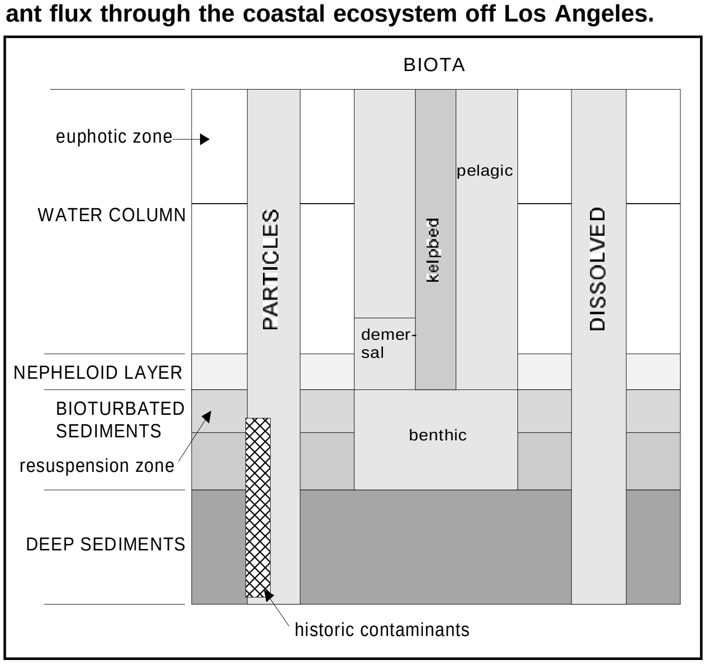
A Conceptual Model of Pollutant Flux Through the Coastal Ecosystem off Los Angeles

Contaminants that are released into the marine environment become distributed among the various compartments (water, sediments, and biota) as a result of complex physical, chemical, and biological processes. The potential risks of these chemicals to marine animals and humans depend on exposure and the subsequent effects. The Santa Monica Bay Restoration Project (SMBRP) sponsored a workshop to develop a conceptual model of pollutant flux through the coastal marine ecosystem off Los Angeles. The model would provide environmental managers and interested parties with a means for evaluating decisions about the effects of contaminant inputs or in-place contaminants on animal populations and risks to human heath. The model would also highlight areas where critical data are lacking.

The workshop was held in December 1992 in Irvine, California. It was attended by 28 scientists and technical representatives from local, state, and federal agencies. A variety of disciplines were represented including ecosystem modeling, oceanography, toxicology, biology, and chemistry. Workshop participants developed submodels for the physical and biological components of the system, and then linked the submodels emphasizing inter-connections and processes. The participants also assessed the current knowledge about pollutant flux and identified areas where more data and knowledge are needed.

FIGURE 1. Framework for the conceptual model of pollutant flux through the coastal ecosystem off Los Angeles.



WORKSHOP GOAL AND OBJECTIVES

The goal of the interdisciplinary workshop was to develop a conceptual model of pollutant flux for the coastal ecosystem off Los Angeles. The conceptual model traces the pollutants from their sources through ecosystem processes to their ultimate physical and biological fates. The objectives of the workshop were to use the process of developing the model to identify gaps in conceptual understanding (research needs) and gaps in information (monitoring or data needs). Some of the biological and physical processes of the conceptual model are poorly understood; these are candidates for more research. Other aspects of the model are reasonably well understood, but data for Southern California are lacking; these are candidates for data collection and monitoring programs.

DEVELOPMENT OF THE CONCEPTUAL MODEL

Framework

The workshop participants developed the framework for the conceptual model based on stratification of the water column and sediments, and the distribution of contaminants among the following compartments (Figure 1):

1. Water column
   a. Sea-surface microlayer (upper few microns at air-water interface)
   b. Euphotic zone (zone of photosynthesis)
   c. Underlying water
   d. Nepheloid layer (particle-rich layer at sediment-water interface)
2. Sediments
   a. Surficial sediments (upper few mm at sediment-water interface)
   b. Bioturbated sediments (sediment mixed layer)
      i. Resuspension layer (~10 cm zone of episodic resuspension)
      ii. Underlying sediments
   c. Deep sediments.

