Decision-support system for risk management of produced water in the offshore petroleum industry

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Abstract: A decision-support system for produced water management (DISSPROWM) in offshore operations is being developed. The system determines the risk and hazards to human and marine species from non-carcinogenic and carcinogenic pollutants, including radionuclides present in produced water. The DISSPROWM also evaluates the best available treatment technology for treating the produced water whose properties are in the database. The system consists of a Windows-based Graphical User Interface (GUI) developed with Microsoft Visual Basic, which integrates a SQL Server database, a risk assessment model and a dilution model for produced water contaminants. The database contains most produced water pollutants and their important properties that are required in dispersion and risk assessment modelling. The database also contains current produced water regulations and information on some of the selected existing treatment technologies with typical cost data required in the decision-support system.

Keywords: best available treatment technology; decision-support system; oil and gas industries; produced water; produced water database; risk assessment.

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1 Introduction

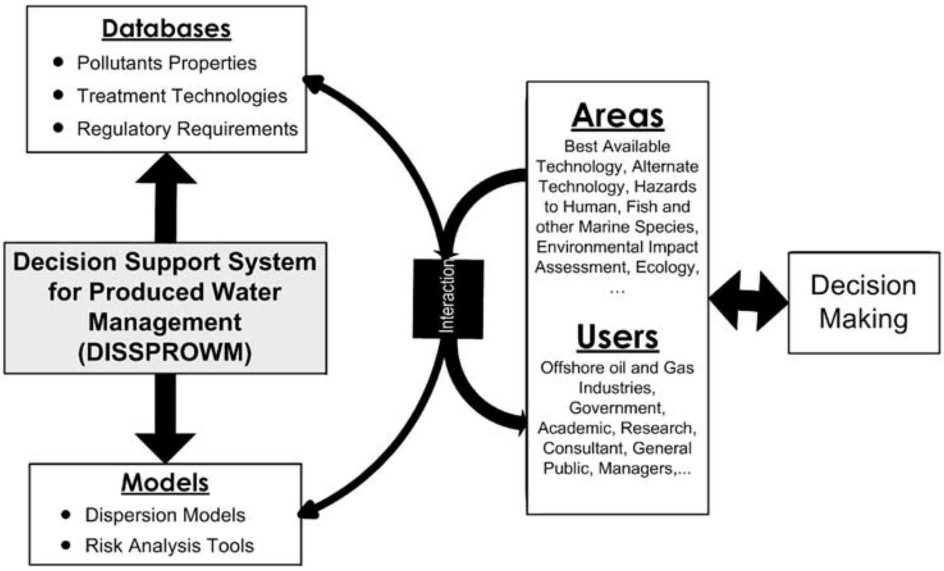
According to the International Association of Oil and Gas Producers (OGP) report, about 17 million m^3 of produced water is produced daily worldwide in combined onshore and offshore operations. This is equivalent to 120 million barrels of oil per day (OGP, 2004). Management of this huge volume of produced water in offshore developments in conjunction with the crude oil and natural gas is a challenge for the industries. A number of disposal options with benefits and impacts are discussed by Kuipers et al. (2004). Common disposal options include produced water treatment (PWT), reinjection (PWRI) and disposal (PWD). New methods are emerging for produced water treatment (Hayes and Arthor, 2004). PWRI has been implemented or planned on several fields in Norway where 'zero harmful discharge to the sea' is a goal set by the Parliament (NPD, 2004). In many cases, discharge of produced water to the sea is an option that can be considered as a part of sound management (OGP, 2005). It is not easy for the oil and gas industries to make a decision about which disposal options to use because this necessitates a detailed study of treatment methods, costing information and regulatory requirements.

The decisions that industries need to make are:

- how clean should the produced water be (design of the treatment facility) before being discharged?
- should the produced water be treated? If so what is the best available technology (BAT) for treatment?
- what are the alternative treatment technologies considering cost and removal?
- should produced water be reinjected into the wells?
- what is the risk involved to the marine organisms and humans if the produced water is discharged into the ocean: in the short term; in the long term?
- what are the regulatory requirements before discharge and are they realistic and sufficient?

DISSPROWM is being developed with the objective to address issues that are critical for the offshore petroleum industry and also to make the tool applicable to industry in their decision making to manage produced water in a cost effective and environmentally safe manner. A schematic of DISSPROWM is shown in Figure 1. As shown in the figure, it contains a comprehensive database with information on chemical properties, toxicity and technology, dilution models, as well as information on best available treatment technology applicable to offshore platforms. The components will be discussed in the following sections.

