The Behavior of Sub-Surface Oil Plumes, in the Real World . . .

and Some Practical Observations on How to Manage Them

LNAPL Seminar

HDOH

April 26, 2013

Pat Hughes

Chevron Energy Technology Company

Site Assessment and Remediation Team

Outline

- **Summary and Key Points (#1)**

- **Introduction / Background**
  - What we'll focus on . . . . And what we won't focus on
  - How we got ourselves into this sort of trouble? ["LNAPL: The Early Years."]
  - Both the "good news" and the "bad news"
  - Define a few terms ("wettability" and "residual NAPL")
  - Some simplifying assumptions we'll make
  - Sand tank studies
  - Introduce our "case study" site

Outline

- Summary and Key Points
- Introduction / Background
- Processes governing LNAPL behavior in "normal" (i.e. inland, Non-Tidal) aquifers
- Processes governing LNAPL behavior in coastal, Tidally Influenced Aquifers
- How we apply all of this stuff to best manage our LNAPL plumes
- Summary and Implications

Quick Summary and Key Points

1) In the "Early Years", we stumbled quite a bit . . .

2) As we've done more research on the movement of shallow NAPL plumes (delving into the petroleum reservoir literature + new university research) . . . . . AND, as we have gathered more <u>actual data</u> in the field, then our understanding of how shallow NAPL plumes behave, has both evolved and improved.

Quick Summary and Key Points

3) We now have a body of both theoretical work and actual field data, which suggests that NAPL plumes generated by **finite** releases of NAPL, will stabilize over time (i.e. become immobile).

4) For NAPL plumes located in coastal (i.e. tidally influenced) areas, there are some additional factors that help to stabilize these even more quickly.

5) The same factors that cause NAPL plumes (from finite releases) to stabilize, also inhibit our ability to continue recovering the NAPL, once NAPL saturations in the plume have dropped below "residual" NAPL saturation" levels.

What we'll focus on . . . and what we won't . . .

We'll focus on . . .

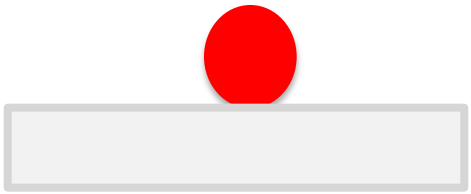
- LNAPLs (both plumes and sheens).
- The normal petroleum hydrocarbons (gasoline, diesel, bunker fuels).
- Granular aquifers (silt, sand gravel, etc.).
- Physical models.

We won't focus on . . .

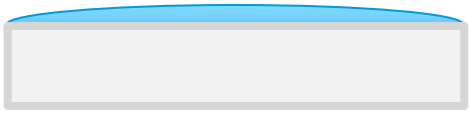
- DNAPLs and dissolved phase plumes.
- Chlorinated hydrocarbons.
- Fractured bedrock / basalt aquifers.
- Mathematical models.

Wettability

- Wettability describes the relative affinity of a given fluid (i.e. air, water, or NAPL), to preferentially spread over a solid surface, (for example, a soil grain).



Non-Wetting fluid



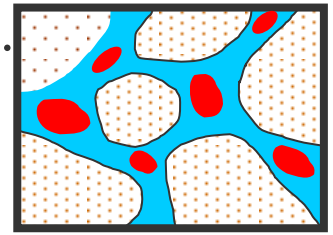
Wetting fluid

From the “API Interactive NAPL Guide”

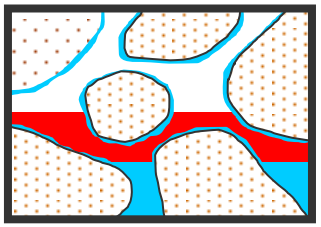
Wettability

1. For "normal" sites:
   a. Water is the wetting fluid with respect to both NAPL and Air
   b. NAPL is the wetting fluid with respect to Air.

2. For a situation where the pore space is filled with a combination of water and NAPL, (Think: the saturated zone), water is the wetting fluid and can therefore move more freely than the NAPL.



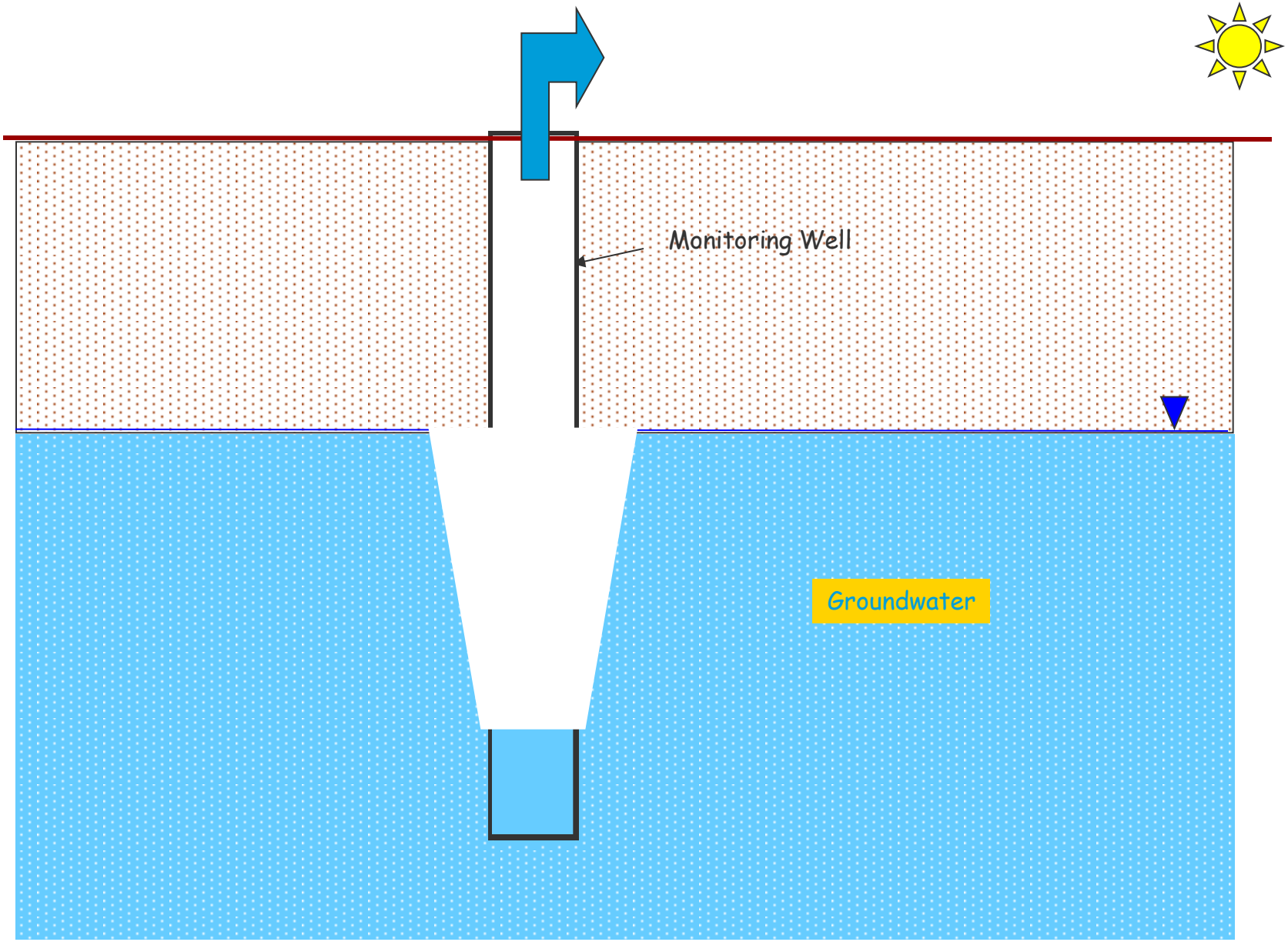
3. For a situation where the pore space is filled with a combination of NAPL and Air, (Think: the unsaturated zone), NAPL is the wetting fluid and can therefore move more freely.



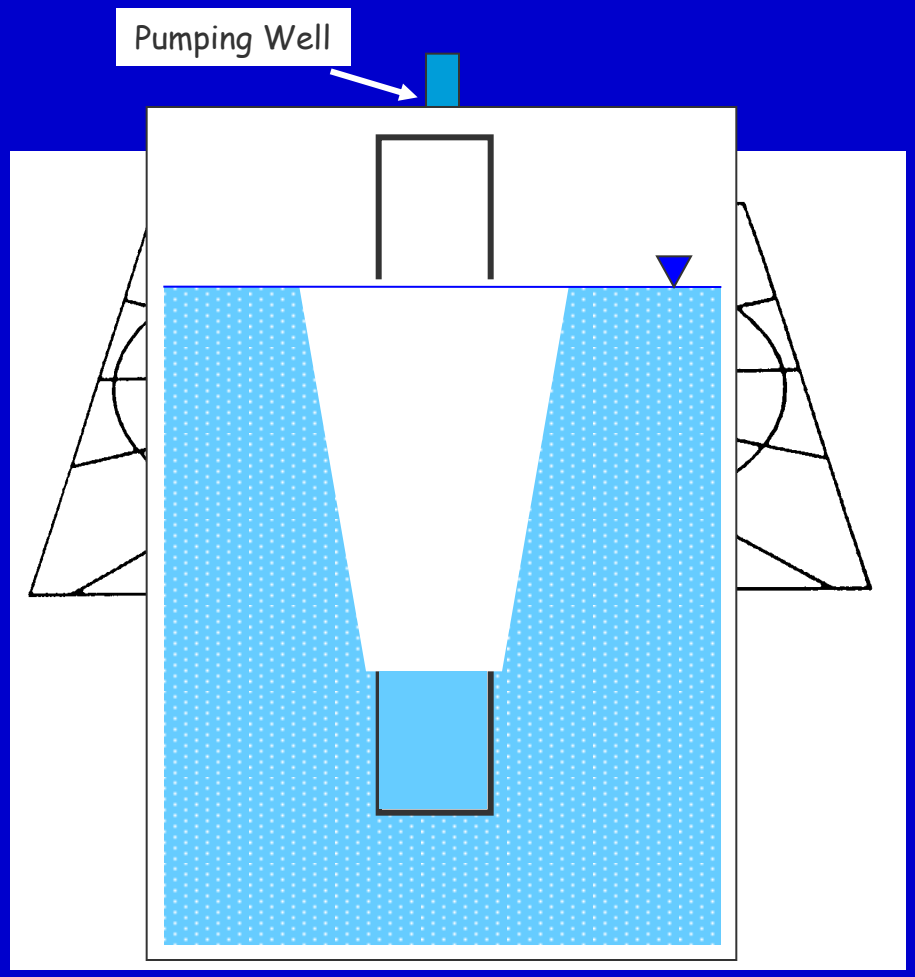
Wettability

For a "3 Phase" system (Water, NAPL and Air):

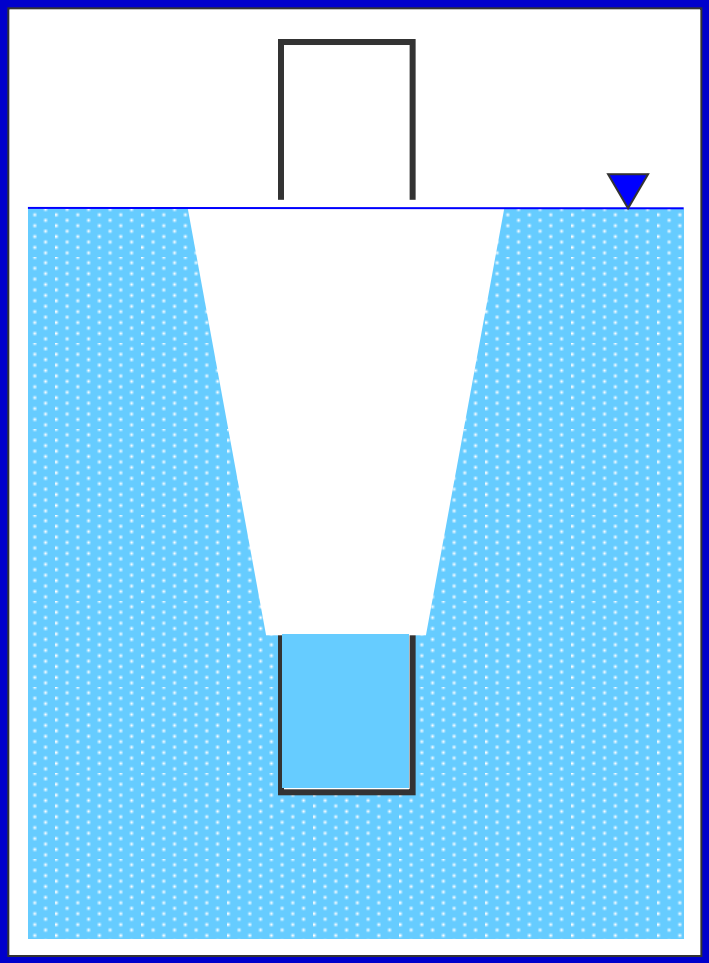
- Water is the wetting phase
- NAPL is the intermediate wetting phase and
- Air is the non-wetting phase

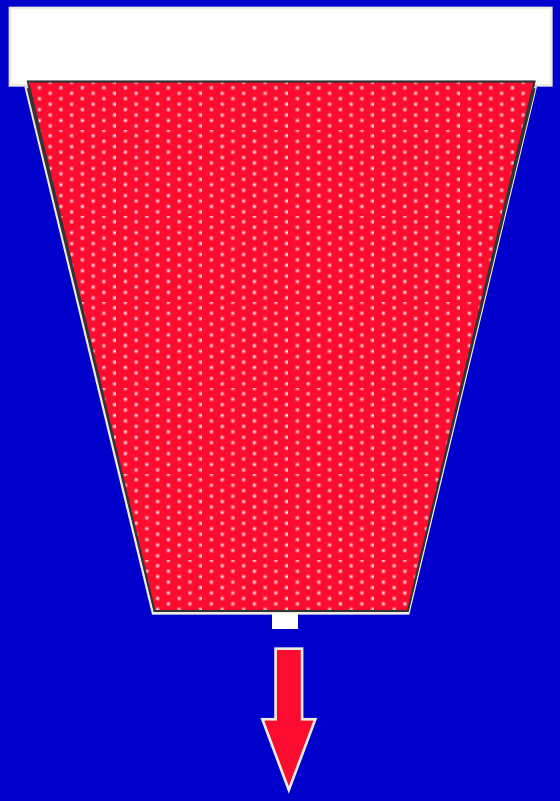

Monitoring Well
Groundwater

General Shape of a Drawdown Cone for a Pumping Well

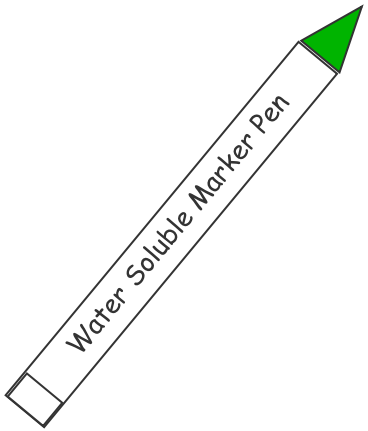


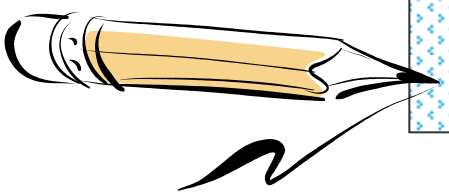
General Shape of a Drawdown Cone for a Pumping Well

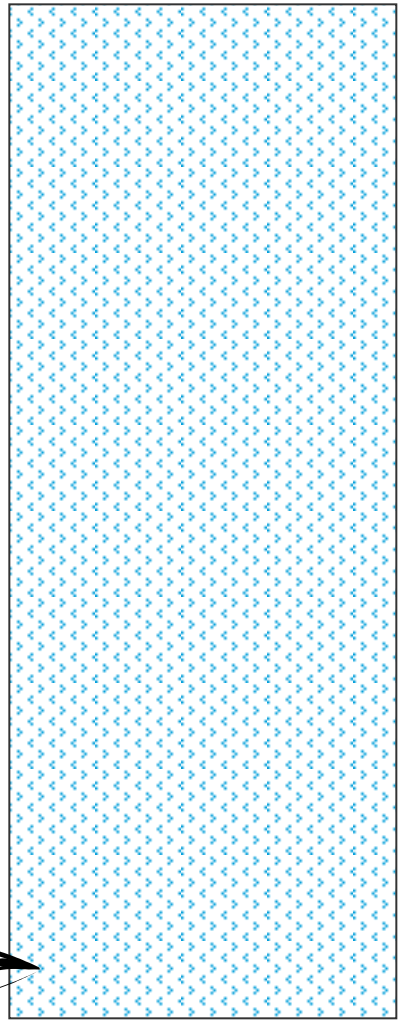




Materials

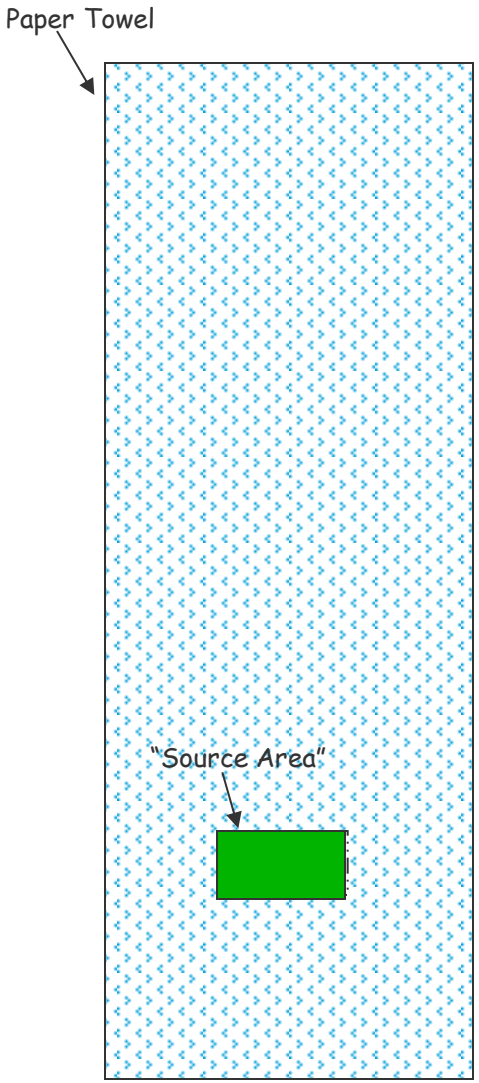






Paper Towel

Container
Of Water



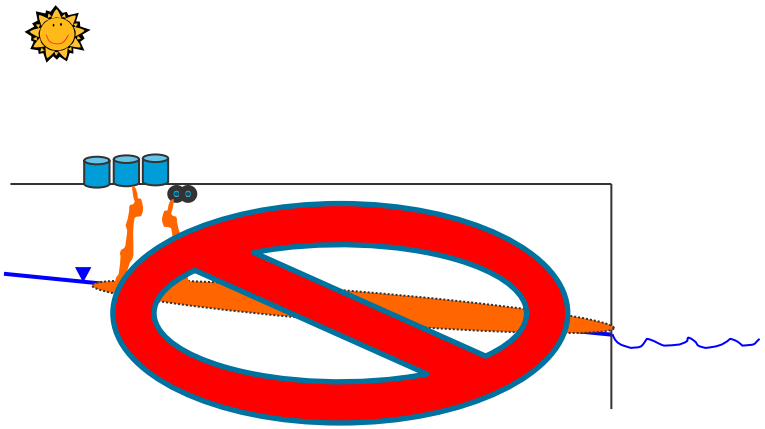
A

A couple of simplifying assumptions for this discussion:

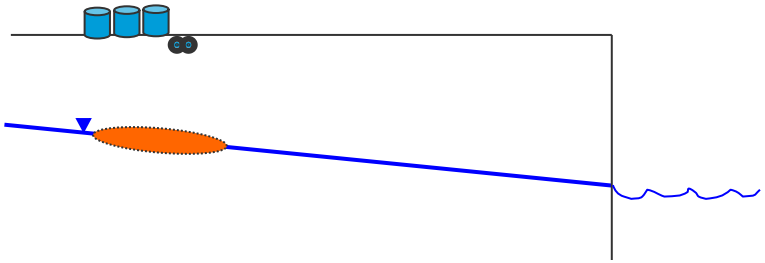
We will be talking about "finite" (rather than continuing) LNAPL releases.

Because of both greatly improved environmental awareness and greatly improved leak detection systems . . . . . .

. . . . . at the vast majority of our current sites, instead of **continuing** releases of LNAPL . . . . .



. . . . we are now dealing with **finite** releases.



The “Scary Version” of the equation:

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)+R=S_s\frac{\partial h}{\partial t}$$

A second simplifying assumption:

We will be using a simplified version of the LNAPL flux equation:

$$a = (b) \quad (c)$$

$$q_n = (k_n) \quad (i_n)$$

NAPL Flow

(Darcy's Law simplified)

$$q_N = K \; i$$

q_N = NAPL flux

K_N = Effective NAPL Conductivity

i_N = NAPL Gradient

K_N = Effective NAPL Conductivity

A measure of how easy it is for this <u>particular NAPL</u> to flow . . .

. . . . through this <u>particular lithology</u> . . .

. . . . with this <u>particular relative (NAPL) saturation</u> . . .

. . . . with these <u>particular other fluids present</u> . . .

