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REVIEW ARTICLE

Industrial water treatment and industrial marine outfalls: Achieving the right balance

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Abstract Industrial water treatment and industrial marine outfalls both function together to reduce the pollutant concentrations in the effluent and mitigate the potential impact on the environment. The former uses environmental treatment technology with energy and material cost considerations, where the latter utilizes the natural assimilation potential of the coastal water environment achievable at the outfall location. Because of their synergistic nature, marine outfalls are now commonly used for the disposal of partially treated domestic and industrial effluents in many coastal cities around the world, with many successful examples of low and acceptable risks to the environment. The objective of this paper is to review their balance from both environmental and economic considerations. We also discuss the end-of-the-pipe and mixing zone approaches for industrial effluents, and give some recommendations particularly for developing countries. Finally, we emphasize that a compulsory and vigorous monitoring program is essential regardless of how the balance is achieved.

Keywords industrial effluent treatment, industrial marine outfalls, economic and environmental considerations

Supplementary Materials

Table S1 Key pollutants and treatment methods in typical industries

Industry	Key pollutants	Treatment methods [targets]	References
Paper and pulp effluent treatment	COD	Pretreatment [neutralization, screening]: Lime precipitation; Chemical substitution	Chen et al., 1998a,b
	BOD	Primary Treatment [SS]: Sedimentation (*remove 80~90% SS*); Flotation/hydrocycloning	Hostachy et al., 1997
	Color	Secondary Treatment [Organics, toxicity]: Aerated and nonaerated stabilization basin (*remove 90% BOD*); Activated sludge system	Tambosi et al., 2006
	SS	including deep shaft process (*remove 73~99% BOD; 50-92% COD*); Anaerobic (*remove 80% COD*) and aerobic biological treatment	Thompson et al., 2001
	Toxicants (Chlorinated phenolic compounds, Adsorable organic halides (AOX))	Tertiary Treatment [toxicity, SS, color]: Chemical oxidation; Flocculation; Membrane processes, especially ultrafiltration; Ozonation and adsorption; Fungal treatment, Coagulation, etc.	Pokhrel and Viraraghavan, 2004
		Notes: main treatment process: pretreatment and primary process; in some case: succeeded by secondary treatment; tertiary process is expensive and rarely used at present	Wang et al., 2004 Wang et al., 2009

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Industry	Key pollutants	Treatment methods [target: strong color]			References
Textile dyeing and finishing	Color Organic load Nutrients (N, P) PH and salt Sulfur Toxicants (Heavy metal, AOX) Refractory Organics	Methods	Advantages	Disadvantages	
		Ozonation;	Application in gaseous state, no alteration of volume	Short half-life (20 min), High cost	Hao et al., 2000
		Fenton reagents	Effective decolourisation of both soluble and insoluble dyes	Sludge generation and its handling	Hao et al., 2000; Meric et al., 2004
		Photochemical	No sludge production	Formation of by-products	Hai et al., 2007
		Sonolysis	No Extra sludge production	Requires a lot of dissolved oxygen, High cost	Adewuyi, 2001
		Adsorption	Excellent removal of wide variety of dyes	Regeneration difficulties, costly disposal of adsorbent	Hao et al., 2000; Fu and Viraraghavan, 2001
		Membrane filtration	Removal of all types of dye	Production of concentrated sludge, high cost	Marcucci et al., 2001
		Ion exchange	Easy regeneration	Not effective for all dyes	Hai et al., 2007
		Electro-coagulation	Good removal of dye	High cost, less electrode reliability	Phalakornkule et al., 2010
		Irradiation	Effective oxidation at lab scale	Not effective for all dyes, high cost	Hai et al., 2007
		Biological Process	Environmental friendly	Slow Process, need of adequate nutrients, narrow operating temperature range	Togo et al., 2008
		Chemical coagulation and flocculation	Economically feasible, excellent color removal	Sludge production	Verma et al., 2012
		Notes: The main challenge is to eliminate the color of effluent, which is due to the remaining dyes. Other typical pollutants are comparable to municipal effluent.			

