ECOLOGICAL RISK ASSESSMENT: HYPOTHETICAL PULP AND PAPER MILL EXAMPLE

In the previous lesson we examined the elements involved in ecological risk assessment (ERA). Now, we will begin to apply those concepts to the hypothetical KL pulp and paper mill example and sketch out a simplified ERA for the anticipated increase in pulp mill discharges to the Mekong River as a result of the mill expansion.

The KL mill began operations in 1978, producing bleached paper products and discharging undiluted effluent into the Mekong River. In 2001, the company proposed a major expansion in order to increase the mill's capacity. The proposed expansion has the potential to significantly impact the local biophysical environment. While the expansion will likely influence several ecological components, including forest resources and air quality, potential impacts to water quality and aquatic biota resulting from increased effluent discharges are of the greatest concern. As a result of these concerns, the KL mill hired a consultant to undertake an ERA to estimate the size and likelihood of adverse effects to the aquatic environment resulting from the expansion.

PROBLEM FORMULATION

An extensive problem formulation was conducted to assess the scope of the risk posed by the proposed mill expansion.

Site Characterization

Site characterization included an assessment of previous site use at the mill site to determine if land uses may have contributed historical contamination to the Mekong River. Prior to the initial construction of the KL mill, the land had been in rice production, an activity that is unlikely to have any long-term adverse impacts on the aquatic environment.

Current land uses adjacent to the mill were evaluated to determine whether other sites were contributing to aquatic pollution. It was determined that the surrounding land was predominantly forested, containing small subsistence farms, with one small fish farming operation located approximately 2 km upstream.

Finally, the characteristics of the aquatic environment near the project site were examined. This included looking at the hydrology of the watershed and the shape and flow of the river (i.e., morphology). This step was important to assess potential dilution of the mill's effluent discharge.

IDENTIFICATION AND CHARACTERIZATION OF STRESSORS

Following site characterization, stressors were identified and characterized. As the primary environmental concerns from the mill expansion centre on potential impacts to water quality and aquatic biota, the ERA focused on identifying and quantifying the potentially toxic components in the mill effluent. Potential stressors typically found in pulp mill effluent include: changes in biochemical oxygen demand, phenols, resins acids, metals, nutrients, and several organochlorine waste by-products known as adsorbable organic halogens (AOX), such as dioxins. Mill waste water currently is discharged untreated into the river, with the effluent plume dispersing both horizontally and vertically. Contaminant concentrations in the effluent are expected to increase with the expansion of the mill's production capacity.

Expected concentrations of various potential stressors in the mill's effluent were obtained using effluent and receiving water data gathered during several rounds of water quality sampling. The concentrations of various biological and chemical pollutants could be compared with the water quality criteria of Vietnam or Thailand, as Cambodia does not yet have their own water quality standards. Effluent concentrations also could be compared to international water quality standards. Comparisons of pollutant concentrations in effluent can help to determine which of the potential stressors are likely to be present at levels high enough to harm aquatic biota. This can help focus the risk assessment on stressors with the potential to pose risks to the aquatic environment. Typically, this comparison results in several contaminants being considered as potential stressors. One of the major contaminant of concern in this example risk assessment will be dioxins, as dioxins are common by-products of pulp and paper processing. More detail on dioxins is provided later in this lesson.

Water Quality Standards

Water quality standards or criteria, as they apply to this ERA example, are numerical limits set for a variety of chemical and biological pollutants in order to protect surface water quality. Water quality standards generally depend on the intended use of the water. For example, standards for drinking water often are more stringent than standards for irrigation water. Some common parameters often included in a country's water quality criteria are: dissolved oxygen, pH, turbidity, hardness, total dissolved solids, total suspended solids, temperature and concentrations of specific chemical pollutants or heavy metals.

Water quality standards are usually one of two types: stream standards or effluent standards. Stream standards refer to the quality of the receiving water downstream from the origin of the waste water discharge. Effluent standards pertain to the quality of the discharge water itself.

Example surface water and effluent criteria for various parameters from Vietnam and Thailand are summarized in Table 1. In addition to stream or effluent quality standards, some countries have also developed water quality standards for the protection of aquatic life. Rather than providing water quality protection for a particular human use of the resource, the health and protection of aquatic biota is the management goal, with standards written accordingly.

