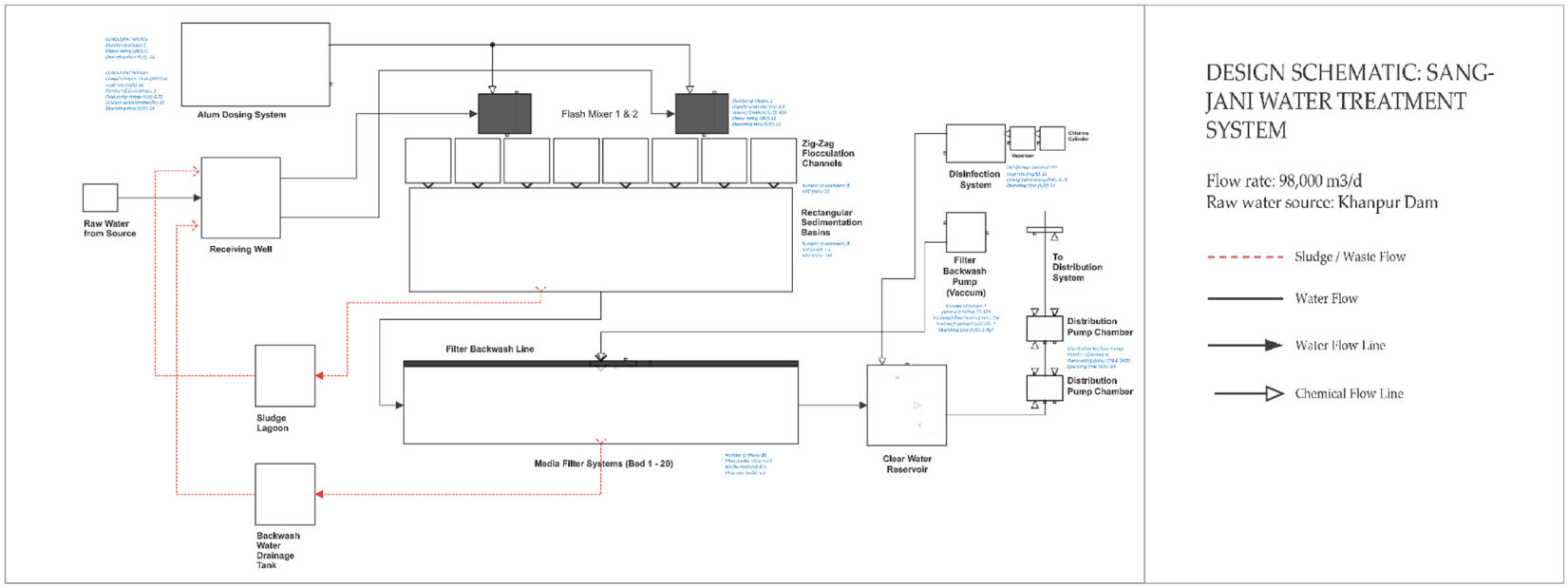


Figure S2: Process design and treatment schematic of Sang-Jani Water Treatment System. The treatment process train with unit process details are listed in notes adjacent to each process. Red dashed lines represent sludge and waste flows while black solid lines represent water flows.

Table S1: Environmental emission pathways relevant to the LCA of the water treatment system studies

Scope	Emission Pathway	Compartment
Off-Site	Electricity consumption for unit process operation	Air, Water, Land
Off-Site	Production of chemicals	Air, Water, Land
Off-Site	Transportation of chemicals	Air, Water, Land
On-Site	Reaction of chemicals during treatment process	Air, Water
On-Site	Maintenance of equipment	Water, Land
On-Site	Administrative and organizational processes	Land

Table S1: Data types and sources indicating the quality and authenticity of inventory dataset

