Lecture 6: Water Pollution

ECON7720: Ecological and Environmental Economics

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Semester 2, 2026 | Required reading: Tietenberg & Lewis, Ch. 9

Recap of Lecture 5

Motivation and context

- Air pollution kills 4.7M people/year ($PM_{2.5}$); exposure is highest in the poorest countries and neighbourhoods. Pollution crosses borders.

Command-and-control

- Technology mandates (NAAQS, BAT) cut US pollution 29–95% since 1980 — but at up to 22× the least-cost allocation.

Market-based approaches

- The SO_2 cap-and-trade programme achieved a 10M-ton reduction; >95% of benefits came from health co-benefits, not the targeted acid rain.
- Key lesson: markets economise on information and state capacity, the regulator sets the cap, the market discovers the least-cost allocation.

Lecture Outline

1. Motivation and context: what makes water pollution different, types of pollutants (fund vs stock), monitoring, and the scale of the problem.
2. Command-and-control approaches: the Clean Water Act, technology mandates, nonpoint sources, oil-spill liability, and the benefits and costs of US water policy.
3. Market-based approaches: emission-based vs ambient-based instruments, watershed trading, the Hunter River scheme, and instrument choice.

Learning Resources

Required readings

- Tietenberg & Lewis, Ch. 9 (*Water Pollution*): read and attempt the self-test exercises.

Recommended readings

- Fisher-Vanden, K. & Olmstead, S. (2013), "Moving Pollution Trading from Air to Water: Potential Problems and Prognosis," *Journal of Economic Perspectives* 27(1), 147–172.

Motivation and Context

Unique aspects of water pollution

- Recreation benefits are much more important for water bodies than for air (swimming, fishing, boating).
- Large economies of scale in treatment create the possibility for large, centralised treatment plants as one control strategy (e.g. municipal sewage treatment).
- Many causes of water pollution are more difficult to trace to a particular source, they come from nonpoint sources (e.g. runoff from streets, agriculture, atmospheric deposition).
- Water has many different uses: drinking, household, irrigation, industrial, recreation, wildlife habitat. Policy must balance these competing demands.

Key distinctions in water pollution

Three questions that shape policy

1. Where does it go? *Surface water* (rivers, lakes, oceans: visible, often reversible) vs *groundwater* (aquifers: invisible, often irreversible).
2. Where does it come from? *Point sources* (pipe, outfall, oil rig: easy to monitor, amenable to permits and trading) vs *non point sources* (agricultural runoff, urban stormwater: diffuse, hard to measure).
3. What is it? *Fund pollutants* (degradable waste, nutrients, heat: the environment has absorptive capacity) vs *stock pollutants* (heavy metals, PFAS, plastics: persist and accumulate).

Types of waste-receiving water

Surface water

- Rivers, lakes, oceans.
- Historically, clean-up policies have focused here.
- Provides drinking water, recreation, and wildlife habitat.
- Contamination is often visible and reversible (if the source is controlled).

Groundwater

- Water beneath the earth's surface in soils, rocks.
- Primarily used for irrigation and drinking water.
- Contamination is often invisible and can be irreversible on human timescales.
- Requires different control policies from surface water.

Since water sources have historically been treated as common property, they have been used as a cheap dumping ground for municipal sewage and industrial waste.

Sources of contamination — point sources

- Discharged at a specific location through a pipe or ditch.
- Primary point sources: industries and municipalities.
- Relatively easy to monitor and predict.
- Amenable to permits, charges, and trading.
- Oil spills are point sources (identifiable vessel or drilling platform), even though the damage spreads over a wide area.
- Heavily regulated in developed countries since the 1970s; coverage and enforcement vary widely elsewhere.



Wastewater outfall discharging into the North Fork Brazos River, TX. CC BY-SA 3.0, Wikimedia Commons.

Sources of contamination — nonpoint sources

- Runoff from diffuse sources, no single pipe or ditch.
- Agricultural runoff (fertiliser, pesticides, eroded topsoil), urban stormwater (oil, heavy metals, sediment).
- Much more difficult to control due to unpredictability and uncertainty about the exact source.
- Now estimated to account for over half of the waste load to rivers and lakes.
- Groundwater contamination (e.g. PFAS from industrial sites) originates at a point source but behaves like nonpoint once it leaches into aquifers — hidden underground, persistent, and difficult to trace.



Livestock near an unfenced stream, Lexington, KY. Manure and sediment enter the waterway as diffuse runoff. Public domain, US EPA.

Ocean pollution — oil spills (1)

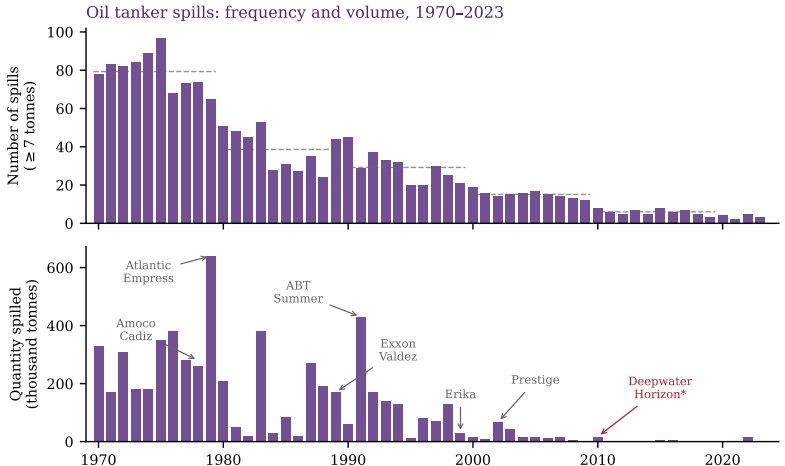
Declining but still catastrophic

- Oil spills have declined sharply since 1970 (see next slide), but catastrophic events persist: Exxon Valdez (1989), Prestige (2002), Deepwater Horizon (2010).
- Oil spills are point sources, the vessel or platform is identifiable, even though the damage spreads over a wide area.



Oil sheen from the *Exxon Valdez* spill, Prince William Sound, Alaska, 1989. Public domain, NOAA.

Ocean pollution — oil spills (2)



Source: ITOPF Oil Tanker Spill Statistics 2024. Dashed lines show decade averages. *Deepwater Horizon was a wellhead blowout, not a tanker spill; included for scale.

Ocean pollution — dumping

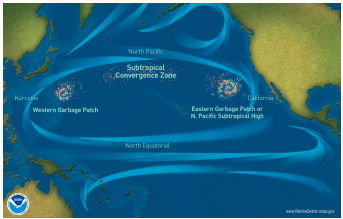
- Dumped materials: sewage sludge, industrial waste, trace metals, and radioactive waste.
- US: the Marine Protection, Research, and Sanctuaries Act (1972) bans ocean dumping of industrial waste, sewage sludge, radioactive material, and chemical/biological weapons.
- International: the London Convention (1972) and London Protocol (1996) ban most dumping, but enforcement on the high seas is weak (an open-access problem).
- Once dispersed, dumped waste is nearly impossible to recover, prevention is the only effective strategy.