NAPL Flow

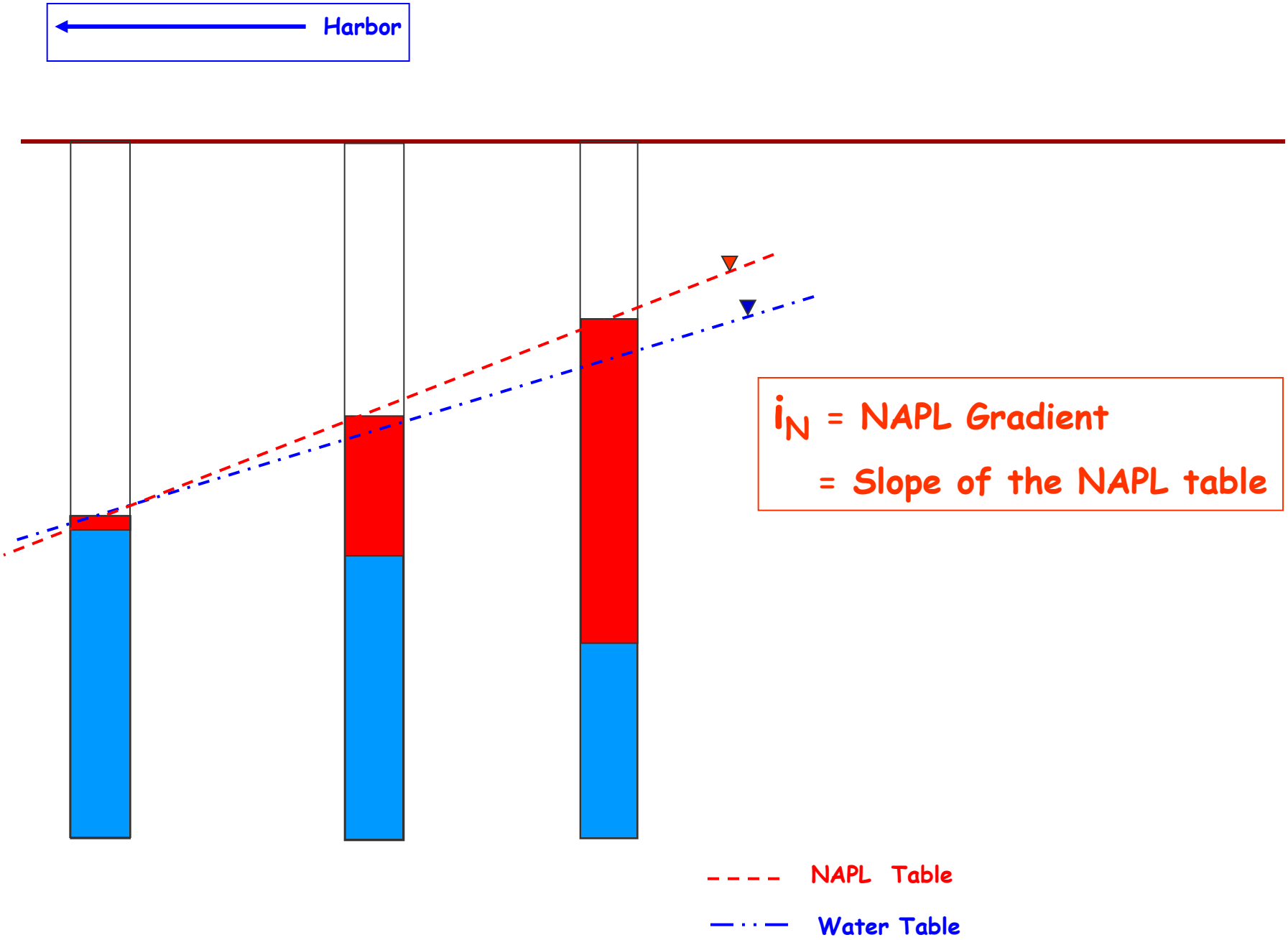
(Darcy's Law simplified)

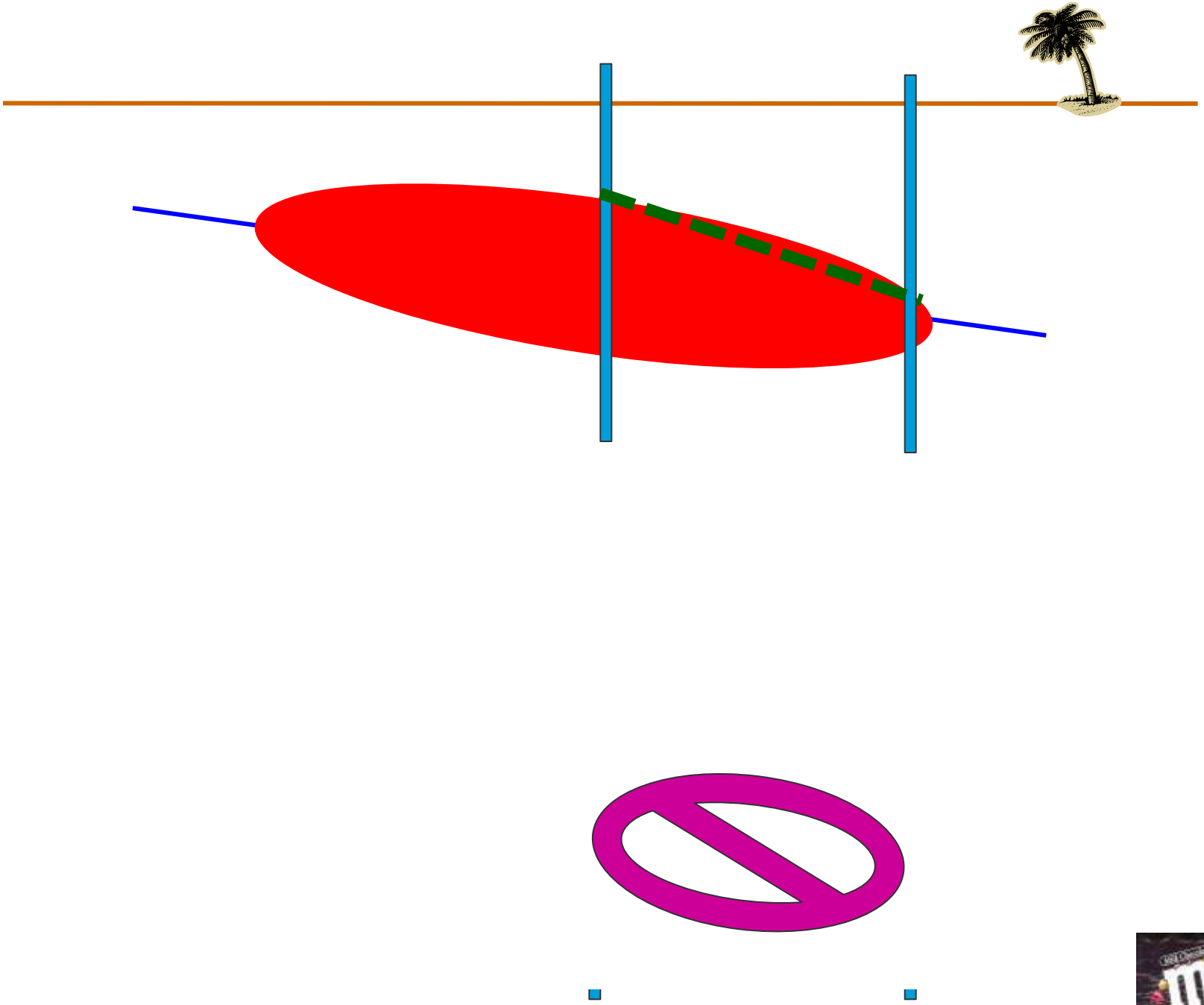
$$q_N = K \; i$$

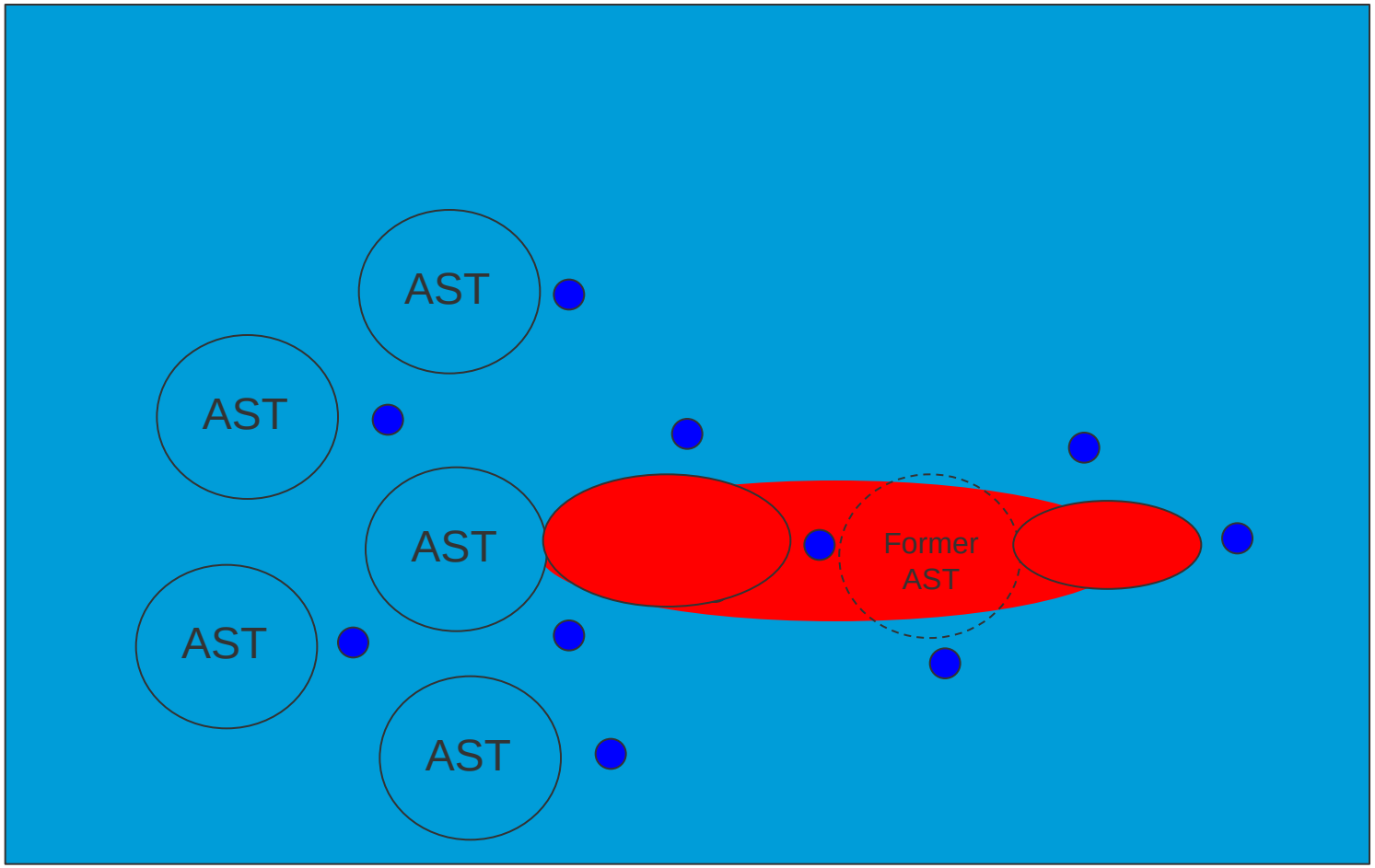
q_N = NAPL flux

K_N = Effective NAPL Conductivity

i_N = NAPL Gradient


Harbor
i_N = NAPL Gradient
= Slope of the NAPL table
NAPL Table
Water Table





MW w/ NAPL

MW w/o NAPL

GW Flow Direction

NAPL Flow
(simplified)

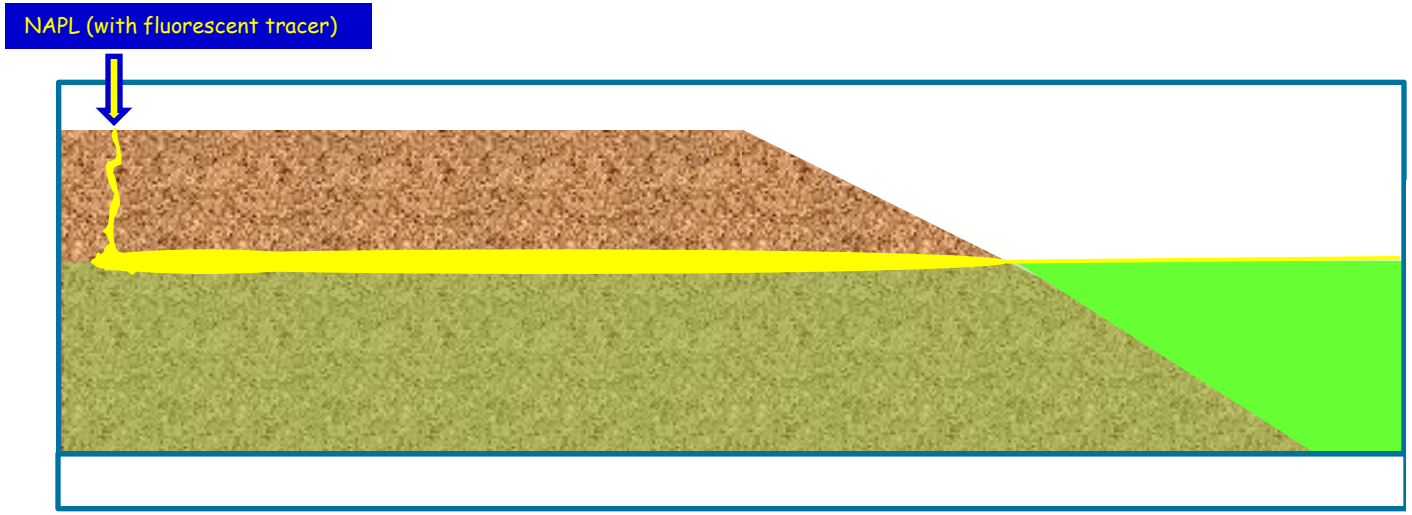
$$q_N = (K_N)\ (i_N)$$

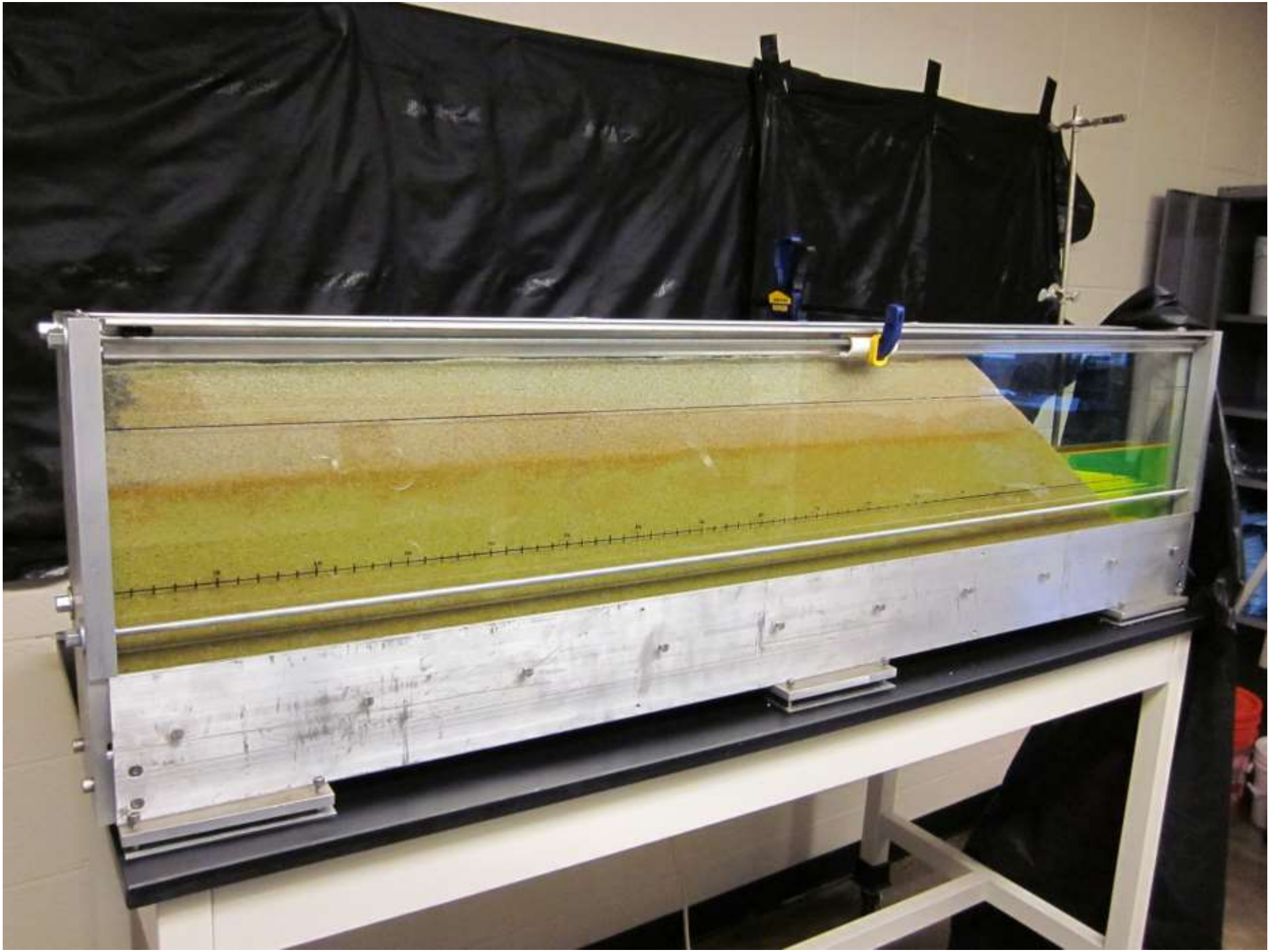
So let's think about
the implications of the this equation . . . . .

During the remainder of today's discussion,
we'll keep coming back to this equation . . . . .

Sand Tank Studies

Sand Tank Experiments





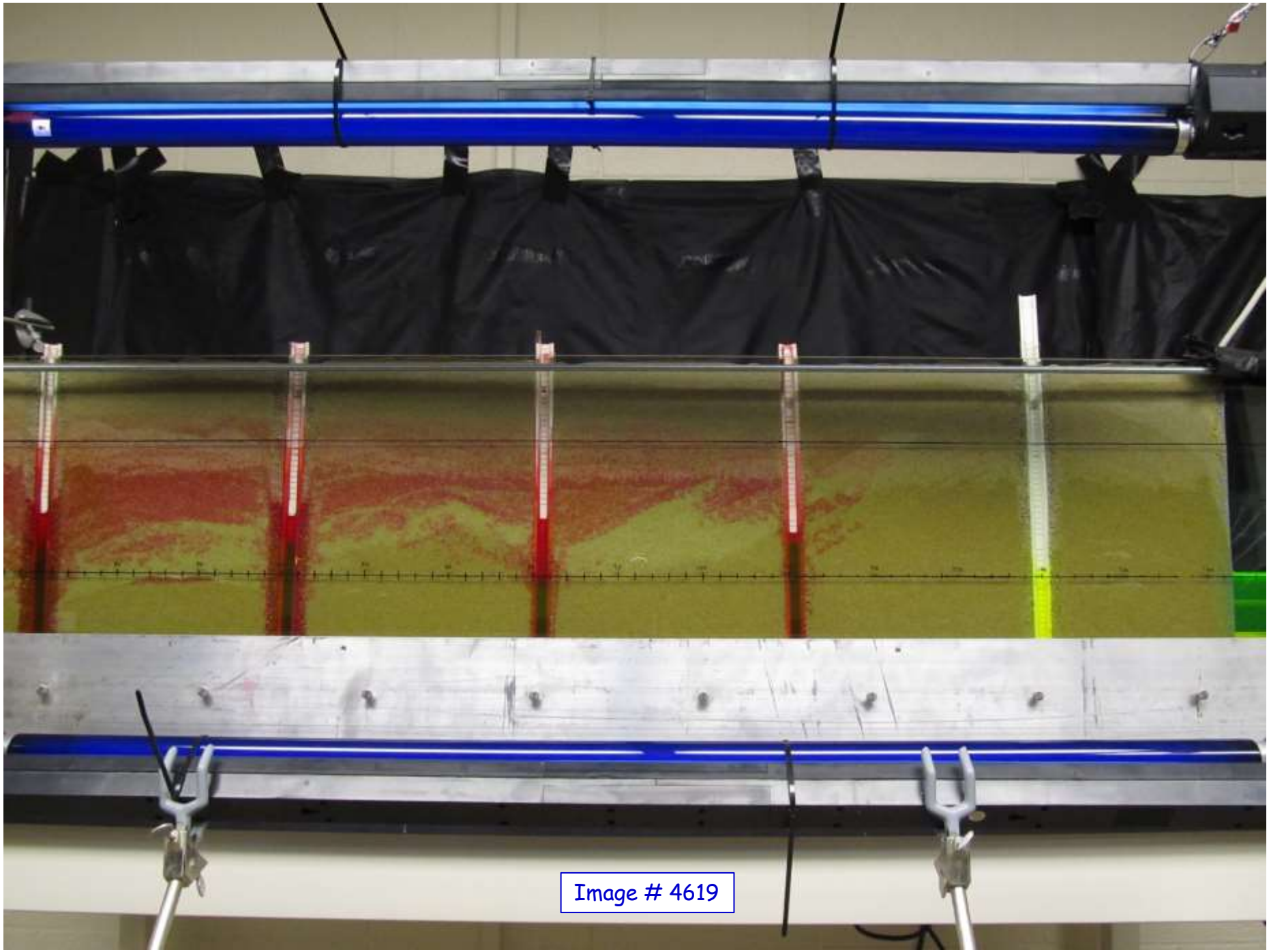
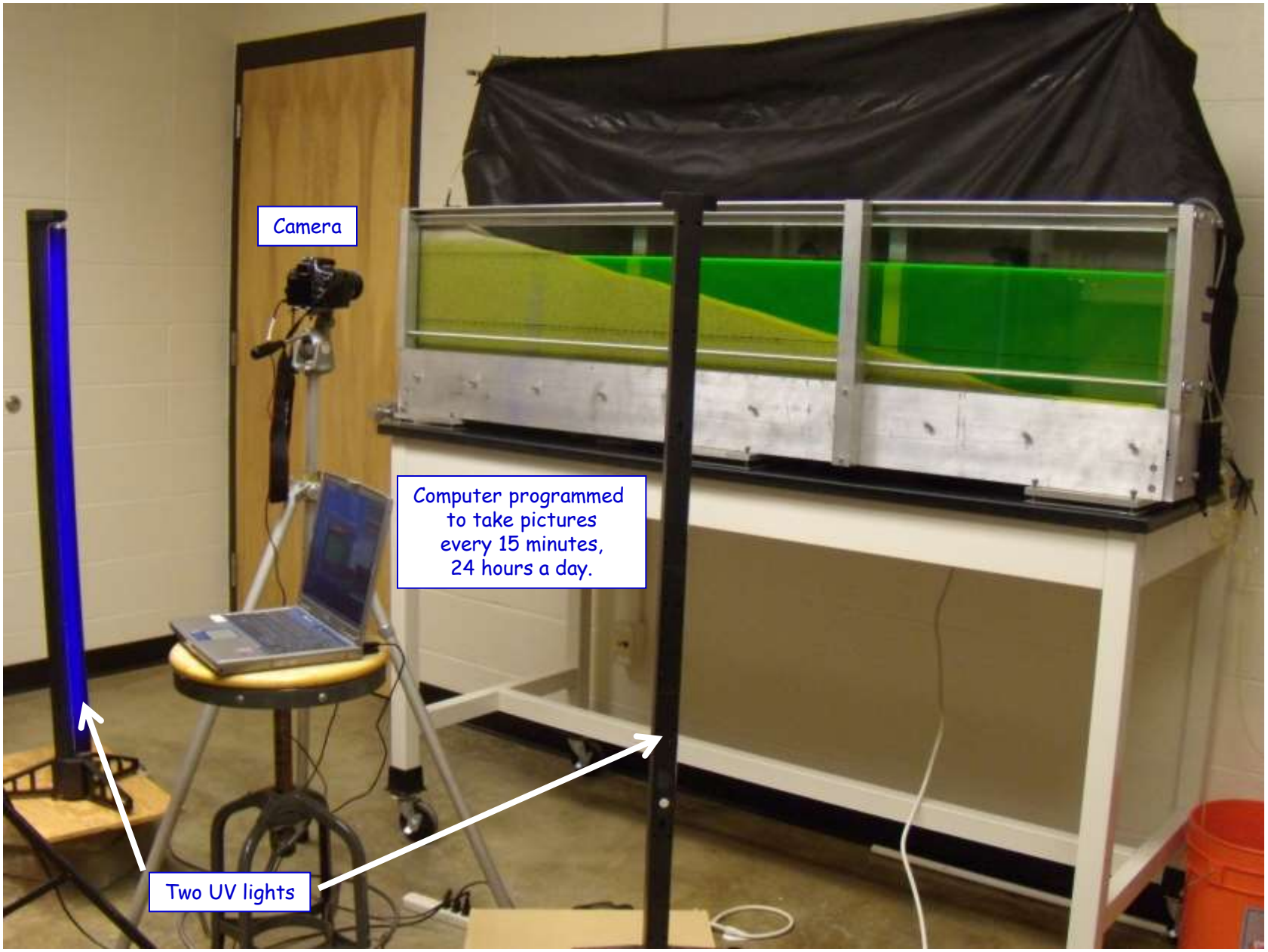
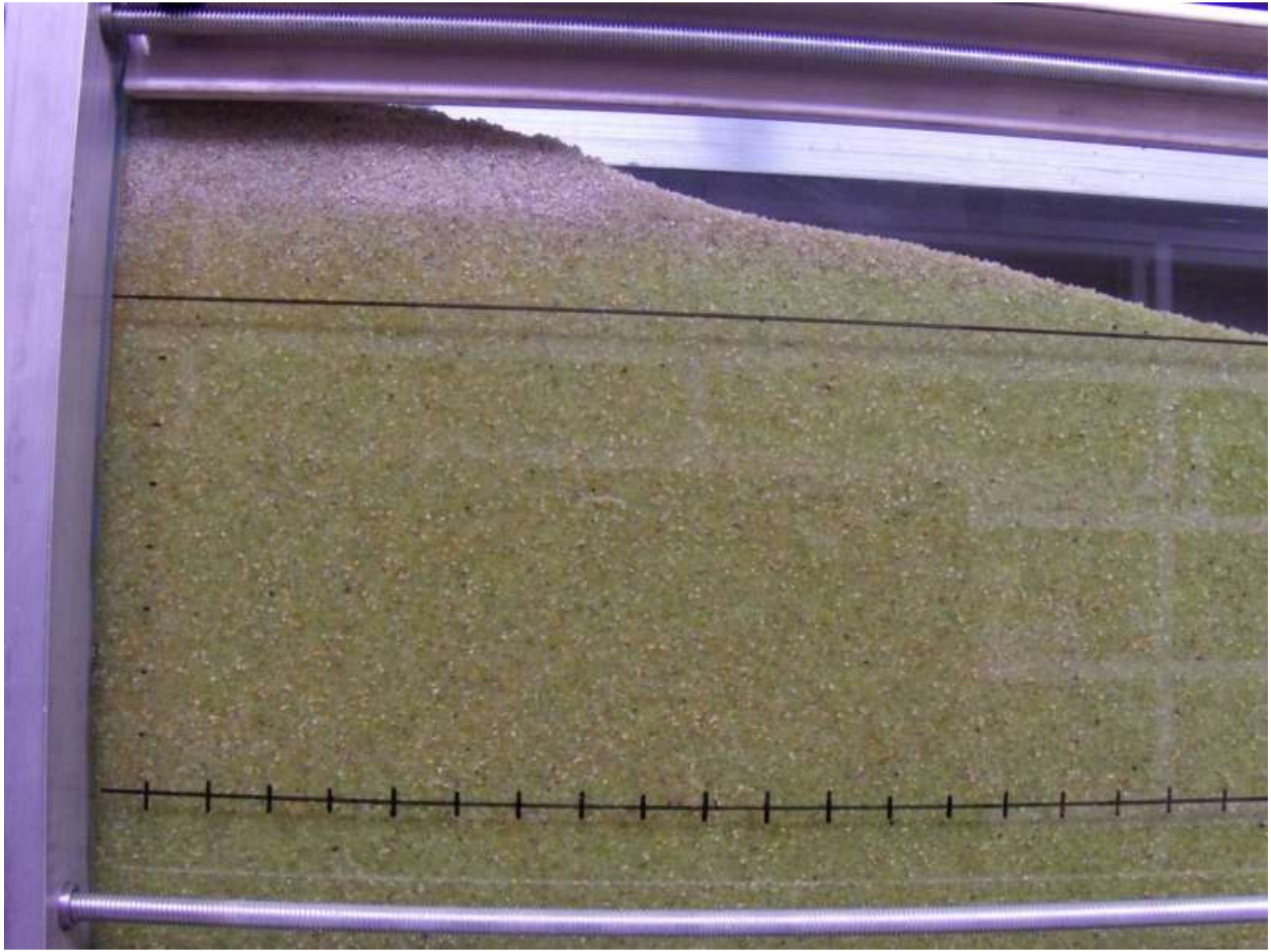