Process	Flow	Category	Regional Definition	Unit	Source/Owner
Electricity, at grid - PK	Electricity, at grid	**Energy**	Pakistan	MJ	UNECE
Electricity, at grid - PK	Electricity, at grid	**Energy**	Pakistan	MJ	UNECE
Sulphuric Acid	Sulphuric Acid	**Material**	Europe	kg	thinkstep AG
Fuel (residual) combusted in industrial boiler	Fuel oil (residual) combusted in industrial boiler	**Energy**	United States	m3	Franklin Associates
Bituminous coal, combusted in industrial boiler	Bituminous coal, combusted in industrial boiler	**Energy**	United States	kg	Franklin Associates
Natural gas, combusted in industrial boiler	Natural gas, combusted in industrial boiler	**Energy**	United States	m3	Franklin Associates
Chlorine production at plant	Chlorine, production mix, at plant	**Material**	United States	kg	Franklin Associates
Aluminum Sulphate	Aluminum Sulphate	**Material**	Europe	kg	thinkstep AG
Calcium hydroxide (Ca(OH)2; dry; slaked lime), solid, density: 2,24 g·cm3 (20 °C), molar mass: 74,10 g·mol1	Hydrated lime dry slaked	**Material**	Europe	kg	thinkstep AG
Sand	Sand	**Material**	Pakistan	kg	Earthworks

Table S2: Characteristic parameters for raw and treated water and sludge for the study systems

Parameters	**Units**	**Guidelines Limits**	**Measured Parameters**	
Water Quality			Raw Water	Treated Water
Appearance	--	Clear	turbid	clear
Temperature	◦C	….	15	15
Turbidity	NTU	5 NTU	17	2.81
pH	--	6.5-8.5	7.49	7.41
Alkalinity	mg/l	500 mg/l	148	128
Hardness as $CaCO_3$	mg/l	500 mg/l	162	140
Conductance	µS/cm	2000µS/cm	720	710
Calcium	mg/l	200 mg/l	50	48
TDS	mg/l	1000 mg/l	360	355
Chlorides	mg/l	200 mg/l	/	/
Residual Chlorine	mg/l	0.5-1.5 mg/l	0	1.2
Nitrite as NO_2^-	mg/l	<1 mg/l	NIL	NIL
Ammonia as NH_3 - N	mg/l	1.5 mg/l	NIL	NIL
Iron as Fe	mg/l	0.3 mg/l	NIL	NIL
Dissolved Oxygen (DO)	mg/l	6 to 10 mg/l	6.7	6.4
Fecal Coliform Count	Colonies/100 ml	Nil/100 ml	60	NIL
Sludge Parameters	**Units**		**Treated Sludge**	
BOD	mg/L		1.44	
CBOD	mg/L		-	
TSS	mg/L		135	
TDS	mg/L		-	
Chlorides	mg/L		-	
Nitrogen	mg/L		3.64	
Ammonia	mg/L		0.482	
Aluminum	mg/L		2.16	
Barrium	mg/L		0.01	
Cadmium	mg/L		-	
Calcium	mg/L		8.73	
Copper	mg/L		0.0693	
Flouride	mg/L		0.684	
Iron	mg/L		4.31	
Lead	mg/L		0.00569	
Magnesium	mg/L		2.58	
Mangenese	mg/L		0.442	
Phosphrous	mg/L		0.423	
Zinc	mg/L		0.316	

Table S4: Electricity consumption in kWh per m³ for unit processes at the study water treatment plants

System	Aeration	Flash Mixing	Coagulation	Flocculation	Disinfection	Lime-Dosing	Service & Distribution	Backwashing	Total
RLWTP	5.55E-03	0.005554717	7.57E-03	1.58E-02	2.72E-04	2.72E-04	1.60E-03	2.19E-05	3.67E-02
SJWTP	0	0	1.67E-02	0	1.84E-04	0	1.107918367	5.25E-04	1.13E+00

Table S5: Transport distances for chemicals and materials used at the study plants

Chemical	Unit	Chlorine Production	Aluminum Sulphate	Sulphuric Acid	Sand
Ocean Transport	tonn*km	0.00358		1.615211074	
Rail Transport		0.0035793	1.2	0.00141238	0.002
Truck Transport			0.2	0.025698948	
Pipeline Transport		0.32643		0.35680802	

Table S6: Environmental impact categories and measurement units for each category for the EF characterization method