Barge loaded with incinerator ash for ocean dumping, Gravesend Bay, New York, 1973. Public domain, NARA.

Ocean pollution — plastics

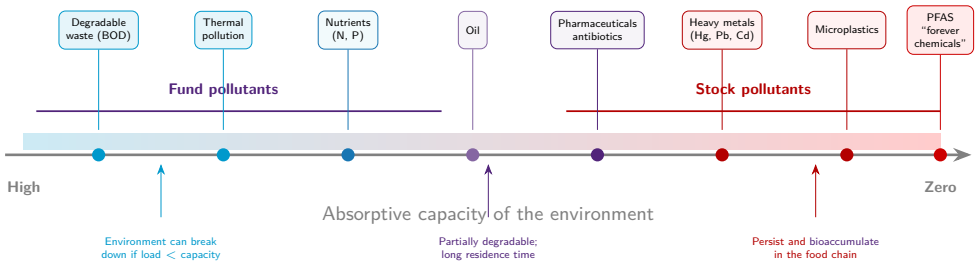
- Plastics are a growing source of ocean pollution: marine debris kills thousands of seabirds and other sea life each year.
- The Great Pacific Garbage Patch is a giant floating accumulation of marine debris in the North Pacific, trapped by converging ocean currents.
- Microplastics (fragments <5mm) enter the food chain and have been detected in seafood, drinking water, and human blood.
- Few laws govern open-ocean trash, an open-access problem where no country has jurisdiction.



The Great Pacific Garbage Patch. Public domain, NOAA.


Marine debris washed ashore. CC BY-SA 2.0, Wikimedia.

Types of water pollutants — the absorptive-capacity spectrum



The pollutant's position on the spectrum determines how urgently we must act: fund pollutants (left) can be managed by keeping loads within absorptive capacity; stock pollutants (right) accumulate indefinitely and demand prevention rather than treatment.

Types of water pollutants — fund pollutants

Degradable waste and absorptive capacity

- Fund pollutants can be assimilated by the environment, but only if the emission rate does not exceed the absorptive capacity.
- Degradable waste: organic residuals broken down by bacteria. Aerobic decomposition consumes dissolved oxygen (DO); if DO falls too low, decomposition switches to anaerobic processes that produce toxic byproducts (methane, hydrogen sulphide).
- Thermal pollution: injection of heat (coolant water) raises temperature, which reduces dissolved oxygen and accelerates aerobic decomposition, compounding the problem.
- Plant nutrients: nitrogen and phosphorus cause algae growth. Too many nutrients cause eutrophication: algal blooms whose decomposition depletes oxygen, killing aquatic life.

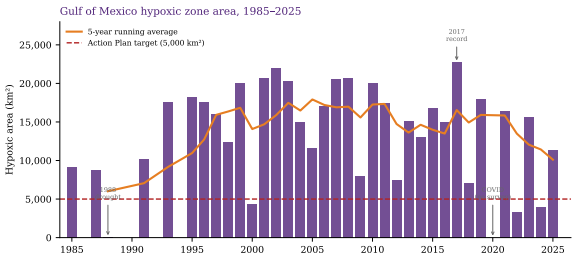
Eutrophication in practice — the Gulf of Mexico dead zone



Sediment and phytoplankton from the Mississippi River spreading into the Gulf of Mexico, 13 February 2023. Public domain, NASA MODIS/Aqua.

- The Mississippi River basin drains 40% of the land area of the continental US, carrying agricultural nitrogen and phosphorus into the Gulf.
- The green and tan plumes visible from space are sediment and phytoplankton fuelled by nutrient runoff.
- Decomposing algae consume oxygen $\Rightarrow$ hypoxic zone where marine life cannot survive.
- A nonpoint-source pollution creating large-scale ecological damage.

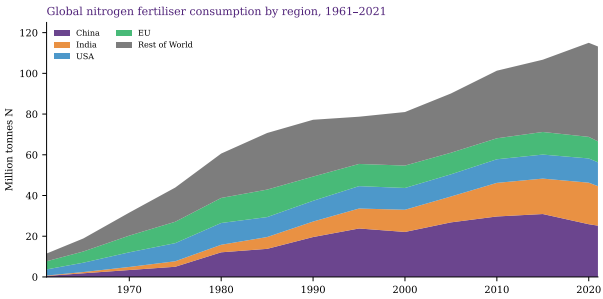
Eutrophication in practice — the Gulf of Mexico dead zone



Source: NOAA/LUMCON annual bottom-water survey; EPA Gulf Hypoxia Action Plan. Note: surveys before 1993 were intermittent (six years not surveyed); sparse early bars reflect data gaps, not a smaller dead zone.

- The Gulf hypoxic zone has averaged $\sim$14,000 km^2 over the past decade, nearly three times the target.
- The Action Plan target of 5,000 km^2 has been met only in drought years (reduced runoff).
- The 2017 record (22,720 km^2) was roughly the size of New Jersey.
- Despite decades of policy effort, the dead zone has not shrunk, nonpoint sources remain largely uncontrolled.

The driver of nonpoint pollution — nitrogen fertiliser



Source: FAO FAOSTAT, Inputs/Fertilizers by Nutrient.

- Global nitrogen fertiliser use has grown ten-fold since 1961, the primary driver of eutrophication.
- China and India now account for ∼40% of global use.
- US and EU use has plateaued, but legacy nutrients persist in soils and groundwater for decades.
- Only a fraction of applied nitrogen is absorbed by crops; the rest runs off into waterways.

Dissolved oxygen and biochemical oxygen demand

Measuring the impact of degradable waste

- Dissolved oxygen (DO): the measure of ambient water quality for conventional fund pollutants. A function of temperature, stream flow, and waste load.
- Biochemical oxygen demand (BOD): the measure of the oxygen demand placed on a stream by any particular volume of effluent.
- Using modelling techniques, effluent measured as BOD at a particular point can be translated into DO measures at various receptor locations along a stream.
- Oxygen sags represent locations where DO is lower than at other points, these are the critical receptors for policy.