Table 1 Water quality criteria for select parameters in Vietnam and Thailand
(All units in mg/L, except for pH and total coliforms)

	VIETNAM		THAILAND	
SURFACE WATER STANDARDS	***Domestic Water Supply***	***All Other Uses***	***Domestic Water Supply***	***All Other Uses***
pH	6-8.5	5.5-9		5-9
dissolved oxygen	6	2	6	4
coliform bacteria	5,000	10,000	5,000	20,000
(MPN/100 ml)			1,000	4,000
total coliforms				
fecal coliforms				
BOD	<4	<25	1.5	2
suspended solids	20	80	--	--
oil and grease	not detectable	0.3	--	--
ammonia	0.05	1	--	--
lead (Pb)	0.05	0.1	0.05	
zinc (Zn)	1	2	1	
mercury (Hg)	0.001	0.002	0.002	
copper (Cu)	0.1	1	0.1	
nickel (Ni)	0.1	1	0.1	
chromium (Cr)	0.05	0.05	0.05	
hexavalent				
total pesticides	0.15	0.15	0.05	
DDT	0.01	0.01	1	
aldrin			0.1	
dieldrin			0.1	
heptachlor			0.2	
phenol compounds	0.001	0.02	0.005	
INDUSTRIAL EFFLUENT STANDARDS				
pH	6-9	5.5-9	5-9	
temperature	40^{o}C	40^{o}C	--	
BOD	20	50	20-60	
suspended solids	50	100	variable	
ammonia	0.1	1	--	
lead (Pb)	0.1	0.5	0.2	
zinc (Zn)	1	2	5	
mercury (Hg)	0.005	0.005	0.005	
copper (Cu)	0.2	1	1	
nickel (Ni)	0.2	1	0.2	
total nitrogen	30	60	--	
residual chlorine	1	2	1	
cyanide	0.05	0.1	0.2	
phenol compounds	0.001	0.05	1	

More on effluent standards

The effluent standard system is often easier to control than the stream standard system, as no detailed stream analyses are needed to determine the exact amount of waste treatment required. However, unless the effluent standards are reviewed and upgraded periodically, they do not provide protection for over-loaded streams.

Standards for effluents are based more on economics and practicality of treatment than on absolute protection of the receiving stream. The best usage of the stream is not the primary consideration. Rather, the usage of the stream will depend on its condition after industrial standards have been satisfied. Upgrading and conservation of natural resources may be somewhat neglected in favor of industrial economic benefits.

In the developing countries of the Lower Mekong Basin, surface waters are still used directly for water supply, often without treatment. Wherever there is a significant population dependent on a stream for drinking water, quality criteria need to be strict and waste water discharges carefully controlled. In particular, the water supply should be protected from pathogenic organisms, such as fecal coliform bacteria.

Developing countries often place more emphasis on the effluent standard system, as it is easier and less costly to monitor and enforce than the stream standard system.

Dioxins in Pulp Mill Effluent

Dioxins are a common by-product of the operations of pulp mills, mainly due to the use of chlorine in bleaching. There are 75 different dioxin compounds, varying in the number and placement of chlorine atoms. Dioxins include 2,3,7,8-tetrachlorodibenzo-*p*-dioxin (2,3,7,8-TCDD), which is considered the most toxic form and is widely distributed in the environment. Dioxins are persistent and are hydrophobic (i.e., hate water) in nature. They tend to bond readily to lipid tissue and are resistant to an organism's attempts to break them down. They also have low water solubility, and therefore tend to accumulate into the sediment. Dioxins move from sediments into organisms via direct accumulation from sediment and pore water into the skin and gills of benthic invertebrates and forage fish. They are then transferred to larger predatory fish and birds via ingestion, with toxic effects known to occur at low doses. They are known to biomagnify through the food chain, with toxicity and reproductive effects concentrated more at the higher trophic levels.