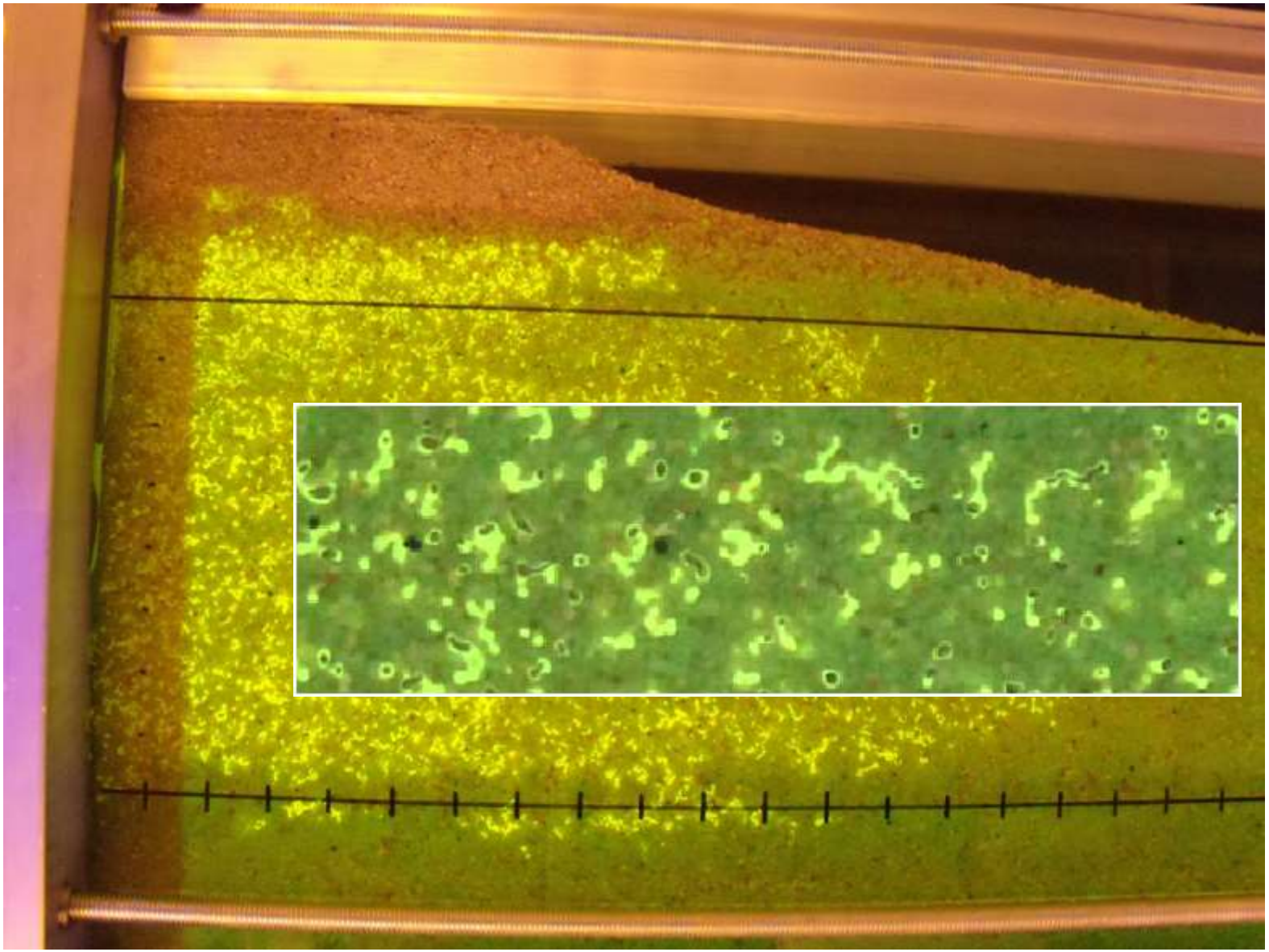
Image # 4619



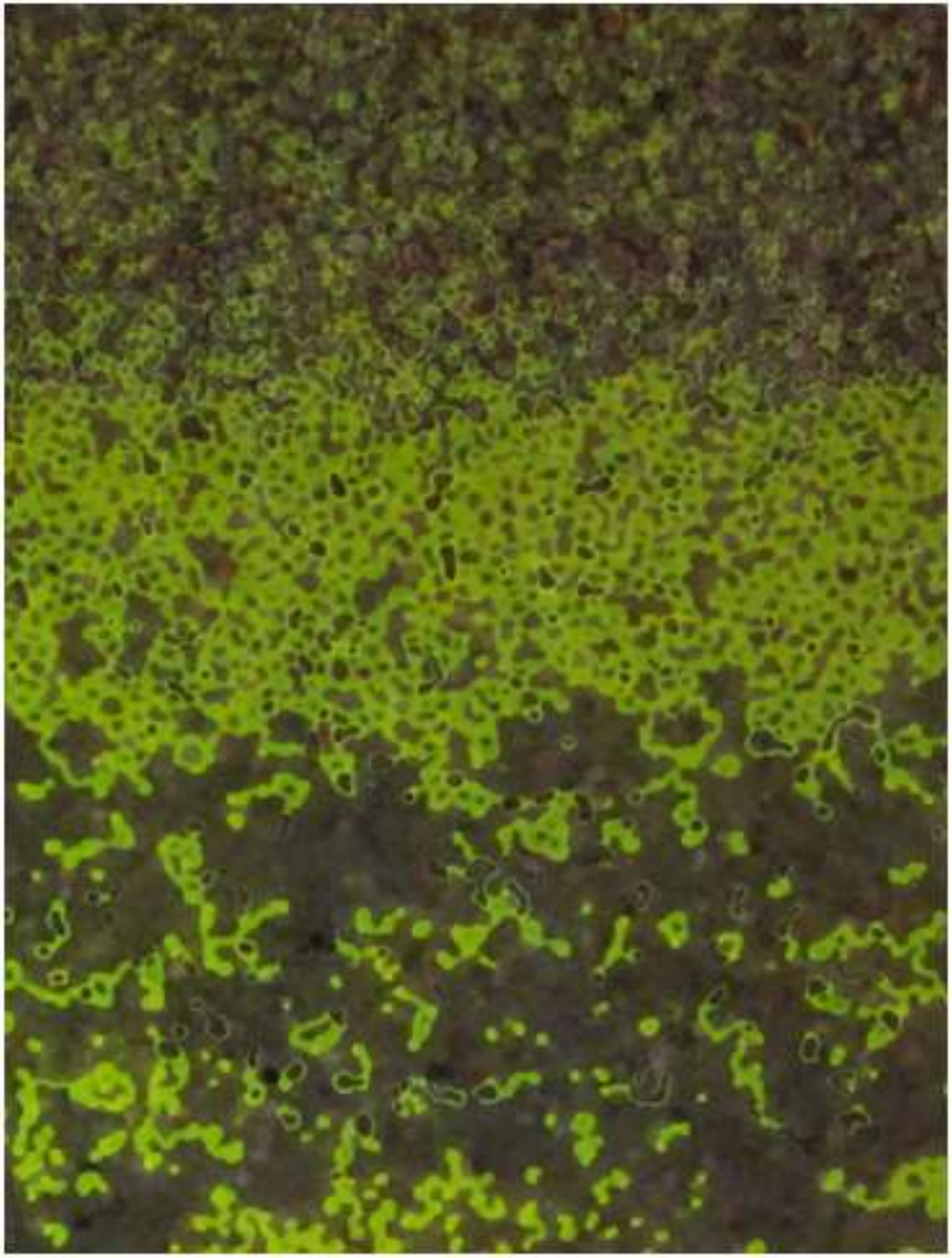
The complete tank set-up (white light).

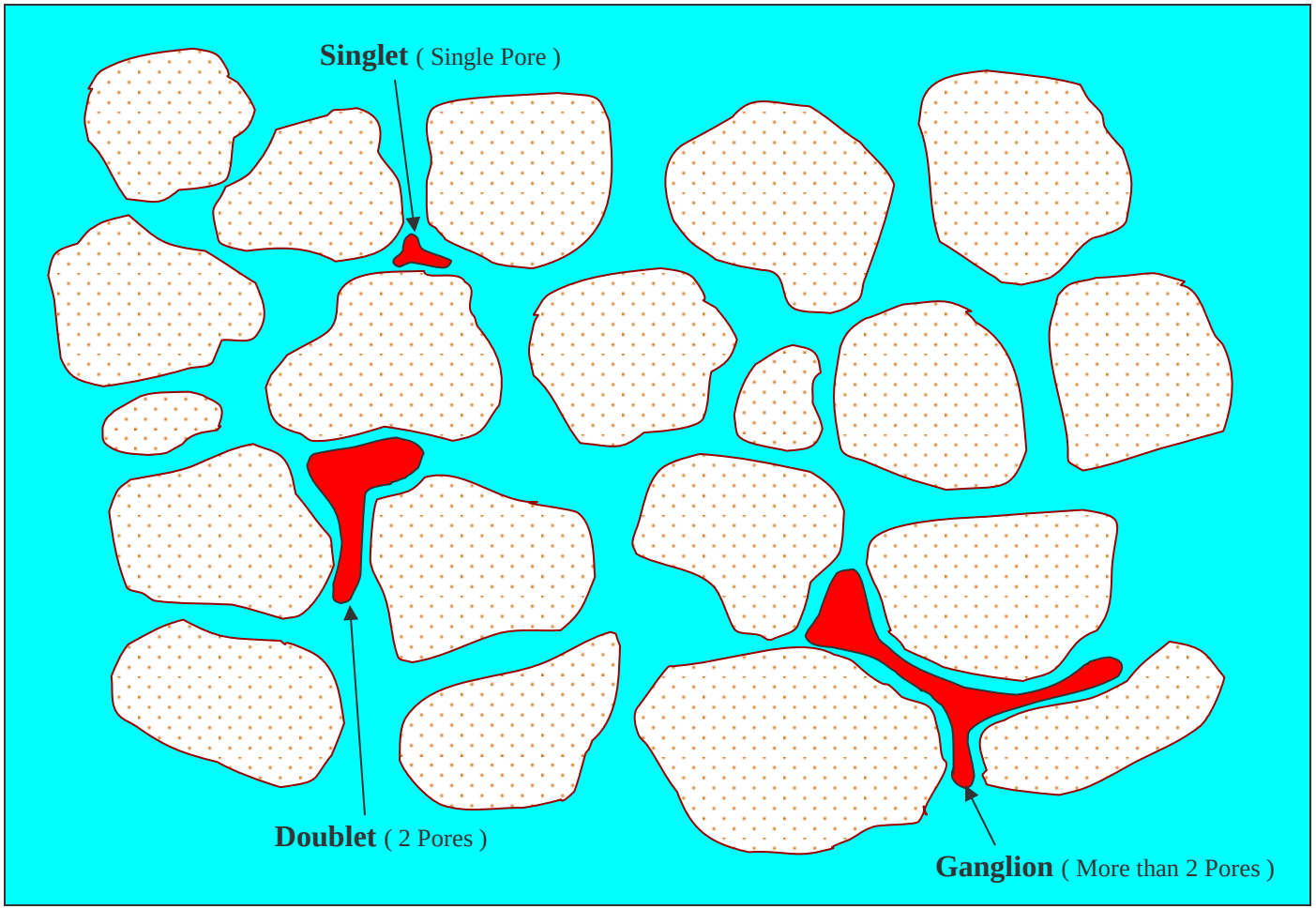


Sand Tank Experiment
Photographed under **White Light**
(the distribution of the NAPL is very difficult to see)



The <u>Same</u> Photograph under **<u>UV Light</u>**
(the distribution of the NAPL (yellow) is much easier to see)