Figure 1 Schematic of the decision support system



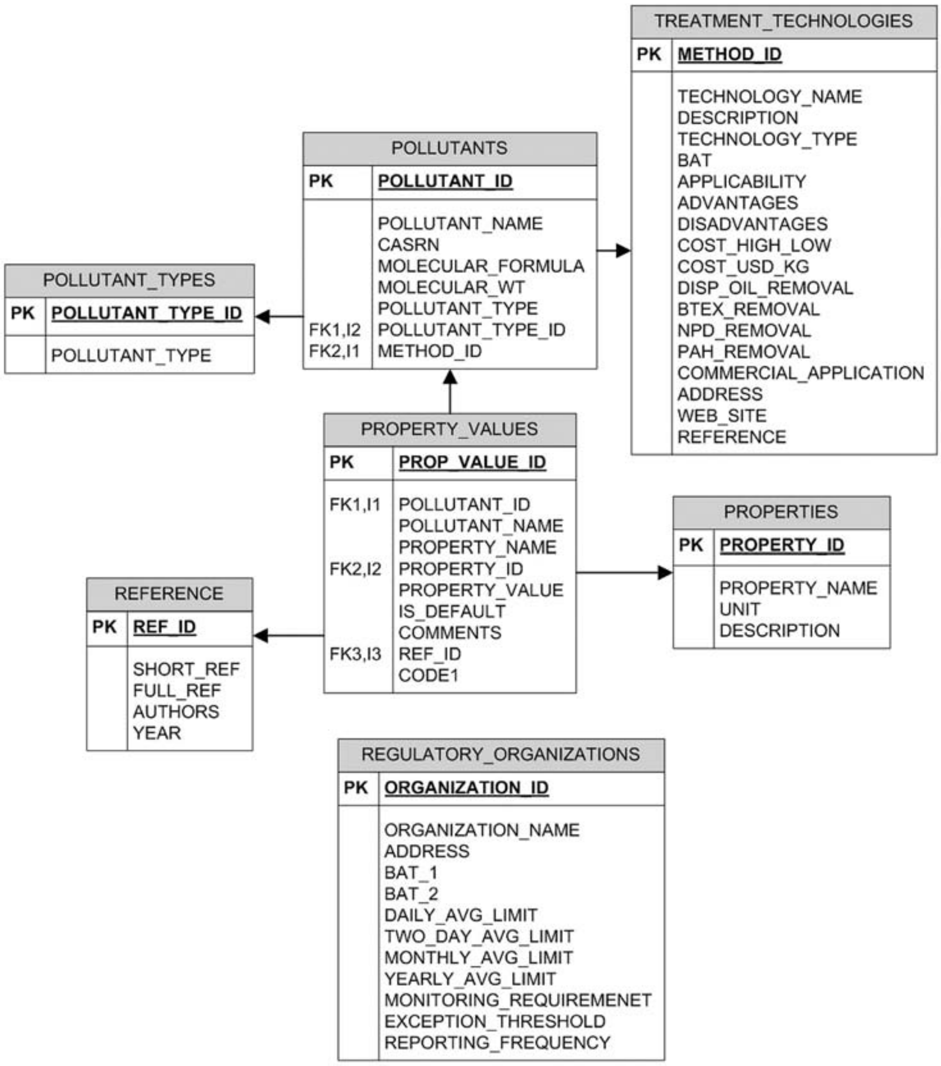
2 DISSPROWM database

Numerous studies have been conducted in the past on produced water contaminants, their fate and transport in the marine environment, and the risk to ecology and human beings. These studies have been compiled in many books and reports (e.g. CAPP, 2001; Ekins et al., 2005; Neff, 2002; OGP, 2005; Ray and Engelhardt, 1992; Reed and Johnsen, 1996). Chowdhury (2004) developed a Microsoft Access based database that contains common produced water pollutants and their properties.

USGS developed a nationally produced water geochemistry database that contains data from several US sites (Otton et al., 2003). Another water compositional database has been recently completed by the Advanced Resources International, Inc. for the US Department of Energy (NETL, 2006). A produced water management system was also developed by Cather et al. (2003). This system is called the New Mexico Water and Infrastructure Data System (NM WAIDS) and was developed for produced water-related issues in southeast New Mexico. All the above databases contain local site-specific data and may not be suitable for a generalised management of produced water.

In DISSPROWM, Chowdhury's (2004) database has been expanded to cover more chemicals and to include more properties and new entities. The database model is shown in Figure 2. The database model has been normalised to third order form (3NF) to eliminate redundancy and to improve data consistency and future enhancements. Apart from the pollutants and pollutant properties, information on existing treatment technologies, their applicability and cost in the offshore environment, information on the regulatory requirements of produced water discharge, and monitoring requirements have also been introduced.

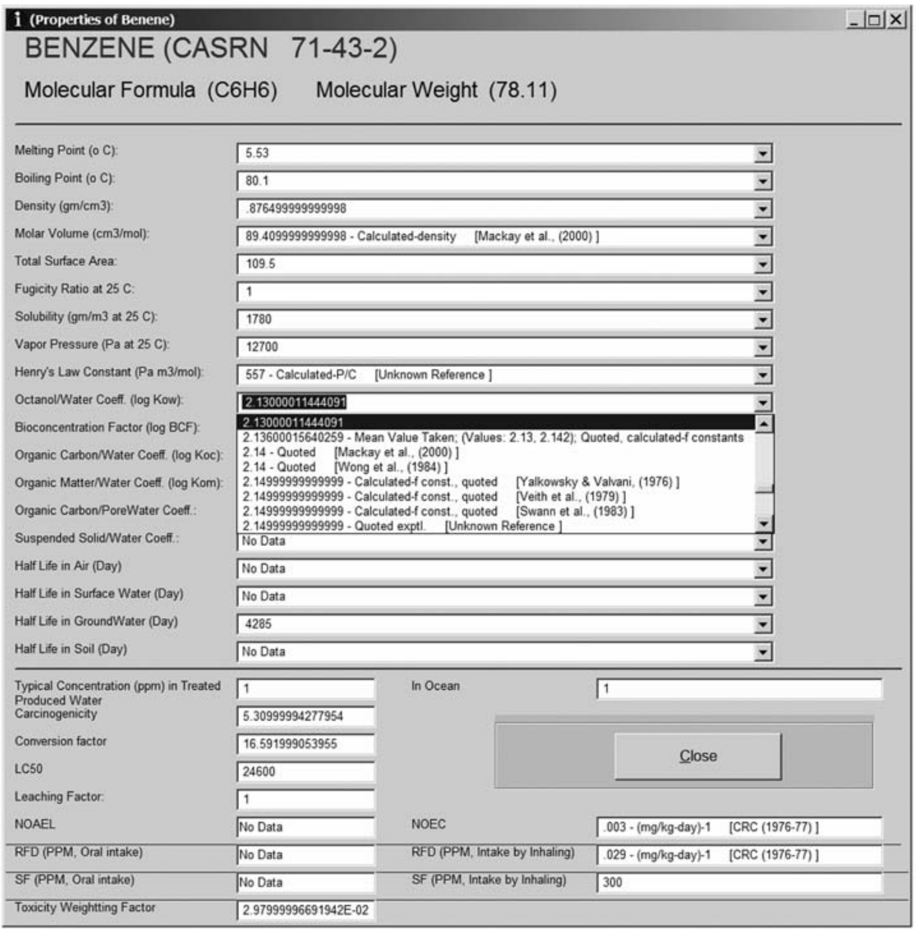
Figure 2 Database model of DISSPROWM



The database currently contains about 700 pollutants taken from about 2700 references. The database has 36 important properties of produced water pollutants. Many of these properties can have multiple values taken from different citations as shown in the screen display presented in Figure 3. Figure 3 shows the various properties of pollutants and units of measurements.

The database has been implemented on a Microsoft SQL Server 2000 database server. The Graphical User Interface (GUI) of DISSPROWM integrates the database, initial dilution model, dispersion model, and risk computation models, all of which, except the dispersion model, have been developed with Microsoft Visual Basic. The dispersion model has been developed with FORTRAN.

