Impact Case Study Year II: Aquitard Hydraulics and Aquifer Transport in the White Lodge Wellfield of the Dedham-Westwood Water District

David W. Ostendorf
CEE Department, UMass Amherst
Christopher J. Kilbridge
KGS, South Weymouth, MA

129th NEWWA Annual Meeting
September 21, 2010
Rockport, Maine

Overview

• Stratified drift deposits and WL #5 supply well

• Neponset River aquitard hydraulics-cascade calibration

• Fowl Meadow Aquifer transport

• Conclusions
Glaciated Bedrock Valley–Neponset River

- Ice contact, stratified drift deposits in glaciated bedrock valleys of New England (Flint 1971)
- Deposits of dramatically different permeability beneath river basin
- Some deposits are aquifers, some are aquitards
- Potential for local water supply if aquifer underlies protective aquitard—artesian recharge
- Fowl Meadow Aquifer, Neponset River, Eastern Massachusetts
- USGS (Klinger 1996), DWWD (Dewberry Goodkind 2003)

Dedham-Westwood Water District

- Drinking water to 38,000 users in two towns
- 1.5 billion gallons per year, groundwater (MWRA emergency backup)
- 15 production wells, 205 miles water main, 2 water treatment plants, and 4 water storage tanks
- White Lodge Wellfield provides over 70% of supply (Ostendorf and Kilbridge 2009)
White Lodge Wells #1-5

I-93/I-95, Dedham/Westwood/Canton streets, MBTA, airport, Neponset River, Fowl Meadow Aquifer

Mass Balance Sampling Network
Split Spoon Samples, Grain Size

• Circles are sand, squares are silt plus sand
• Fowl Meadow Aquifer, about 10 m thick (-30 to -20 mmsl)
• Neponset River aquitard, about 10 m thick (-20 to -10 mmsl)

Cross Section, Looking South

- Floodplain deposit
- Neponset River aquitard
- Fowl Meadow Aquifer
- Bedrock
- Ground surface
- Water table
Aquitard Permeability-Site Average Linear Leakage Steady Pumping (Ostendorf and Kilbridge 2009)

\[ h = h_s - \frac{Q}{2\pi T} K_o \left( r \sqrt{\frac{g k'}{v T b'}} \right) \]
\[ k' = 2.3 \times 10^{-17} \text{ m}^2/\text{ft/day} \]

Aquitard Consolidation Coefficient-Attenuation of Cyclic Pumping (Ostendorf et al. 2010)

\[ h = \int_0^t \frac{dh_0}{d\tau} \text{erfc} \left[ \frac{z}{2 \sqrt{c_v(t-\tau)}} \right] d\tau \]
\[ 7.8 \times 10^{-6} < c_v < 1.4 \times 10^{-3} \text{ m}^2/\text{s} \]
Aquitard Permeability-Wellscreen
Overdamped Slug Test (Bouwer and Rice 1976)

\[ h = h_0 \exp(-\lambda t) \]

\[ 1 \cdot m(\text{horizontal}) \]

\[ 0.028 < K' < 0.30 \text{ ft/day} \]

\[ h = h_0 \exp(-\lambda t) \]

\[ 1.3 \times 10^{-14} < k'(\lambda) < 1.4 \times 10^{-13} \text{ m}^2 \]

Aquitard Permeability-Wellscreen
Extended Slug Test (Ostendorf and DeGroot 2010)

\[ h = h_0 \exp(-\lambda t) + \frac{K}{\lambda} \left[ \lambda t + \exp(-\lambda t) - 1 \right] \]

\[ 1 \cdot m(\text{horizontal}) \]

\[ 3.6 \times 10^{-5} < K' < 9.2 \times 10^{-5} \text{ ft/day} \]

\[ 1.7 \times 10^{-17} < k'(\lambda) < 4.3 \times 10^{-17} \text{ m}^2 \]
Aquitard Consolidation Coefficient-Partial Piezocone Pore Pressure Dissipation Tests

\[ h = h_M \exp\left[ -\frac{4 c_H t_M}{r_S} \left( \sqrt{\frac{t}{t_M}} - 1 \right) \right] \]

\[ 8.0 \times 10^{-6} < c_H < 6.7 \times 10^{-5} \text{ m}^2 / \text{s} \]

Cascade Calibration of Neponset River Aquitard Hydraulics

- Steady WL#5 pumping boring logs-site averaged (1 km horizontal, decadal) \( k_{H}'b \)
- Cyclic attenuation-cluster wells (3 m vertical, diurnal) \( c_v = k_v' / (\mu \alpha) \)
- Slug tests-cluster wells (1 m horizontal, hourly-seasonal) \( k_{H}' \)
- Piezocone dissipation test (30 cm vertical, hourly) \( c_{H}' = k_{H}' / (\mu \alpha) \)
- Laboratory permeameters-intact core samples (3 cm vertical, minutes) \( k_{H}^v, \alpha \)

All confirm protective nature of the Neponset River Aquitard, decouples WL#5 from local runoff, floodplain deposit, and River
Cluster Well B Profiles

Aquitard decouples Aquifer from floodplain and river

Chloride in White Lodge Well #5

- Average WL5 pumping $Q=0.0368 \, m^3/s$
- Ambient $c_O=98 \, mg/L$
- Input $c_{INPUT}=234 \, mg/L$
- Aquifer volume $V_{AQUIFER}=2.11 \times 10^7 \, m^3$
- Aquifer porosity (0.35), thickness (10 m) imply $r_A=820 \, m$