EF End-Point Impact Category	EF Mid-Point Impact Category	Description	Reference unit
Additional Category	Solid waste	Solid waste produced from the system	kg
Climate Change	GWP 100a	Radiative forcing as global warming potential (GWP100)	kg CO2-Eq
Ecosystem Quality	Freshwater and terrestrial acidification	Accumulated Exceedance (AE)	mol H+-Eq
Ecosystem Quality	Freshwater ecotoxicity	Comparative Toxic Unit for ecosystems (CTUe)	CTUh.m3.yr
Ecosystem Quality	Freshwater eutrophication	Fraction of nutrients reaching freshwater end compartment (P)	kg P-Eq
Ecosystem Quality	Ionising radiation	Human exposure efficiency relative to U235	mol N-Eq
Ecosystem Quality	Marine eutrophication	Fraction of nutrients reaching marine end compartment (N)	kg N-Eq
Ecosystem Quality	Terrestrial eutrophication	Accumulated Exceedance (AE)	mol N-Eq
Human Health	Carcinogenic effects	Comparative Toxic Unit for humans (CTUh)	CTUh
Human Health	Ionising radiation	Human exposure efficiency relative to U235	kg U235-Eq
Human Health	Non-carcinogenic effects	Comparative Toxic Unit for humans (CTUh)	CTUh
Human Health	Ozone layer depletion	Ozone Depletion Potential (ODP)	kg CFC-11-Eq
Human Health	Photochemical ozone creation	Tropospheric ozone concentration increase	kg ethylene-Eq
Human Health	Respiratory effects, inorganics	Impact on human health	kg PM2.5-Eq
Resource	Water use	World water scarcity	m3 world eq. deprived
Resources	Land use	Erosion resistance	kg Soil Organic Carbon
Resources	Mineral, fossils and renewables	Mineral, fossils and renewables	kg Sb-Eq

Table S7: Lifecycle impact and percentage contribution for electricity generation option most applicable to the Pakistan electricity grid mix

Generation process	% contribution to grid mix	Climate change total	Freshwater and terrestrial acidification	Freshwater ecotoxicity	Freshwater eutrophication	Marine eutrophication	Terrestrial eutrophication	Carcinogenic effects	Ionising radiation	Non-carcinogenic effects	Ozone layer depletion	Photochemical ozone creation	Respiratory effects, inorganics	Dissipated water	Fossils	Land use	Minerals and metals
		Carbon di oxide fossil	**Sulphur trioxide**	**Proxy**	**Phosphorous**	**Nitrogen**	**Proxy**	**Proxy**	**Uranium-235**	**Proxy**	**Methane dichlorodifloro**						**Cadmium, in ground**
		[kg CO2-Eq]	[mol H+-Eq]	[CTU]	[kg P-Eq]	[kg N-Eq]	[mol N-Eq]	[CTUh]	[kg U235-Eq]	[CTUh]	[kg CFC-11.]	[kg NMVOC-.]	[disease i.]	[m3 water-.]	[megajoule]	[points]	[kg Sb-Eq]
Coal	27.1	1.02E+00	1.73E-03	4.72E-01	4.89E-04	5.14E-04	4.97E-03	7.34E-09	8.74E-03	1.14E-07	1.04E-08	1.25E-03	2.51E-08	1.23E-01	1.41E+01	2.43E+00	5.25E-07
Natural gas	32.62	4.34E-01	3.26E-04	1.16E-01	1.97E-05	4.96E-05	7.49E-04	1.33E-09	9.24E-03	7.49E-09	6.66E-08	2.25E-04	1.33E-09	5.02E-02	7.86E+00	1.95E-01	2.43E-07
Hydro	24.71	1.47E-01	4.15E-04	3.97E-01	1.26E-05	9.54E-05	1.04E-03	2.56E-09	1.16E-02	2.17E-08	3.40E-08	3.85E-04	9.45E-09	1.58E-02	2.24E+00	2.45E+00	6.06E-07
Nuclear	8.87	5.29E-03	4.28E-05	2.70E-02	6.45E-06	8.20E-05	9.70E-05	5.51E-10	1.43E-02	5.50E-09	4.62E-10	2.65E-05	2.21E-09	1.31E-01	1.64E+01	6.25E-02	3.33E-07
PV	1.73	3.72E-02	3.34E-04	6.99E-02	3.93E-05	5.12E-05	5.10E-04	1.63E-09	9.76E-03	1.38E-08	7.18E-09	1.43E-04	2.31E-09	2.72E-02	6.64E-01	4.43E-01	7.21E-06
Wind	4.97	1.24E-02	5.28E-05	7.48E-02	6.67E-06	1.39E-05	1.26E-04	6.56E-09	1.03E-03	2.98E-09	6.71E-10	4.63E-05	7.06E-10	7.52E-03	1.75E-01	1.08E-01	6.75E-07