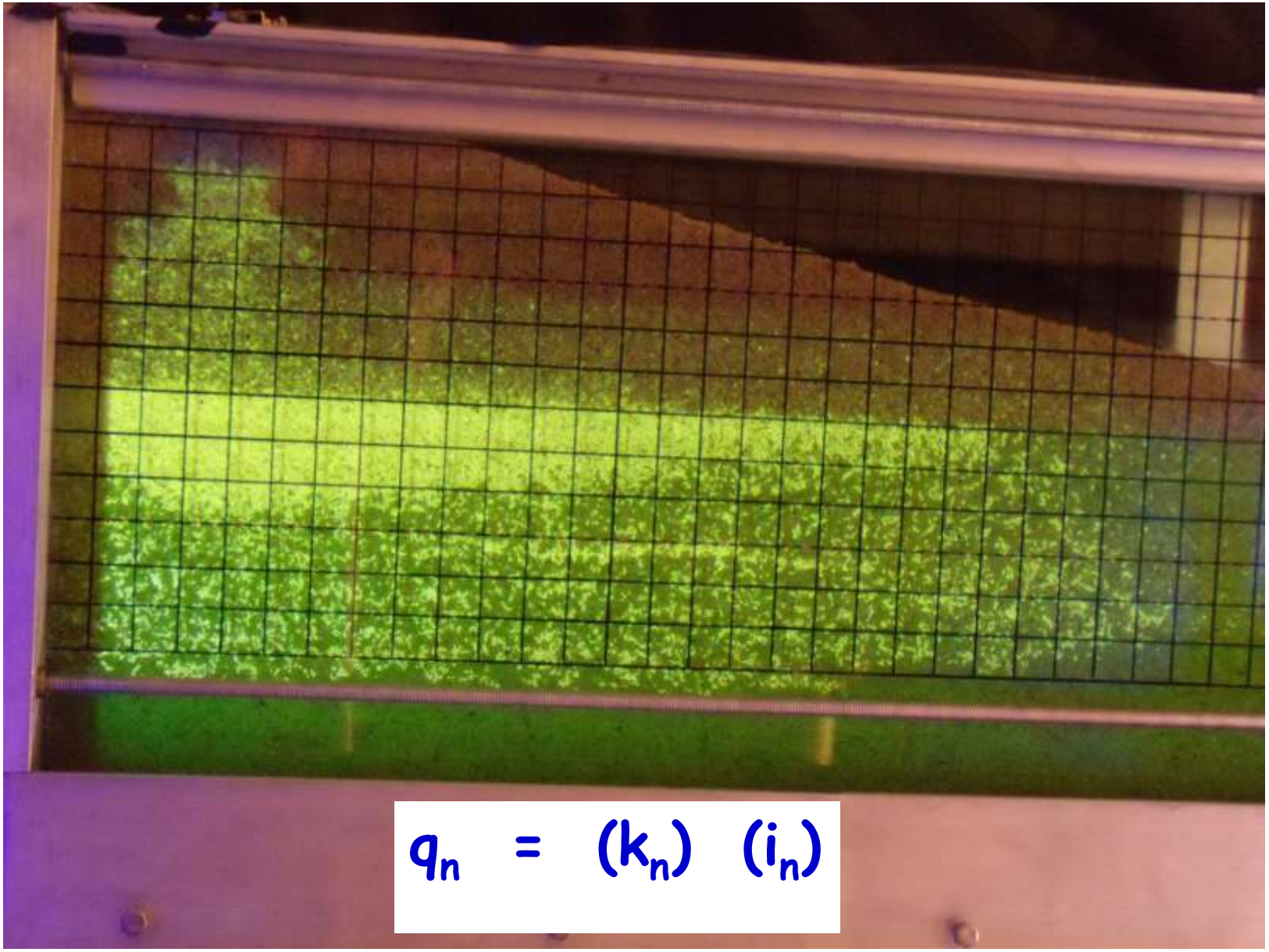




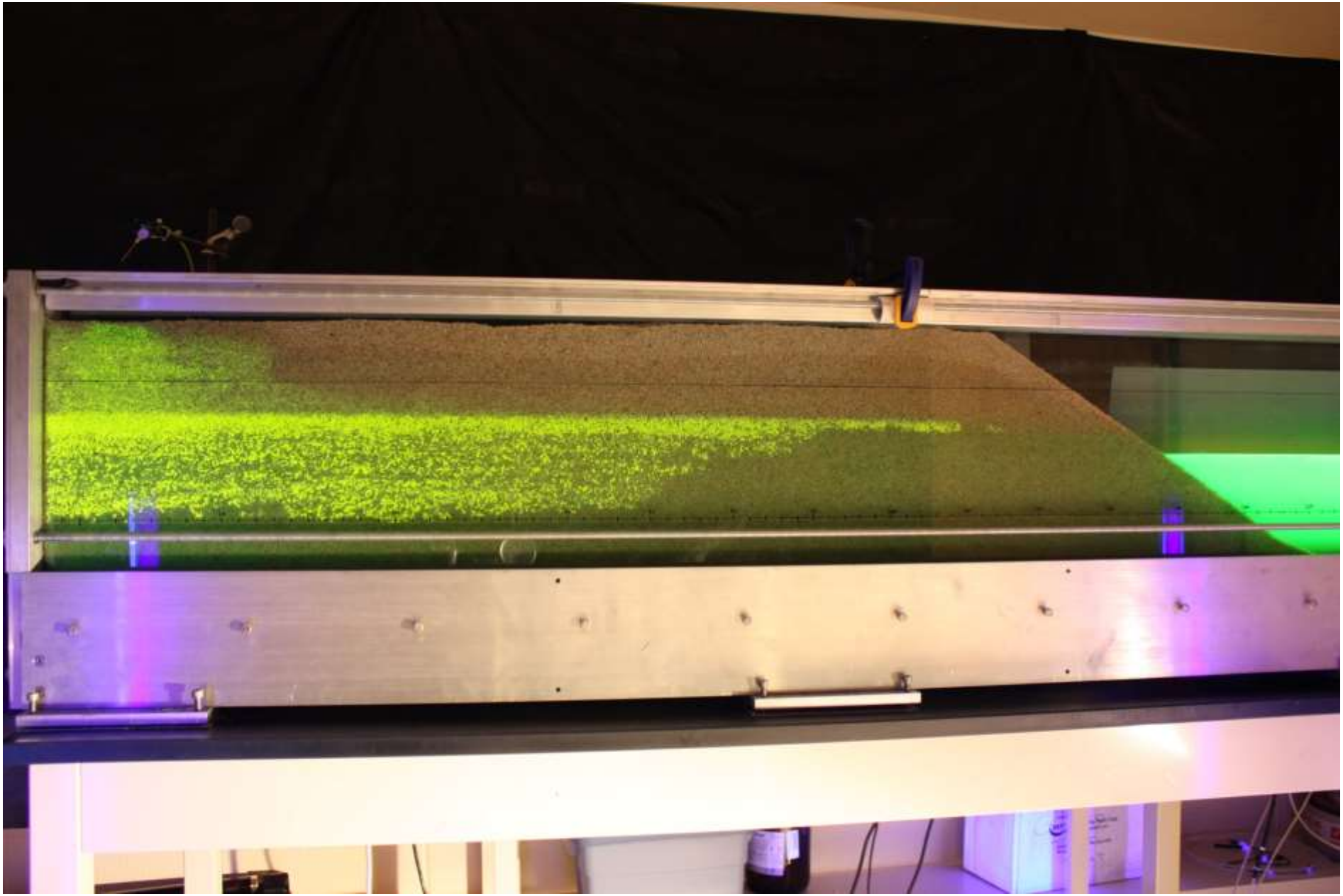
Soil Particle

Water

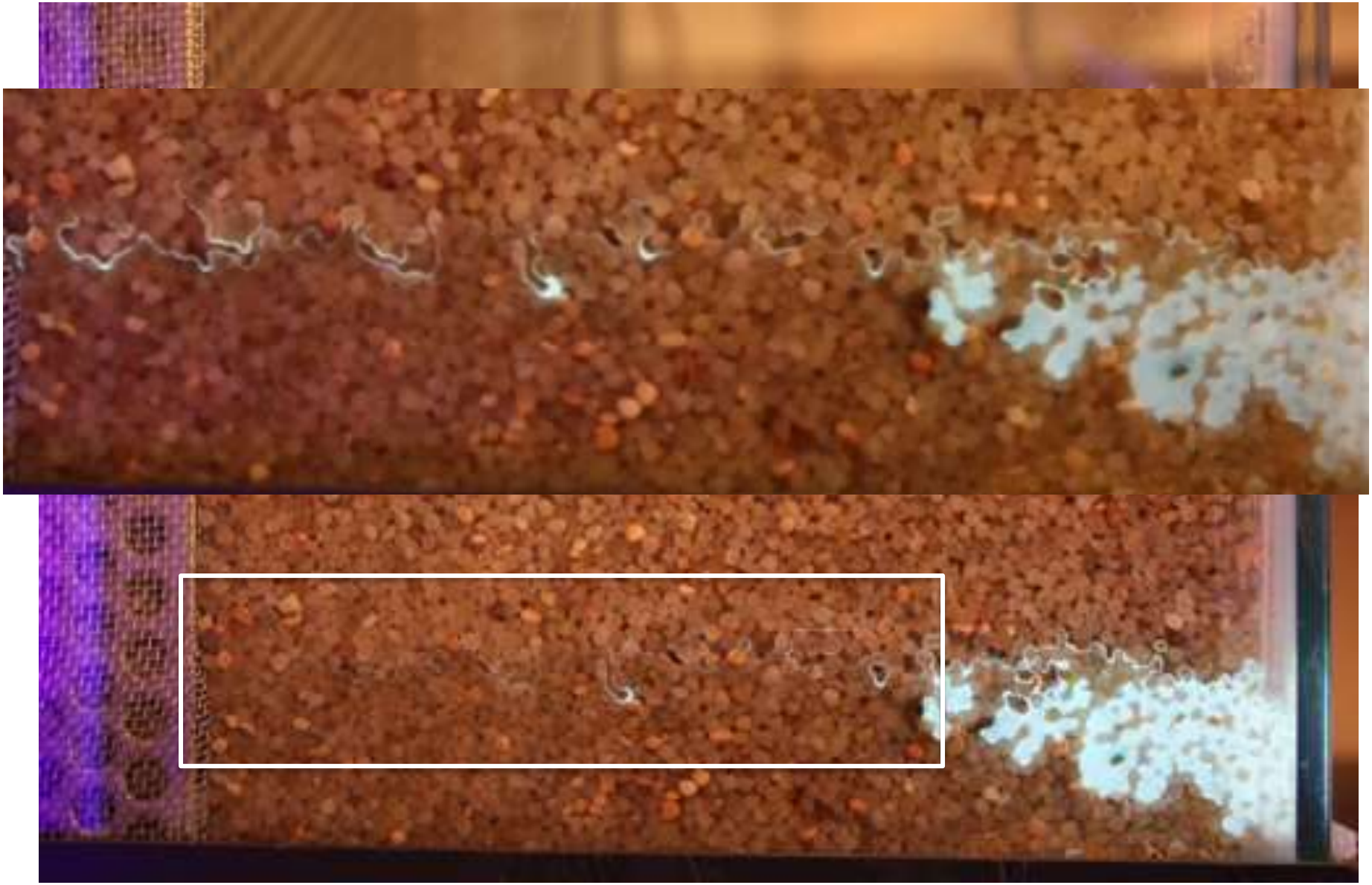
Hydrocarbon



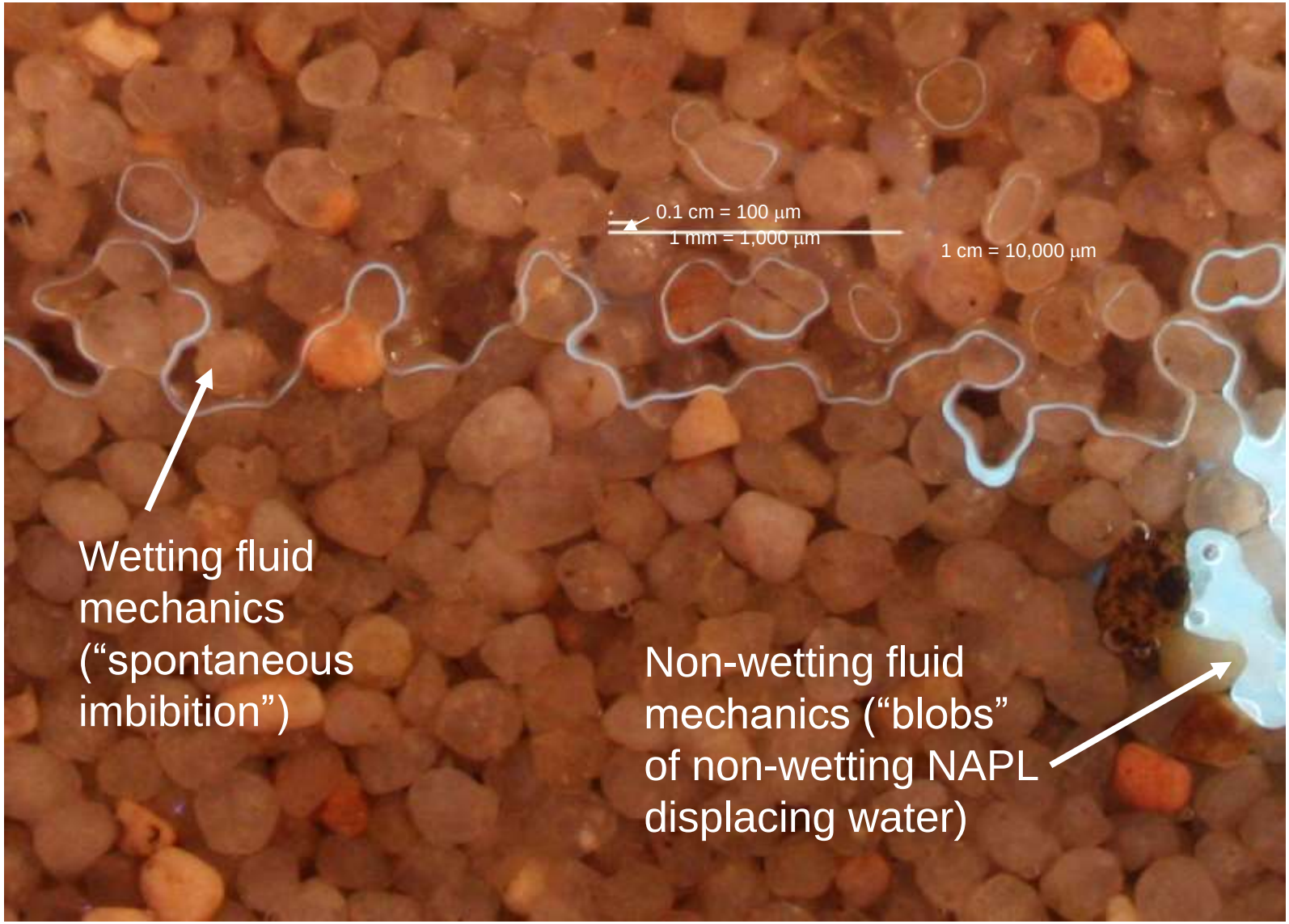
$$q_n = (k_n)\ (i_n)$$

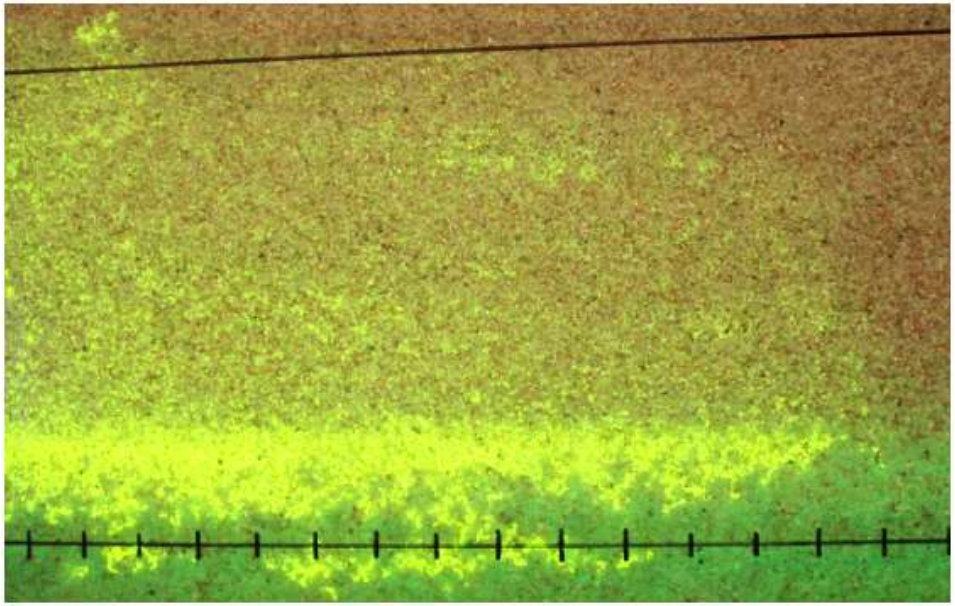


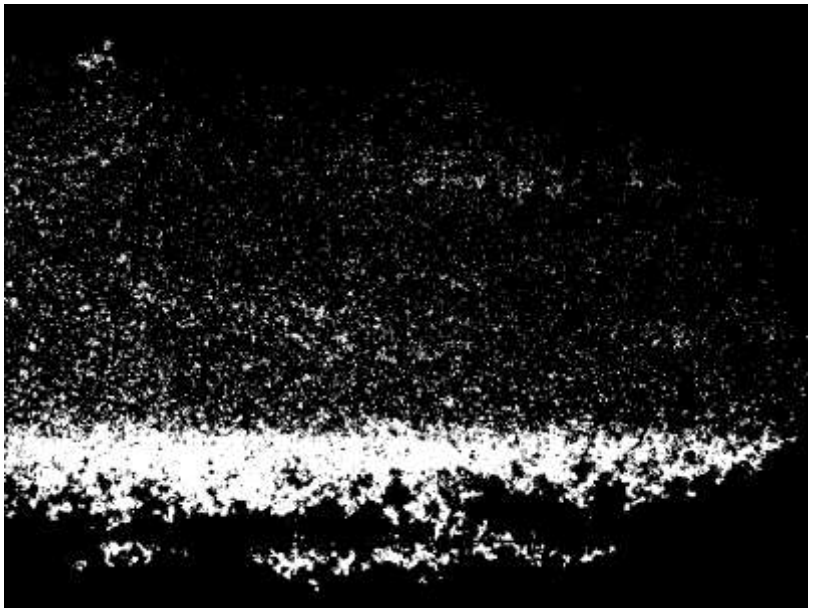
Aquarium Experiments : **Diesel (spreading)**

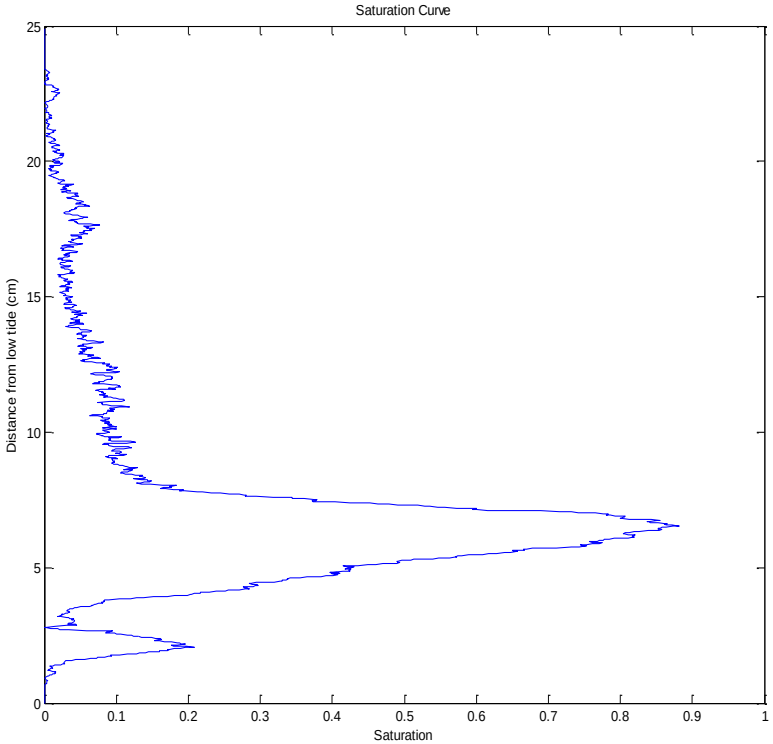


Thin films of spreading NAPL in groundwater are in the order of 10-100 μm



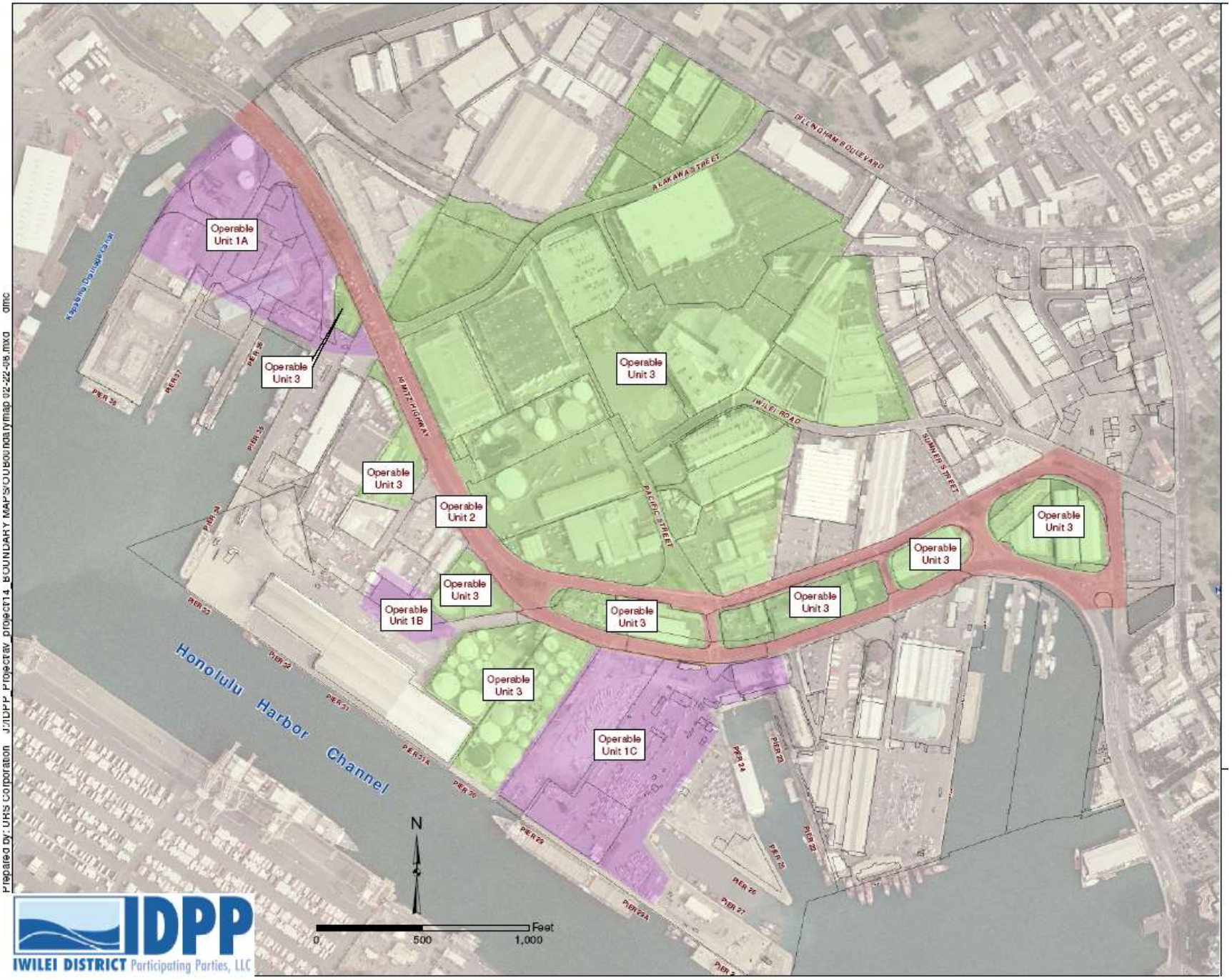






"Digital Imaging"
(using binarization)

Case Study Field Site



Prepared by: URS Corporation J:\IDPP_Project\av_project\14_BOUNDARY MAPS\OUBoundarymap 02-22-08.mxd dmc

IDPP
IWILEI DISTRICT Participating Parties, LLC

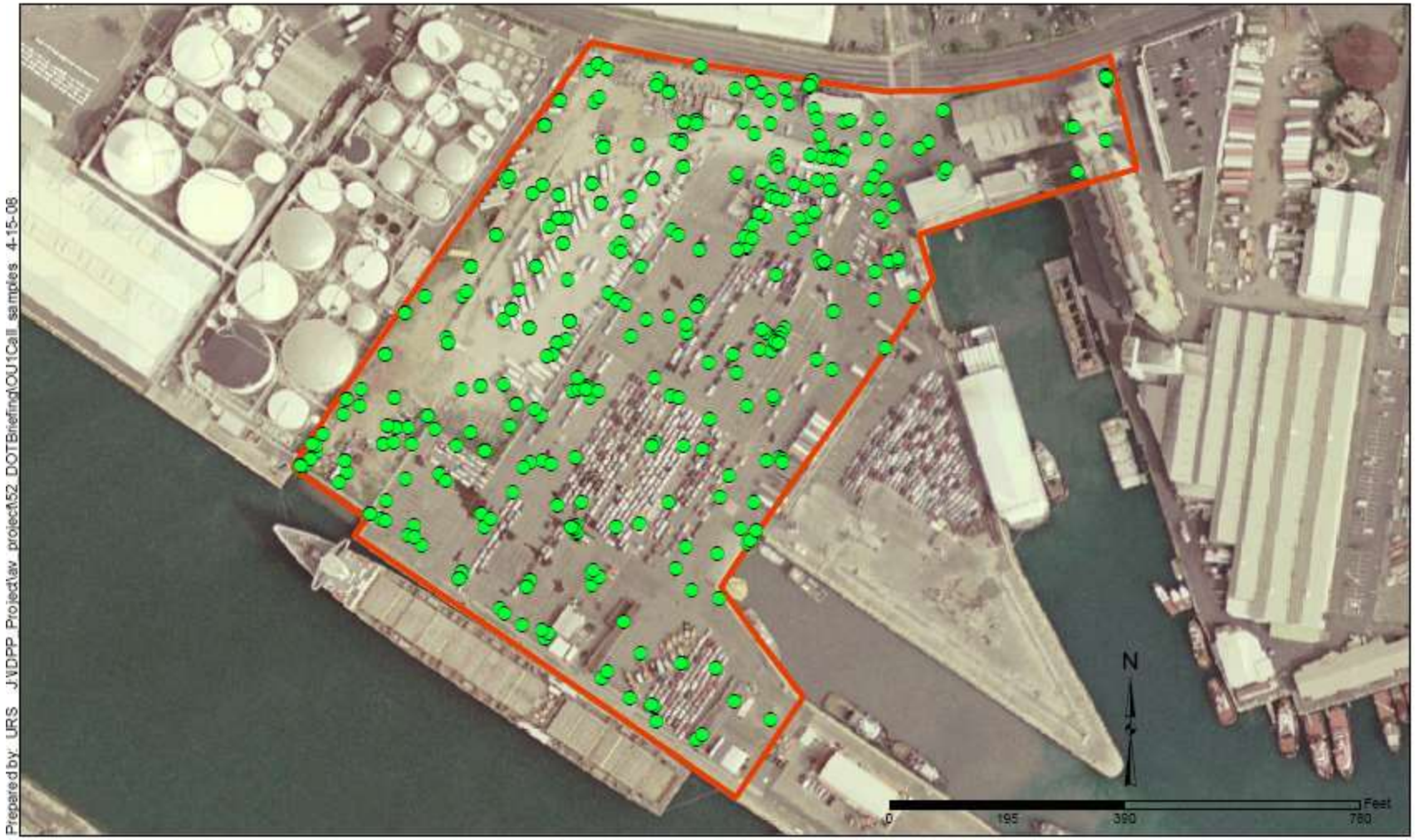

ENVELOPE OF SPH > 0.01 FOOT
ENVELOPE OF SPH > 1 FOOT

Prepared by: URS J:\IDPP_Project\ay_projectM1_OU boundaries\OU1C boundary 11x8.5 4-15-08