Two approaches to monitoring waste loads

Ambient monitoring

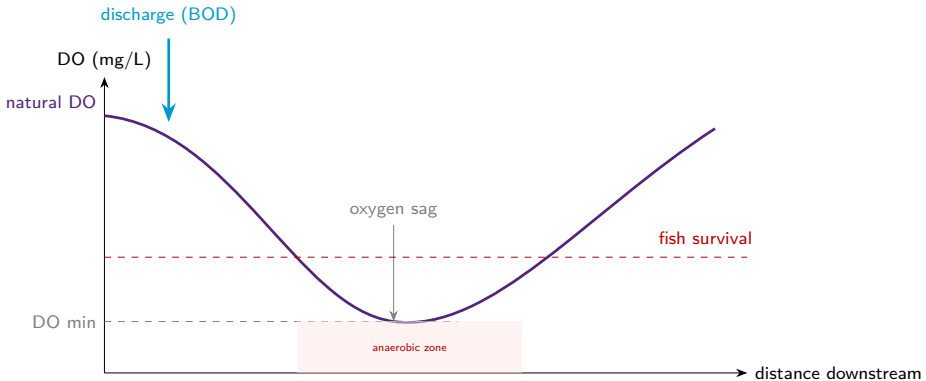
- Measures DO, nutrients, turbidity, pH in the watercourse itself.
- Captures the cumulative effect of all sources, including nonpoint.
- Tells us whether water is safe, but not who is responsible.

Effluent monitoring

- Measures BOD, suspended solids, and chemicals at the discharge pipe.
- Assigns a load to each source, essential for permits, charges, and trading.
- Feasible for point sources only; impractical for nonpoint (runoff).
- Linking effluent to ambient quality requires transfer coefficients a_{ij}.

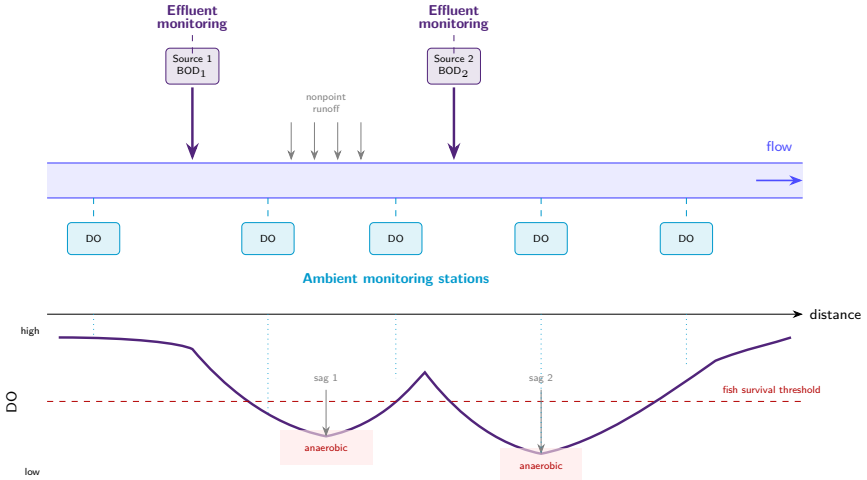
Both are needed: ambient monitoring tells us whether the water is safe; effluent monitoring tells us who is responsible.

The oxygen sag



A point-source discharge (biochemical oxygen demand, BOD) consumes oxygen via aerobic decomposition, creating an oxygen sag downstream. If DO drops near zero, decomposition switches to anaerobic processes (methane, H_2S). The sag's depth and location depend on flow, temperature, and load.

Monitoring and the oxygen sag



Effluent monitoring (purple) measures BOD at each discharge. Ambient monitoring (cyan) measures DO along the river. Each discharge creates an oxygen sag; where DO drops below the threshold, anaerobic conditions develop. Nonpoint sources affect ambient DO but cannot be monitored at source.

Types of water pollutants — stock pollutants

Persistent and accumulating

- Stock pollutants have no (or negligible) absorptive capacity, they persist and accumulate.
- Examples: heavy metals (Hg, Pb, Cd), PCBs, PFAS ("forever chemicals"), persistent pesticides.
- Bioaccumulation: tissue concentrations rise at each trophic level, damage depends on what is in fish and food, not just in the water.
- Monitoring is difficult: water-column concentrations can be low while tissue concentrations are lethal. The same discharge can be harmless in one river and toxic in another (depends on pH, temperature, salinity).

Monitoring stock pollutants — where to sample?

Water column

- Current dissolved concentrations, a snapshot that varies with flow.
- May be below detection even when ecological damage is occurring.

Sediment

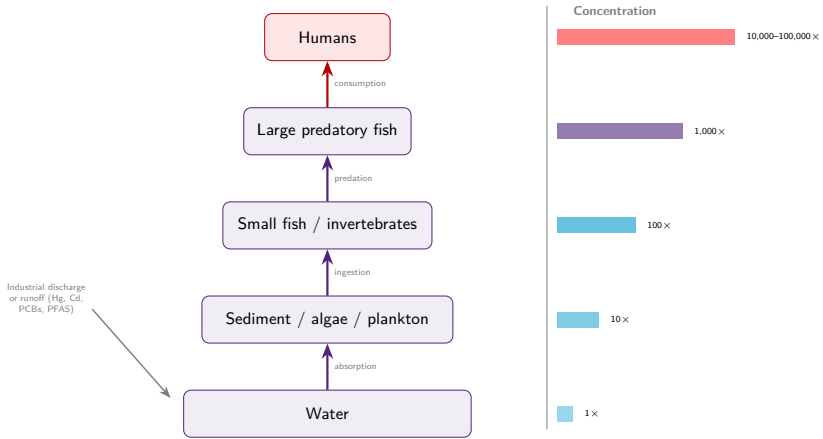
- Contaminants bind to particles on the riverbed, a historical record (years to decades).
- Can become a secondary source when floods or dredging remobilise them.

Biological tissue

- Concentrations in fish and shellfish, the metric that matters for human health.
- Basis for consumption advisories (e.g. mercury; Shimshack et al. 2007).

Water column = what is flowing now; sediment = what has accumulated; tissue = what enters the food chain. Effective monitoring requires all three.

Bioaccumulation — from water to the food chain



Stock pollutants bioaccumulate: each trophic level concentrates the substance further. By the time a predatory fish is eaten by humans, tissue concentrations can be orders of magnitude above the level in the surrounding water. Concentration factors are illustrative (Woodwell, Wurster & Isaacson, 1967, *Science*).

Emerging water pollutants (1/2)

Pharmaceuticals in the water supply

- A USGS national reconnaissance sampled 139 streams across 30 states: 80% had detectable organic wastewater contaminants, pharmaceuticals, hormones, and antibiotics (Kolpin et al. 2002).
- A follow-up found that pharmaceutical formulation facilities produced effluent with 10 to 1,000 times higher concentrations than typical wastewater plants (Phillips et al. 2010).
- Antibiotics and drugs from animal-feeding operations are another significant source.
- Microplastics and PFAS ("forever chemicals") are increasingly detected, regulatory frameworks are still catching up.
- Conventional wastewater treatment was never designed to remove these substances.