Vertical stratification of the water column and sediments is determined by biological and physical processes. The thickness of the water and sediment layers varies on time scales of days and longer.

The compartments containing the anthropogenic contaminants were defined as:

1. Contaminants in the particulate phase within the water column and sediments;
2. Contaminants in the dissolved phase within the water column and sediment pore water; and
3. Contaminants in biota in the benthic, demersal, and pelagic food webs, including the biota associated with kelp beds and rocky reefs.

Contaminant Sources

The sources of contaminants to the coastal zone include municipal and industrial wastewater discharges, surface runoff, ocean dumping, aerial deposition, groundwater percolation, shipping and boating, current advection, coastal erosion, oil seeps, and historic sediment deposits (Table 1). Municipal wastewater discharge was responsible for the majority of contaminant inputs to the Southern California Bight during the early 1970s. Mass inputs from municipal wastewaters have declined significantly in the past two decades due to improved and increased treatment and source control (see *Characteristics of Effluents from Large Municipal Wastewater Treatment*

TABLE 1. Categorization of contaminant inputs to the Southern California Bight [after SCCWRP (1973) and Eganhouse (1982)].

	LOCATION	SPATIAL LOCI	DISPERSION	FLOW	TEMPORAL DURATION EVENT/SYSTEM	VARIABILITY	MASS INTENSITY CONCENTRATION
MUNICIPAL OUTFALLS	Bottom Nearshore	Localized Few	Discrete	Continuous	Long/Long	Low	Concentrated
INDUSTRIAL OUTFALLS	Surface/Bottom Nearshore	Localized Many	Discrete	Continuous	Long/Long	Unknown	Concentrated
OCEAN DUMPING	Surface Near-/Offshore	Localized Few	Discrete	Intermittent	Long/Short Aperiodic	High	Concentrated
STORM	Surface Nearshore	Localized Many	Discrete	Intermittent	Long/Short Periodic/Aperiodic	High	Concentrated
DRY	Surface Near-/Offshore	Localized Many	Discrete	Continuous	Long/Long	Unknown	Concentrated
GROUNDWATER	Bottom Nearshore	Extensive	Diffuse	Unknown	Unknown	Unknown	Dilute?
RAIN	Surface Near-/Offshore	Extensive	Diffuse	Intermittent Periodic/Aperiodic	Long/Short	Unknown?	Dilute
DRY	Surface	Extensive	Diffuse	Continuous	Long/Long	Unknown?	Didlute
EROSION	Surface Nearshore	Localized Many	Diffuse	Intermittent	Long/Short Aperiodic	High	Concentrated
OIL SEEPS	Bottom Near-/Offshore	Localized Many	Discrete	Continuous	Long/Long Aperiodic	Low	Concentrated
OIL PLATFORMS	Surface Near-/Offshore	Localized Few	Discrete	Continuous/ Intermittent	Long/Short	Unknown	Concentrated
SHIPPING & BOATING	Surface Near-/Offshore	Extensive Many	Discrete	Intermittent Aperiodic	Long/Short	Low	Concentrated
CURRENT ADVECTION	Surface to Bottom Near-/Offshore	Extensive	Diffuse	Continuous/	Long/Short	Unknown Intermittent	Dilute
UPWELLING	Surface to Bottom Nearshore	Localized Few	Diffuse	Intermittent	Short	Unknown	Dilute
HISTORIC SED. DEPOSITS	Bottom Nearshore	Localized Few	Discrete	Intermittent Aperiodic	Long/Short	Unknown?	Concentrated

TABLE 2. Estimated annual mass inputs to the Southern California Bight from municipal wastewater discharge, surface runoff, and ocean dumping. Estimates within a factor of two or three for a particular compound from a particular source probably are not significantly different.