OU1C

IWILEI DISTRICT Participating Parties, LLC

Honolulu, Oahu, Hawaii



Prepared by: URS JWDPP Project\av project\52 DOTBriefing\OU1Call samples 4-15-08

OU1C

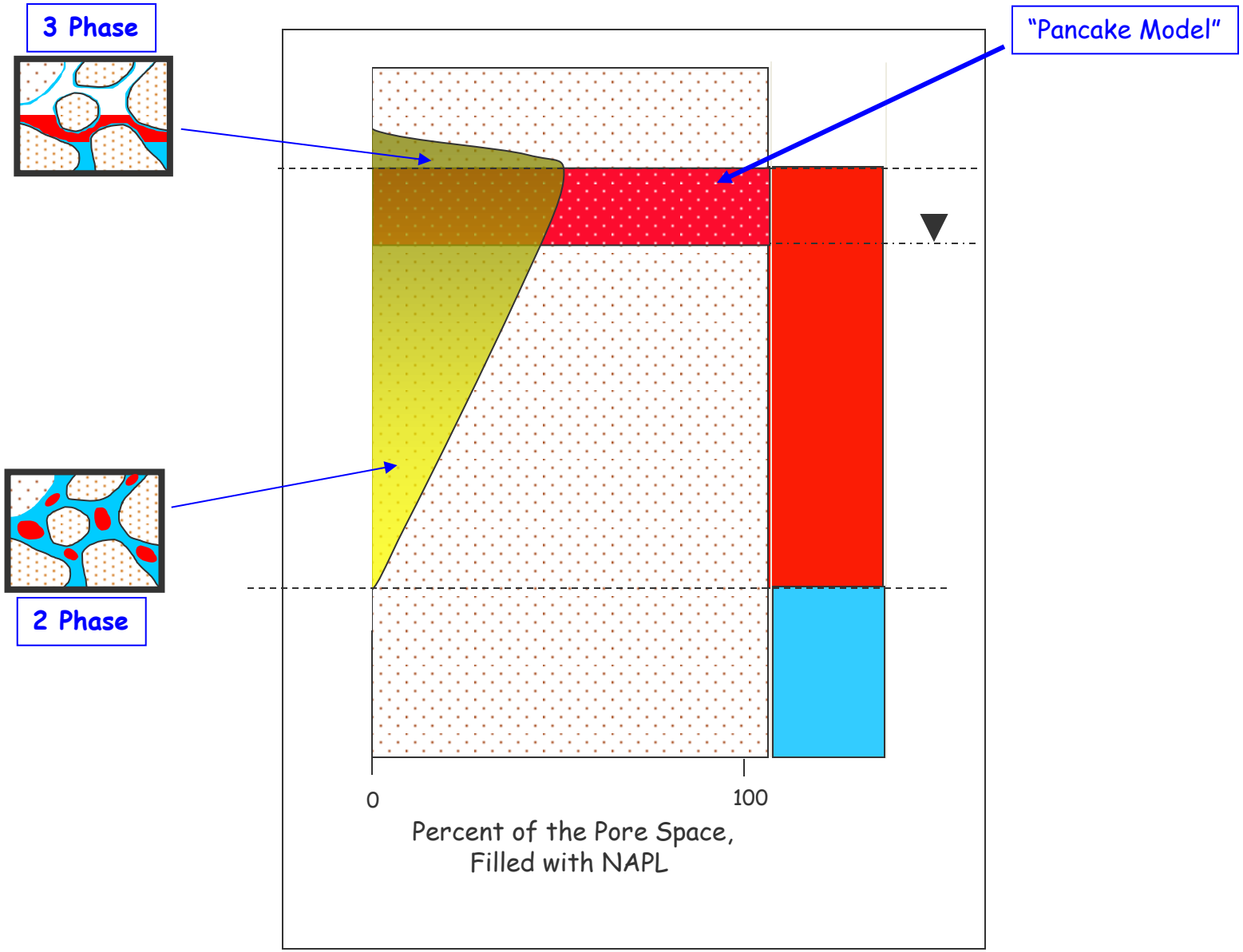
Sample Locations
Honolulu, Oahu, Hawaii

IDPP
IWILEI DISTRICT Participating Parties, LLC

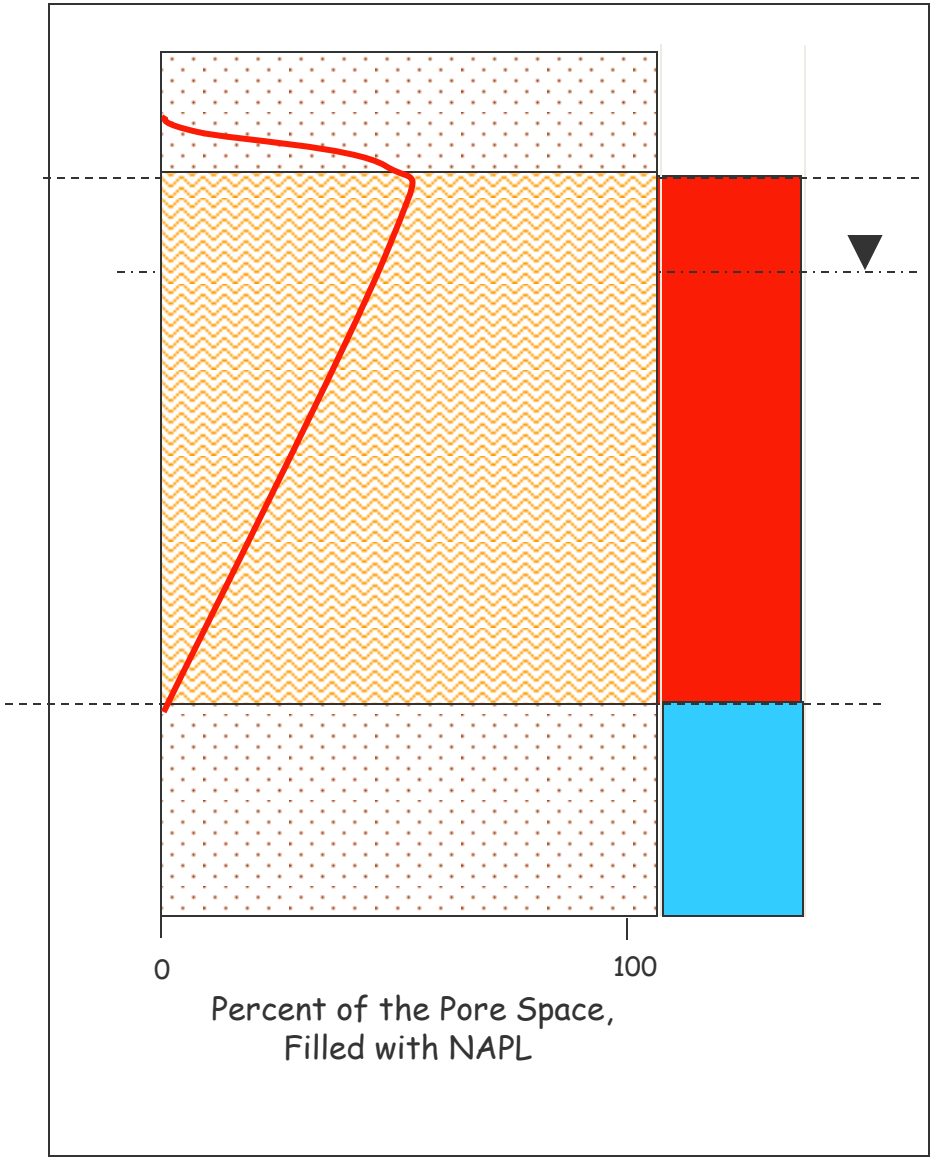
Outline

- Summary and Key Points
- Introduction / Background
- Processes governing LNAPL behavior in "normal" (i.e. inland, Non-Tidal) aquifers

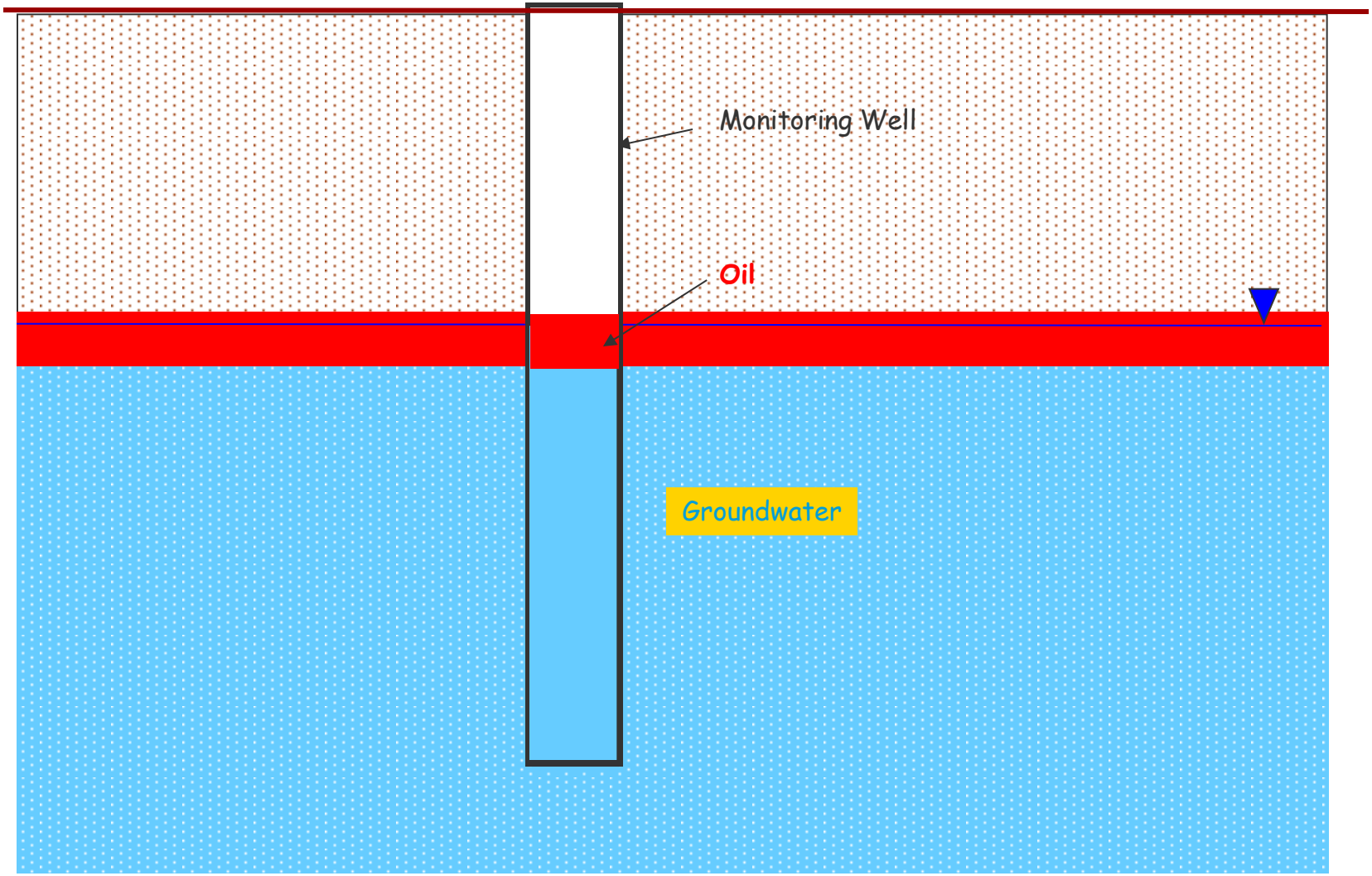
The Distribution and Behavior of NAPL in the Subsurface

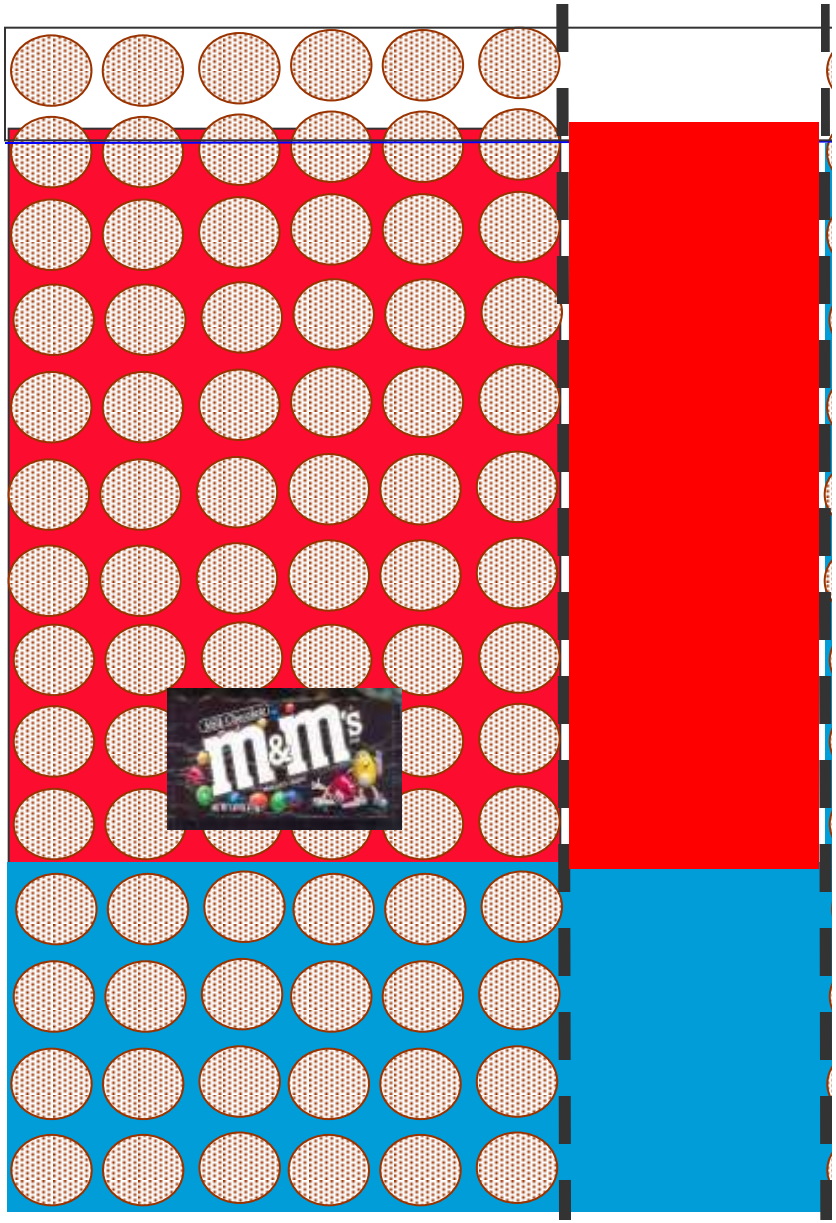


"Vertical Equilibrium Model"



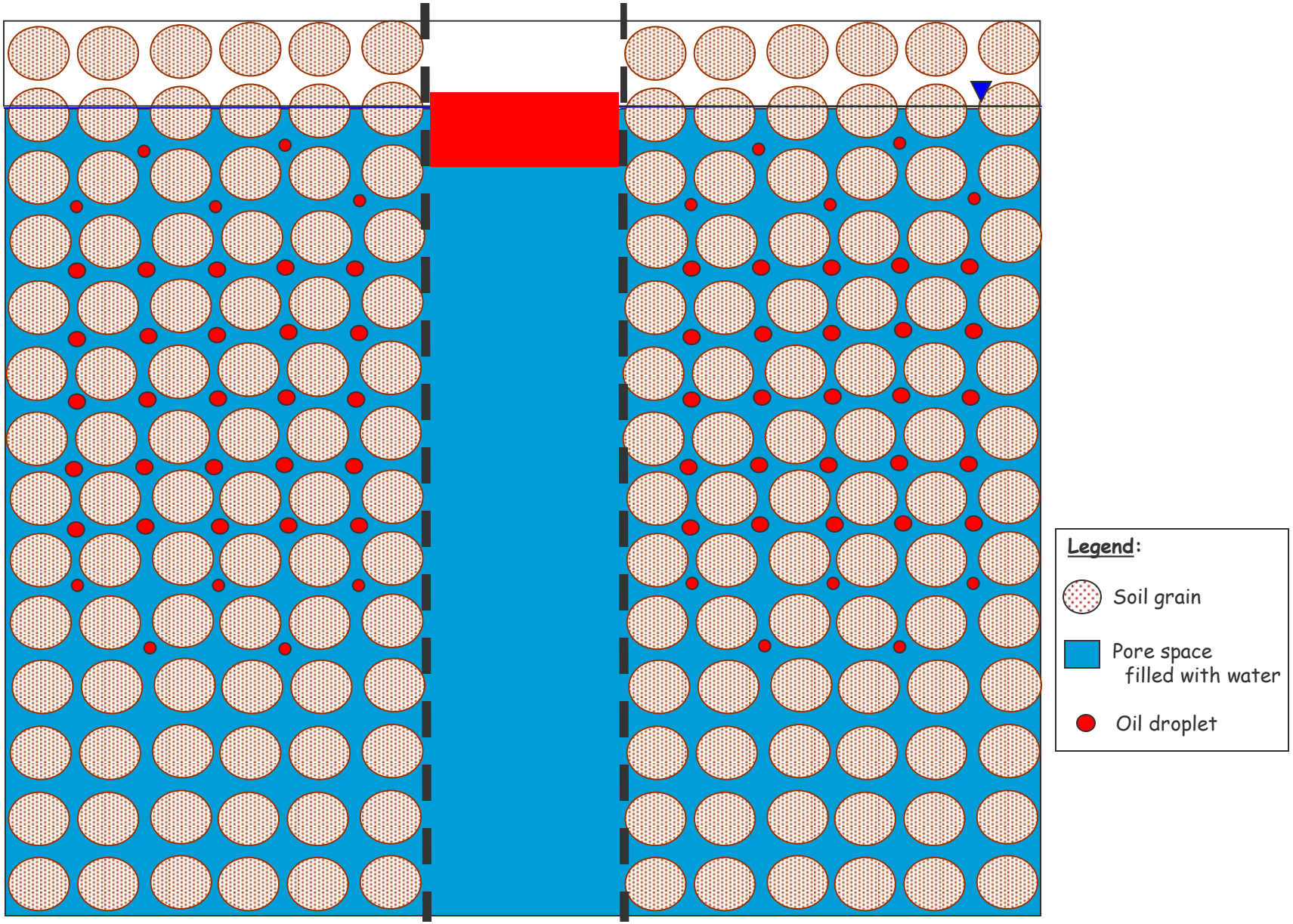
The current model
(assumes vertical equilibrium)

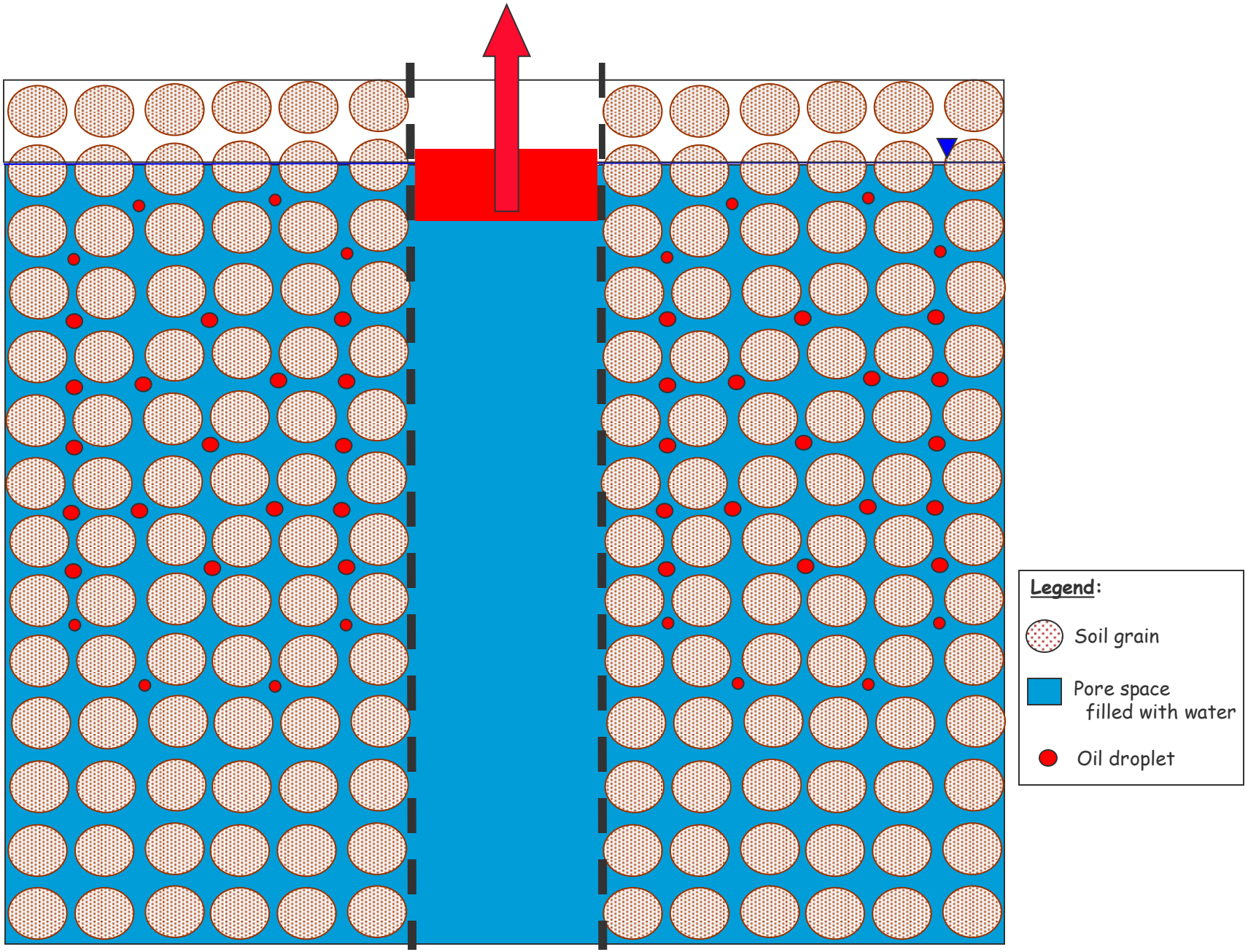




Legend:

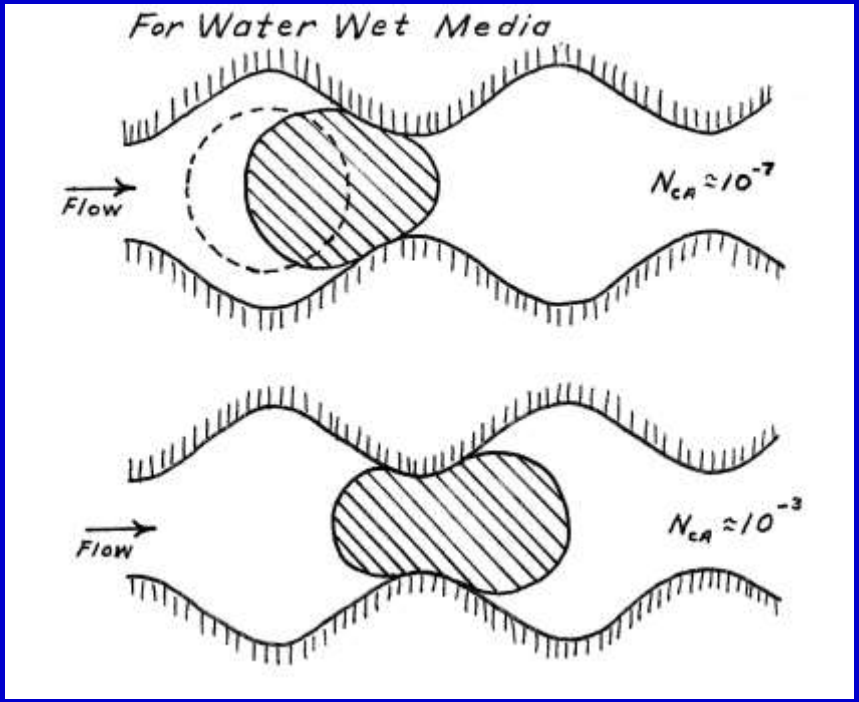
- Soil grain
- Pore space filled with water
- Oil droplet