Emerging water pollutants (2/2)

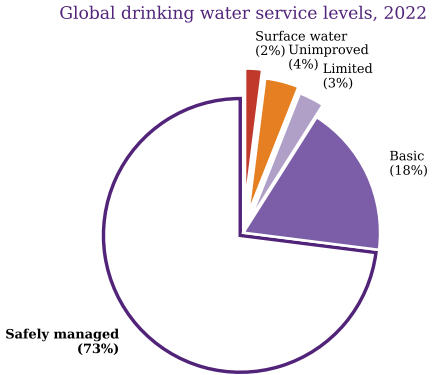
Illicit drugs in waterways — the River Thames

- 41 pharmaceuticals plus cocaine detected along the full length of the River Thames (White et al. 2019).
- Even low concentrations could cause physiological damage in aquatic species, muscle, behaviour, reproduction (Capaldo et al. 2018).
- Cocaine found in freshwater shrimps at all 15 sites across Suffolk, entering via sewage overflows (Miller et al. 2019).
- These substances might pass through treatment plants unremoved.



European eel (*Anguilla anguilla*), a critically endangered species found to be affected by cocaine residues in London's waterways. CC0, Wikimedia Commons.

Water and poverty



Safely managed: accessible on premises, available when needed, free from contamination. Basic: improved source within 30 min round trip. Limited: improved source >30 min. Unimproved: unprotected well or spring. Surface water: river, lake, or pond. Source: WHO/UNICEF Joint Monitoring Programme (JMP) 2023 update.

- ∼505,000 diarrhoeal deaths/year from contaminated drinking water; total deaths from unsafe water, sanitation, and hygiene exceed 1 million (WHO, 2023).
- ∼2.2 billion people lack safely managed services; ∼115 million rely on untreated surface water (WHO/UNICEF JMP, 2023).
- Progress slowest in Sub-Saharan Africa and fragile states.
- Improved water supply reduces diarrhoea by 6–25%; improved sanitation by 32% (Fewtrell et al. 2005).

Command-and-Control Approaches to Water Pollution

The Clean Water Act (1972)

Before the CWA, US water law evolved from navigation (1899 Refuse Act) to ambient standards (1965 Water Quality Act), but enforcement was weak and plans were vague. The CWA replaced this with a fundamentally different approach.

The CWA set two ambitious goals:

1. "That the discharge of pollutants into navigable waters be eliminated by 1985."
2. "That wherever attainable, an interim goal of water quality . . . for fish, shellfish, wildlife and recreation be achieved by June 1, 1983."

Key features:

- Permits required for all dischargers.
- Permits granted only when dischargers met technology-based effluent standards, a shift away from ambient standards.
- Standards uniformly imposed within categories, could not depend on local water conditions.

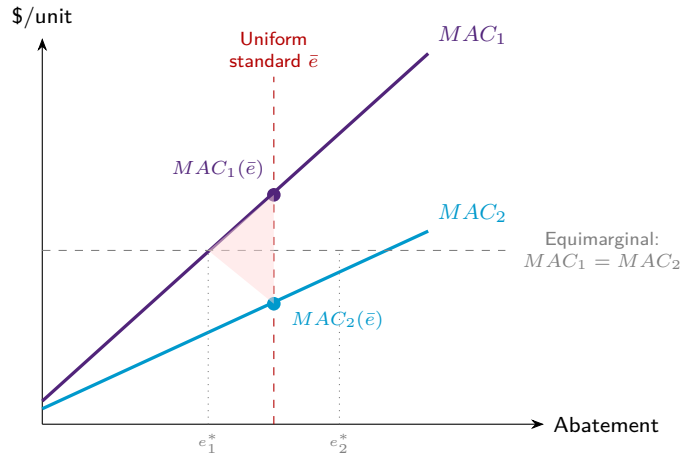
Technology-based effluent standards

- By 1977: industrial dischargers must meet standards based on "best practicable control technology currently available" (BPT).
- By 1983: the more stringent "best available technology economically achievable" (BAT).
- The 1977 amendments distinguished conventional from toxic pollutants:
  - Conventional pollutants: new standard based on "best conventional technology" (BCT).
  - Toxic pollutants: still governed by BAT.
- The EPA had to identify the technology and set the standard at the emission level that technology would achieve, regardless of local water quality.

The efficiency problem with technology mandates

- Ambient standards (1965 approach) target *concentration at the receptor*, allowing flexibility in *how* sources comply $\Rightarrow$ scope for the equimarginal allocation.
- Uniform technology mandates (1972 CWA) require the *same technology* regardless of local water quality or abatement cost $\Rightarrow$ violate equimarginal and ignore site-specific damages.
- This is doubly inefficient:
  - ignores variation in receiving-water quality (a discharge into a fast river does less harm than into a still lake);
  - ignores variation in abatement cost across sources.
- Cost-effectiveness requires individual standards for each source, but the EPA chose general standards for broad categories.

The efficiency problem

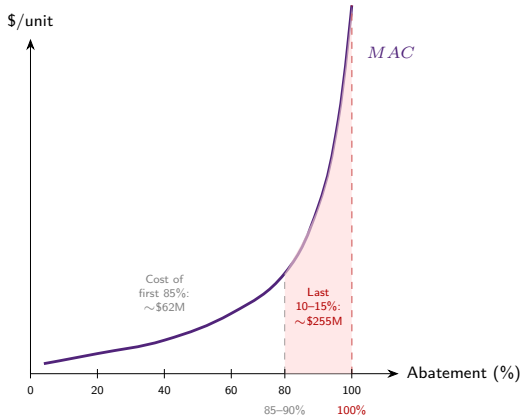


The CWA imposes the same standard $\bar{e}$ on both firms. Cost-effectiveness requires $MAC_1 = MAC_2$: firm 1 (high cost) should abate less, firm 2 (low cost) should abate more. The shaded triangle is the deadweight loss from uniform mandates.

The zero-discharge goal

Aspiration vs reality

- The CWA's goal of zero discharge by 1985 was extraordinarily ambitious and unrealistic.
- EPA estimated zero-discharge cost at \$317M, 5× the cost of removing 85–90% (\$62M).
- The zero-discharge goal does not distinguish among pollutant types.
- Enforcement became impossible, virtually all deadlines were missed and extended.



The convex MAC curve makes the last increments astronomically expensive.

Municipal subsidies and pretreatment

Perverse incentives in wastewater treatment

- The CWA subsidised up to 75% of construction costs for municipal sewage treatment plants (reduced to 55% in 1981).
- Subsidies covered construction but not operation and maintenance $\Rightarrow$ gold-plated plants, then poorly maintained. Only $\sim$half performed satisfactorily.
- The 1977 amendments added pretreatment standards for waste sent to public treatment systems, designed to prevent toxic pollutants from inhibiting the treatment process.
- Both subsidies and pretreatment standards share the same deficiency: they are not cost-effective.