Table S8: Mid-Point hot-spot analysis from the environmental life cycle impact assessment of study water treatment plants. The blue bars represent horizontal correlation. The heat map colors represent vertical correlation

End Point	Mid Point	Unit	Raw Water Abstraction	Aeration	Flash Mixing	Coagulation	Flocculation	Filtration	Disinfection	Lime-Dosing	Service & Distribution	Backwashing
Climate change	Climate Change - GWP 100a	kg CO2-Eq	0.00E+00	3.09E-03	6.09E-03	5.86E-01	8.83E-03	5.96E-03	2.23E-03	1.50E-04	6.18E-01	3.94E-05
	Freshwater & Terrestrial Acidification	mol H+-Eq	0.00E+00	5.88E-06	1.16E-05	2.23E-03	2.23E-03	1.14E-05	4.20E-06	2.88E-07	1.17E-03	7.50E-08
	Freshwater Ecotoxicity	CTUh.m3.yr	0.00E+00	2.98E-03	5.88E-03	1.81E-02	1.81E-02	5.72E-03	1.40E-03	1.50E-04	5.96E-01	3.81E-05
	Freshwater Eutrophication	kg P-Eq	0.00E+00	8.77E-07	1.73E-06	4.50E-06	4.50E-06	1.68E-06	4.10E-07	4.29E-08	1.70E-04	1.12E-08
Ecosystem quality	Marine Eutrophication	kg N-Eq	0.00E+00	1.43E-06	2.82E-06	4.86E-04	4.86E-04	2.80E-06	7.44E-07	6.99E-08	2.80E-04	1.82E-08
Resources	Mineral, Fossils and Renewables	kg Sb-Eq	0.00E+00	1.28E-08	2.52E-08	7.50E-08	7.50E-08	2.45E-08	5.97E-09	6.25E-10	2.55E-06	1.62E-10
	Carcinogenic Effects	CTUh	0.00E+00	2.98E-11	5.87E-11	3.49E-10	8.49E-11	5.71E-11	1.39E-11	1.46E-12	5.94E-09	3.79E-13
	Ionising Radiation	kg U235-Eq	0.00E+00	1.00E-04	2.00E-04	3.90E-04	3.90E-04	1.99E-04	4.86E-05	5.09E-06	2.08E-02	1.32E-06
	Non-Carcinogenic Effects	CTUh	0.00E+00	3.09E-10	6.09E-10	4.77E-09	4.77E-09	5.93E-10	1.45E-10	1.51E-11	6.18E-08	3.94E-12
	Ozone Layer Depletion	kg CFC-11-Eq	0.00E+00	3.12E-10	6.14E-10	1.16E-07	1.16E-07	9.57E-10	1.70E-08	1.53E-11	6.22E-08	3.97E-12
	Photochemical Ozone Creation	kg ethylene-Eq	0.00E+00	4.54E-07	8.95E-07	1.36E-03	1.36E-03	1.02E-06	1.21E-06	2.22E-08	9.08E-05	5.79E-09
Human health	Respiratory Effects (Inorganics)	kg PM2.5-Eq	0.00E+00	2.99E-07	5.89E-07	7.62E-05	7.62E-05	5.75E-07	1.49E-07	1.46E-08	5.96E-05	3.81E-09
Additional Category	Solid Waste	kg	0.00E+00	2.33E-22	1.07E-22	1.93E-06	1.93E-06	1.04E-22	1.29E-07	2.25E-17	1.09E-20	8.27E-25
Ecosystem quality	Terrestrial Eutrophication	mol N-Eq	0.00E+00	1.43E-05	2.82E-05	5.36E-03	5.36E-03	2.80E-05	7.51E-06	6.99E-07	2.85E-03	1.82E-07
Resources	Water Use	m3 world eq	2.38E+05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Table S9: End-Point hot-spot analysis from the environmental life cycle impact assessment of study water treatment plants

