Integrated Water Resources Management for Bathing Water Compliance

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Water Security - Typical Challenges

The ancient Romans had better water quality than half the people alive now.

Source: http://water.org/learn-about-the-water-crisis/
General Challenges

- Security of clean water supply will become an increasing challenge over the next 30 years
- Concern about water quality in river, estuarine and coastal basins is increasing worldwide
- Traditionally hydraulic engineers and researchers have focused attention on hydraulics & hydrology
- Increasing emphasis now also being focused on epidemiological process modelling etc. in hydro-environmental impact assessment studies
Some Specific Challenges

- Many widely used water quality model systems:
  - Treat 1-D and 2-D models as independent
  - Treat dispersion and diffusion as constants
  - Treat bacterial decay as a constant
  - Assume mean hourly or daily load inputs
  - Ignore bacteria ↔ sediment interactions
  - Treat FIO-sediment partitioning as a constant
  - Ignore organic content of sediments
Legislative Drivers

Guidelines for safe recreational water environments
VOLUME 1
COASTAL AND FRESH WATERS

Review of epidemiological studies on health effects from exposure to recreational water

Predominant likelihood of gastrointestinal illness from sea bathing: results from prospective exposure

WATER RESEARCH

DIRECTIVE 2000/60/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL
concerning the management of drinking-water quality and amending Directive 98/83/EC
of 27 January 2000

HRC Hydro-Environmental Research Centre

UNIVERSITY OF CARDIFF

PRIF Y SARDINIA
50% Loss in UK Blue Flag Beaches
Historical Approaches

- Simplistic environmental understanding
  - Uniform bathing day water quality
  - Uniform quality of inputs from rivers etc.
  - Diffuse catchment sources poorly characterised
  - Intermittent discharges poorly quantified

- Models poorly parameterised
  - Bathing water compliance used for calibration
  - Inputs from catchments poorly characterised
  - $\log_{10}$ order accuracy often regarded acceptable
Cloud to Coast System and Services

Models need to include: hydrodynamics, water quality and sediment transport

Particle travels from Cloud to Coast (picking up pollutants etc.) does not know which part of system it’s in at any given time
Ribble River Basin and Fylde Coast U.K.
Acknowledgements

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- **Natural Environment Research Council**
  Reference: NE/I008306/1

Partners:

- **Environment Agency**
- **United Utilities**
- **CH2M HILL**
- **defra**
- **Lancaster University**
- **NFU**
- **Ribble Rivers Trust**

www.shef.ac.uk/c2c
Ribble and Fylde Coast - NW England

- Fleetwood
- Blackpool
- Lytham St Anne’s
- Southport

Compliance point

River Wyre

Ribble Estuary

London
Background in 1990s

- Failure to meet EU Bathing Water standards
- Storm sewers and sewage works discharging along coast thought to be main problem
- Combined storm water and sewer overflows discharging into water courses and rivers
- Field surveys undertaken to establish inputs and failure levels at compliance points
  - Surveys unable to provide definitive conclusions
  - Data could not allow for impact of future proposed capital improvements to works to be assessed
Water Asset - Investments in 1990s

- $800 million invested from 1993 – 1996
- 3 major sewage treatment works
- 5 pumping stations with storm outfalls along coast
Objectives

- Refine HRC hydro-environmental modelling tools
- Quantify impact of sewage inputs into Ribble basin on coastal bathing water quality
- Investigate influence of various parameters such as wind, tides, river discharge, etc
- Allow for continuous and intermittent inputs
- Incorporate land use changes and diffuse source inputs as boundary fluxes when data available
- Propose management strategies for basin
Study Area

- Tidal limit for rivers Ribble, Darwen and Douglas
- Seaward boundary close to 25m contour in Irish Sea
- Narrow rivers feed into wide estuary and coastal zone
  - Riverine boundary limit < 10m
  - Coastal boundary limit > 40km
- Many effluent discharges occur along river reaches
- Complex hydrodynamic processes in estuarine zone
Linked 2-D and 1-D Models
Current Calibration

11 Milepost
3/12/98

$E_{\text{max}} = 4.7\%$

$E_{\text{min}} = 1.9\%$

$E_{\text{max}} = 13.0\%$

$E_{\text{min}} = 9.7\%$

$E_{\text{min}} = 2.2\%$
Ribble Estuary

Model Calibration
11 milepost

11 May 1999 Wet Weather Neap Tide
Ribble Estuary

Model Calibration
11 milepost

19 May 1999 Dry Weather Spring Tide
Coliform Predictions

Fylde Coast and Ribble Estuary, UK

Compliance Points
- St Anne's Pier
- Southport

Simulation Time: 49:36

Faecal Coliform (cfu/100 ml)
- 0 - 100
- 100 - 1000
- 1000 - 5000
- 5000 - 50000
- > 50000