We will focus on dioxins in this example risk assessment because these compounds are a common component of pulp mill effluent and they are known hazards to both people and wildlife. Although effluent and receiving water samples will be collected as part of the ERA, analysis of the samples may not detect dioxins. They are very difficult to detect, and analysis can be quite expensive and time-consuming. However, due to the nature of the chemical to partition to lipid tissue, we can expect tissue sampling to reveal elevated dioxin levels. A number of local people depend on fish as a food source, and the mill has been discharging untreated effluent for years. In the interest of public health, dioxin levels in fish tissue will be monitored.

IDENTIFICATION AND CHARACTERIZATION OF RECEPTORS

With dioxin identified as the stressor, the resident biota were then evaluated to select potential receptors. The selected receptors are known to be exposed to dioxins in the water column, sediments and pore water and in food. Three major ecological groups were selected based on environmental, social and economic importance.

Benthic Invertebrates

Benthic invertebrates are considered important receptors because their relative lack of mobility makes it difficult for them to avoid undesirable environmental conditions. As they are generally in direct contact with the sediment, benthic invertebrates represent a major pathway for sediment-bound dioxins to reach fish and birds. Though benthic invertebrates often do not exhibit effects from dioxins, they are an important monitoring variable because they provide a good measure of exposure. If exposure can be documented in the benthos (i.e., which form the base of the aquatic food chain) then we can assume that dioxins will be found in the tissues of fish and other aquatic life.

Fish

Two species were chosen as fish receptors. The first species was the Giant catfish (*Pangasianodon gigas*). This species feeds predominantly on aquatic plants and periphyton and may be exposed to dioxins in the sediments and pore water as it forages along the river bottom. Additionally, this fish species is endangered in Asia, and its presence in the Mekong River may be imperiled by the increased effluent discharge. A second fish, the Shortbarbel pangasius (*Pangasius micronemus*), was also chosen. This species consumes detritus and benthic organisms and is an important food source for the nearby villages, as well as providing an income to fishers who sell their catch at local markets.

Birds

This group is represented by the Black Crowned Night heron (*Nycticorax nycticorax*). This species nests in colonies downstream of the mill and appears to breed there year-round. This bird species has been observed in the shallow waters of the Mekong River eating fish, aquatic invertebrates and amphibians.

Once the receptors were chosen, assessment endpoints were selected. These are defined as environmental values to be protected. Assessment endpoints were:

- The viability of the benthic invertebrate community
- The viability of the Shortbarbel pangasius and the endangered Giant catfish populations
- The viability of the Black Crowned Night heron colony.

Based on these assessment endpoints, measurement endpoints were then selected. These are the measurable responses to stressors that are linked to assessment endpoints. Endpoints selected to measure the effects of the increased effluent discharge were:

- The diversity of the downstream benthic invertebrate community
- The survival and reproduction of the downstream Giant catfish and Shortbarbel pangasius populations
- The reproduction and development of the Black Crowned Night heron residing in the downstream colony.

Conceptual Model

A conceptual model to demonstrate how the stressors might affect the receptors was then prepared (Figure 1). The model demonstrates the transport of dioxins from the KL pulp and paper mill discharge into the aquatic receiving environment, and subsequent uptake of dioxins by aquatic biota. Dioxins may be found in the following areas:

Pelagic zone – dioxins may be present in the water column, becoming increasingly dilute with increasing distance from the mill.

Sediments – dioxins may accumulate in the sediments downstream of the mill's effluent discharge, as they tend to partition into the sediment.

Tissues – dioxins may bioconcentrate from water and sediments to aquatic animals and then biomagnify up the food chain.

Exposure Assessment

Following the completion of the problem formulation, an exposure assessment was completed to determine contact between the stressors and receptors. It first examined the contaminant source and release and found that the mill currently discharges undiluted effluent on a daily basis into the Mekong River. The effluent contains dioxins at a concentration in the parts per trillion level, with approximately 100 to 150 grams of dioxins being discharged each year. Dioxin loadings are expected to increase proportionally following the mill expansion.

Dioxin transport and fate was examined next, involving an assessment of the chemical and physical characteristics of dioxins. These characteristics influence availability to the receptors. It was determined that, once discharged, dioxins have low water solubility and therefore tend to accumulate in the sediments, which act as a significant 'sink' for dioxins. Once they enter the sediments, dioxins are very slow to degrade. Dioxins are known to bioconcentrate from water to aquatic biota and then biomagnify up the food chain.