End Point	Aeration	Flash Mixing	Coagulation	Flocculation	Filtration	Disinfection	Lime-Dosing	Service & Distribution	Backwashing
Human health	2.98E-11	5.87E-11	3.49E-10	8.49E-11	5.71E-11	1.39E-11	1.46E-12	5.94E-09	3.79E-13
Climate change	3.09E-03	6.09E-03	5.86E-01	5.86E-01	5.96E-03	2.23E-03	1.50E-04	6.18E-01	3.94E-05
Ecosystem quality	2.99E-03	5.90E-03	2.08E-02	2.08E-02	5.74E-03	1.41E-03	1.51E-04	5.98E-01	3.82E-05
Resources	1.28E-08	1.28E-08	7.50E-08	7.50E-08	2.45E-08	5.97E-09	6.25E-10	2.55E-06	1.62E-10
Human health	1.01E-04	2.01E-04	1.83E-03	1.83E-03	2.01E-04	4.99E-05	5.12E-06	2.09E-02	1.33E-06
Additional Category: Solid Waste	2.33E-22	1.07E-22	1.93E-06	1.93E-06	1.04E-22	1.29E-07	2.25E-17	1.09E-20	8.27E-25
Ecosystem quality	1.43E-05	2.82E-05	5.36E-03	5.36E-03	2.80E-05	7.51E-06	6.99E-07	2.85E-03	1.82E-07

Table S10: Lifecycle Environmental Impact Assessment and the characterized impacts for all the possible pathways