Figure 3 Searching pollutant properties in the database



3 Features of DISSPROWM

DISSPROWM has the following characteristics and functionalities:

- It has a rich database containing produced water contaminants, treatment technologies, case studies, costing, and regulatory guidelines.
- It integrates the database of produced water contaminants dispersion models with risk computation models.
- It has interactive data entry for produced water contaminants and dispersion model parameters.
- From a known concentration of produced water contaminates the system can decide the best available technology (BAT), and its approximate cost. Based on the extent of treatment, it is possible to estimate risk to fish and marine species and human beings and hence a tradeoff between cost and risk can be developed.

As shown in the DISSPROWM flow chart (Figure 4), the system takes a series of user input in sequence and decides the best available technology and risk to marine habitats and human health. In addition to the best available technology, the system also selects an alternate technology (i.e. the second best) based on the cost and treatment efficiency. One of the data entry screens of DISSPROWM showing the toxicology data is shown in Figure 5. These data are used in the risk computation and can be modified by DISSPROWM users. Selection of pollutants and specifications of pollutant concentrations are done in the previous two steps. DISSPROWM is a menu driven system with a common toolbar for frequently used functionalities.

Figure 4 Flow chart of the decision support system

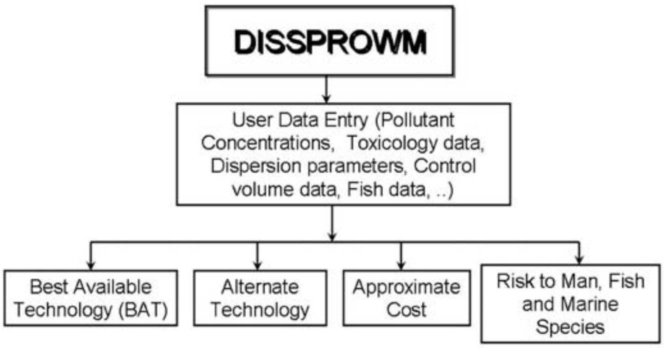
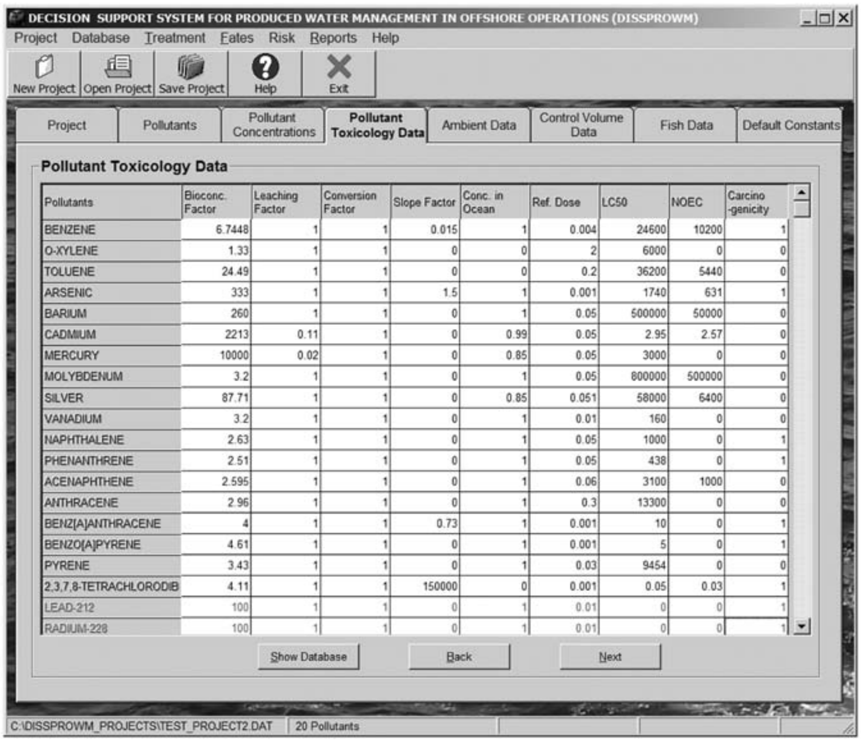


Figure 5 Viewing and modifying toxicology data of pollutants in DISSPROWM



Pollutants	Bioconc. Factor	Leaching Factor	Conversion Factor	Slope Factor	Conc. in Ocean	Ref. Dose	LC50	NOEC	Carcino -genicity
BENZENE	6.7448	1	1	0.015	1	0.004	24600	10200	1
O-XYLENE	1.33	1	1	0	0	2	6000	0	0
TOLUENE	24.49	1	1	0	0	0.2	36200	5440	0
ARSENIC	333	1	1	1.5	1	0.001	1740	631	1
BARIUM	260	1	1	0	1	0.05	500000	50000	0
CADMIUM	2213	0.11	1	0	0.99	0.05	2.95	2.57	0
MERCURY	10000	0.02	1	0	0.85	0.05	3000	0	0
MOLYBDENUM	3.2	1	1	0	1	0.05	800000	500000	0
SILVER	87.71	1	1	0	0.85	0.051	58000	6400	0
VANADIUM	3.2	1	1	0	1	0.01	160	0	0
NAPHTHALENE	2.63	1	1	0	1	0.05	1000	0	1
PHENANTHRENE	2.51	1	1	0	1	0.05	438	0	1
ACENAPHTHENE	2.595	1	1	0	1	0.06	3100	1000	0
ANTHRACENE	2.96	1	1	0	1	0.3	13300	0	0
BENZ[A]ANTHRACENE	4	1	1	0.73	1	0.001	10	0	1
BENZO[A]PYRENE	4.61	1	1	0	1	0.001	5	0	1
PYRENE	3.43	1	1	0	1	0.03	9454	0	0
2,3,7,8-TETRACHLORODIB	4.11	1	1	150000	0	0.001	0.05	0.03	1
LEAD-212	100	1	1	0	1	0.01	0	0	1
RADIUM-228	100	1	1	0	1	0.01	0	0	1

The *Database* menu is used to query, retrieve, export and print information from the database. The *Treatment* menu is used to display suggested treatment technologies. The *Fate* menu is used to compute the predicted environmental concentration (PEC), exposure concentration and fish tissue concentrations. The *Risk* menu is used to compute hazards and risks to fish, human and other marine species. The *Report* menu is used to generate high quality reports for pollutants, references, treatment technologies and regulatory requirements. DISSPROWM is also equipped with context sensitive help for users that can be displayed using the Help menu or toolbar. The data entered for a particular problem can be saved and retrieved later.