	1970-72[a] (mt)			1988-90[b] (mt)		
	Municipal Wastewater	Surface Runoff	Ocean Dumping	Municipal Wastewater	Surface Runoff	Ocean Dumping
Cadmium	54	1.2	14	1.9	1.9	1.4
Chromium	649	25	28	15	31	32
Copper	567	18	28	62	62	56
Lead	211	90	28	11	109	38
Nickel	313	17	28	43	24	9.3
Silver	15	1.1	1.5	10	—[c]	0.6
Zinc	1,680	101	56	127	256	114
Total DDT	19	0.12	14	0.02	0.06	0.05[d]
Total PCB	9.7	0.25	28	nd[e]	0.10	0.03

[a]Data from SCCWRP (1973).
[b]Data from SCCWRP (1990a,b, 1992a,b).
[c]Not measured.
[d]Total pesticides.
[e]Not detected.

Facilities in 1993 in this volume). Today, the magnitude of contaminant inputs from nonpoint sources and ocean dumping is comparable to contaminant inputs from municipal wastewater discharge (Table 2).

Definition of Submodels

The conceptual model was divided into three submodels:

1. Physical transport - the physical movement and physico-chemical transformations of materials (accounts for contaminant concentrations in dissolved and particulate phases in the water column);
2. Animal-sediment relations - biological and chemical processes within and at the surface of the sediments (accounts for contaminant concentrations in the sediments, including biota); and
3. Food web transfer - benthic, demersal, reef, and pelagic food webs (accounts for contaminant concentrations in the biota).

Physical Transport

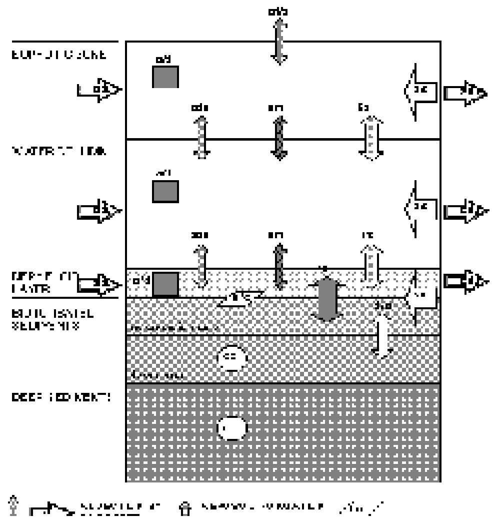
Dissolved and particulate contaminants that reach the coastal marine environment join the natural background of particles and water in the “circulation machine.” The initial partitioning of most contaminants of concern is predominantly onto particles (based on their hydrophobic nature). Partitioning varies with particle size, composition, surface coating, and biological activity. Small particles adsorb more contaminants than large particles because of their higher surface area to mass ratio. The fate of most contaminants, especially those with high equilibrium distribution (partition) coefficients ($K_D > 10^6$), is determined by the behavior of particles (Figure 2).

The size and nature of particles and their associated contaminants are modified by physico-chemical processes (e.g., aggregation and dissolution) and biological processes (e.g., ingestion, metabolism, and defecation). Removal rates of particles and their contaminants from the water column (scavenging) is highest in estuaries and decreases with distance offshore. Scavenging is increased by biological activity (primary production, filter feeding, and grazing). Dissolved contaminants are incorporated into particulate matter by adsorbing onto surfaces of inorganic or organic particles, and by incorporation into biological tissues (Figure 3).

Physical dispersion in the water column is due to advection and diffusion and the transport of contaminated particles over long distances is not uncommon. Dispersion is complicated by non-conservative particle behavior, biological packaging, and uncertainties about processes controlling particle resuspension from the bottom. The primary removal mechanism of particles from the euphotic zone is their incorporation into biogenic particles with large sinking rates.

Once in the sediments, contaminants can be chemically modified and released from particles into the pore water. Transport to the overlying water can occur via molecular diffusion through the pore water, and in sediments containing animals, by biological transport. Animals living in the

FIGURE 2. Conceptual model of physical processes for particulates in the coastal ecosystem off Los Angeles.



sediments can also mix pollutant bearing particles deeper into the sediments.

Contaminants on particles and in pore waters can re-enter the water column by resuspension. Contaminants on these “aged” particles may be less bioavailable than contaminants on “younger” particles. Resuspension can re-introduce contaminants on sediment particles and in pore water to the water column where the chemical environment is quite different. The basic processes of particle dispersion are understood, but data on the rate of dispersion are lacking for the shelf off Los Angeles so predictions are semi-quantitative at best.