Nonpoint source pollution

The unregulated half of the problem

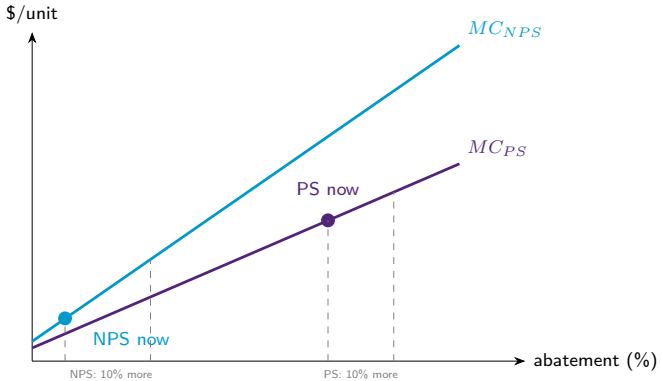
- The CWA gave the EPA no specific authority to regulate nonpoint sources, seen as a state responsibility.
- The 1987 reauthorisation provided $400 million for a new programme to help states control runoff, but chief responsibility remained with the states.
- Most common tools: voluntary programmes and cost-sharing with landowners.

The shift from point to nonpoint

Where the marginal cost argument leads

- The government has tried to compensate for poor control of nonpoint sources by placing more intensive controls on point sources.
- But as point sources have been controlled to higher degrees, the marginal control cost rises, making controlling nonpoint sources more cost-effective.
- Studies suggest that some nonpoint sources could be controlled at low costs: Schwabe (2001) finds a uniform 30% nitrogen rollback is the most cost-effective strategy for the Neuse River.

The shift from point to nonpoint



PS now: current point-source abatement level (high MC after decades of CWA regulation). NPS now: current nonpoint-source abatement level (low MC, largely unregulated).

- Point sources have been heavily regulated ⇒ their marginal cost is now high.
- Nonpoint sources are barely regulated ⇒ current marginal cost is low, cheap reductions still available.
- The equimarginal principle says the next dollar should target the nonpoint margin.
- But nonpoint sources are diffuse and hard to monitor.

The Safe Drinking Water Act

Standards for the tap

- The Safe Drinking Water Act (1974) provides more stringent standards for drinking water than the CWA provides for surface water.
- Primary regulations set maximum allowable concentrations for bacteria, turbidity, and chemical contaminants.
- Secondary standards for odour and aesthetics were also set.
- Approximately 60,000 public water systems are subject to these standards.

Benefits and costs of US water pollution control

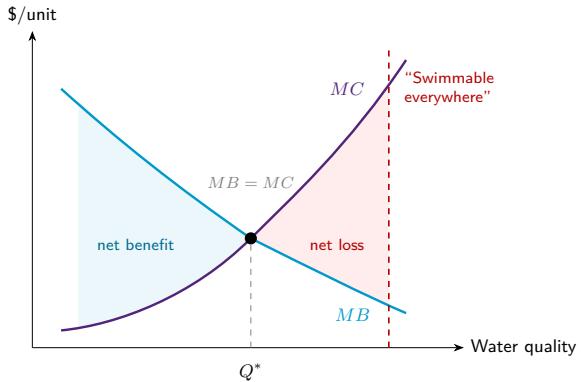
Has the investment paid off?

- US spent $1.9 trillion on water pollution abatement (1960–2014) — more than on air pollution control.
- Water quality improved (Keiser & Shapiro 2019), but benefits are hard to monetise: recreation and ecosystem values vs easily valued avoided mortality for air.
- Carson & Mitchell (1993): aggregate costs likely exceed benefits for the last increments of water quality.

	Clean Air Act	**Clean Water Act**
Benefit–cost ratio	30:1	unclear
Benefits easy to value?	Yes (avoided deaths)	No (recreation, ecosystems)
Market instruments used?	Extensively	Rarely

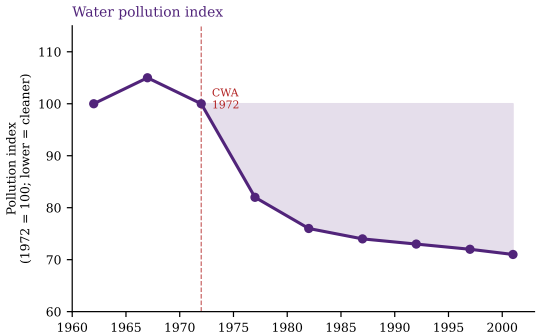
Comparison based on Keiser & Shapiro (2019), Carson & Mitchell (1993), EPA (2011), and T&L Ch. 8–9.

Benefits and costs — the marginal view



- Net benefits are positive up to Q^*, where $MB = MC$.
- The CWA's "swimmable everywhere" target pushes past Q^* into the net loss region where $MC > MB$.
- Carson & Mitchell (1993): the last increments of water quality cost more than they are worth.
- Contrast with air: the CAA's benefits exceeded costs 30:1; for water, the answer is far less clear.

US water quality — has the CWA worked?



Source: Keiser & Shapiro (2019, *QJE*).

- Composite index of DO, BOD, faecal coliform, pH, and total suspended solids; lower = cleaner.
- Water quality improved sharply after the CWA (1972), then continued to decline more gradually.
- From 1972 to 2001, the index fell from 100 to ∼71, a ∼29% reduction in pollution concentration (individual pollutants declined 1–2.5% per year).
- But the rate of improvement slowed after the 1980s, consistent with rising marginal abatement costs as the "easy" gains were exhausted.

Limited liability and precaution (1)

Ocean pollution — oil spills and liability

- The Clean Water Act prohibits discharges of "harmful quantities" of oil into navigable waters, virtually all discharges are prohibited.
- If a spill occurs, it must be immediately reported. Failure to report can result in a fine up to $10,000 and/or imprisonment.
- The discharger must either contain the spill or pay the cost of cleanup by a responsible government agency.
- The discharger's liability for removal costs is limited to $50 million unless willful negligence or misconduct can be proved.
- Cleanup costs include compensation for natural resource damages.

Note: the Oil Pollution Act of 1990 (post-Exxon Valdez) revised these caps upward, but the economic logic is unchanged — any cap below expected damages creates under-precaution.