4 Regulations for produced water discharge

Produced water discharge regulations vary greatly from country to country (CAPP, 2001). This is largely due to the experience of a country in dealing with oil and gas including its particular societal values. Some of the more recently built oil and gas platforms have relaxed regulations on produced water discharge while other platforms have very strict regulations, and some follow zero discharge regulations. When considering these regulations, we also have to look at the chemical concentration and toxicological characteristics of the produced water which vary from place to place, as shown in Table 1.

Table 1 Typical concentrations of different pollutants in different regions (Units are in μg/l otherwise stated

Parameter	*North sea (6 platforms)*			*Gulf of Mexico*			*Java Sea (6 platforms)*			*Bass straits*
	Min	*Ave*	*Max*	*Min*	*Ave*	*Max*	*Min*	*Ave*	*Max*	
As	NR	NR	NR	NR	NR	NR	1.5	4.7	9	<1.5
Ba	12,000	27,430	42,100	NR	NR	NR	NR	NR	NR	NR
Cd	20	6670	10,000	0	27	98	ND	0.5	ND	<5
Cr	0.05	13.2	40	0	186	390	7.5	124	185	<5
Cu	2	128.8	600	0	104	1455	ND	5.2	ND	<5
Fe	4	20.57	23	NR	NR	NR	NR	NR	NR	NR
Hg	1.9	4	9	NR	NR	NR	0.004	0.006	0.0012	0.044
Ni	NR	NR	NR	0	192	1674	45	95	143	<5
Pb	50	112.5	270	2	670	5700	12	193	260	23
Zn	0.26	47	200	17	170	1600	ND	ND	ND	<30
Benzene	1417	4430	6853	2	1318	8722	69.3	1720	3000	24
Toluene	2174	2571	2947	60	1065	4902	90.8	650	1300	NR
Ethylbenzene	425	961	1503	26	68	110	26	41	56	
Xylene	675	2201	3411	160	440	720	13	247	480	
BTX	1100	15,740	66900	NR	NR	NR	NR	NR	NR	NR
Naphthalene	38	272	398	0	132	1179	8.4	35	99	1.6
Phenol	33	1934	5100	0	1049	3660	NR	NR	NT	NR
226_{Ra} (pCi/l)	NR	NR	NR	4	262	584	NR	NR	NR	NR
228_{Ra} (pCi/l)	NR	NR	NR	18	277	586	NR	NR	NR	NR

Note: NR: data were not reported; ND: not detected; Min: Minimum; Ave: Average; Max: Maximum.

Source: Data compiled from Neff (2002); Roe et al. (1996); Smith et al. (1996); Stagg et al. (1996); and Stephenson (1992).

Table 2 shows the current regulatory requirements of produced water discharge standards adopted by various countries. The best available technology adopted by these countries is also shown in the table. The effluent limits shown are in mg/l of total oil and gas or dispersed oil and gas as indicated in the table. These regulatory requirements are also entered in the DISSPROWM Database.

Table 2 Produced water treatment standards comparison

Country	*'BAT'*	*Effluent limits*	*Monitoring requirements*	*Exception thresholds*	*Routine reporting*
US	Gas flotation	29 mg/l monthly avg. 42 mg/l daily max.	Total O&G Gravimetric	Any exception	Annual
UK	Gas flotation Hydrocyclone	40 ppm monthly avg. 30 ppm annual avg.	Dispersed O&G 1/day composite O&G 1/year comprehensive	>100 ppm	Monthly O&G Annual comprehensive
Norway	Gas flotation Hydrocyclone	40 ppm monthly avg.	Dispersed O&G 1/day composite O&G 1/year comprehensive	>40 ppm Monthly avg.	Quarterly O&G Annual comprehensive
Canada	Not stated	40 ppm 30 day avg. 80 ppm 2 day avg.	Dispersed O&G 2×1 day	Any exception	Monthly

Source: adapted from CAPP, 2001.

5 Risk to the marine environment from components of produced water

Some produced water pollutants, including petroleum hydrocarbons, metals, and radionuclides, have the potential of being accumulated in fish tissue and other marine organisms by a bioaccumulation process, although many studies have revealed that the level of accumulation of these pollutants is very low in natural environments due to high dilution rates (CAPP, 2001). In most cases, increases of tissue concentrations were too small to measure.

The fate and effects of produced water discharge depends on the fate of the individual components and how their concentrations change with time. Physical and chemical mechanisms that determine fate are dilution, volatilisation, chemical reaction, adsorption on suspended solids, and biodegradation (Stephenson et al., 1994). Dilution is mainly thought of as occurring in two phases. There is the initial dilution or near-field phase which occurs in the first few minutes, and the far dilution phase that happens several hours later (Baumgartner et al., 1992, Brandsma et al., 1992).

Components of produced water have been classified in various ways by various researchers. The main groups of contaminants that are of primary concern in produced water are:

- BTEX – monocyclic aromatic compounds: benzenes, toluene, ethylbenzene, and xylene (ortho, meta, and para isomers)
- NPD – 2–3 ring aromatic compounds: naphthalene and phenanthrene and dibenzothiphene, including their C1–C3 alkyl homologues
- PAHs –16 polycyclic aromatic hydrocarbons (3–6 ring compounds), listed by the US Environment Protection Agency (Ekins et al., 2005)
- phenolic compounds – class of chemical compounds consisting of a hydroxyl group (-OH) attached to an aromatic hydrocarbon group
- heavy metals – a group of elements between copper and lead on the periodic table of the elements having atomic weights between 63.546 and 200.590 and specific gravities greater than 4.0
- radionuclides – mainly isotopes of radium and lead.

Most of the aromatic hydrocarbons (BTEX, NPD, PAHs) and phenols are bioavailable to marine species due to bioconcentration, bioaccumulation and biomagnification. These compounds are therefore harmful to fish and humans. A number of heavy metals are also toxic for humans and fish due to bioconcentration and biomagnification.