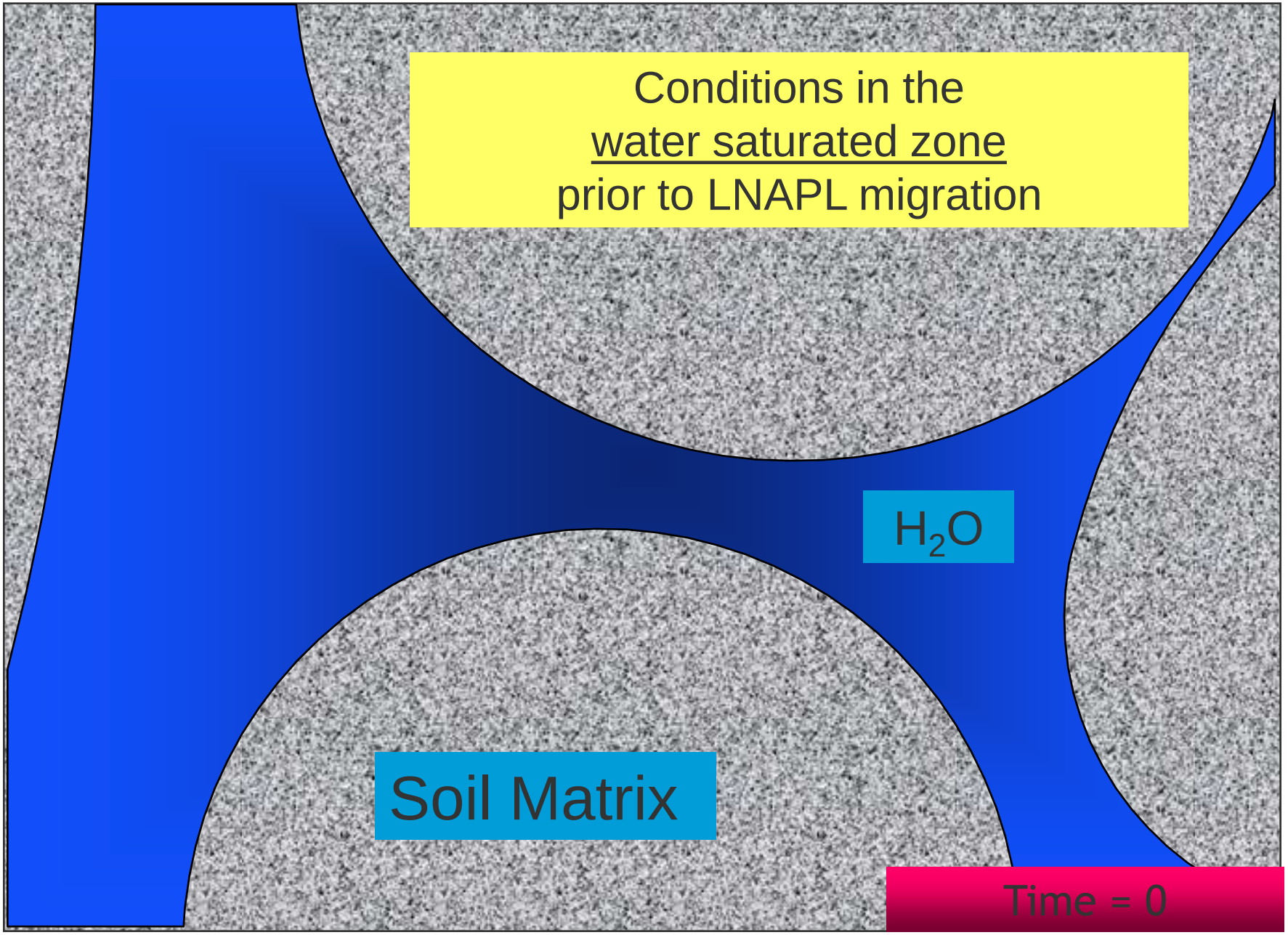


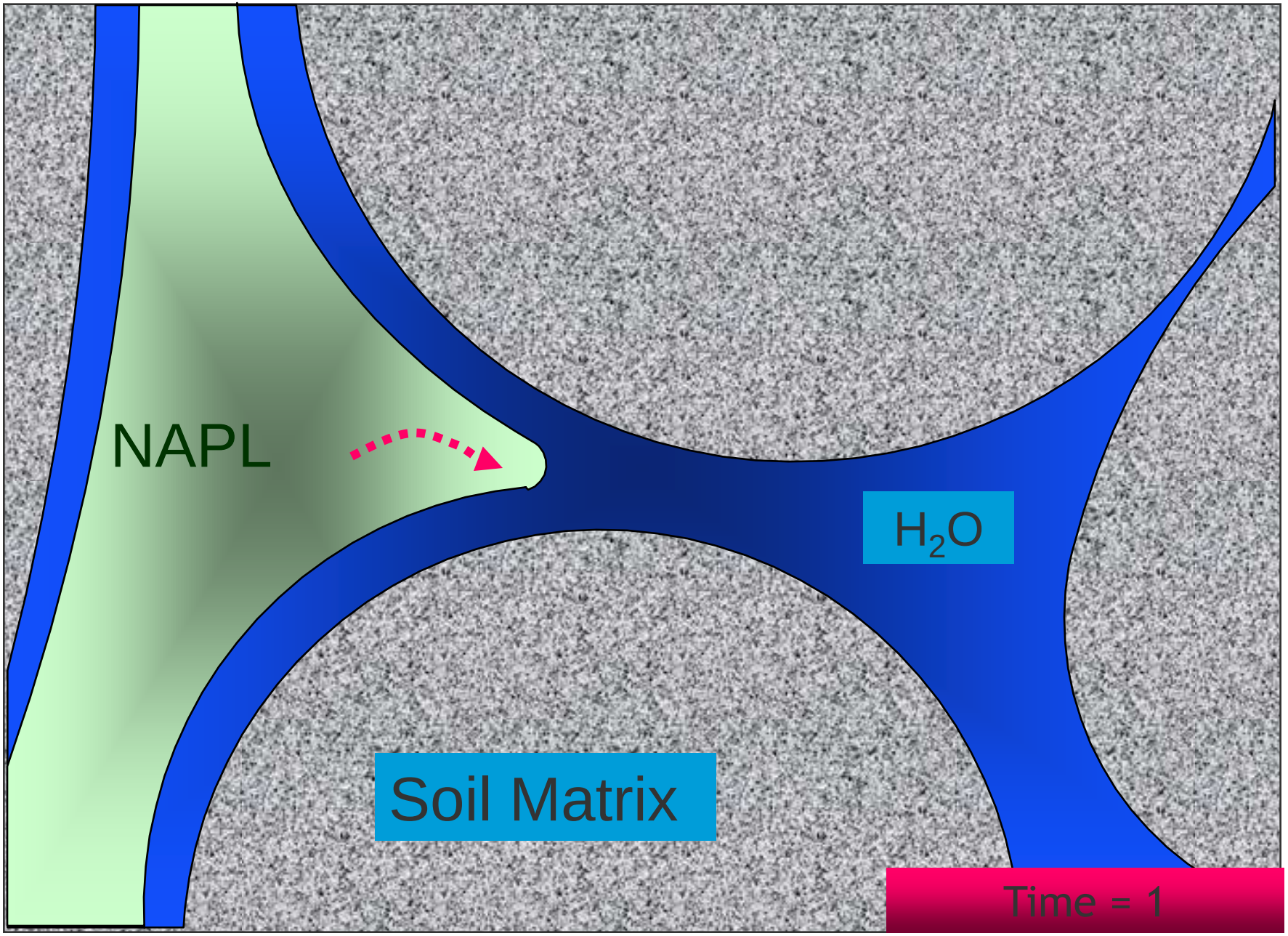
Processes governing LNAPL behavior in "normal" (i.e. Inland / Non-Tidal) aquifers)

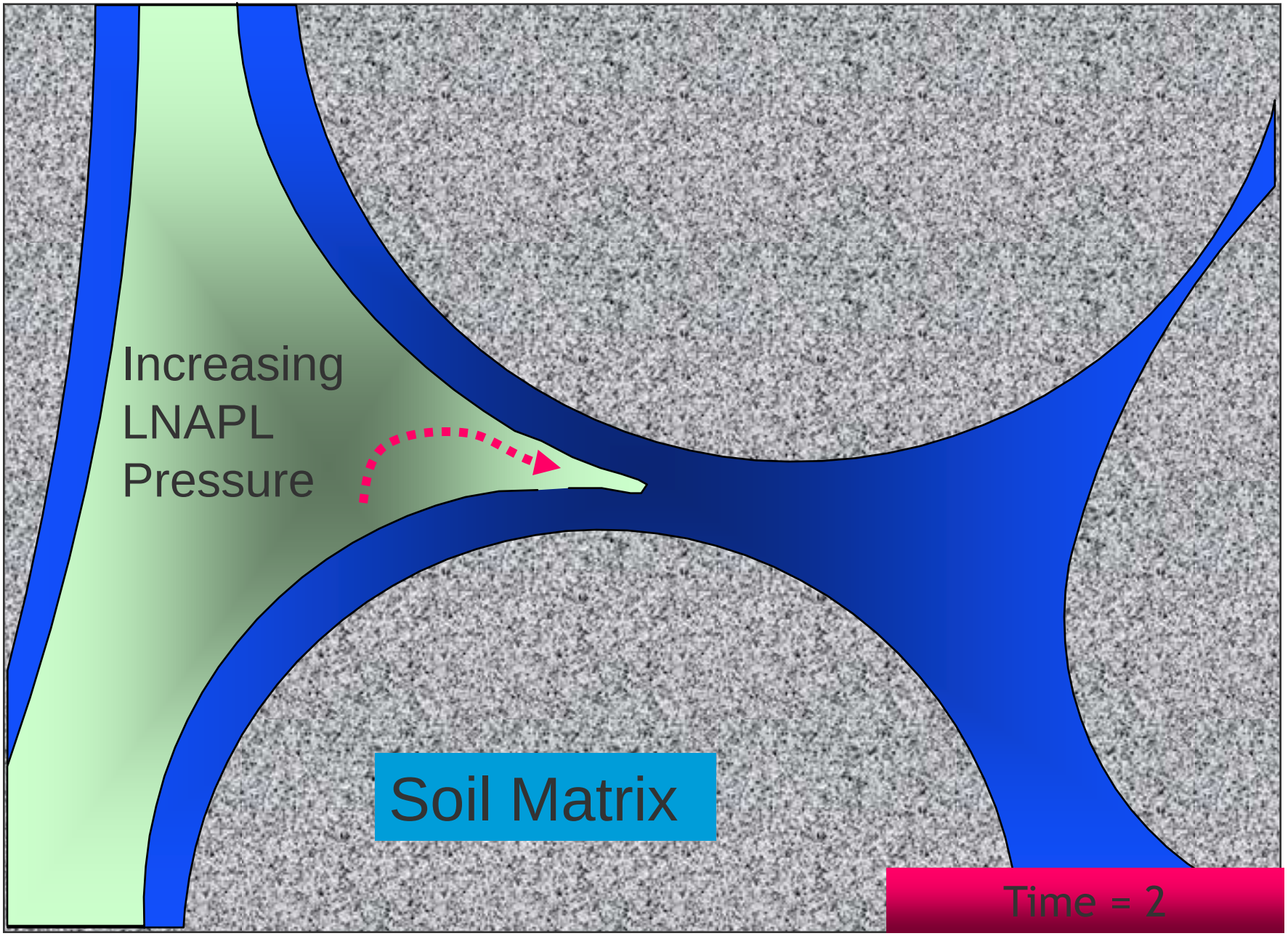
1) Aquifer materials have a pore entry pressure; non-wetting fluids (like NAPL) cannot intrude into adjacent pores without a sufficient pressure driving it.

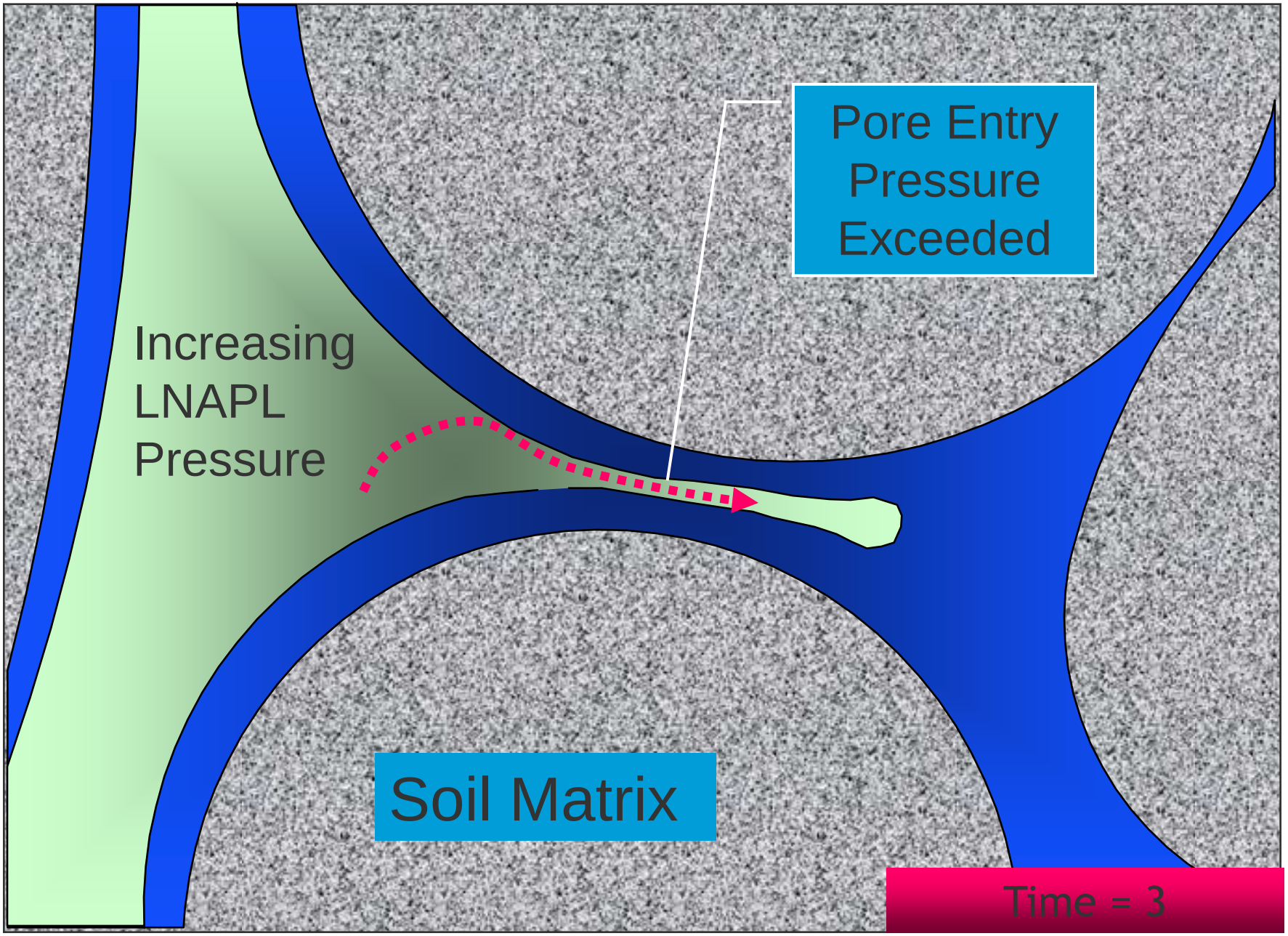


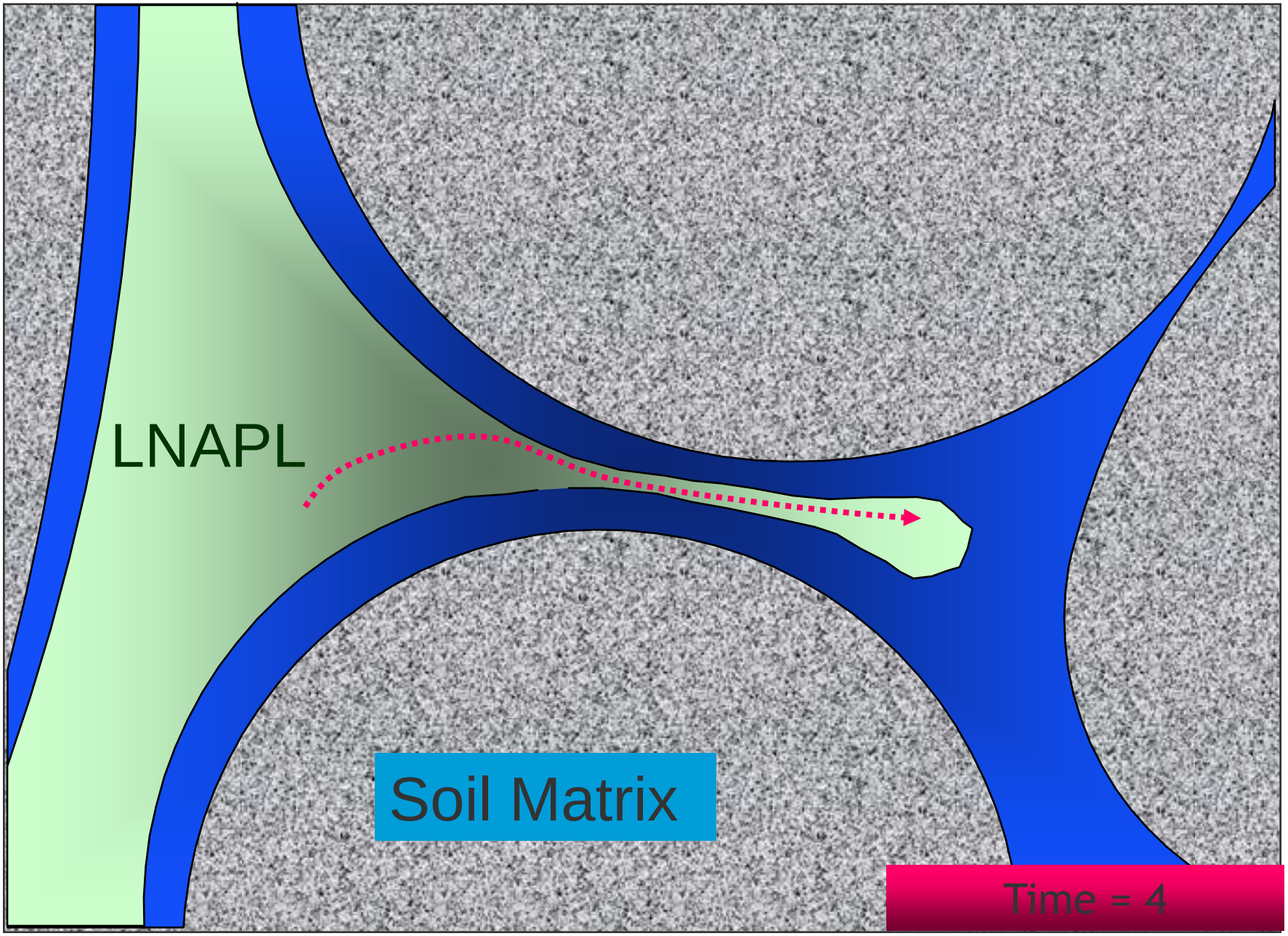
"Entry Pressure" must be exceeded before LNAPL can enter a water filled pore.