Limited liability and precaution (2)

Under-precaution from capped liability

The vessel owner chooses precaution Q to minimise total cost:

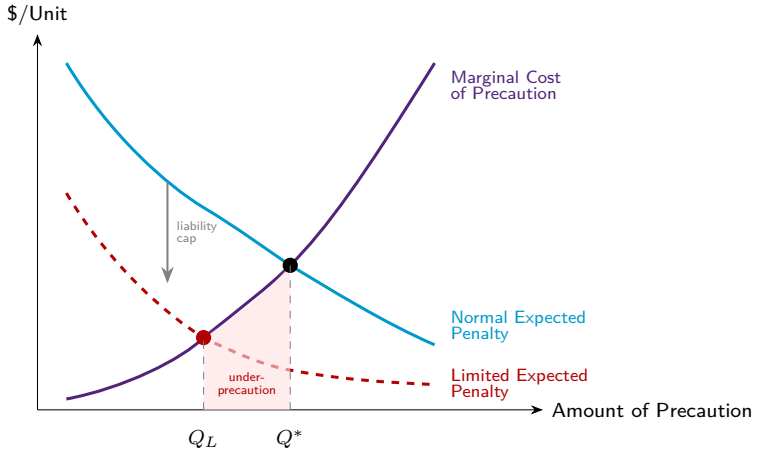
$$\min_{Q} \quad \underbrace{C(Q)}_{\text{cost of precaution}} + \underbrace{\rho(Q) \cdot P(Q)}_{\text{expected penalty}}$$

where $\rho(Q)$ is the probability of being found liable and $P(Q)$ is the penalty if liable. The first-order condition is:

$$\underbrace{MC(Q)}_{\text{marginal cost of precaution}} = \underbrace{-\frac{d}{dQ}\left[\rho(Q) \cdot P(Q)\right]}_{\text{marginal reduction in expected penalty}}$$

- If $P =$ actual damage and $\rho = 1$: owner internalises full cost $\Rightarrow$ efficient outcome Q^*.
- Limited liability: P is capped at $\bar{P}$, so $P <$ damage for large spills $\Rightarrow$ expected penalty falls $\Rightarrow$ $Q_L < Q^*$.
- Low ρ: not all cases go to court $\Rightarrow$ further reduces the expected penalty.

Limited liability and precaution (3)



With full liability, the vessel owner chooses efficient precaution Q^*. Limited liability caps the downside, shifting the expected-penalty curve inward and inducing too little precaution (Q_L). The shaded area is the under-precaution caused by the cap.

Limited liability and precaution (4)

The Deepwater Horizon spill (2010)

- 134 million gallons of oil, the largest spill in US history (Gulf of Mexico, 2010).
- Damages: fisheries, tourism, ecosystems, and long-term health effects on cleanup workers.
- British Petroleum (BP) paid over $65 billion, far exceeding the $50m statutory cap (court found willful negligence).
- A case of under-precaution from limited liability ($Q_L < Q^*$).



The Deepwater Horizon rig burning, 21 April 2010. Public domain, US Coast Guard.

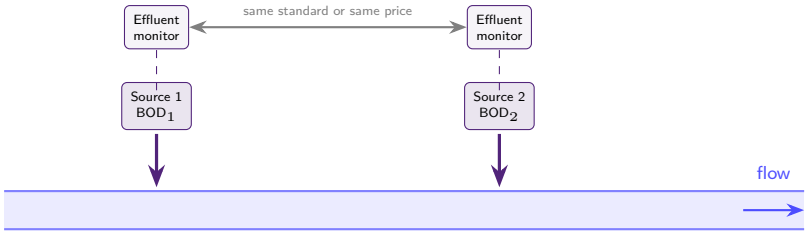
Market-Based Approaches to Water Pollution

Policy options for fund pollutants

Emission-based vs ambient-based approaches

- Emission-based: a general BOD reduction target applied to all sources, emission permits or emission charges. Simple but ignores location.
- Ambient-based: aimed at reaching a particular DO target at the oxygen sags, ambient permits or ambient charges. Accounts for the location of the emitter via transfer coefficients (exactly as in Lecture 4).
- The ambient approach is more cost-effective but requires more information (transfer coefficients, dispersion models).

Emission-based instruments



Effluent charge

Regulator sets price t per unit of BOD.
Every source pays the same rate:
$t \times e_i$ for emissions e_i.
Sources abate until $MAC_i = t$.

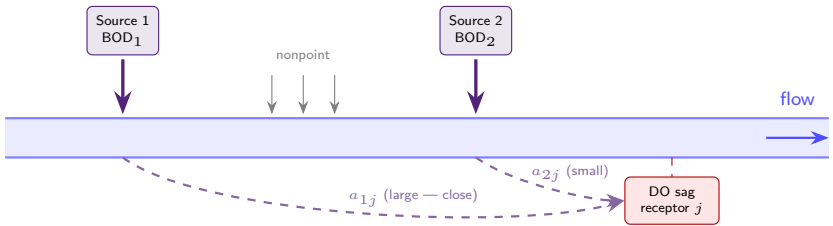
Cap-and-trade (emission permits)

Regulator sets aggregate cap $\bar{E}$.
Permits traded 1:1 — location does not matter.
Sources abate until $MAC_i = p$.

Both ignore where the discharge enters the river —
a unit of BOD upstream of the sag does more damage than one downstream.

Emission-based instruments monitor BOD at the pipe and apply a uniform price or cap across all sources. They achieve cost-effectiveness across sources (equimarginal) but not across locations, a discharge near the oxygen sag is treated the same as one far away.

Ambient charges vs ambient permits



Both instruments target ambient quality at the receptor, not emissions at the pipe. The transfer coefficient a_{ij} links each source's discharge to the DO sag, sources with a larger impact face a stronger incentive to abate, whether through a higher charge or a higher permit price.

The ambient approach — transfer coefficients for water

Let e_i be the BOD discharge from source i, and a_{ij} the transfer coefficient from source i to receptor j. Then:

$$\underbrace{DO_j}_{\text{ambient quality}} = DO_j^{\text{natural}} - \sum_i a_{ij}\, e_i$$

- The ambient charge on source i is: $T_i = \sum_j F_j \cdot a_{ij}$ where F_j is the monetary fee at receptor j.
- Sources with high a_{ij} (close to the sag, slow river) face a higher charge $\Rightarrow$ they have a stronger incentive to abate.
- This is the cost-effective allocation: each source faces a charge proportional to its marginal contribution to ambient damage, the equimarginal principle applied across locations.

The cost-effective allocation for water

The regulator chooses abatement levels q_i for each source i to:

$$\min_{q_1,\ldots,q_n} \sum_{i=1}^{n} C_i(q_i) \qquad \text{s.t.} \quad DO_j^{\text{natural}} - \sum_i a_{ij}\,(u_i - q_i) \;\geq\; \overline{DO}_j \quad \forall\, j$$

- $C_i(q_i)$ is source i's abatement cost; u_i is its uncontrolled emission; $\overline{DO}_j$ is the DO standard at receptor j.
- The Lagrangian is ($F_j \geq 0$):

$$\mathcal{L} \;=\; \sum_i C_i(q_i) \;-\; \sum_j F_j \Big[\, DO_j^{\text{natural}} - \textstyle\sum_i a_{ij}(u_i - q_i) - \overline{DO}_j \,\Big]$$

- Differentiating w.r.t. q_i gives the first-order condition:

$$MAC_i(q_i^*) \;=\; \sum_j F_j \cdot a_{ij} \;=\; T_i$$

- Each source abates until its MAC equals its ambient charge T_i, exactly the equimarginal principle from Lecture 4, applied to multiple receptors along the waterway.
- Sources with larger impact on the binding receptor (higher a_{ij}) face a higher charge and abate more.