Radionuclides are very common constituents in produced water. The two isotopes that are of main concern are ^{226}Ra and ^{228}Ra. They are more important because they are highly soluble in water, and have the potential to bioaccumulate in marine organisms (Hamilton et al., 1992).

In the DISSPROWM database, pollutants have been divided into 24 different categories, namely alcohols, aldehydes and ketones, alkanes, BTEX, carboxylic acids, chlorobenzenes, esters, ethers, halogenated hydrocarbons, hazardous air pollutant, herbicides, hydrocarbons/alkanes, ions, MAHs (monoaromatic hydrocarbons), metals, nitrogen and sulphur compounds, NPDs, PAHs, PCBs, PCDDs, PCDFs, phenolic compounds, radionuclides (NORM) and solvents.

6 Dilution models

A number of dilution models (Huang et al. 1998; Lee and Cheung, 1991; Mukhtasor, 1991; Proni et al., 1996) have been summarised by Chowdhury (2004). Mukhtasor's model, which is a modified version of Huang et al.'s model (1998), has been used in DISSPROWM. The model equations developed by Mukhtasor (2001) are as follows:

$$\frac{SQ}{uz^2} = 0.13\left(\frac{z}{l_b}\right)^{-0.31} + 0.46e^{(-0.22/(z/l_b))} \tag{1}$$

$$\frac{SQ}{uz^2} = (0.13 \pm 0.02)\left(\frac{z}{l_b}\right)^{(-0.31\pm0.03)} + (0.46 + 0.02)e^{((-0.22\pm0.04)/(z/l_b))} + N(0,0.092) \tag{2}$$

where: S=initial centreline dilution; Q=effluent discharge (m^3/s); U=ambient water velocity (m/s); Z=height of water surface from discharge point (m); l_b=vertical distance at which effluent velocity reduced to ambient velocity (m); $N(0,0.092)$=normally distributed error term with mean 0 and standard deviation=0.092.

$$l_b = \frac{Qg(\rho_a - \rho_0)}{u^3 \rho_a} \tag{3}$$

where: g=acceleration due to gravity=9.81 m/s^2; ρ_a=ambient water density (kg/m^3); ρ=effluent density (kg/m^3).

In this equation, both the buoyancy dominated near field (BDNF) and buoyancy dominated far field (BDFF) were connected through a transition zone model. This model compared favourably with the models of Lee and Cheung (1991) and Huang et al. (1998). Mukhtasor's model was selected for two reasons:

- it gives a smoother more realistic result over the transition region
- predicted parameters of the model had good statistical agreement.

The near field mixing is applicable for deep-water conditions where a distinct buoyant jet rises to the surface and dilution occurs as a result of turbulent jet entrainment (Jirka and Lee, 1994).

7 Risk assessment methodology

Produced water contaminants pose potential risks to humans both for non-carcinogenic and carcinogenic effects. The dominant pathway for uptake of pollutants is ingestion of contaminated fish. Bioaccumulation of pollutants in the risk assessment equations used in DISSPROWM is discussed in detail by Chowdhury (2004). A brief description of the risk assessment methodology is given below.

The human health hazard for non-carcinogen is estimated as (Louvar and Louvar, 1998):

$$HQ = \frac{CDI}{RfD} \tag{4}$$

where: HQ=hazard quotient; RfD=reference dose (mg/kg-day); and is stored in the DISSPROWM database; CDI=Chronic daily intake (mg/kg-day) and is computed by DISSPROWM (Chowdhury, 2004). The target organ depends on the pollutant and can be the skin, liver, kidney, lungs, blood and the nervous, reproductive and immune systems.

$$CDI = \frac{C_f \times FIR \times FR \times EF \times 10^{-6}}{BW \times 365} \tag{5}$$

where: FIR=fish ingestion rate (g/day; according to USEPA (1996), FIR=170); FR= fraction of fish from contaminated source (a value of 0.50 (50%) may be used); EF= exposure frequency (days/year; according to USEPA (1991), EF=350 days; BW= average human bodyweight over the exposure period (kg); 10^{-6}=resulted conversion factor for fish tissue concentration and fish ingestion; 365=conversion of averaging time from year to days; C_f=concentration in fish tissue (μg/kg of fish; given by Chowdhury, 2004).

$$C_f = \frac{W_c}{F_{epr} \times W_t} \tag{6}$$

where: F_{epr}=ratio between the weight of edible part to the weight of whole fish; W_t=weight of fish (kg). W_t is taken as the average weight of the fish during the exposure period. In DISSPROWM this is computed from the initial weight of the fish and the fish growth model suggested by Chowdhury (2004).

$$\ln\left(\frac{W_t}{W_o}\right) = \frac{c}{a}\left(1\text{-}e^{-a\,t}\right) \tag{7}$$

where: W_c=total accumulated contaminants in a fish (μg). W_c is computed from the exposure concentration (C_{exp}) of the pollutant, its bioconcentration factor, fraction of lipid content of the fish and the weight of the fish as follows (Chowdhury, 2004):

$$W_c = C_L\, W_L = C_L\, (W_t\, F_L) = (C_{exp}\, BCF)\, (W_t\, F_L) \tag{8}$$

where: C_L=concentration of contaminant in lipid of a fish (μg/kg); F_L=fraction of lipid content in a fish (μg/kg); BCF=bioconcentration factor; C_{exp}=exposure concentration (μg/l), which is computed from (Chowdhury, 2004):

$$C_{exp} = C_w \times p \times BAF \tag{9}$$

where: C_{exp}=exposure concentration for fish; p=exposure probability; BAF= bioavailable fraction=leaching factor multiplied by conversion factor. Both of these parameters are stored in the DISSPROWM database. C_w=predicted environmental concentration (PEC). It is predicted using Muktashor's (2001) dilution model.

