Land Use Effects on Water Quality: Building a Framework for Chicago River Watershed

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Presentation Outline

• **Background**: Land use effects, urban watershed modeling, Chicago river watershed

• **Research Objectives**: Data warehouse, water quality-quantity framework, modeling, and optimization

• **Outputs of Research**

• **Work In Progress**

• **Research Summary**
Land Use Effects on Surface Water

- Examining the different types of land use and land cover within a watershed can reveal important information about potential sources of contamination to its water bodies.
- Contamination by point and nonpoint sources is a major concern due to the excessive contamination of water bodies.
- Land cover refers to the type of feature e.g. agricultural fields, lakes, rivers, roads, parking lots.
- Land use refers to human activities on the land e.g. recreation, urban, or agricultural.
Major Land Uses in USA (2002)

- Grassland pasture and range: 25.9%
- Forest-use land: 28.7%
- Special-use areas: 13.1%
- Urban areas: 2.6%
- Miscellaneous other land: 10.1%
- Cropland: 19.5%

Source: USDA, Economic Research Service
Impaired Waters and TMDL’s Program

• **Clean Water Act (CWA)** - States to develop lists of impaired waters, and develop *Total Maximum Daily Loads (TMDLs)*

• **TMDL = WLA + LA + MOS**
  
  WLA = Waste Load Allocation (i.e., loadings from point sources);
  LA = Load Allocation (i.e., loadings from nonpoint sources including natural background);
  MOS = Margin of Safety

• **USEPA estimates 40% of the monitored national water supplies do not meet established water quality standards**

• **Causes:** chemical, physical, and biological contaminants

• **Sources:** municipal sewage treatment plants, factories, storm sewers, modification of hydrology, agricultural runoff, and runoff from city streets (**Land use**)
Watershed Approach: Watershed Simulation

• CWA programs evolved to more holistic watershed based strategies

• Watershed unit provides comprehensive, sensible water resources decisions and strategies, and addresses more effectively the full range of concerns

• Watershed models:
  – water resources assessment tool,
  – development and management.
  – dynamic interactions between climate and land-surface hydrology

• Models are classified based on (1) process descriptions; (2) time scale; (3) space scale; (4) techniques of solution; (5) land use, and (6) model use (Singh, 2005)
Urban Watershed Modeling

• **Imperviousness**
  - Storm water runoff and urban land use effluents major sources of pollutants to surface water
  - Not only affects total quantities of pollutant loads but affects transport pathways as well

• **AS A RESULT**: Urban ecological environment is threatened

• **WHAT TO DO**: Urban Watershed Modeling to understand the intrinsic environmental informatics

![Diagram showing the impact of impervious surfaces on runoff and infiltration.](image)
Chicago River Watershed

• Chicago Waterway System (CAWS) is the main component of the Chicago River Watershed:
  – Economic value,
  – Transportation route,
  – Treated effluent conveyance (70% effluent),
  – Recreational water body,

– Issues:
  – Invasive species,
  – Flooding,
  – Water quality
Study Area

- The Chicago River Basin (hydrologic unit 07120003)
- Located in northern Illinois and drains approximately 645 mi²
- The North Branch Chicago River joins the South Branch of the river in downtown Chicago flows into the Chicago Sanitary and Ship Canal with the Calumet River, they then join with the Des Plaines River as a tributary of the Illinois River
- 80% urban land use
- Impairments mainly due to phosphorus, fecal, chloride, DO, pH, and temperature

Source: http://www.chicagoriver.org/
One example of sub categorization of Residential Land as keyed to the standard land use code would be:

Level 1
1. Urban or built-up

Level II
11. Residential
111. Single-family Units
112. Multi family Units
113. Group Quarters
114. Residential Hotels
115. Mobile Home Park
116. Transient Lodging
117. Other

Urban Level (I)

Urban Level (II)
Why Chicago River Watershed?

• Replenishment for Lake Michigan
• Water quality impairments (main nutrient contributor to Illinois River and hence gulf of Mexico dead zone+ disinfection issues)
• CSO (TARP)  (flooding+ disinfection) issues
• Asian Carp (adaptive vs. technical solutions)
  – Close locks  flooding
  – River re-reversing
    • debates about if hydrological separation guarantee ecological separation)
    • Effluent need to be treated to higher standards
• Required watershed level assessment studies, No WQS, No TMDLs
  • A thorough understanding of the watershed is essential!
Questions?