Watershed-based trading

Applying the equimarginal principle to water

- Organised by watershed: trades within a catchment, usually under a Total Maximum Daily Load (TMDL) cap. 57 programmes worldwide.
- Point-to-point (e.g. two treatment plants) or point-to-nonpoint (e.g. a plant buying credits from a farmer).
- The equimarginal logic: sources purchase cheaper reductions from those with lower MAC, significant cost savings (EPA 2008).



Blue Plains Advanced Wastewater Treatment Plant, Washington DC — the largest in the world. Point sources like this can trade nutrient credits with other dischargers. CC BY-SA 4.0, Sdkb.

Trading ratios in water (1)

Why 1:1 does not work

If source i (buyer) increases emissions by 1 unit, source j (seller) must reduce by r_{ij} units to keep ambient quality unchanged:

$$r_{ij} = \frac{a_{ij}}{a_{jj}} \qquad \text{(ratio of transfer coefficients at the critical receptor)}$$

- Location: a discharge upstream of the oxygen sag has a higher $a_{ij} \Rightarrow$ ratio $r_{ij} > 1$ if the buyer is closer to the sag than the seller.
- Uncertainty: for nonpoint sources, reductions are harder to verify, ratios are often inflated (e.g. 2:1) to build in a safety margin.
- Equivalence: different pollutant forms (e.g. organic vs inorganic nitrogen) may not be interchangeable.

Without trading ratios, trades could worsen water quality at sensitive locations.

Trading ratios in water (2)

Cost minimisation under a tradeable-permit system with trading ratios

Each source i holds permits ℓ_i and can buy from or sell to source j at ratio r_{ij}. The regulator's problem is:

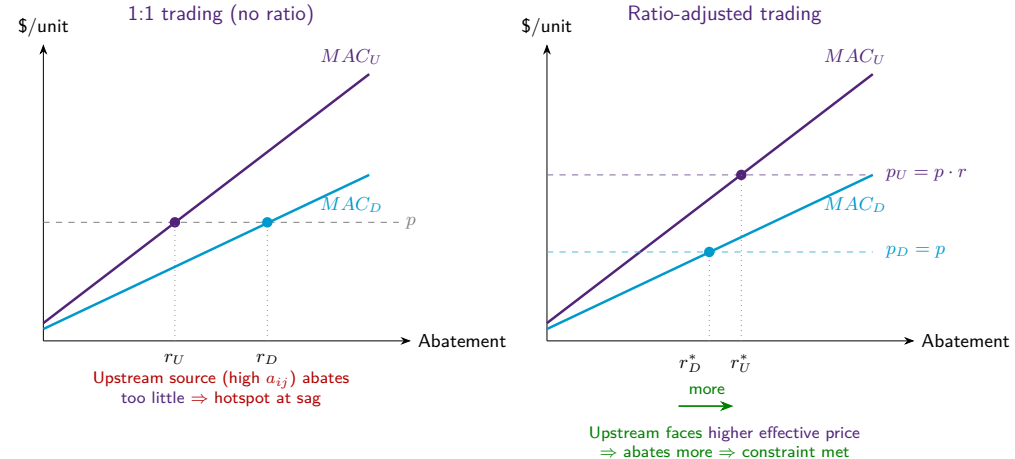
$$\min_{e_1,\ldots,e_n} \sum_i C_i(e_i) \qquad \text{s.t.} \quad \sum_i a_{ij}\, e_i \;\leq\; \bar{A}_j \quad \forall\, j$$

- $\bar{A}_j$ is the maximum allowable ambient load at receptor j (set by the TMDL).
- In a competitive permit market, the equilibrium permit price faced by source i is:

$$p_i \;=\; \sum_j F_j \cdot a_{ij} \qquad \Rightarrow \qquad MAC_i(e_i^*) = p_i$$

- A trade between sources i and j is welfare-improving whenever $MAC_i \neq MAC_j \cdot r_{ij}$, the trading ratio $r_{ij} = a_{ij}/a_{jj}$ ensures the ambient constraint is not violated by the trade.
- This delivers the same cost-effective allocation as the ambient charge, but through a quantity instrument.

Trading ratios in water (3)



With 1:1 trading, both sources face the same price p — the upstream source (high a_{ij}) abates too little, creating a hotspot. The trading ratio $r = a_{Uj}/a_{Dj} > 1$ raises the upstream source's effective price, restoring the cost-effective allocation.

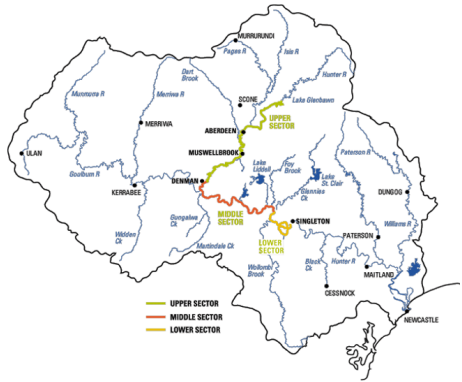
Point–nonpoint trading

The biggest potential, the hardest design

- The largest cost savings come from point–nonpoint trades: the most significant gains come where marginal abatement costs differ widely.
- But nonpoint reductions are difficult to measure, verify, and enforce, the MRV problem.
- Thin markets: where there are few traders or when cost differentials are slight, there will be very few feasible trades.
- Water quality trading is frequently complicated by measurement and enforcement challenges, abatement cost differentials, sufficient trading volumes, and trading flexibility.

Case — the Hunter River Salinity Trading Scheme

- The Hunter River catchment is the largest coastal catchment in NSW: agriculture (wineries, horse breeding) alongside over 40 coal mines and three power stations.
- Salty water results from both natural processes and industrial discharge.
- "The scheme has been responsible for restoring the waters of the Hunter to an unprecedented level of freshness."



Hunter River Salinity Trading Scheme sectors.

Hunter River — how the scheme works (1)

Flow-dependent discharge

- When the river is in low flow: no discharges are allowed.
- When the river is in high flow: limited discharge is allowed, controlled by a system of salt credits.
- The amount of discharge allowed depends on the ambient salinity in the river, so it can change daily.
- This flow-dependent design directly exploits the river's absorptive capacity, discharge only when the water body can handle it.

Hunter River — how the scheme works (2)

Credits and trading

- The river is divided into numbered blocks.
- There are a total of 1,000 salt discharge credits in the scheme.
- Licence holders can only discharge salt into a river block in proportion to the credits they hold: 1 credit allows a discharge of 0.1% of the total allowed.
- An online trading system allows licence holders to trade quickly and simply.
- Trades can be for one or many blocks, flexibility in both time and location.