7.1 Computation of total hazard

The total hazard can be computed from individual hazards using the probability equations (Louvar and Louvar, 1998). If $E_1, E_2, E_3, \ldots E_n$ represents the events that cause hazards, $HQ_1, HQ_2, HQ_3, \ldots HQ_n$, then the total hazard, also called hazard index (HI) is:

$$HQ_{total} = P\left(E_1 \bigcup E_2 \bigcup E_3 \ldots \bigcup E_n\right)$$

The above equation is based on the assumption that the target organ for all pollutants is the same. If it is different for different pollutants, the hazard index is computed and reported separately by DISSPROWM. Assuming the occurrence of exposure to each of the contaminants is independent:

$$P\left(E_1 \bigcup E_2\right) = P(E_1) + P(E_2) - P(E_1)P(E_2) = HQ_1 + HQ_2 - HQ_1 HQ_2$$

$P(E_1 \bigcup E_2 \bigcup E_3)$ can be computed by adding $P(E_3)$ with the result of $P(E_1 \bigcup E_2)$. This procedure can be repeated to compute $P(E_1 \bigcup E_2 \bigcup E_3 \ldots \bigcup E_n)$. This technique is incorporated with a small computer programming loop in DISSPROWM.

7.2 Risk computation for carcinogens

The human health risk for carcinogens is predicted by a modified version of Equation (6) (Chowdhury, 2004):

$$CDI_C = \frac{C_f \times FIR \times FR \times EF \times ED \times 10^{-6}}{BW \times AT} \tag{10}$$

where: CDI_C=chronic daily intake of carcinogen (mg/kg-day); EF=exposure frequency (days/year); ED=exposure duration (years); AT=Averaging time in days; for high human development countries, the life expectancy=77.1 years

The human risk of cancer from a pollutant is given by Chowdhury (2004):

$$CR = CDI_C \times SF \tag{11}$$

where: CR=cancer risk; CDI_C=chronic daily intake of carcinogen (mg/kg-day); SF=slope factor $(mg/kg\text{-}day)^{-1}$ of the pollutant that is a parameter in the database.

7.3 Radionuclide carcinogens

The cancer risk from radionuclide carcinogen is given by:

$$CR_{RAD} = I_T \times SF \tag{12}$$

where: CR_{RAD}=cancer risk from a radionuclide; I_T=total radionuclide intake (pCi) which is given by Louvar and Louvar (1998) as:

$$I_T = C_{flrad} \times FIR \times EF \times ED \times FR \times GI \times 10^{-3} \tag{13}$$

where: GI=gastrointestinal absorption factor. A value of 0.20 may be used.

C_{fllra}=radionuclide concentration in the edible part of fish (pCi/kg) and is given by Chowdhury (2004):

$$C_{flrad} = \frac{W_{rad}}{[x + (1 - x)y] \times W_t} \tag{14}$$

where: C_{fllra}=radionuclide concentration in edible part (pCi/kg); $C_{bonerad}$=radionuclide concentration in bone/shell/exoskeleton (pCi/kg); W_{rad}=total radionuclide accumulated in fish (pCi); x=edible part of a fish; $y=(C_{bonerad}/C_{flrad})$.

Like non-radionuclides (Equation 8), W_{rad} is computed from the bioconcentration factor, exposure concentration and weight of fish as follows:

$$W_{rad} = C_{rad}\,W_t = (C_{exp}\,BCF)\,W_t \tag{15}$$

7.4 Computation of total risk

The total risk can be computed from individual risk using the probability equations as described earlier in this section. DISSPROWM computes fish tissue concentration of pollutants at different times over the exposure period, lipid content, individual hazard and the total hazard to fish. DISSPROWM also computes human carcinogenic risk from assumed ingestion of contaminated fish. The parameters used for human risk assessment are fish ingestion rate, exposure frequency, fraction of contaminated fish ingestion, average human body weight, gastrointestinal adsorption factor and average human life expectancy. The hazards to other marine species (molluscs, bivalves, crustaceans, crustaceans larvae, echinoderms, sea star, amphipod, gastropods, gastropods larvae, shrimp, rotifers, copepod, mysid, crab, polychaetes, polychaetes larvae, decapod, sea urchin, oyster, mussels, phytoplankton, clams, pelecypod, annelids and algae) are under development but can be assessed by comparing with the NOEC and LC50 values stored in the database.

8 Produced water treatment technologies

Numerous studies have been done on treatment technologies, their applicability, advantages, disadvantages, cost, commercial applications and other factors. Information on produced water treatment technologies are scattered and are being continuously compiled in the DISSPROWD database.

There are a large number of techniques that are already deployed to treat produced water. The focus of this section is those advanced abatement techniques most likely to be deployed to comply with the stricter regulatory requirements. In 1995 the American Petroleum Institute, (API, 2000), made its recommendation on the Best Available Technology for Produced Water Management on Offshore Gas and Oil Installations (New Logic Research, 2003).

Significant technological advances have been made since 1995 including the introduction of several treatment methods. A recent overview of treatment methods and their applicability may be found in Hayes and Arthor (2004)

Several other commercial treatment methods are available in the market as shown in Table 3. Most of these treatment technologies are stored in the DISSPROWM database. A DISSPROWM screen showing the best available technology and alternate technology is shown in Figure 6.

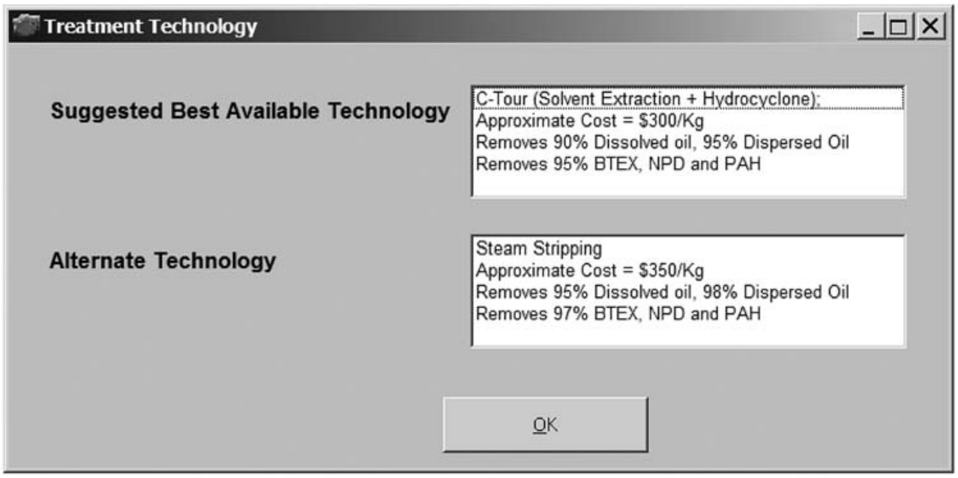
Table 3 Types of technology available to treat produced water discharge