Finally, an assessment of potential exposure pathways for dioxin from the discharge to the receptors was conducted. Exposure pathways identified are summarized in the following sections.

Benthic Invertebrates

Benthic invertebrates may be exposed to dioxins through direct contact and ingestion of sediment particles and pore water or by eating contaminated food items (e.g., periphyton and/or other benthic invertebrates).

Fish

The Giant catfish and the Shortbarbel pangasius may be exposed to dioxins through direct contact with contaminated river water, contact and ingestion of sediment particles and interstitial pore water, or by eating contaminated food items (e.g., plants, benthic invertebrates, other fish).

Birds

The Black Crowned Night heron may be exposed to dioxins through the ingestion of contaminated river water, prey species (e.g., fish, benthic invertebrates, and amphibians) and/or

Figure 1 Potential contaminant exposure pathways in the lower Mekong River ingestion and direct contact with sediments and pore water during foraging.

EFFECTS ASSESSMENT

Once it was determined that there was contact between the stressors and the receptors, the amount of exposure was estimated. Based on the concentration of dioxin in the effluent, and the dilution and bioaccumulation of the contaminant, a mathematical model was used to help quantify exposure to the receiving environment and the receptors. An example model is presented in detail in Lesson 6. While modeling can be useful to gauge the amount of dioxin available in different media of the aquatic environment, sampling of biotic tissue is required to determine concentrations of the contaminant in aquatic life.

Specific data regarding toxicity of dioxins to various fish and bird species of the Mekong River Basin (MRB) currently do not exist. However, studies completed in other countries have examined the link between dioxin concentration levels and induced effects such as mortality, reduced reproduction or physical impairment in fish and riparian wildlife.

The effects assessment is used to link the effect of dioxin discharge into the Mekong River to a biological response in the receptors. There are several options available for determining the potential effects of dioxin on receptors, including:

- Determining body tissue concentrations of dioxin in benthic invertebrates and the selected fish and bird species. These tissue concentrations can be compared to previous studies where lethal and sublethal toxicity values were determined through exposure of test organisms to varying concentrations or doses of dioxins.
- Knowledge of benthic tissue concentrations and the feeding habits of selected fish species can be useful in determining the potential quantity of dioxins different species may ingest.
- Performing toxicity tests where selected local species (e.g., such as the catfish or smaller, more abundant forage fish) are exposed to various levels of dioxins. Laboratory and on-site toxicity testing can be useful in developing effects-based tissue concentrations, or thresholds above which an organism is expected to suffer chronic or acute effects. Both lethal and sublethal esposure concentrations can be determined. Based on toxicity testing, lethal and sublethal tissue concentrations can potentially be determined. Toxicity data can be combined with knowledge of the characteristics of dioxin and the receiving environment in an effort to determine the worst-case dioxin toxicity to the receptors.

Examples of effects-based exposure concentrations for the receptors are summarized in the following sections.

Benthic Invertebrates

The effects of dioxin on benthos may not be readily observable, as benthic invertebrates have shown to be comparatively resistant to dioxins. Often, benthic invertebrates serve as useful indicators of the presence of a potential contaminant in a particular ecosystem. Monitoring benthic invertebrates is relatively easy and cheap. If the benthic tissue shows exposure to dioxins, scientists will know to proceed with an examination of tissue of higher trophic-level organisms, such as fish, aquatic birds and humans.

Fish

A recent study found that the 'no observed effects concentration' or NOEC (i.e., the highest concentration at which there are no adverse effects) for rainbow trout (e.g., growth, survival, and behaviour) was 0.00004 μg/L 2,3,7,8-TCDD (i.e., the most toxic dioxin isomer). Other studies found several fish species, such as carp, suffered adverse reproductive effects at 2,3,7,8-TCDD concentrations ranging from 0.00006 to 0.00023 μg/L. Based on the current research, it has been suggested that water dioxin concentrations should not exceed 0.01 ppt in order to protect aquatic life.

Birds

Data from toxicity studies revealed that a general NOEC for birds was 4 μg/kg. A different study reported that birds suffered adverse effects after being fed 2,3,7,8-TCDD ranging from 15 to 810 μ/kg of body weight, depending on the species.