Notes: References in Table S1

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Table S2 Selected industrial outfalls

No.	Nominal Const. Year	Name/Location	Pipe Size & Material	Length (m)	Max. Water Depth (m)	Details (industry type; treatment; outfall details; impact)	Reference
1	1978	Aracruz Celulose No.1, Aracruz, Brazil	1000 mm o.d., 923 mm i.d.; Polypropylene	1000	17	Open coast pulp mill discharge; Primary and biological treatment; outfall installed by float and sink; design flow 2 m^3/s, unburied; DL=200 m; 50 wall ports of 100 mm; best practices icon but still at risk	Toven, 2005
2	1978	Altamira, Tamaulipas México	380 mm; Steel	1500	16	Industrial effluent (produce pigment) ; No treatment before discharge	Pérez, 1984
3	1979	Irvine Valley, Troon, Scotland	Twin 1168 mm o.d. steel in 2900 mm; Concrete-lined tunnel	1925	13	Industrial effluent; design pick flow 6.28 m^3/s, offshore disposal with 10 risers each with four 140 mm ports; riser holes drilled by jackup	Henry & McCall, 1982
4	1979	Barceloneta, Puerto Rico	1220 mm Prestressed Concrete	850	30	Industrial effluent (containing volatile organic compounds); Secondary treatment; 100 (2 diffusers, Y) 39 ports	Kennicutt et al., 1984
5	1979	Petróleos Mexi-canos (PEMEX) - Salina Cruz, Oaxaca, Mexico	9140 mm; Protected steel	2680	15	Industrial effluent; Secondary treatment; Discharge to pacific ocean; Diffuser length=38.5; 28 ports (d=17.5 cms)	Rivera, 1986

6	1980	Bo'ness (Grangemouth), Firth of Forth, Scotland	500 mm o.d., 469 mm i.d., steel	1850	4	Petrochemical and Refining effluent discharge (containing polycyclic aromatic hydrocarbon) into estuary; Biological treatment, but full sewage treatment is likely to be some years off; 400 mm CWC and cement lining; 21 port diffuser in frame; 500 mm nozzles, bottom-pull (31 strings)	Richardson et al., 2001

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7	1981	Stevenston (Ardeer No.2, Irvine), Strathclyde, Scotland	500 mm i.d., HDPE, cement grout, 660 mm o.d.; Steel (sleeve)	2361	24	Industrial effluent; DL=135 m; 20 ports; seven strings bottom-pulled; construction cost £2.6 million	Grace, 2009
8	1981	Tso-Ying, Kaohsiung City	1.5 m steel with CWC	5080	20	Mainly industrial effluent (Plastics plant, Industrial Zones, Petroleum Refinery); Effluent treatment since 2008; diffuser length 347 m, step-down diffuser; design-build	Yang, 1995
9	1982	Tanajib, Saudi Arabia	1035 mm i.d.; Steel	1800	-	Industrial bine outflow; nine strings bottom-pulled into predug trench; one riser, one 1066 mm opening; CWC	Azis et al., 2000
10	1982	Cork, Ireland	1420 mm steel with CWC	2500	-	Industrial effluent	Grace, 2009
11	1984	Mondi, Richards Bay, Natal, South Africa	1000 mm o.d., 40 mm wall offshore (50 mm inshore) HDPE	5450	27	Buoyant, fibrous pulp mill effluent; Primary Treatment, build secondary treatment in 2004; open coast (ocean)	Mondi in South Afric Stakeholder Report, 2004
12	1984	Triomf, Richards Bay, Natal, South Africa	900 mm o.d., 40 mm wall, HDPE	4290	23	Heavy fertilizer plant effluent (gypsum slurry); open coast (ocean)	Grace, 2005
13	1984	FERTIMEX, Industrial Port of Lázaro Cárdenas	9140 mm; Polypropilene	1250	26	Industrial effluent; Secondary treatment; two lines, 3 ports/line (d=35.6 cms)	Pérez, 1984