Weather: Dry
Coliform Predictions

Fylde Coast and Ribble Estuary, UK

Compliance Points
- St Anne’s Pier
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Simulation Time
49:36

Faecal Coliform (cfu/100ml)
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- 1000 - 5000
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Weather: Wet
Motivation for Re-Visiting Study

● Growing concern about impact of recent land use changes on estuary and coastal water quality

● Re-occurrence of non-compliance of EU BWD

● Needed to include model of catchments into linked model - C2C holistic approach

● Needed to model both rural and urban catchment inputs - together with land use changes

● Significantly improve ability to predict exposure to, and health impact of, pathogens in coastal waters
Objectives of New Study

- Develop an integrated Cloud-to-Coast model
- Estimate urban point and diffuse loads of FIOs
- Collect new data on FIO loads and fluxes
- Calibrate and validate overall process models
- Produce qualitative health impact assessment
- Create an emulator of model - “Predict & Protect”
- Produce recommendations for policy and make: models, data, formulae available to stakeholders
C2C: Integrated Modelling Domain

- Includes: catchment, river, & coastal models of flow, sediment & FIO processes
- Includes: extended coastal domain around Ribble with tides, waves, sediment and FIO processes
- Includes: climate and land use changes + urban point sources to assess bathing water compliance
C2C: Integrated Model Set Up

2D/3D Irish Sea Model

2D/3D Coastal Estuary Model

HSPF Catchment Model

1D/2D River Network Model

InfoWorks Model
C2C: Integrated Model Configuration

BIT Spreadsheet → InfoWorks → Urban FIO Generator → HSPF → 1/2D River Network Model → 2/3D Estuarine/Coastal Model
HSPF Catchments

- 28 very different catchments, including: rural & urban, steep & mild slope, arable & pasture and forested land use etc.
US EPA Bacterial Indicator Tool (BIT)

- Splits sub-catchments by land use: mountainous, heath, bog, pastureland, forest, built-up areas, cropland and water
- Accounts for: stocking densities, FIO production rates, decay, manure application, wildlife, etc.
- Includes continuous point sources: septic tanks, cattle in streams etc.
- Washoff: applied manure, grazing, wildlife
- Other default values chosen from stakeholder engagement - ensuring appropriate values
Catchment 2 - BIT Manure Application

- Cattle Manure Application - BIT1
- Cattle Manure Application - BIT2
- Horse Manure Application - BIT1
- Horse Manure Application - BIT2
- Pig and Chicken manure - BIT1
- Pig and Chicken manure - BIT2

FIO build-up rate (cfu/acre/day)
Catchment 2 - BIT Pasture Grazing

- Dairy cattle grazing - BIT1
- Dairy cattle grazing - BIT2
- Beef cattle grazing - BIT1
- Beef cattle grazing - BIT2
- Horse grazing - BIT1
- Horse grazing - BIT2
- Sheep grazing - BIT1
- Sheep grazing - BIT2
- Wildlife - BIT1
Catchment 2 - Septic Tanks Removed
Urban Inputs - E. coli Data Summary

- **Geometric Mean Confirmed E Coli MLGA**

<table>
<thead>
<tr>
<th>Site</th>
<th>Wet Geometric mean Confirmed E coli MLGA</th>
<th>Dry Geometric mean Confirmed E coli MLGA</th>
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</thead>
<tbody>
<tr>
<td>Blackburn</td>
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<tr>
<td>Burnley WwTW, Secondary treated FE</td>
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<td>Chorlton WwTW, Secondary treated FE</td>
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<td>Colne WWTW, Secondary treated FE</td>
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<td>Darwen WWTW, Secondary treated FE</td>
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<td>Hyndburn WWTW, Secondary treated FE</td>
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<td>Leyland WWTW, Secondary treated FE</td>
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<tr>
<td>Walton-le-Dale WWTW, Secondary treated FE</td>
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<tr>
<td>Wigan WWTW, pre-UV channel</td>
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<tr>
<td>Wigan WWTW, UV channel</td>
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<td></td>
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<tr>
<td>Burnley, Crude inlet</td>
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<td></td>
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<tr>
<td>Colne, Crude inlet</td>
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<tr>
<td>Walton-le-Dale, Crude inlet</td>
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<td>Wigan WWTW, Storm Tank Overflow</td>
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<td>Hyndburn WWTW, Storm Tank Overflow</td>
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<td>Wigan WWTW, Storm Tank Overflow</td>
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<td>Field Nr Railway, City</td>
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<tr>
<td>Harrison's Farm CSO, WLN0020</td>
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<td>Hennel Lane CSO, Colne</td>
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<tr>
<td>Whitewalls CSO, Pen0059</td>
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</table>
Urban Inputs - E.coli Annual Loads