What is a watershed?

What constitute a watershed?
Watershed Elements

- Water Quality
- Water Quantity
- Land Use
- Climate
- Watershed Characteristics

Problems
Conflicts
Needs
Targets
Answers!

• Historical Data Records
  – Water Quality and Quantity
  – Land use
  – Climate
  – Watershed Characteristics

• Watershed Perspective
  – Integrated watershed framework for Chicago River watershed
Research Objectives

• Data Warehouse to easily access, retrieve, fill data gaps, analyze, and manage data records

• Data driven model to predict water quality and quantity-Data Driven Algorithms

• Physical model to simulate land use effect on water quality (local export coefficients)-BASINS/HSPF

• Optimization approach for land use tradeoff-Goal Attainment
Chicago River Watershed Framework

Data Warehouse

Data Integration

Data Presentation

Research Topic

Data Analysis & Watershed Assessment

Data Mining

Data Analysis

Watershed Assessment

Modeling & Export coefficient

Optimization
Building the Framework

1. Review of Watershed Elements
2. Data sources identification: Historical records evaluation, data analysis, location, and type
3. Data gap identification and resolution
4. Data integration in a multi-dimensional model
5. Models (data driven and physical): selection, development, calibration, and use (data predictions, nutrient export coefficients, scenarios and optimization)
Data: Sources and Type

- U.S. Geological Survey, USGS, 27 stations
- The Metropolitan Water Reclamation District of Greater Chicago, MWRDGC, 58 stations
- Water reclamation plants, WRP, 2 sites
- Combined sewers overflow, CSO, 200 locations
- Chicago Metropolitan Agency for Planning, CMAP, land use inventory
- Others

location, discharge
location, water quality data
location, discharge/effluent
location, discharge/effluent
location, land use
Geospatial and hydro-meteorological data
Data: Challenges

- Heterogeneity of data compiled from different sources:
  - different storage systems, formats, and retrieval systems
- Data gaps both in space and time
- Data accuracy and consistency
- Data collection frequency
- **Data Integration** ➔ Data warehouse
Data Warehouse

“A data warehouse is a collection of consistent, subject-oriented, integrated, time-variant, non-volatile data and processes on them, which are based on available information and enable people to make decisions and predictions about the future”, (Inmon, 2005)
Bus Architecture Matrix (BAM)

- Facts (watershed process)
- Dimensions (Date, Location, etc.)
- (BAM) To conform the dimension across the different processes and establish possible linkages

<table>
<thead>
<tr>
<th>Watershed Processes</th>
<th>Date</th>
<th>Location</th>
<th>Source Agency</th>
<th>Measurement Details</th>
<th>Land Use Type</th>
<th>Watershed Characteristics Type</th>
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</tbody>
</table>
Star Schema Model

• Star schema consists of one or more fact tables referencing any number of dimension tables

• A dimension model contains the logical design of a data warehouse for the most atomic data collected

• Lowest most atomic grain provides maximum analytic flexibility
Multi-Dimensional watershed Model
Chicago River Watershed Dashboard
Adhoc Analysis for Chicago River Watershed
Chicago River Watershed Framework

Research Topic

Data Warehouse

- Data Integration
- Data Presentation

Data Analysis & Watershed Assessment

- Data Mining
- Data Analysis
- Watershed Assessment

Modeling & Export coefficient

Optimization
Data Driven Algorithms

- Data driven modeling is the study of algorithms that improve automatically through experience.

Source: Preis et al., 2007
Watershed Simulation

• **BASINS** is a multi-purpose environmental analysis system that provides a framework to integrate several key environmental data sets with improved analysis techniques (EPA, 2012)

• **HSPF** is a comprehensive, conceptual, continuous simulation watershed scale model that simulates nonpoint source hydrology and water quality, combines it with point source contributions, and performs flow and water quality routing in the watershed reaches (Singh, 2005)
EIA vs. TIA

- The effective impervious area (EIA) as a portion of the total impervious area (TIA) should be determined within a basin that is directly connected to the drainage collection system (Sutherland, 2000)

- Alley et al., 1983,
  \[ EIA = 0.15 \times TIA^{1.41} \]

- Laenen, 1983
  \[ EIA = 3.6 + 0.43 \times TIA \]