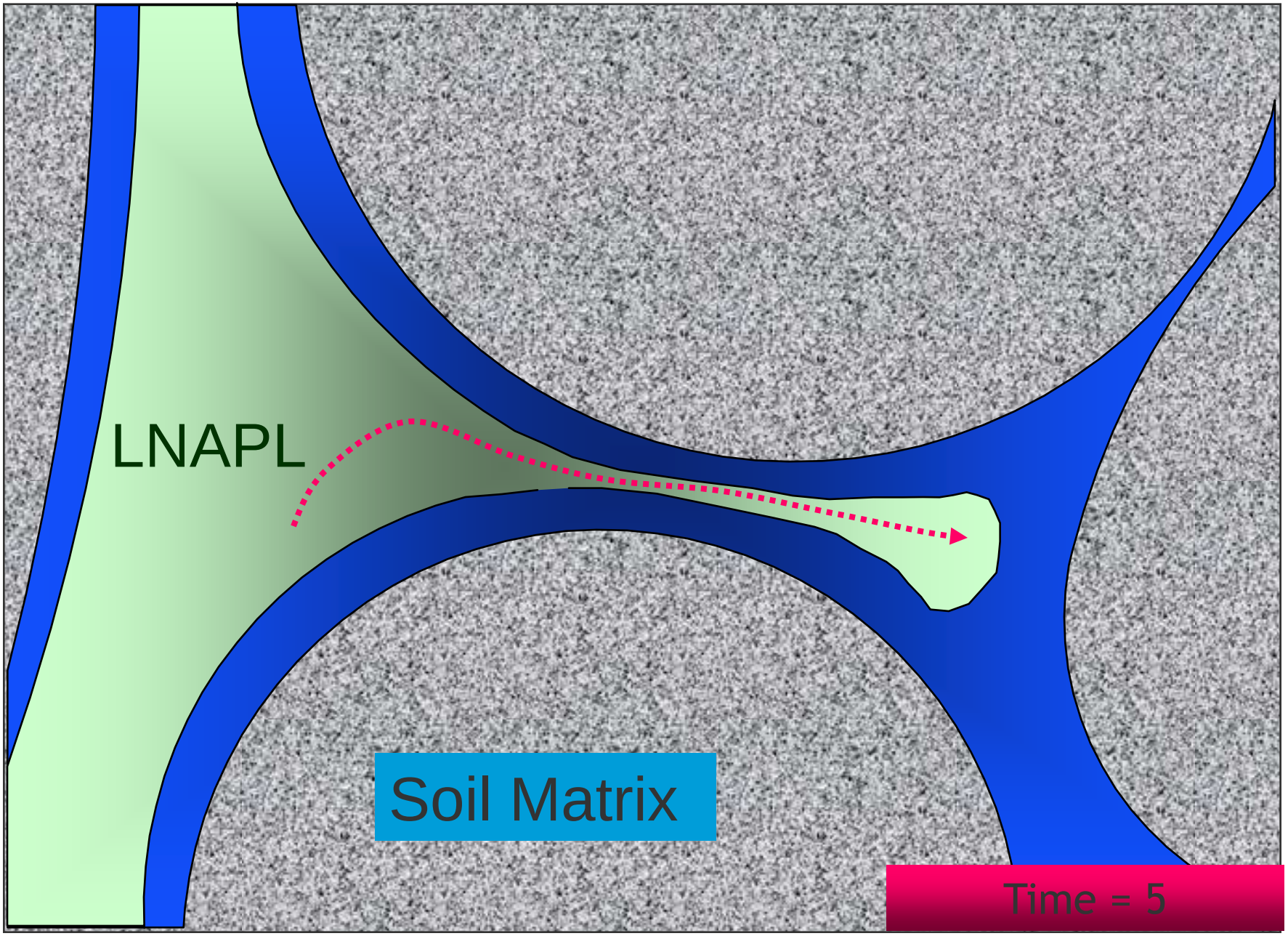


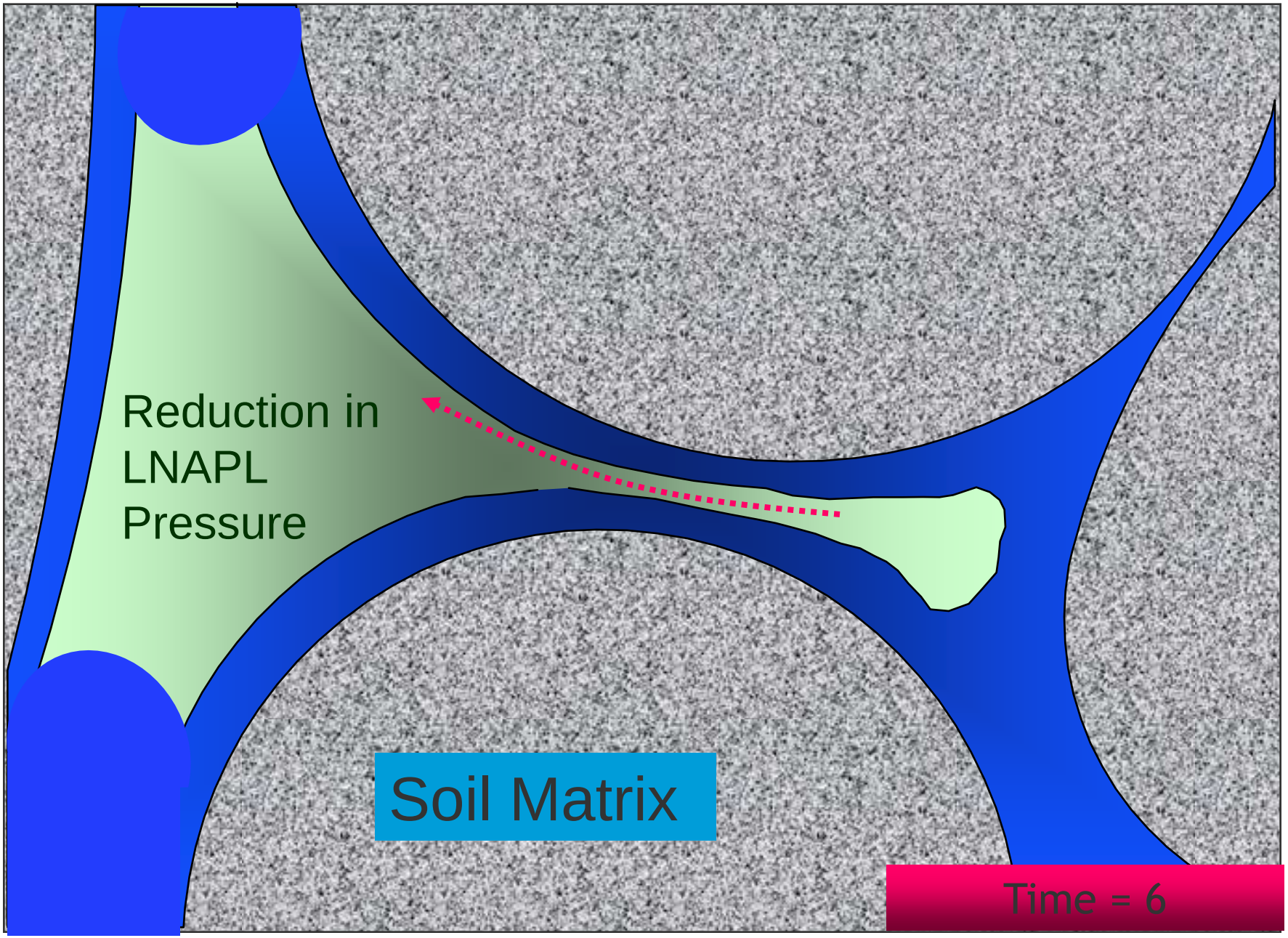


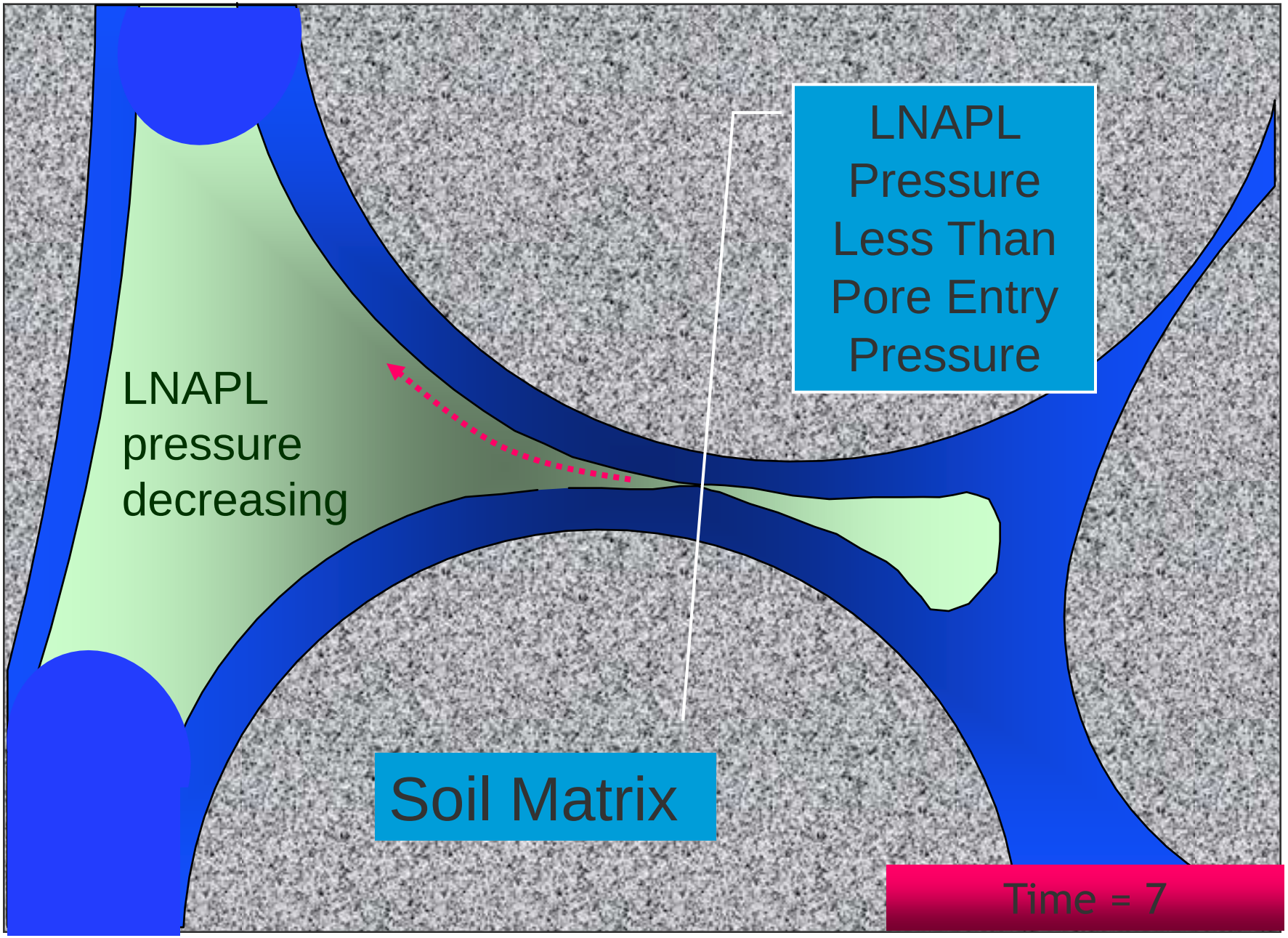


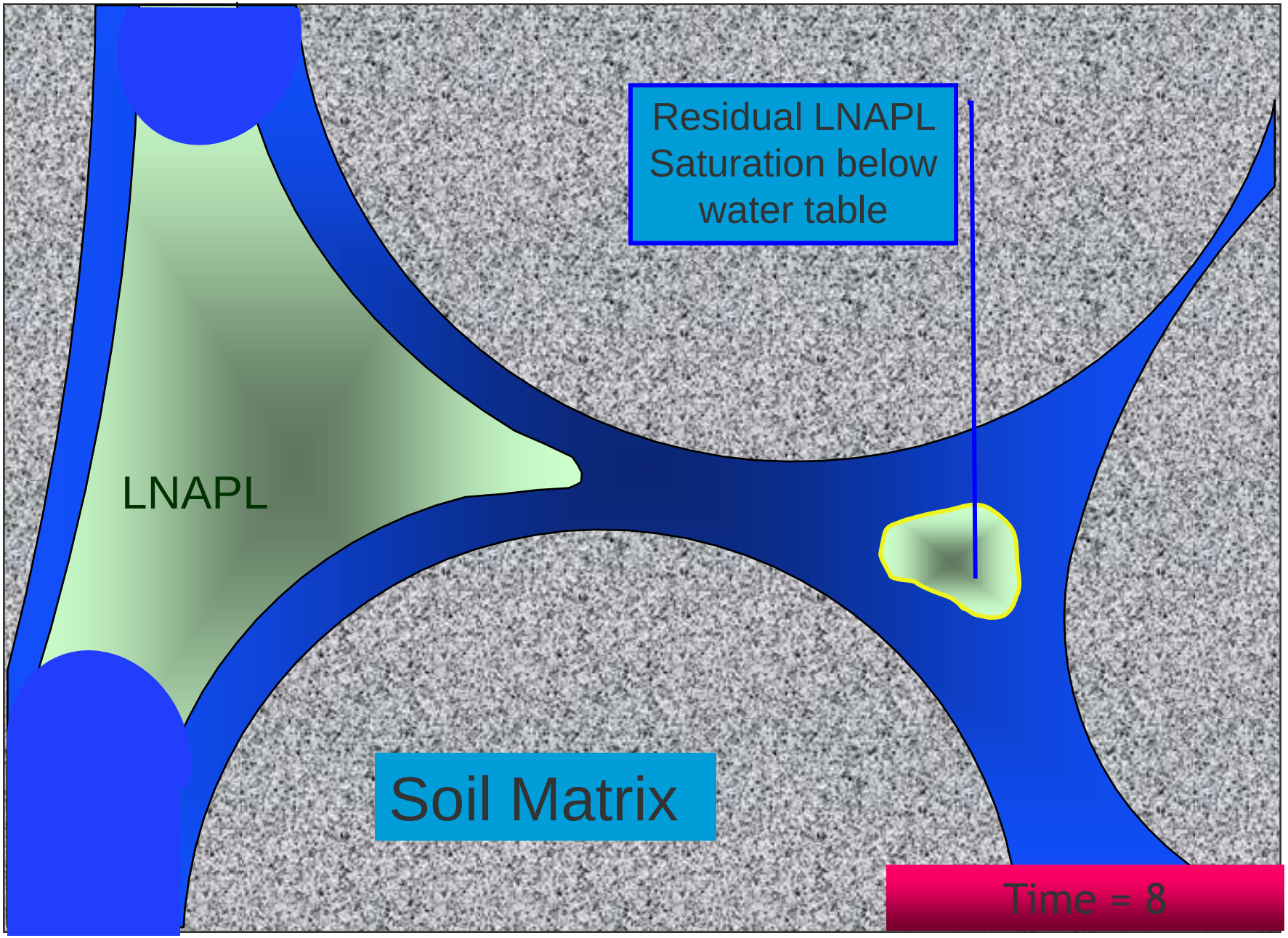








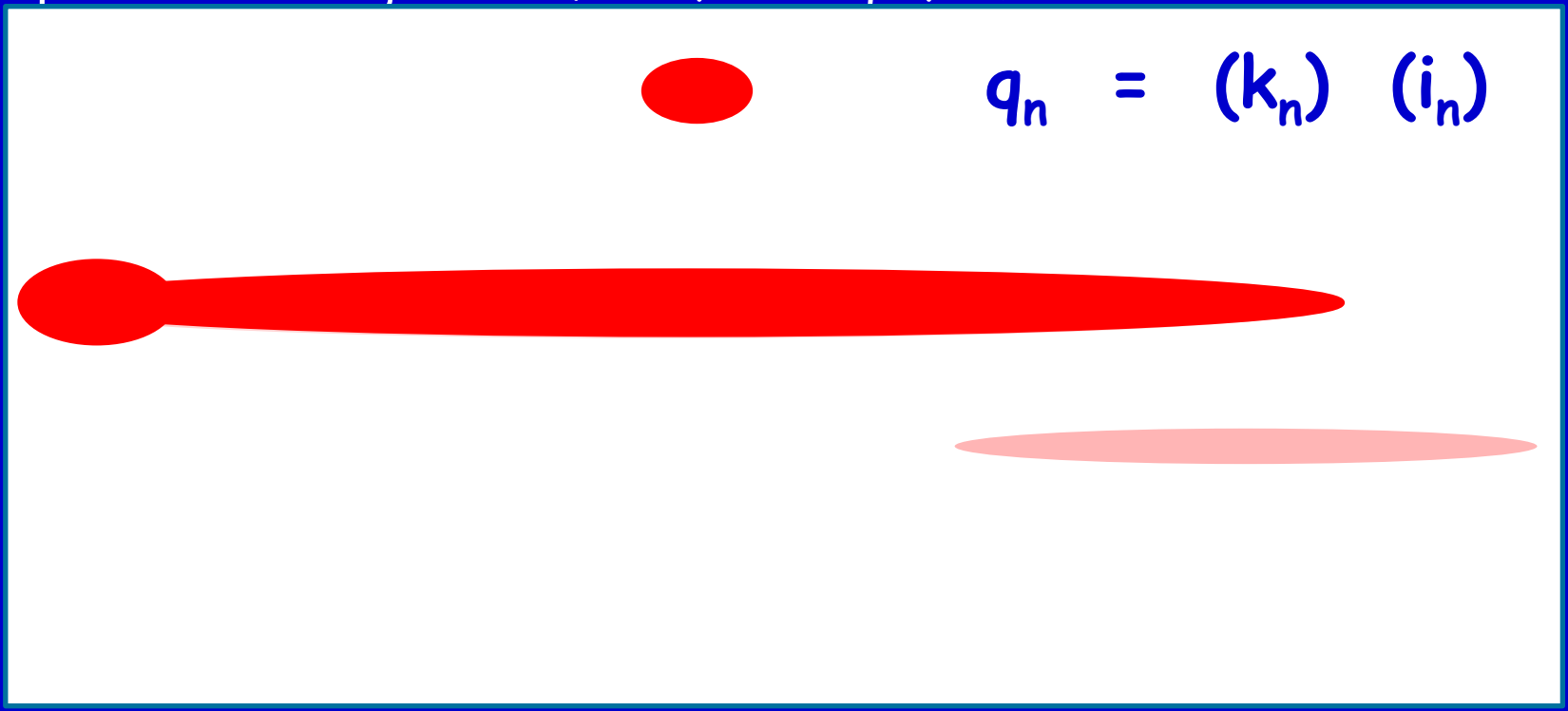


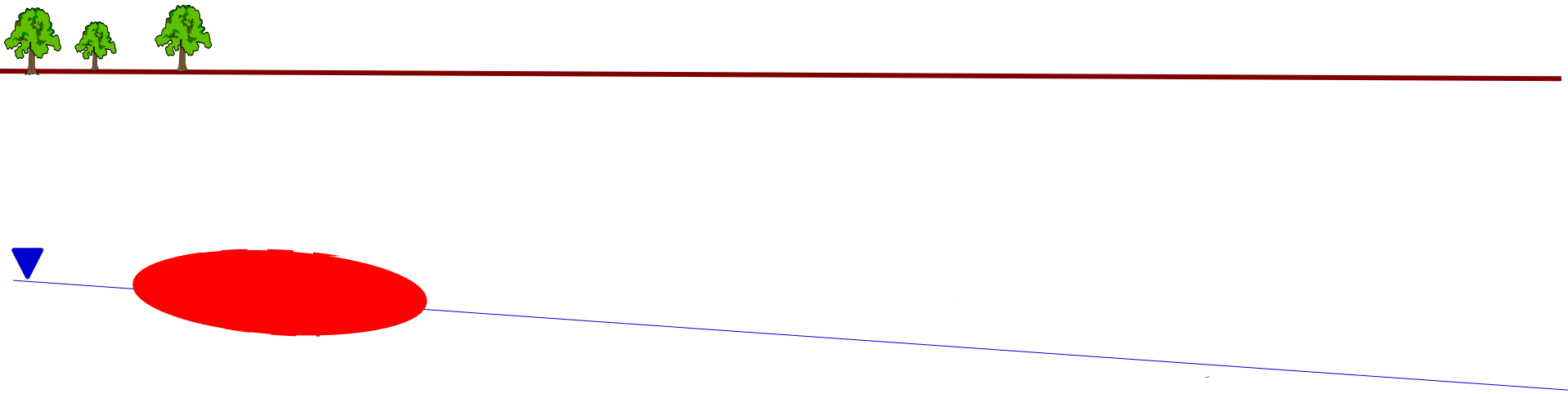


Processes governing LNAPL behavior in "normal" (i.e. Inland / Non-Tidal) aquifers)

1) Aquifer materials have a pore entry pressure; non-wetting fluids (like NAPL) cannot intrude into adjacent pores without a sufficient pressure.

2) The NAPL saturation – and hence, the effective conductivity (K_N) – diminishes through time, as the finite volume of oil is spread over larger volumes of the aquifer.





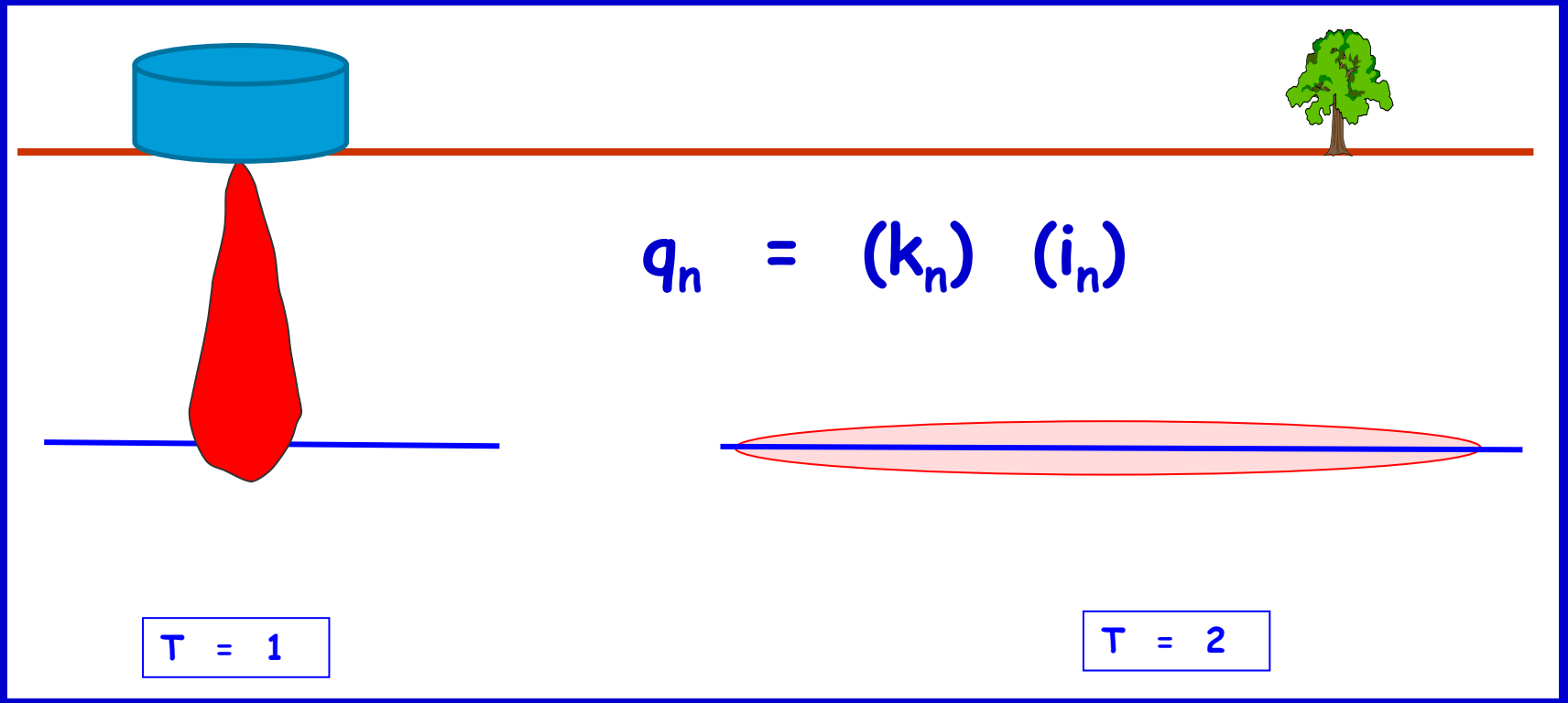
Processes governing LNAPL behavior in "normal" (i.e. Inland / Non-Tidal) aquifers)