$c = c_O + (c_{INPUT} - c_O) \exp \left(-\frac{Qt}{nV_{AQUIFER}}\right)$
**Flux of Chloride Input to WL#5**

\[ Q_{c_{INPUT}} = Q \sum (\kappa c_{DEEP}) \]

- \( c_{INPUT}(WL#5\ data) \)
- \( c_{DEEP}(14\ deep\ wells,\ shown\ in\ mg\ Cl/L) \)

- Observed \( c_{DEEP} \) implies \( \kappa = 0.72 \) deep wells characterize WL#5 source

- \( Q_{c_{INPUT}} = 2.7 \times 10^5 \) kg Cl/yr, towards WL#5

- Most (75%) chloride comes from northwest quadrant

---

**WL#5 Water Balance-Northwest Quadrant**

- \( 0.25Q = 0.0092 m^3/s \) leaves through WL#5

- \( Ppt \times (1 - \text{evap}) \times A_{RECH} \) (Aquifer/Floodplain) enters the Aquifer

- Evap = 0.55 (25”/yr, Linsley et al. 1982)

- \( A_{RECH} = 1.4 \times 10^6 \) m²
dotted line is topographic divide

- Aquifer/Floodplain = 0.40
WL#5 Water Balance-Cross Section, Looking North

- Recharge
- Ground Surface
- Neponset River
- Water Table
- Aquitard (No Flow)
- Bed Rock
- 60%
- 40%
- Fowl Meadow Aquifer (Artesian)

WL#5 Cl Balance-Town/State Attribution

- 2.0x10^5 kg Cl/yr towards WL#5 (NW, 75% of total)
- 11 miles of Town roads distributed over (NW) A_{RECH}
- Town=0.40*11 lane miles*town application rate (rest to floodplain/river)
- State=0.67*7.3 lane miles*state application rate (rest to floodplain/river)
State and Town Salt Application Rates

State Rate
• Canton Facility-84 lane miles
• 5 seasons
• 2.73x10^4 kg Cl/lane mile
• 2.73x10^4 kg Cl/lane mile year
• Applied to I95 in study area

Town Rate
• Dedham Facility-110 lane miles
• 1 season
• 1.37x10^4 kg Cl/lane mile year
• Applied to Town roads in study area

WL#5 Cl Balance-Town/State Attribution

• Town contributes 6.0x10^4 kg Cl/yr towards WL#5, as areal source (“country drainage”) distributed over NW quadrant, diluted, low strength flux

• State contributes 1.32x10^5 kg Cl/yr in NW through linear source (closed I95 drainage system) in NW quadrant, concentrated flux (not much water)

• Remaining quadrants 25% conservatively (from Town’s point of view) assigned to the State

22% Town/78% State contribution of salt towards WL#5
Pavement vs Weir Concentrations

**Pavement**
- Applied mass/annual volume
- Volume = ppt * lane miles
- ppt = 45.3 "/yr
- \( c_{\text{PAVEMENT}} = 3,700 \text{ mg CL/L (State)} \)
- \( c_{\text{PAVEMENT}} = 1,800 \text{ mg CL/L (Town)} \)

**Weirs**
- \( c_{\text{I95}} = 1,400 \text{ mg/L (freeway) dilution factor of 2.6, focused, closed drainage source} \)
- \( c_{\text{Canton}} = 426 \text{ mg/L (commercial) dilution factor of 4.2, intermediate behavior} \)
- \( c_{\text{Calvin}} = 171 \text{ mg/L (residential) dilution factor of 10.5, distributed in the recharge} \)

**And The Weir Concentrations Are Measured**
- Fifteen minute sampling interval-onsite ppt gage
- Telemetry via dedicated cell phone lines (can you hear me now? $$)
- Significant events without mobilization
- Specific conductivity a useful surrogate for deicing agents (major ions)
- Monthly average concentrations (advective chloride flux/water flux)
Measured vs NW Mass Balance Concentration

Town Contribution

$6.03 \times 10^4 \text{ kg Cl/0.25Q}=208 \text{ mg Cl/L (Mass balance)}$

$c_{\text{Calvin}}(171)<208<c_{\text{Canton}}(426 \text{ mg Cl/L})$

Town contributes high Q, low c runoff to WL#5 (open drainage)

State Contribution

$c_{95}=1,400 \text{ mg/L (weir) vs maximum } c_{\text{DEEP}}=854 \text{ mg/L (MW3D)}$

Closed drainage system into upgradient (westerly) recharge area
Lateral input to Aquifer, little gw dilution, not local leakage through aquitard

Year II Conclusions-Aquitard Hydraulics and Aquifer Transport

- Neponset River aquitard protects WL#5
- 10 m thick, cascade calibration
- $10^{-17}\text{(large scale)}<k'<10^{-13}\text{ m}^2\text{(smaller scale)}$
- $c_{\text{INPUT}}=234 \text{ mg Cl/L approaching WL#5}$
- NW sources, laterally upgradient, not leakage
- 78% State salting and closed drainage system, high concentration, low discharge
- 22% Town salting and open drainage, low concentration, high discharge
References

Bouwer and Rice (1976), WRR 12: 423.
Flint (1971), Glacial and Quaternary Geology, Wiley, NY.
Klinger (1996), WRIR 93-4142, USGS, MA.
Ostendorf and Kilbridge (2009), JNEWWA 123: 238.
Ostendorf, DeGroot, Judge, and LaMesa (2010), Hydrogeol J 18: 595.

Acknowledgements and Thanks for Listening

Massachusetts Department of Transportation Highway Division--ISA 56565

Dedham Westwood Water District
Consultant KGS

Views and opinions are those of the Authors, and do not necessarily reflect MassHighway or DWWD official views or policies. The talk does not constitute a standard, specification, or regulation

Questions??