RISK CHARACTERIZATION

The final step in the ERA was risk characterization. This step combines the results of the exposure assessment and the effects assessment to evaluate the likelihood that adverse effects will occur as a result of exposure to the stressor and the magnitude of effects.

The risk estimate could be calculated for each receptor using a variation of the hazard quotient method. Based on the results of the modeling and some preliminary tissue testing, the expected environmental concentration (EEC) for each receptor species can be divided by the benchmark concentration (BC) for each receptor. As there are no regulatory criteria for dioxins in the MRB, we can use the NOEC identified in the effects assessment as the benchmarks.

Using the following formula:

$$HQ = \frac{EEC}{BC}$$

Benthic invertebrates

$$\text{HQ} = \frac{0.00002ug}{0.00004ug} = 0.1 = \text{low risk}$$

Fish

$$\text{HQ} = \frac{0.0063ug}{0.00004ug} = 15.75 = \text{high risk}$$

Birds

$$\text{HQ} = \frac{50ug}{4ug} = 12.5 = \text{low risk}$$

Based upon these calculations, it was determined that the risk for benthic invertebrates is quite low. However, the risk to the Giant catfish, the Shortbarbel pangasius and the Black Crowned Night heron are high; therefore, more in-depth sampling and analysis is recommended.

UNCERTAINTY ANALYSIS

The major sources of uncertainty in the assessment of risk are as follows:

Identification of Stressors – no previous data were available during the problem formulation phase to help identify contaminants. It is possible that other potential stressors may be present, such as wastes from the upstream fish farm (e.g., antibiotics, high BOD). For the purposes of the risk assessment, it was assumed that the fish farm had no effect on the downstream environment. However, this assumption could be incorrect; the fish farm waste water could be contributing to the degradation of downstream water quality.

Identification of Receptors – multiple potential aquatic and terrestrial receptors exist in the Mekong River. Only three receptors were chosen to represent particular ecological niches relevant to the environmental issues at the mill site. These receptors may not be representative of the most sensitive species present in the receiving environment.

Estimation of Exposure Concentrations – the exposure assessment was based on models of dioxin concentration in the effluent. However, these may not represent the worst-case concentration. Long-term site-specific sampling data are required.

Literature-Based Effects Assessment – the effects assessment was based on toxicity data for 2,3,7,8-TCDD, the most toxic dioxin compound. This provides a worst-case scenario that may not reflect the actual toxicity of the dioxins. In addition, available toxicity data was not based on the receptor species. The test species may not reflect the sensitivity of the receptors. Extrapolation factors may be required to apply existing toxicity data to the three receptor species. In general, the use of extrapolation factors is a conservative approach for dealing with just this type of uncertainty. The approach usually involves adjusting a point estimate, such as a known toxicity value for a particular test organism, by an arbitrary factor to estimate an acceptable concentration for a substance in a specific environment.

Ecological Significance

The results of the ERA for our hypothetical example KL mill expansion indicate high risks to the fish and bird receptors due to increased dioxin levels in the aquatic receiving environment. It would appear that the Black Crowned Night heron and both fish species are likely to be at risk due to the tendency for dioxins to bioaccumulate and biomagnify up the food chain. While risk exists throughout the year due to the continuous discharge of effluent, risk may be minimal during high flow periods in the Mekong River as this will dilute the discharge. Long-term sampling of the receiving water will help to determine annual patterns or changes in dioxin concentrations.

Based on these results, it was recommended that the KL pulp and paper mill incorporate mitigation and effluent reduction strategies (e.g., installation of cleaner technologies which use chlorine substitutes in the pulping process) to minimize the risk posed to the aquatic environment.

Risk Management

On completion of the ERA, findings were presented to the KL mill management and responsible government agencies. The goal of the ERA was reiterated, as was the connection between the measurement and assessment endpoints. The magnitude and extent of the effects on receptors was then explained, along with the assumptions used and the uncertainties encountered during the risk assessment. Based on these findings, mill management and responsible government agencies will be able to make decisions about the potential ecological risks involved with the proposed mill expansion.