- Sutherland, 2000
  - Extremely disconnected basins
    \[ EIA = 0.01 \times TIA^{2.0} \]
  - An average basin with some infiltration measures
    \[ EIA = 0.04 \times TIA^{1.7} \]
  - Average basins, no infiltration measures, roofs disconnected
    \[ EIA = 0.1 \times TIA^{1.5} \]
  - Highly connected basins, no infiltration measures, roofs connected
    \[ EIA = 0.4 \times TIA^{1.2} \]
  - Totally connected basins
    \[ EIA = TIA \]
BASINS/HSPF

Data included:
- Streams - Reach File 1, NHD
- Watershed boundaries
- Point source locations
- Monitoring locations

Select data layers to display

Zoom to area of interest
Simulation Results
% of Land Use Area in Upper Chicago River Basin (Level III)
% of Total Annual Nitrogen Loads in Upper Chicago River Basin
% of Total Annual Phosphorus Loads in Upper Chicago River Basin

- Residential Single Family: 5.60%
- Residential Multi Family: 5.80%
- Urban Mix W/ Parking Lot: 6.14%
- Open Space Cons: 3.12%
- Industrial W/ Parking Lot: 47.66%
- Government: 6.66%
- Vacant/ Grass: 5.60%
- Retail Center: 4.20%
- Other Roadway: 3.20%
- Residential Mobile Home: 1.80%
- Other vacant: 1.60%
- Medical: 0.88%
- Warehouse/ Distribution/ Wholesale: 0.80%
- Cultural/ Entertainment: 0.72%
- Mall: 0.72%
- Open Space Linear: 0.72%
- Communication: 0.66%
- Residential Farm: 0.54%
- Water: 0.54%
- Independent Auto Parking: 0.42%
- Cultural/ Entertainment: 0.42%
- Mall: 0.42%
- Government: 0.34%
- Vacant/ Grass: 0.32%
- Residential Mobile Home: 0.32%
- Other vacant: 0.26%
- Construction Residential: 0.26%
- Independent Auto Parking: 0.24%
- Residential Farm: 0.20%
- Water: 0.14%
- Water: 0.10%
- Water: 0.06%
- Water: 0.02%
- Water: 0.00%
- Water: 0.00%
- Water: 0.00%
- Water: 0.00%
- Water: 0.00%
- Water: 0.00%
- Water: 0.00%
- Water: 0.00%
Average Export Coefficients for Nitrogen in Upper Chicago River Basin

![Graph showing average export coefficients for nitrogen across various land use types.](Image)
Average Export Coefficients for Phosphorus in Upper Chicago River Basin

![Bar Chart](chart.png)

**Land Use Type**

- Urban Mix W/ Parking Lot
- Industrial W/ Parking Lot
- Business W/ Parking Lot
- Government
- Transportation
- Mall
- Institutional/Other
- Independent Auto Parking
- Manufacturing/Production
- Office/Commercial
- Medical
- Lake/Reservoirs/Lagoon
- Rivers/Canals
- Residential Multi Family
- Education
- Religious
- Retail Center
- Urban Mix No Parking Lot
- Cultural/Entertainment
- Construction Residential
- Construction Non-Residential
- Residential Mobile Home
- Hotel/Motel
- Communication
- Single Office
- Residential Single Family
- Residential Farm
- Open Space Cons
- Other vacant
- Nursery/Greenhouse/Orc
- Crops/Grain/Graz
- Water
- Wetland
- Golf Course
- Vacant/Grass
- Open Space Recreational
- Open Space Private
- Open Space Linear
- Open Space Other
- Cemetery
Multi-Objective Optimization

- Pareto optima-Goal Attainment: to resolve conflicting objectives and arrive at a solution that represents an acceptable or desired balance.

\[
F(X) = [f_1(X), f_2(X), ..., f_m(X)]^T
\]

preset design goals \([f_1^*, f_2^*, ..., f_m^*]^T\)

weight coefficients \([w_1, w_2, ..., w_m]^T\)

Minimize \(\gamma\);

where \(\gamma \in \mathbb{R}\)

subject to:

\[
f_i(X) - w_i \cdot \gamma \leq f_i^*; \quad \forall i = 1, ..., m
\]
Work In Progress

• Data Driven Model

• Scenarios and Optimization: approaches, investigation, and implementation
Research Summary

• A watershed framework approach will be introduced: Data, model, and optimization
• Chicago River watershed will be assessed for previous, existing and future conditions
• Land use effect on water quality will be quantified for highly urbanized watershed
• Land use and load allocation multi-objective optimization approach will be investigated
Thank you!

Questions?