Animal-Sediment Relations

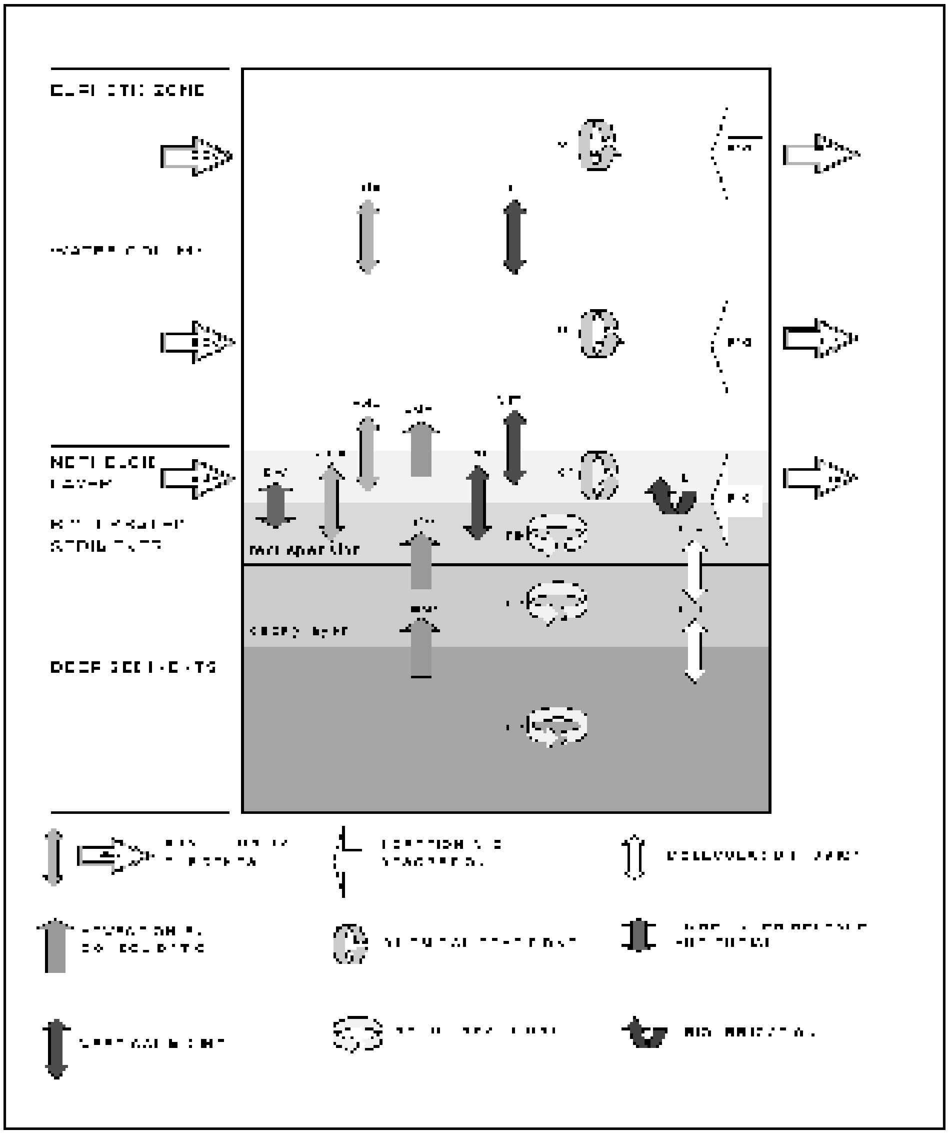
Equilibrium partitioning of contaminants between sediments and pore water is the key process in animal-sediment relations. The transformation of chemicals in the water column and sediments can produce toxic or non-toxic forms. The primary transformation mechanisms for organic contaminants are hydrolysis, redox reactions, and biodegradation. The primary transformation mechanisms for metals are precipitation, ion exchange, and complexation (sequestering, chelation). Pore water has an oxygen gradient from the surface to depth and bioturbation can break down that gradient and thus change the chemistry of the sediments.