Atmospheric deposition

- Airborne pollutants (SO_2, NO_x, mercury) eventually settle into water bodies via wet deposition (rain) and dry deposition (particles falling by gravity).
- Acid rain from SO_2/NO_x damages lakes and rivers far from the emission source, a regional, cross-media externality.
- Mercury from coal combustion enters aquatic food chains and bioaccumulates in fish tissue.
- Implication: controlling air pollution generates water-quality co-benefits that are often uncounted in standard benefit–cost analyses. The external benefits from air quality improvements are likely to be quite large.
- This highlights the need for coordination between air and water regulations.

Instrument choice for water pollution

	Effluent charge	**Cap-and-trade (emission permits)**	**Ambient charge**	**Ambient permits**
What is set	Price per unit of BOD	Aggregate emission cap	Price at each receptor	DO cap at each receptor
Location	Ignored (uniform)	Ignored (1:1 trades)	Via transfer coefficients a_{ij}	Via trading ratios r_{ij}
Cost-effective?	Across sources only	Across sources only	Fully (sources & locations)	Fully (sources & locations)
Information needed	Low	Low	High (dispersion models)	High (dispersion models)
Nonpoint sources	Hard to apply	Hard to include	Can incorporate via a_{ij}	Can incorporate via ratios

Emission-based instruments (left) are simpler but ignore location. Ambient-based instruments (right) are cost-effective but require transfer-coefficient models, feasible for well-studied catchments.

Appendix

References

Glossary of key terms (1/2)

BOD	Biochemical oxygen demand, the oxygen consumed by bacteria breaking down organic waste in water.
DO	Dissolved oxygen, the concentration of oxygen in water; the key indicator of water quality for aquatic life.
Oxygen sag	The dip in DO downstream of a pollution discharge, caused by aerobic decomposition of organic waste.
Eutrophication	Excessive nutrient enrichment (N, P) causing algal blooms; decomposing algae deplete oxygen, creating hypoxic "dead zones."
Fund pollutant	A pollutant the environment can break down if the emission rate stays below the absorptive capacity (e.g. degradable waste, heat, nutrients).
Stock pollutant	A pollutant that persists and accumulates because the environment has no (or negligible) absorptive capacity (e.g. mercury, PFAS, microplastics).
Bioaccumulation	The build-up of a contaminant in an organism's tissues over time; *biomagnification* is the increase in concentration at each successive trophic level.

Glossary of key terms (2/2)

Point source	A discharge from an identifiable location (pipe, outfall, oil rig); amenable to permits, charges, and trading.
Nonpoint source	Diffuse pollution with no single discharge point (agricultural runoff, urban stormwater); hard to monitor and regulate.
Transfer coefficient	The factor a_{ij} linking a unit of emission from source i to the change in ambient quality at receptor j.
TMDL	Total Maximum Daily Load, the maximum pollutant load a water body can receive while meeting quality standards; creates a catchment-level "cap."
Trading ratio	The rate $r_{ij} = a_{ij}/a_{jj}$ at which permits must be exchanged between sources to keep ambient quality unchanged.
BPT / BAT / BCT	Technology-based effluent standards under the CWA: Best Practicable, Best Available, and Best Conventional Technology.
PFAS	Per- and polyfluoroalkyl substances, synthetic "forever chemicals" that do not break down in the environment.

Data sources for water pollution research

Water pollution data

- UNEP/GEMS Water — Global Environment Monitoring System for freshwater quality
- US EPA WATERS — water quality assessments, impaired waters (303(d) list), discharge permits
- EEA WISE — European water quality and quantity indicators under the Water Framework Directive
- BoM Water Data — Australian water quality, streamflow, and groundwater data
- World Bank Open Data — cross-country indicators on water/sanitation access and pollution
- WHO WASH — drinking water quality, sanitation, and hygiene monitoring
- GEMStat — global surface and groundwater quality statistics (UN)

References (1/3)

- Capaldo, A., Gay, F., Caputo, I. et al. (2018), "Effects of Environmental Cocaine Concentrations on the Skeletal Muscle of the European Eel (*Anguilla anguilla*)," *Science of the Total Environment* 640–641, 862–873.
- Carson, R.T. & Mitchell, R.C. (1993), "The Value of Clean Water: The Public's Willingness to Pay for Boatable, Fishable, and Swimmable Quality Water," *Water Resources Research* 29(7), 2445–2454.
- Fewtrell, L., Kaufmann, R.B., Kay, D. et al. (2005), "Water, Sanitation, and Hygiene Interventions to Reduce Diarrhoea in Less Developed Countries: A Systematic Review and Meta-Analysis," *The Lancet Infectious Diseases* 5(1), 42–52.
- Fisher-Vanden, K. & Olmstead, S. (2013), "Moving Pollution Trading from Air to Water: Potential Problems and Prognosis," *Journal of Economic Perspectives* 27(1), 147–172.

References (2/3)

- Keiser, D.A. & Shapiro, J.S. (2019), "Consequences of the Clean Water Act and the Demand for Water Quality," *Quarterly Journal of Economics* 134(1), 349–396.
- Kolpin, D.W., Furlong, E.T., Meyer, M.T. et al. (2002), "Pharmaceuticals, Hormones, and Other Organic Wastewater Contaminants in U.S. Streams, 1999–2000: A National Reconnaissance," *Environmental Science & Technology* 36(6), 1202–1211.
- McCann, L. & Easter, K.W. (1999), "Transaction Costs of Policies to Reduce Agricultural Phosphorous Pollution in the Minnesota River," *Land Economics* 75(3), 402–414.
- Miller, T.H., Ng, K.T., Bury, S.T. et al. (2019), "Biomonitoring of Pesticides, Pharmaceuticals and Illicit Drugs in a Freshwater Invertebrate to Estimate Toxic or Effect Pressure," *Environment International* 129, 595–606.

References (3/3)

- Phillips, P.J., Smith, S.G., Kolpin, D.W. et al. (2010), "Pharmaceutical Formulation Facilities as Sources of Opioids and Other Pharmaceuticals to Wastewater Treatment Plant Effluents," *Environmental Science & Technology* 44(13), 4910–4916.
- Schwabe, K.A. (2001), "Nonpoint Source Pollution, Uniform Control Strategies, and the Neuse River Basin," *Review of Agricultural Economics* 23(2), 352–369.
- Shimshack, J.P., Ward, M.B. & Beatty, T.K.M. (2007), "Mercury Advisories: Information, Education, and Fish Consumption," *Journal of Environmental Economics and Management* 53(2), 158–179.
- White, D., Lapworth, D.J., Civil, W. & Williams, P. (2019), "Tracking Changes in the Occurrence and Source of Pharmaceuticals Within the River Thames, UK; From Source to Sea," *Environmental Pollution* 249, 257–266.
- Woodwell, G.M., Wurster, C.F. & Isaacson, P.A. (1967), "DDT Residues in an East Coast Estuary: A Case of Biological Concentration of a Persistent Insecticide," *Science* 156(3776), 821–824.