Technology	*Description*	*References*
VSEP (vibratory shear enhanced process)	Vibrating membrane mechanism is used to avoid membrane fouling. The method is claimed to deliver higher throughput per square foot of membrane when compared to other membrane systems.	New Logic Research, 1295 67th Street, Emeryville, CA 94608 USA 510–655–7305 510–655–7307 www.vsep.com
USFilter	US based company, USFilter, offers a complete range of equipment and processes to satisfy treatment requirements for enhanced oil recovery and to solve produced water treatment problems. Designed to meet rigorous oil field production standards, and to withstand harsh operating environments.	USFilter – North America, Middle East, Europe, Africa, Latin America, Asia/Pacific, China www@usfilter.com
Epcon compact flotation unit technology	The Epcon compact flotation unit (CFU) is a multiphase (oil/water/gas) separator with no moving parts. Is consists of several combined processes, including gas flotation and induced centrifugal inertia forces, which act on the fluid components of different specific gravities. It requires no external energy. It is claimed to be highly efficient in the separation of water, oil and gas and to achieve a high standard of treated water.	Epcon Offshore AS, London, Norway http://www.epconoffshore.com
CTour process (solvent extraction and hydocyclones)	CTour Process Systems AS (C-Tour) is a Norwegian company and is an enhancement to the hydrocyclone technique based on the extraction of hydrocarbons from water using gas condensate.	CTour Process Systems AS, Forusbeen 78, P.O. Box 236, 4066 Stavanger, Norway www.ctour.com

Table 3 Types of technology available to treat produced water discharge (continued)

Technology	*Description*	*References*
Filtra Systems technology	Filtra-Systems Company is in the market for design, fabrication, and installation of coolant filtration systems. The company is claimed to have developed the 'Best Available Technology' for produced water filtration and other oily wastewater applications.	2003 Filtra Systems, Inc. www.filtrasystems.com
PTTC technology	Downhole oil/water separators (DOWS) or gas/water separators (DGWS) technology that can help reduce water handling costs and produce more hydrocarbons to the surface per day. Its features include a high water-to-oil ratio, the presence of a suitable injection zone that is isolated from the production zone, compatible water chemistry between the producing and injection zones, and a properly constructed well with good mechanical integrity.	Petroleum Technology Transfer Council, 2916 West T. C. Jester, Suite 103, Houston, TX 77018 toll-free 1–888-THE-PTTC www.pttc.org
Sorption (SMZ) and air striping (VPB)	These are low-cost, simple technologies for produced water treatment by sorption and air stripping. Sorption of organics by surfactant-modified zeolite (SMZ) followed by air stripping and subsequent treatment of the off-gas by a vapour-phase bioreactor (VPB).	Water treatment technology for oil and gas produced water. EJ Sullivan (LANL), RS Bowman (New Mexico Tech), L. Katz (UT Austin), and K. Kinney (UT-Austin) www.unm.edu
MPPE technology (macro porous polymer-extraction)	Field-proven removal of dissolved and dispersed hydrocarbons at commercial scale from offshore produced water.	Produced Water Workshop www.akzonobelmppsystems.com

Figure 6 Treatment technology suggested by DISSPROWM



9 Conclusions and recommendations

A tool for risk assessment for produced water discharges from the offshore oil and gas industries is being developed. DISSPRWOM is very simple, but very easy and powerful. It has very rich documentation and online help for all level of users. The authors are continuously upgrading the database for new pollutants and toxicology data, new treatment technology and costing information. It is planned to integrate a new hydrodynamic model being developed by our team, risk assessment and risk management tools taking into account data uncertainty and commercially available treatment technologies to manage produced water in offshore oil and gas operations in cost-effective and environmentally safe manners.

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References

Baumgartner, D.J., Frick, W.E., Roberts, P.J.W. and Bodeen, C.A. (1992) 'Dilution models for effluent discharges', Standards and Applied Science Division, Office of Science and Technology, Oceans and Coastal Protection Division, Office of Wetlands, Oceans, and Watersheds, Pacific Ecosystems Branch, ERL-N, 2111 S. E. Marine Science Drive, Newport, Oregon 97365–5260, US Environmental Protection Agency.

Brandsma, M.G., Smith, J.P., O'Reilly, J.E., Ayers Jr., R.C. and Holmquist, A.L. (1992) 'Modeling offshore discharges of produced water, in J.P. Ray and F.R. Englehardt (Eds), Produced Water*,* New York: Plenum Press, pp.59–71.

CAPP (2001) 'Offshore produced water waste management', Canadian Association of Petroleum Producers, Technical Report.

Cather, M., Lee, R., Gundiler, I. and Sung, A. (2003) 'NM WAIDS: a produced water quality and infrastructure GIS database for New Mexico oil producers', Third Semi-Annual Technical Progress Report.

Chowdhury, S.H. (2004) 'Decision support system for produced water discharges in offshore operations', MS thesis, Faculty of Engineering and Applied Science, Memorial University of Newfoundland.

Ekins, P., Vanner, R. and Firebrace, J. (2005) 'Management of produced water on offshore oil installations: a comparative assessment using flow analysis', Final report, March 2005.

Hamilton, L.D., Meinhold, A.F. and Nagy, J. (1992) 'Health risk assessment for radium discharged in produced waters', in J.P. Ray, and F.R. Engelhardt (Eds), *Produced Water, Technological/Environmental Issues and Solutions*, New York: Plenum Press, pp.303–314. Available from: http://www.ogp.org.uk/pubs/324.pdf

Hayes, T. and Arthor, D. (2004) 'Overview of emerging produced water treatment technologies', The 11th Annual International Petroleum Environmental Conference, Albuquerque Hilton Hotel Albuquerque, NM, October 12–15.

Huang, H., Fergen, R.E., Proni, J.R. and Tsaij, J.J. (1998) 'Initial dilution equations for buoyancy dominated jets', *Journal of Hydraulic Engineering*, Vol. 24, No. 1, pp.105–108.

Jirka, G.H. and Lee, J.H.W. (1994) 'Waste disposal in the ocean; water quality and its control', in Mikio and Hino (Eds) *Hydraulic Structure Design Manual*, pp.193–242.