The mass transport of chemicals within sediments is affected by the physical structure of the sediments (particle size, shape, density, cohesion, bed roughness, porosity, stratification), the current regime, shear stress of the overlying water on the sediments, bio-irrigation, and bioturbation (Figure 4). Benthic animals move particles and water vertically, and larger animals move more sediments and pump more water. Animals mix sediments by conveyor processes and they mix pore water by irrigation processes. Benthic animals transport contaminants to the overlying water by mixing sediments vertically and by irrigating their burrows. The infauna can also increase the sediment burden of contaminants by deep mixing of pollutant bearing particles.

The bioavailability of contaminants depends on the nature of the contaminated particle, the specific contaminant, and the animal species in question. Once a contaminated particle is in the gut of an organism, availability depends on the type and strength of binding of the contaminant to the particle, and the presence or absence of a transfer mechanism from the particle to the cells of the organism. Contaminant material not desorbed in the gut, or incorporated into the organism, will be excreted in particulate pellets.

The flux of contaminants into and out of benthic animals affects their growth, reproduction, and mortality, and can lead to changes in population size and community composition. The impact of contaminants on the biological community will vary with the concentration, toxicity, persistence, magnification, and chemical mobility of the pollutants. For many contaminants, there is a positive

FIGURE 3. Conceptual model of physical processes for dissolved components in the coastal ecosystem off Los Angeles.



correlation between concentrations in the sediment (or a specific phase of the sediment) and concentrations in animal tissues. Using this relation, the concentration in benthic organisms can be predicted to a first order by knowing the concentrations in the sediments.

Foodweb Transfer

The uptake of contaminants by the benthic biota, and their predation by epibenthic and pelagic organisms, transfers pollutants out of sediments and into foodwebs. Four important foodwebs exist in the coastal ecosystem off Los Angeles: soft-bottom epibenthic, pelagic, reef/kelp bed, and bay and estuary (Figure 5). There are overlaps among these foodwebs and some species do not fit neatly into any of the categories.

The primary classes of contaminants of concern are the hydrophobic organics, hydrophilic organics, anthropogenic fraction of metals, organometallics, carbon, and pollutants associated with organic enrichment. The pollutants of concern in the food webs off Los Angeles are those contaminants that bioaccumulate, i.e., hydrophobic organics (e.g., PCBs and DDTs) and organometallics (e.g., tributyltin and methylmercury).

The processes of foodweb transfer and contaminant distribution are inherently spatial and temporal. Each animal in a population feeds in a specific area that may contain several food sources or habitats and a range of contaminant concentrations. The time spent feeding in these habitats determines the contribution of the food sources and contamination to the individual's diet.