		Michoacán, Mexico					
14	1987	Burcom (Tioxide), Humber Estuary, England, UK	500 mm i.d., 715 mm o.d., composite steel and MDPE	2450	-	Industrial effluent to estuary; sheet pile cofferdam across beach; construction cost £4.4 million	Grace, 2009

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No.	Nominal Const. Year	Name/Location	Pipe Size & Material	Length (m)	Max. Water Depth (m)	Details (industry type; treatment; outfall details; impact)	Reference
15	1988	Dumbarton (Castlegreen), Firth of Clyde, Schotland	1400 mm steel	423	3	Industrial effluent	Grace, 2009
16	1990	Mobil North Sea, St. Fergus, Scotland	323 mm	800	-	Industrial effluent; pull ashore, then burial by trenching machine	Grace, 2009
17	1992	Upper Pyewipe, Grimsby Humber Estuary, England, U.K.	HDPE, 500 mm o.d., 45 mm wall	1395	8	Industrial effluent; lay barge; problems of very shallow water and soft (flowing) mud	Grace, 2009
14	1992	Delray Beach (Latrobe valley), Ninety Mile Beach, Vitoria, Austtralia	800 mm o.d., 727 mm i.d.; HDPE	1267	18	Effluent from a dozen each of towns and Latrobe Valley industries, the latter from treatment lagoon; open coast; float and sink installation (three strings); pipe exposed, except for landfall, with concrete blocks; DL=170 m; 51(140-mm) opening with duckbill valves; design flow 0.7 m^3/s; 350 m long trestle during construction	Samson & Howard, 1987
15	1993	Atul, Valsad, Gujarat, India	800 mm i.d., 900 mm o.d.; HDPE	600	-	Industrial pipe; design flow 4500 m^3/d; multiport diffuser; concrete collars; discharge to Par River estuary; replaced later by longer pipe	Grace, 2009
16	1993	Humboldt County, California, US	-	-	-	Louisiana-Pacific (now owned by Evergreen Pulp, Inc.) pulp mill waste water (40 million gallons per day)； Using Elemental Chlorine Free (ECF) or Totally Chlorine Free (TCF) process to eliminate chlorine; Long (effective) outfall	http://beachapedia.org/Pulp_Mills
17	1994	Besós No.2,	2100 mm i.d.;	2900	54	Services northern metropolitan area; 40% of flow from	Salas, 2000

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No.	Nominal Const. Year	Name/Location	Pipe Size & Material	Length (m)	Max. Water Depth (m)	Details (industry type; treatment; outfall details; impact)	Reference
		Barcelona, Spain	Concrete-coated			Industrial source	
18	1994	Chevron extension, El Segundo, California, U.S.	1549 mm o.d.; HDPE	914	-	Refinery effluent; DL=90 m; 60 duckbill valves; dry weather flow about 0.3 m^3/s; wet weather flow approximately 0.9 m^3/s; manholes at two ends; old outfall about 150 m long	Marine outfall in California Annual Report, 1988
19	1996	Emu Bay, near Burnie, Tasmania, Australia	1000 mm; HDPE	1230	11	Paper mill outfall; No treatment in the beginning resulting disastrous on the environment, later build treatment plant; design-build project	http://soer.justice.tas.gov.au/2003/cem/7/issue/55/index.php
20	1997	Wheatcrof, Cayton Bay, Scarborough, Yorkshire, England, U.K.	273 mm o.d., 255 mm i.d.; Steel	1970	18	Effluent from food processing plant; capacity 95 L/s; open-coast discharge; 50 mm CWC over 6 mm	Grace, 2009
21	1998	Grangemouth, Firth of Forth, Scotland	710 mm o.d., 606 mm i.d.; HDPE	1424	2	Industrial effluent; environmentally sensitive mudflats led to use of HDD; three construction lengths towed to site from Norway and welded together on barge; pilot borehole drilled from shore in 26 hours; reamer attached and pulled back; pipe pulled back separately at roughly 10 m/min; dredging for and installation of diffuser pip work, three 2.5 m high risers, domed protectors, and rock protection followed; 500 mm ports; design flow 1389 L/s	Grace, 2009
22	1998	Gujarat Alkalies and Chemicals Ltd., Dahej, Gulf of Cambay, India	400 mm o.d., 315 mm i.d., HDPE	4250	-	Outfall for industrial complex; cast iron vertebra anchors; 1875 m long extension being added in 2002-2003, to terminate at chart datum water depth of 10 m	Grace, 2009
23	1998	Ucluelet, western Vancouver Island, British Columbia, Canada	450 mm HDPE	1480	28	Fish-processing wastes dominate; DL=30 m; six 150 mm outlets with duckbill valves; stabilization via articulated concrete block mattresses	Grace, 2009