Dotted lines = Max Geo Mean; Dashed Lines = Min Geo Mean; Solid Line = Local Geo Mean
Local value not available for storm tank cons for this network
1D RNM - Model Configuration

- 1031 cross-sections
- 5 branched channels
- Linked HSPF & InfoWorks

- Time step: 30s
- 1 year run: 40m
1D RNM - Stage Verification

Bathing Season

Annual Change
1D RNM - Discharge Verification

Discharge (m³/s)

Date

23/12/2011 01/04/2012 10/07/2012 18/10/2012

QMeas713056
QPred713056

23/12/2011 01/04/2012 10/07/2012 18/10/2012

QMeas713019
QPred713019
## 1D RNM - SSC Verification

<table>
<thead>
<tr>
<th>Date</th>
<th>Measured</th>
<th>Predicted</th>
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<td>713122</td>
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**Concentration (mg/l)**

<table>
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<tr>
<th>Date</th>
<th>11MPExp</th>
<th>11MpCal</th>
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<tbody>
<tr>
<td>06-03</td>
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<td>06-05</td>
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**SSC (mg/l)**

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<td>713122</td>
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</tbody>
</table>

**Map**

- Locations: L2, L4, 22, 23, Bullnose, MP03, MP07, MP11, 700306, 720517, 710305, 712615, 71610, 713019, 700306
1D RNM - Typical E. coli Verification

103: Ribble, Mitton Bridge
1D RNM - Typical Scenario Predictions

River Reach

Estuary Reach
Annual Loads of FIO into Estuary

Drop due to FIO decay
Predicted FIO - Estuary for Aug/2008

At 11 Mile Post
Boundary Inputs for Coastal Model

- 203 river boundary inputs around coastal model
- Discharges and sediment flux data from catchment and river network models
- Offshore tidal boundary data from EFDC Irish Sea model and MIKE Global
- EFDC refined for dynamic decay & ad/desorption
Field Data Monitoring

- Continuous offshore data sampling for elevations, currents, meteorological and FIO data
- ADCP deployment at 6 sites
- 2 tracer surveys for source apportionment
- Continued processing of catchment data
- $T_{90}$ experiments from samples to determine day and night time decay rates
- Virus sampling and analysis
Offshore Boat Surveys

- Comprehensive estuarine and offshore surveys
- Drogue tracking, WQ and irradiance depth profiles, and sediment samples
Tracer Studies in Estuary and Coast
## Measured $T_{90}$ Values (Kay *et al.*)

<table>
<thead>
<tr>
<th></th>
<th>$n$</th>
<th>Mean $T_{90}$ (Hours) Irradiated</th>
<th>Mean $T_{90}$ (Hours) Dark</th>
<th>Mean Total Irradiation $D_{90}$ (MJ m$^{-2}$) (Visible+UVA+UVB)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>E. coli</strong></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Freshwater</td>
<td>68</td>
<td>13.61</td>
<td><strong>355.51</strong></td>
<td>6.65</td>
</tr>
<tr>
<td>Estuarine</td>
<td>32</td>
<td>8.56</td>
<td>*30.64</td>
<td>5.17</td>
</tr>
<tr>
<td>Saline</td>
<td>20</td>
<td>2.33</td>
<td>33.77</td>
<td>1.41</td>
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<tr>
<td><strong>Confirmed Enterococci</strong></td>
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<tr>
<td>Freshwater</td>
<td>68</td>
<td>14.87</td>
<td>65.70</td>
<td>8.99</td>
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<tr>
<td>Estuarine$^\dagger$</td>
<td>32</td>
<td>11.08</td>
<td>84.63</td>
<td>6.70</td>
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<tr>
<td>Saline</td>
<td>20</td>
<td>4.98</td>
<td>57.39</td>
<td>3.01</td>
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</tbody>
</table>

* Excludes one experiment where no decay was observed

** Excludes two experiments where no decay was observed

$^\dagger$ Estuarine data includes a wide range of salinity (1-30 ppt)
EFDC - Verification of Tidal Elevations
EFDC - Verification of Tidal Currents

**ADCP Velocity**

- Plot showing velocity data over time for different dates.
- Blue line: U_L5_Pred.
- Red line: U_L5_Meas.