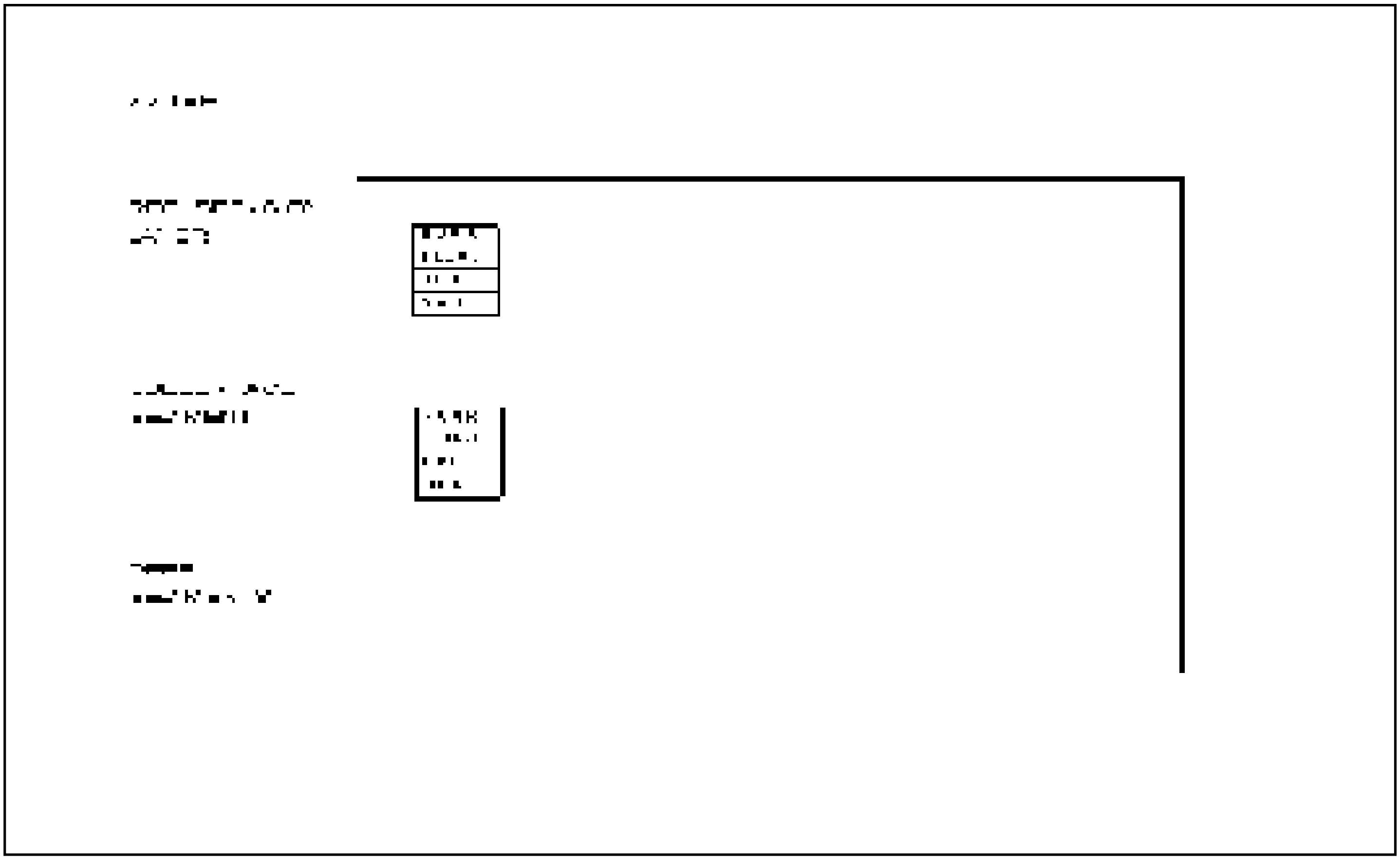
Each of the four primary food webs off Los Angeles could be modeled and the models could be used to identify the principal contaminant transfer pathways in the ecosystem. However, it is unrealistic to define all possible trophic interactions and biomagnification relations in each of the food webs. Instead of incorporating all trophic levels of the food webs in the models, it may be more useful to focus on several key species to determine whether the health of the ecosystem and public health are being protected. Key species that span various trophic levels off Los Angeles might be sea lion, pelican, bonito, white croaker, anchovy, sea urchin, and kelp.

DATA AND RESEARCH NEEDS

Data Needs of All Groups

1. Current meter records.
2. Cohesiveness of sediments; dynamic observations on the benthic boundary layer (e.g., peak shear stress).
3. Dispersion of contaminants from storm drains.
4. Vertical distribution of particles by size, with contaminant concentrations, in the sediment bioturbation layer.
5. Free-water contaminant concentrations in overlying water and sediment pore water.
6. Appropriate methods to measure lipids and their concentrations in benthos and fish.

FIGURE 4. Conceptual model of animal sediment relations in the coastal ecosystem off Los Angeles.



7. Sediment characteristics, including biota and contaminants, on the shelf (spatial).
8. Sediment characteristics, including contaminants, in sediment cores on the shelf (temporal).