Kuipers, J.R., McHardy, K., Merschant, K. and Myers, T. (2004) 'Coal bed methane produced water management options for sustainable development', First annual coal bed natural gas research, Monitoring and applications conference, Laramie, Wyoming, August 17–19.

Lee, J.H.W. and Cheung, V. (1991) 'Mixing of buoyancy dominated jets in a weak current', *Proc. Instn. Civ. Engrs*, Part 2, Paper No. 9697, pp.113–129.

Louvar, F.J. and Louvar, D.B. (1998) *Health and Environmental Risk Analysis: Fundamentals With Applications*, Prentice Hall.

Mukhtasor (2001) 'Hydrodynamic modeling and ecological risk based design of produced water discharge from an offshore platform', doctoral dissertation, Memorial University of Newfoundland.

National Energy Technical Laboratory (NETL) (2006) 'Rocky Mountain Basins Produced Water Database'. Available from: http://www.netl.doe.gov/technologies/oil-gas/Software/database.html#ROCKY

Neff, J.M. (2002) *Bioaccumulation in Marine Organisms; Effects of Contaminants from Oil Well Produced Water*, Kidlington, Oxford, UK: Elsevier Science Ltd, pp 191–202.

Norwegian Petroleum Directorate (NPD) (2004) 'Seminar', 12 Oct, advertisement on internet http://www.npd.no/English/Emner/Ytre+miljo/seminar_vannreinjeksjon_okt2004.htm

OGP (2004) *Fate and effects of naturally occurring substances in produced water on the marine environment – a new review*, Draft sent to OSPAR's meeting of the offshore industry committee (15–19 March 2004, Agenda item 3, OIC 04/3/Info.1-E) by The International Association of Oil and Gas Producers (OGP).

Proni, J.R., Huang, H. and Tsai, J.J. (1996) 'Probabilistic analysis of ocean outfall mixing zones', *Journal of Environmental Engineering*, Vol. 122, No. 5, pp.359–367.

Ray, J.P. and Engelhardt, F.R. (1992) *Produced Water: Technological/Environmental Issues and Solutions*, New York: Plenum Press.

Reed, M. and Johnsen, S. (1996) *Produced Water 2: Environmental Issues and Mitigation Technologies*, New York: Plenum Press.

Roe, T.I., Johnsen, S. and Norwegian Oil Industry Association (1996) 'Discharges of produced water at North Sea', in M. Reed and S. Johnsen (Eds) *Produced Water 2 – Enviromental Issues and Mitigation*, New York: Plenum Press, pp.13–25.

Smith, J.P., Tyler, A.O., Rymel, M.C. and Shidharta, H. (1996) 'Environmental impact of produced water in the Java Sea, Indonesia', *Proceedings of SPE Asia Pacific Oil and Gas Conference*, Australia, pp.28–31.

Stagg, R., Gore, D.J., Whale, G.F., Kirby, M.F., Blackburn, M., Bifield, S., McIntosh, A.D., Vance, I., Flynn, S.A. and Foster, A. (1996) 'Field evaluation of toxic effects and dispersion of produced water discharges from North Sea Oil Platforms, implications for monitoring acute impacts in he environment', in M. Reed and S. Johnsen (Eds) *Produced Water 2, Environmental Issues and Mitigations*, New York: Plenum Press, pp.81–99.

Stephenson, M.T. (1992) 'A survey of produced water studies', in J.P. Ray and F.R. Engelhardt (Eds), *Produced Water Technological/Environmental Issues and Solutions*, New York: Plenum Press, pp.1–10.

Stephenson, M.T., Ayers, R.C., Bickford, L.J., Caudle, D.D., Cline, J.T., Cranmer, G., Duff, Garland, E., Herenius, T.A., Jacobs, R.P.W.M., Inglesfield, C., Norris, G., Petersen, J.D. and Read, A.D. (1994) 'North Sea produced water: fate and effects in the marine environment', Report No. 2, 62/204, E&P Forum, London, England, p.48.

USEPA (1991) 'Technical support document for water quality based toxics control', EPA 505/2–90–001 PB 91–127415, Office of Water, US Environmental Protection Agency Washington DC, USA.

USEPA (1996) *Exposure Factor Handbook; Vol. II; Food Ingestion Factors*, EPA l600-p-95/002Bp, Washington DC: US Environmental Protection Agency.

Bibliography

Author: The references in blue are not cited in the text. Please insert relevant citation where appropriate in the text or delete them from this list.

API (2000) 'Overview of exploration and production waste volumes and waste management practices in the United States', prepared by ICF Consulting for the American Petroleum Institute, Washington, DC, May.

Khatib, Z. and Verbeek, P. (2003) 'Water to value – produced water management for sustainable field development of mature and green fields', *Journal of Petroleum Technology*, Jan., pp.26–28.

National Research Council (NRC) (2003) *Oil in the Sea III: Inputs, Fates, and Effects* (committee on Oil in the Sea, J.N. Coleman, J. Baker, C. Cooper, M. Fingas, G. Hunt, K. Kvenvolden, J. McDowell, J. Michel, K. Michel, J. Phinney, N. Rabalais, L. Roesner and R.B. Spies), Washington, D.C.: National Academy Press, p.265.

OGP (2002) 'Aromatics in produced water: occurrence, fate and effects, and treatment', OGP January, Report No. 1.20/324.

Otton, J.K., Breit, G.N., Kharaka, Y.K. and Rice, C.A. (2003) 'A National Produced-Water Geochemistry Database'. Available from: http://energy.cr.usgs.gov/prov/prodwat/data2.htm.

Stephenson, M.T. and Supernaw, I.R. (1990) 'Offshore Operators Committee 44 Platform Study Radionuclide Analysis Results', Offshore Operators Committee, New Orleans, Louisiana.

Trefry, J.H., Trocine, R.P., Naito, K.L. and Metz, S. (1996) 'Assessing the potential for enhanced bioaccumulation of heavy metals from produced water discharges to the Gulf of Mexico', in M. Reed and S. Johnsen (Eds) *Produced Water 2. Environmental Issues and Mitigation Technologies*, New York and London: Plenum Press, pp.339–354.

Veil, J.A., Puder, M.G., Elcock, D. and Redweik, R.J. (2004) 'A white paper describing produced water from production of crude oil, natural gas and coal bed methane', Prepared for US Department of Energy.