End-Point	Mid-Point	Unit	System	Raw Water Abstraction	Aeration	Flash Mixing	Coagulation	Flocculation	Filtration	Disinfection	Lime-Dosing	Service & Distribution	Backwashing
Human health	Carcinogenic Effects	CTUh	RLWTP	0.00E+00	2.98E-11	2.98E-11	1.50E-10	8.49E-11	2.86E-11	1.48E-12	1.46E-12	8.57E-12	2.62E-13
			SJWTP	0.00E+00	0.00E+00	2.89E-11	1.99E-10	0.00E+00	2.86E-11	1.24E-11	0.00E+00	5.94E-09	1.17E-13
Climate change	Climate Change - GWP 100a	kg CO2-Eq	RLWTP	0.00E+00	3.09E-03	3.09E-03	2.90E-01	8.83E-03	2.98E-03	1.54E-04	1.50E-04	8.90E-04	2.72E-05
			SJWTP	0.00E+00	0.00E+00	3.00E-03	2.95E-01	0.00E+00	2.98E-03	2.08E-03	0.00E+00	6.17E-01	1.22E-05
Ecosystem quality	Freshwater & Terrestrial Acidification	mol H+-Eq	RLWTP	0.00E+00	5.88E-06	5.88E-06	1.11E-03	1.68E-05	5.70E-06	2.95E-07	2.88E-07	1.69E-06	5.18E-08
			SJWTP	0.00E+00	0.00E+00	5.70E-06	1.12E-03	0.00E+00	5.70E-06	3.91E-06	0.00E+00	1.17E-03	2.32E-08
	Freshwater Ecotoxicity	CTUh.m3.yr	RLWTP	0.00E+00	2.98E-03	2.98E-03	6.61E-03	8.51E-03	2.86E-03	1.52E-04	1.50E-04	8.60E-04	2.63E-05
			SJWTP	0.00E+00	0.00E+00	2.90E-03	1.15E-02	0.00E+00	2.86E-03	1.25E-03	0.00E+00	5.95E-01	1.18E-05
	Freshwater Eutrophication	kg P-Eq	RLWTP	0.00E+00	8.77E-07	8.77E-07	1.53E-06	2.50E-06	8.41E-07	4.36E-08	4.29E-08	2.53E-07	7.71E-09
			SJWTP	0.00E+00	0.00E+00	8.51E-07	2.97E-06	0.00E+00	8.41E-07	3.66E-07	0.00E+00	1.70E-04	3.45E-09
Human health	Ionising Radiation	kg U235-Eq	RLWTP	0.00E+00	1.00E-04	1.00E-04	1.95E-04	3.00E-04	9.97E-05	5.16E-06	5.09E-06	2.99E-05	9.14E-07
			SJWTP	0.00E+00	0.00E+00	1.00E-04	1.95E-04	0.00E+00	9.97E-05	4.34E-05	0.00E+00	2.07E-02	4.09E-07
Ecosystem quality	Marine Eutrophication	kg N-Eq	RLWTP	0.00E+00	1.43E-06	1.43E-06	2.42E-04	4.08E-06	1.40E-06	7.11E-08	6.99E-08	4.11E-07	1.26E-08
			SJWTP	0.00E+00	0.00E+00	1.39E-06	2.44E-04	0.00E+00	1.40E-06	6.73E-07	0.00E+00	2.80E-04	5.63E-09
Resources	Mineral, Fossils and Renewables	kg Sb-Eq	RLWTP	0.00E+00	1.28E-08	1.28E-08	2.42E-08	3.64E-08	1.23E-08	6.34E-10	6.25E-10	3.68E-09	1.12E-10
			SJWTP	0.00E+00	0.00E+00	1.24E-08	5.08E-08	0.00E+00	1.23E-08	5.33E-09	0.00E+00	2.55E-06	5.03E-11
Human health	Non-Carcinogenic Effects	CTUh	RLWTP	0.00E+00	3.09E-10	3.09E-10	2.13E-09	8.82E-10	2.97E-10	1.54E-11	1.51E-11	8.91E-11	2.72E-12
			SJWTP	0.00E+00	0.00E+00	3.00E-10	2.64E-09	0.00E+00	2.97E-10	1.30E-10	0.00E+00	6.17E-08	1.22E-12
	Ozone Layer Depletion	kg CFC-11-Eq	RLWTP	0.00E+00	3.12E-10	3.12E-10	5.79E-08	8.89E-10	4.79E-10	4.90E-11	1.53E-11	8.98E-11	2.74E-12
			SJWTP	0.00E+00	0.00E+00	3.02E-10	5.84E-08	0.00E+00	4.79E-10	1.69E-08	0.00E+00	6.22E-08	1.23E-12
	Photochemical Ozone Creation	kg ethylene-Eq	RLWTP	0.00E+00	4.54E-07	4.54E-07	6.81E-04	1.30E-06	5.10E-07	2.46E-08	2.22E-08	1.31E-07	4.00E-09
			SJWTP	0.00E+00	0.00E+00	4.41E-07	6.81E-04	0.00E+00	5.10E-07	1.18E-06	0.00E+00	9.06E-05	1.79E-09
	Respiratory Effects (Inorganics)	kg PM2.5-Eq	RLWTP	0.00E+00	2.99E-07	2.99E-07	3.78E-05	8.52E-07	2.87E-07	1.49E-08	1.46E-08	8.60E-08	2.63E-09
			SJWTP	0.00E+00	0.00E+00	2.90E-07	3.83E-05	0.00E+00	2.87E-07	1.34E-07	0.00E+00	5.96E-05	1.18E-09
	Solid Waste	kg	RLWTP	0.00E+00	2.33E-22	5.44E-23	1.93E-06	1.55E-22	5.22E-23	2.57E-10	2.25E-17	2.00E-23	6.12E-25

Additional Category			SJWTP	0.00E+00	0.00E+00	5.28E-23	1.64E-22	0.00E+00	5.22E-23	1.28E-07	0.00E+00	1.09E-20	2.14E-25
Ecosystem quality	Terrestrial Eutrophication	mol N-Eq	RLWTP	0.00E+00	1.43E-05	1.43E-05	2.67E-03	4.07E-05	1.40E-05	7.11E-07	6.99E-07	4.11E-06	1.26E-07
			SJWTP	0.00E+00	0.00E+00	1.39E-05	2.69E-03	0.00E+00	1.40E-05	6.80E-06	0.00E+00	2.85E-03	5.63E-08
Resources	Water Use	m3 world eq	SJWTP	1.07E+05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
			SJWTP	1.31E+05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00