Research Needs of All Groups

1. Better understanding of sediment processes: mechanics of accumulation, burial, mixing, and mixing by infauna (radiogeochemistry dating of sections in sediment cores can be used to assess accumulation rates, burial rates, and mixing).
2. Successional changes of infauna related to anthropogenic and natural perturbations.
3. Biodiffusion rates between deep and shallow sediments (bio-diffusion coefficients and advection rates).
4. Characteristics of the benthic boundary layer (sediment-water interface) during transport events; better under standing of sediment resuspension and contaminant fluxes between sediments and water column.
5. Management strategies to deal with historic contaminant deposits buried in sediments (e.g., DDT on the Palos Verdes Shelf) and risk-benefit analyses of remediation choices.

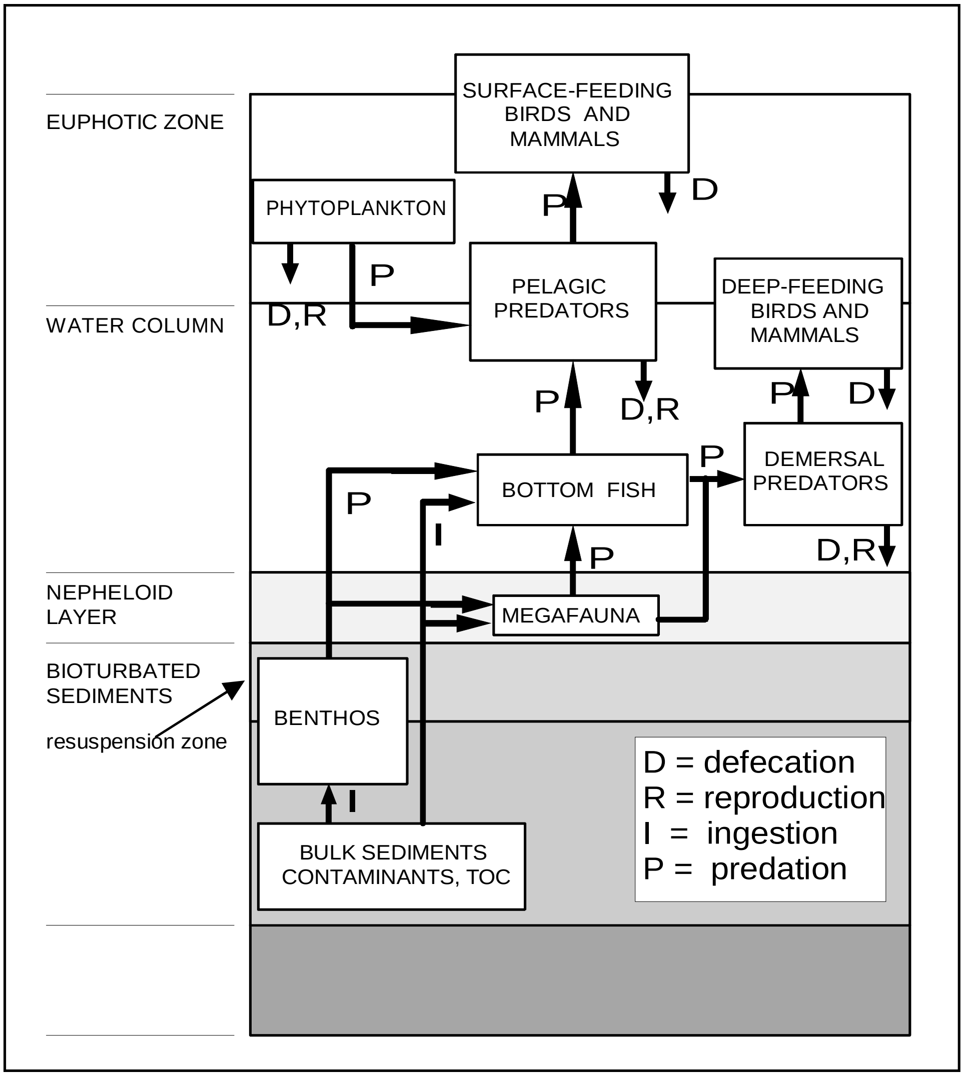
Research Needs of Physical Transport Group

1. Systematic program of current measurements and circulation shoreward of shelf break; better understanding of circulation in the Southern California Bight.
2. Systematic wave climate observations throughout the bight (part of the flow of energy through the area that drives transport).
3. Particle aggregation processes in the water column (natural/natural, effluent/effluent, natural/effluent); better understanding of the physical and biological processes that lead to particle deposition.
4. Evaluation of existing physical models and computational schemes of contaminant movements.