**Tracer Velocity**

- Two sub-plots for different locations:
  - Sport_407:
    - Blue line: U_Tracer_Pred.
    - Red dots: U_Tracer_Meas.
  - St_An_408:
    - Blue line: U_Tracer_Pred.
    - Red dots: U_Tracer_Meas.
EFDC - Verification of Current Profiles
Dispersion Coefficient

• 1D River network (Fischer et al. 1979):

\[ D_x = 0.007 \cdot \left( \frac{W}{H} \right)^{2.1} \cdot \left( \frac{U}{U_*} \right)^{0.7} \cdot H \cdot U_* \quad (1) \]

\[ U_* = \sqrt{gHJ} \quad (2) \]

• River Network dispersion coefficients ranged from: 1 - 10 m²/s in upper and middle reaches - governed by flow

• Estuary dispersion coefficients much larger than rivers: with range of: 1 - 500 m²/s
EFDC - SSC Verification

Graphs showing concentration (mg/l) over dates 06-03 to 06-05 for 11MPExp and 11MpCal, and 7MPExp and 7MpCal.

Map with various locations marked, including Barrow, Leasowe, Connah's Quay, and Heysham.
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**FC Concentration (10^5 cfu/100ml)**

- **7MpExp**
- **7MpCal**
- **11MpExp**
- **11MpCal**
- **3MpExp**
- **3MpCal**
- **BullnExp**
- **BullnCal**

---

**Map of EFDC - E.coli Verification**

- **BARRON**
- **ROADISLAND**
- **Haul Pole**
- **Way Shoul**
- **HEYSHAW**
- **FLEETWOOD**
- **53-40/03-43W stage**
- **BottomUp**
- **BottomLow**
- **GLASTON_DOCK**
- **LIVERPOOL**
- **HILBERT_ISLAND**
FIO in River Column, SSC and Bed

- FIO distribution in river water, on suspended sediments and on bed sediments

![Graph showing FIO distribution over time](image)

- SumFioChanWat
- SumFioChanSS
- SumFioChanBed
High Faecal Concentration Region (HFCR), from 1,000 to 10,000 cfu/100ml, located mainly in river region and salt marshes in Ribble
Health Risk Analysis (Continued)

- Daily Swimming Risk of GI from FIOs:

\[
P(\text{ill})_{FC,\text{day}} = 1 - \left[ 1 + \left( \frac{D_{FC,\text{oral}}}{N_{50}} \right) \times \left( 2^{1/\alpha} - 1 \right) \right]^{-\alpha}
\]

\(P(\text{ill})\) = daily GI probability associated with FIOs, 
\(D_{FC,\text{oral}}\) = number of FIOs ingested, 
\(N_{50}\) = median infective dose that causes half of population to be infected, and 
\(\alpha\) = slope parameter

\(N_{50}\) and \(\alpha\) set to 5.96 \times 10^5 and 0.49 respectively
Health Risk Analysis (Continued)

- Spatial & temporal distribution of risk of acquiring GI per 1000 swimmers predicted for various tides
- FIO levels acceptable for compliance against UK & US criteria for bathing water beaches
General Conclusions

- Hydro-environment Engineering and Research is a subject of increasing global significance
- Integrated Water Resources Management needs holistic C2C solutions and integrated CFD models
- Many water quality process models include crude representations of biochemical/kinetic processes
- Considerable scope for further experimental and field studies to improve hydro-bio/geochemistry
- Considerable scope for improved FIO and health risk assessment in river and coastal waters
Specific Conclusions

- FIO levels in Ribble Estuary and Fylde Coast highly dependent on inputs from catchments
- Adsorbed FIO levels on SSC is an important mechanism for transport of FIOs with flow
- FIO levels very highly dependent upon dispersion coefficients and particularly dynamic decay rates
- Extensive synchronous data are vital for proper model calibration and validation
- Storm water and CSO inputs are generally less critical in non-compliance than diffuse inputs
Thank You

Professor Roger A. Falconer
Email: FalconerRA@cf.ac.uk