No.	Nominal Const. Year	Name/Location	Pipe Size & Material	Length (m)	Max. Water Depth (m)	Details (industry type; treatment; outfall details; impact)	Reference
24	2006	Clandeboye, Timaru, New Zealand	900 mm o.d., HDPE	810	-	Industrial effluent; Now upgrading effluent treatment, before that using millscreen with existing outfall	Timaru District council Annual Report, 2012
25	-	Alaska	-	-	-	Alaska Pulp Corporation (APC) Sitka pulp mill effluent; Secondary treatment	https://dec.alaska.gov/spar/csp/sites/apc.htm

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No.	Nominal Const. Year	Name/Location	Pipe Size & Material	Length (m)	Max. Water Depth (m)	Details (industry type; treatment; outfall details; impact)	Reference
26	-	Reunion Island (Southwest Indian Ocean)	Two pathway: Surface discharge; deep underground injection	-	-	Industrial sugar mill (0.8~1.1 tons of fine particulate dry matter; 0.023 g/L of total organic matter, turbidity of 41.8 NTU), The thermic power plant (0.33~0.98 TDM/d, 0.021 g/L of TOM, turbidity of 35NTU) directly discharge to sea Distillery effluent (large volumes, around 420 m^3/d during 6 months each year; high loads of fine terrigenous particulates (2.2 TDM/d, turbidity up to 200 NTU) and high organic content (COD of 105 g/L) and nutrients (K^+ 9 g/L, Cl^- 6g/L) underground injection 120 m depth	Bigot et al., 2006
27	-	Nellore Coast, East Coast of India	-	-	-	untreated industrial wastes containing heavy metals, agricultural and aquacultural waste	Jayaraju et al., 2008
28	2001 (stage I)	HATs, Hongkong	-	-	-	domestic and industrial effluent effluents; Chemically enhanced primary treatment (CEPT)(stage I), Biological treatment (stage II); The outfall tunnel is connected to a 1.2km diffuser pipeline laid in a pre-dredged trench on the seabed through two riser pipes. The effluent is dispersed into the tidal stream through 24 diffusers installed along the diffuser pipeline.	Xu et al., 2011
29		La Trobe River, Victoria, Australia	-	-	-	Pulp and paper mill effluent (Australian Paper Manufacturers Ltd, APM, 55 million L/day) Tertiary treatment (101 ha pond, residence time 3 weeks); Effluent treatment had successfully avoided the major environmental problems often associated with pulp and paper mills	Harris et al., 1992

30		Near Usgo Beach in the north coast of Spain	478 mm i.d. stainless steel pipe and a wall thickness of 6 mm	666	14 m	industrial waste (company Solvay Química S.L) 40º C with a very high concentration of carbonate suspended solids (22 gr/l), and a density higher than that of the sea water	Álvarez et al., 2004

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