Research Needs of Animal-Sediment Group

1. Population structure (biomass by age class) of the benthic biota.
2. Assimilation efficiencies of ingested particles by benthic biota.
3. Effects of tissue residues on life histories of benthic biota.
4. Microbial degradation of contaminants in sediments and water column.

FIGURE 5. Conceptual model of foodweb transfer in the coastal ecosystem off Los Angeles.



Research Needs of Foodweb Group

1. Pollutant dose-response relationships of local biota.
2. Chemical concentrations in water, sediments, and biota near pollutant hot spots.
3. Assimilation, consumption, and depuration rates.
4. Spatial distribution of biomass.
5. Spatial and temporal feeding distributions; composition of diets.
6. Spatial averaging of animal exposure.
7. Benthic-pelagic coupling, including diel and vertical migrations and emergent infauna.
8. Benthic-pelagic coupling with kelp beds and reefs, including horizontal diel migrations, and identification of sheltering and feeding areas.

REFERENCES

Eganhouse, R.E. 1982. Organic matter in municipal wastes and storm runoff: Characterization and budget to the coastal waters off Southern California. Ph.D. Diss., Univ. California, Los Angeles.

SCCWRP. see *Southern California Coastal Water Research Project.*

Southern California Coastal Water Research Project. 1973. The ecology of the Southern California Bight: Implications for water quality management. Tech. Rep. 104. Southern California Coastal Water Research Project, El Segundo. 531 pp.

Southern California Coastal Water Research Project. 1990a. Characteristics of effluents from large municipal wastewater treatment plants in 1989. pp. 8-15, In: Southern California Coastal Water Research Project, Annual Report 1989-90. Southern California Coastal Water Research Project, Long Beach.

Southern California Coastal Water Research Project. 1990b. Characteristics of effluents from small municipal wastewater treatment plants in 1989. pp. 16-24, In: Southern California Coastal Water Research Project, Annual Report 1989-90. Southern California Coastal Water Research Project, Long Beach.

Southern California Coastal Water Research Project. 1992a. Estimated of ocean disposal inputs to the Southern California Bight. pp. 39-48, *In*: Southern California Coastal Water Research Project, Annual Report 1990-91. Southern California Coastal Water Research Project, Long Beach.

Southern California Coastal Water Research Project. 1992b. Surface runoff to the Southern California Bight. pp. 19-28, *In*: Southern California Coastal Water Research Project, Annual Report 1990-91. Southern California Coastal Water Research Project, Long Beach.

ACKNOWLEDGMENTS

The workshop was funded by the Santa Monica Bay Restoration Project. Author Jeffrey Cross thanks the following participants: R. Brodberg (CalEPA); W. Davis (US EPA); J. Dorsey (City of Los Angeles); B. Everitt (facilitator, ESSA Limited); T. Fleming (US EPA); M. Gold (Heal The Bay); I. Haydock (County Sanitation Districts of Orange County); M. Helvey (NOAA); T. Hendricks; R. Hoenicke (San Francisco Estuary Institute); R. Horvath (County Sanitation Districts of Los Angeles County); G. Jackson (Texas A & M University); H. Lee (US EPA); K. Ludwig (City of Los Angeles); M. Lyons (California Regional Water Quality Control Board); P. McCall (Case Western Reserve University); A. Mearns (NOAA); S. Pavlou (EBASCO Environmental); R. Smith (EcoAnalysis, Inc.); W. Straub (City of Los Angeles); J. Stull (County Sanitation Districts of Los Angeles County); M. Suffet (UCLA); D. Swift (Old Dominion University); B. Thompson (San Francisco Estuary Institute); C. Wilson (California State Water Resources Control Board); D. Young (US EPA).