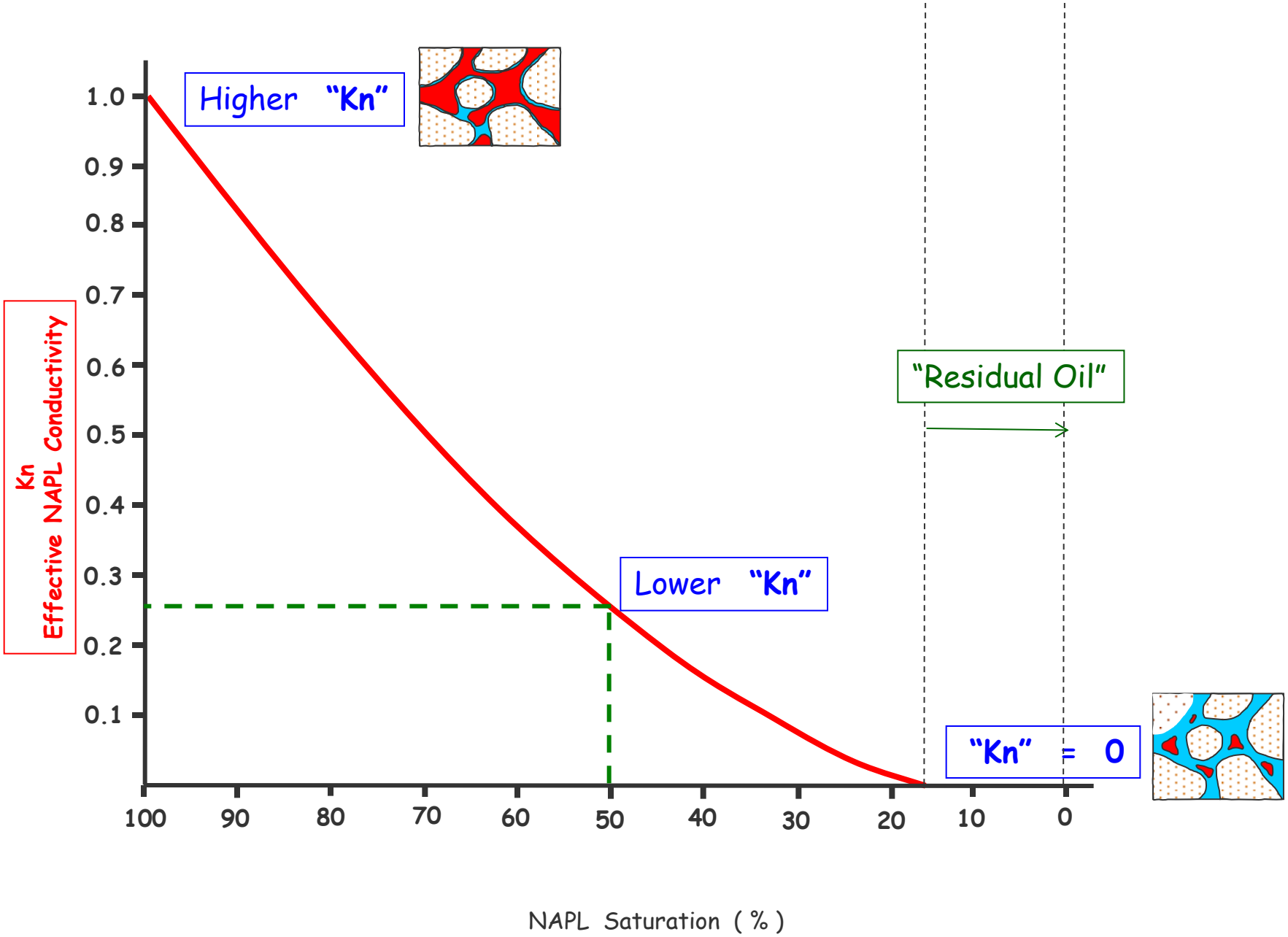
MVI_8848.MOV

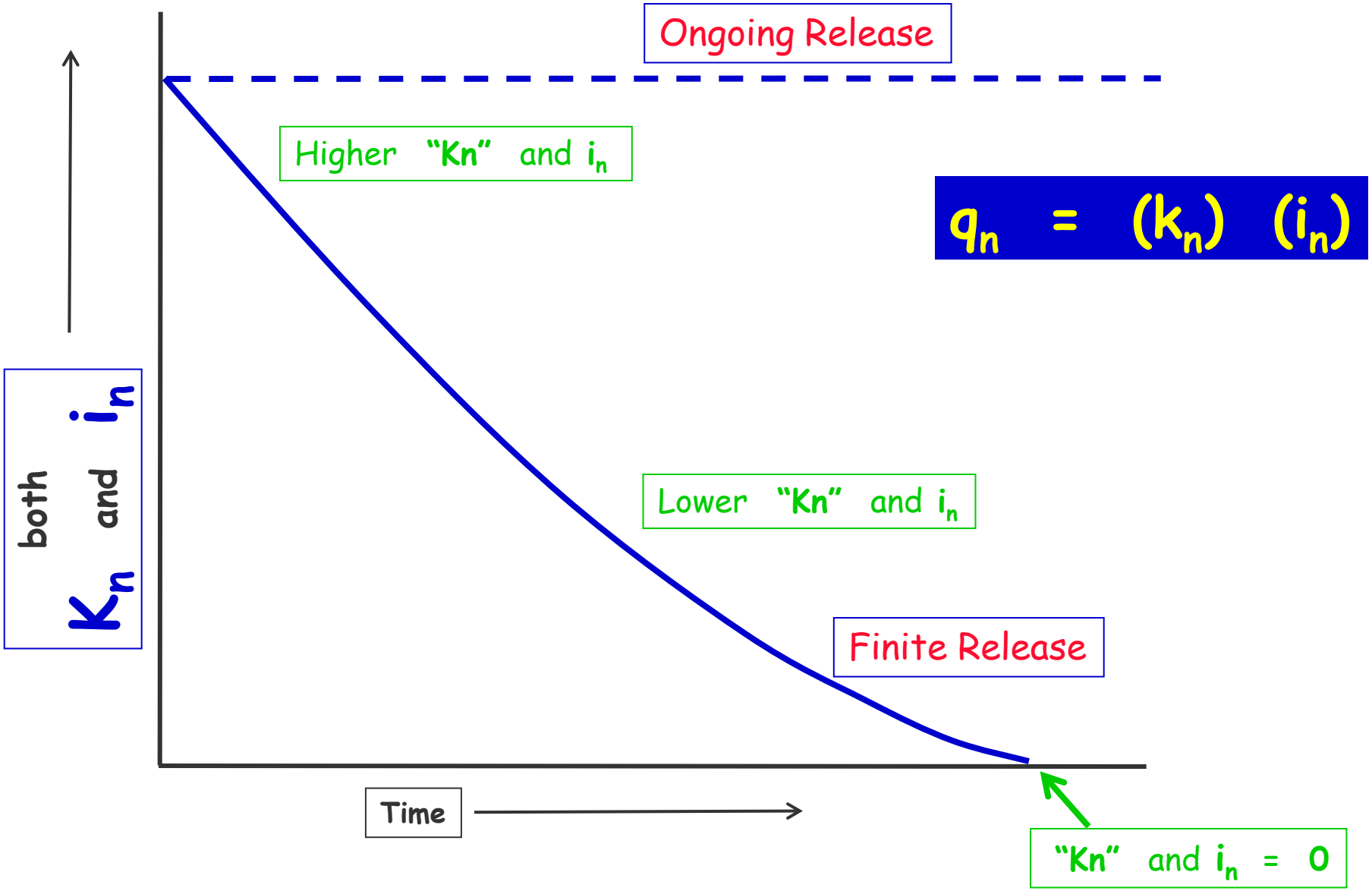
1) Aquifer materials have a pore entry pressure; non-wetting fluids (like NAPL) cannot intrude into adjacent pores without a sufficient pressure.

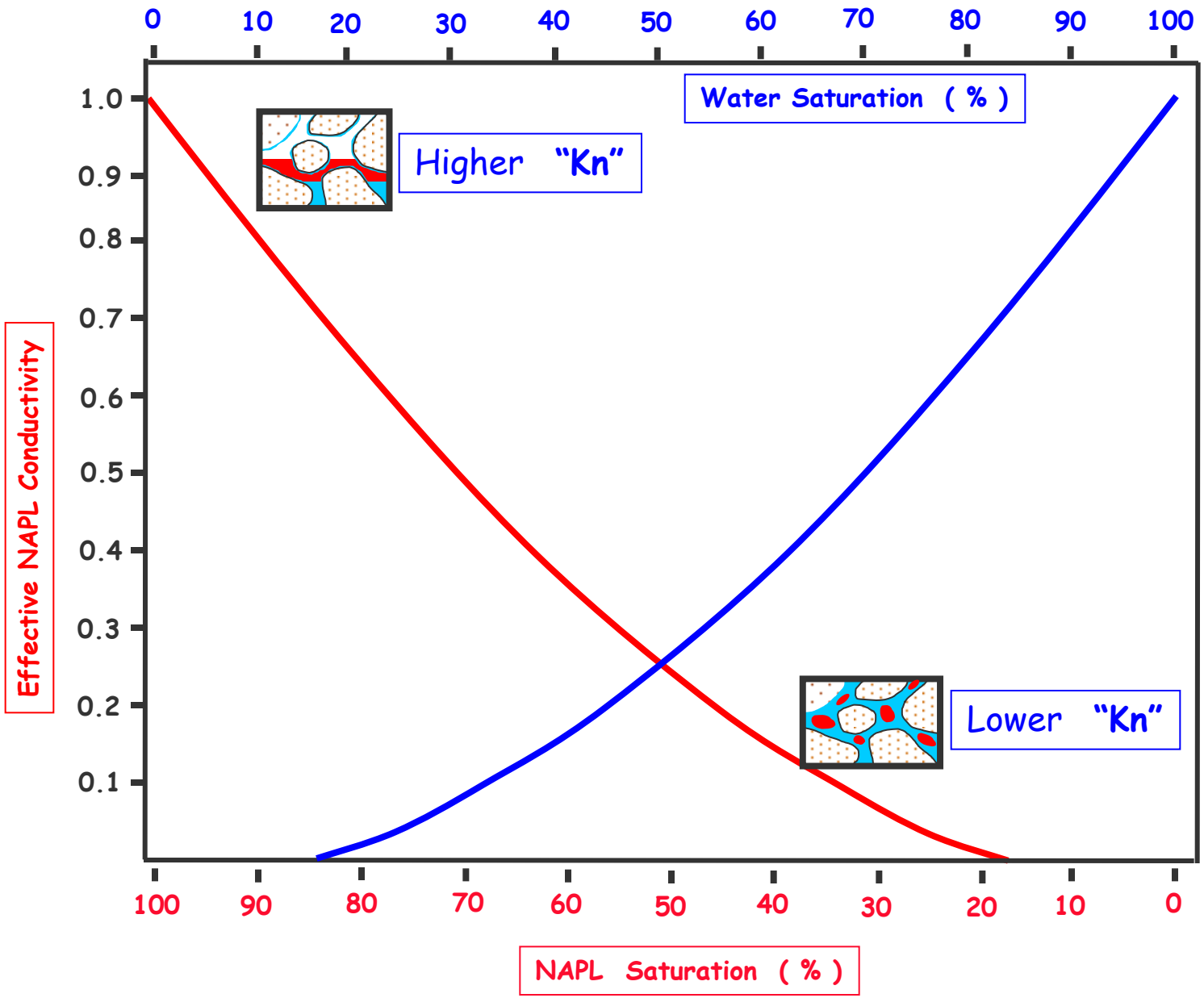
2) The NAPL saturation – and hence, the effective conductivity (K_N) – diminishes through time, as the finite volume of oil is spread over larger volumes of the aquifer.

3) The NAPL gradient (i_N) also diminishes through time, as the NAPL head cannot be sustained without an ongoing release.




Higher "Kn"
Lower "Kn"
"Residual Oil"
"Kn" = 0
Kn
Effective NAPL Conductivity
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
100
90
80
70
60
50
40
30
20
10
0
NAPL Saturation (%)


Ongoing Release
Higher "Kn" and i_n
$q_n = (k_n)\ (i_n)$
both K_n and i_n
Lower "Kn" and i_n
Finite Release
Time
"Kn" and i_n = 0


0
10
20
30
40
50
60
70
80
90
100
Water Saturation (%)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
Effective NAPL Conductivity
Higher "Kn"
Lower "Kn"
100
90
80
70
60
50
40
30
20
10
0
NAPL Saturation (%)

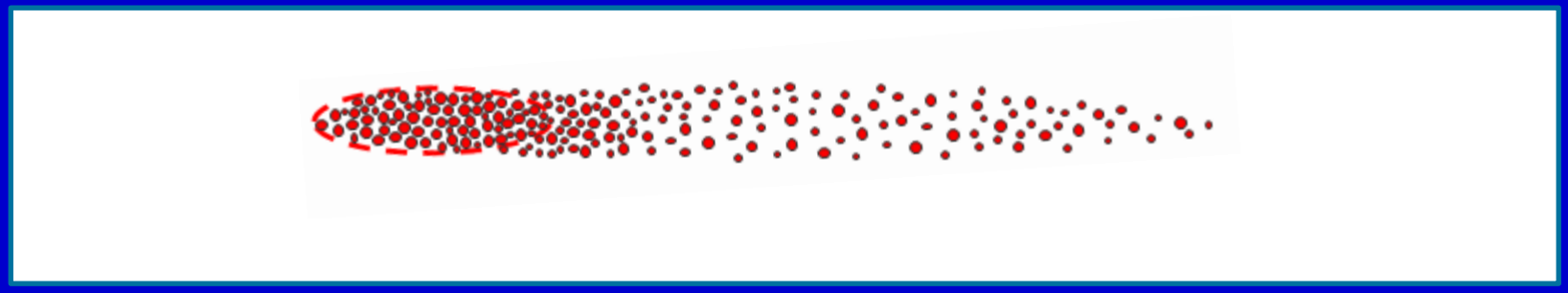
A quick review of processes governing LNAPL behavior in aquifers:

1) Aquifer materials have a pore entry pressure; non-wetting fluids (like NAPL) cannot intrude into adjacent pores without a sufficient pressure.

2) The NAPL saturation – and hence, the effective conductivity (K_N) – diminishes through time, as the finite volume of oil is spread over larger volumes of the aquifer.

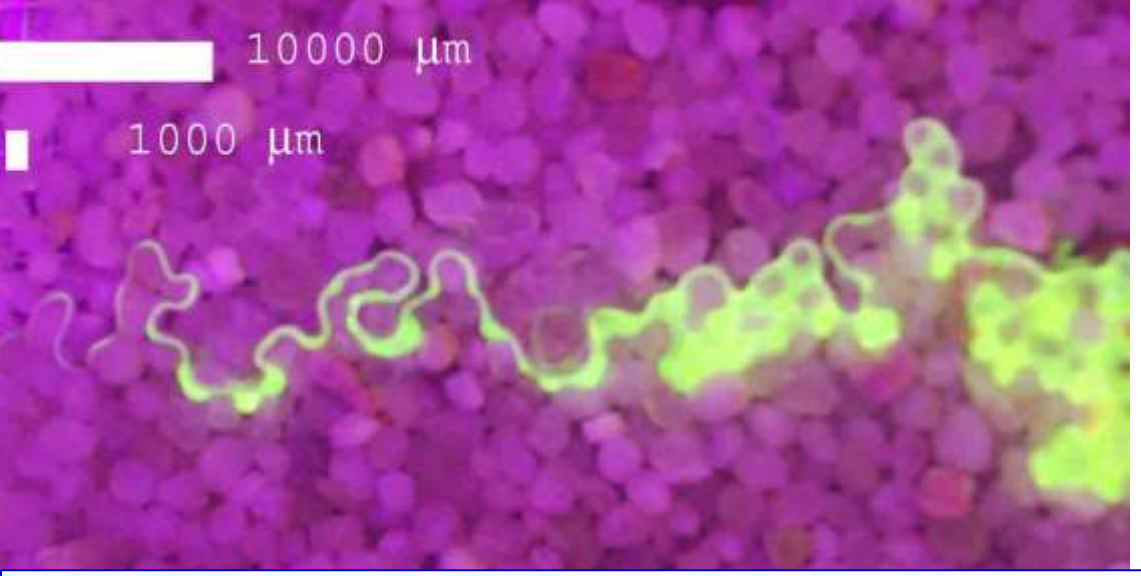
3) The NAPL gradient (i_N) also diminishes through time, as the NAPL head cannot be sustained without an ongoing release.

4) Soil has a capacity to hold oil against drainage / movement as residual oil. All of this means that an entire finite NAPL release will theoretically be retained as residual oil, at some maximum spreading distance.



NAPL Flow Mechanism #1: Pushing out from the Source Area

(Advective Flow) Examples: A classic "LNAPL Plumes" and "Seeps"



NAPL Flow Mechanism #2: Pulling out from the Source Area

(Capillary Flow) Examples: "Sheens"

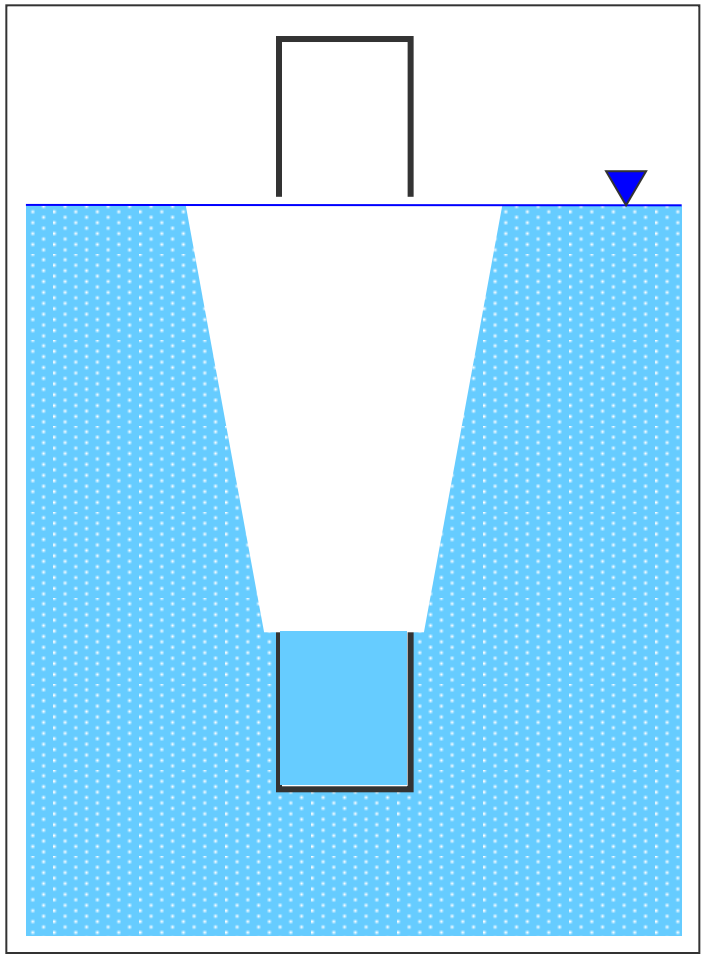
NAPL Flow Mechanism #2: Pulling out from the Source Area

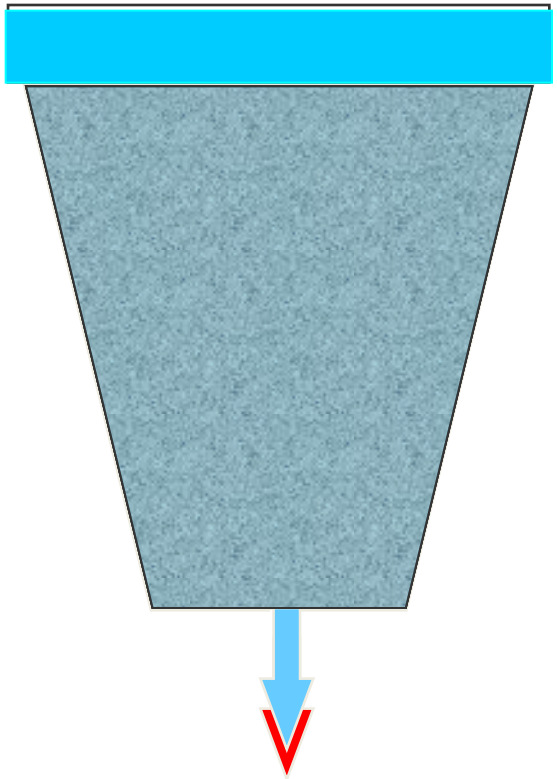
(Capillary Flow) Examples: "Sheens"

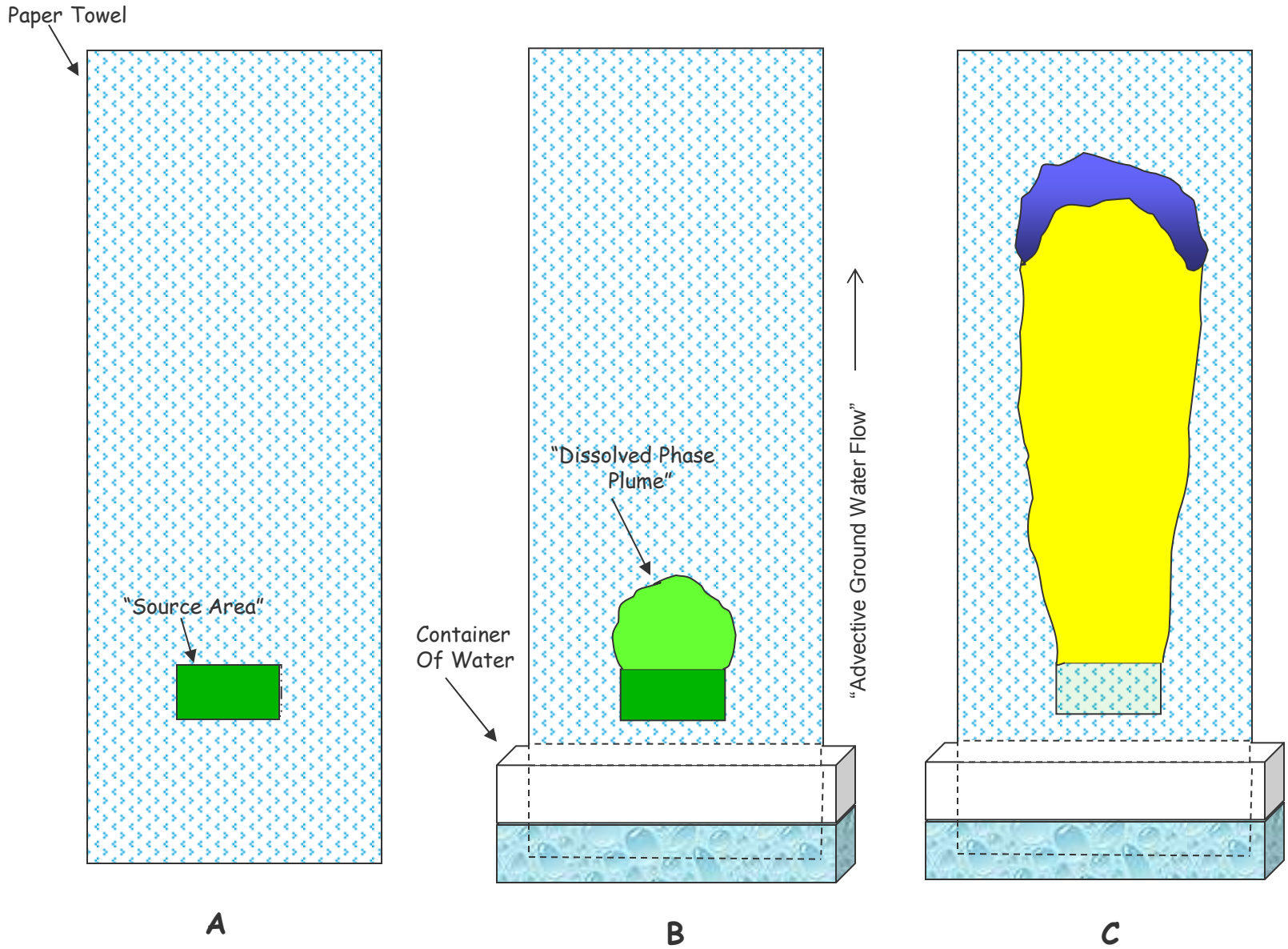
Check on the progress of our “Oil Spill” and Paper Towel Experiments

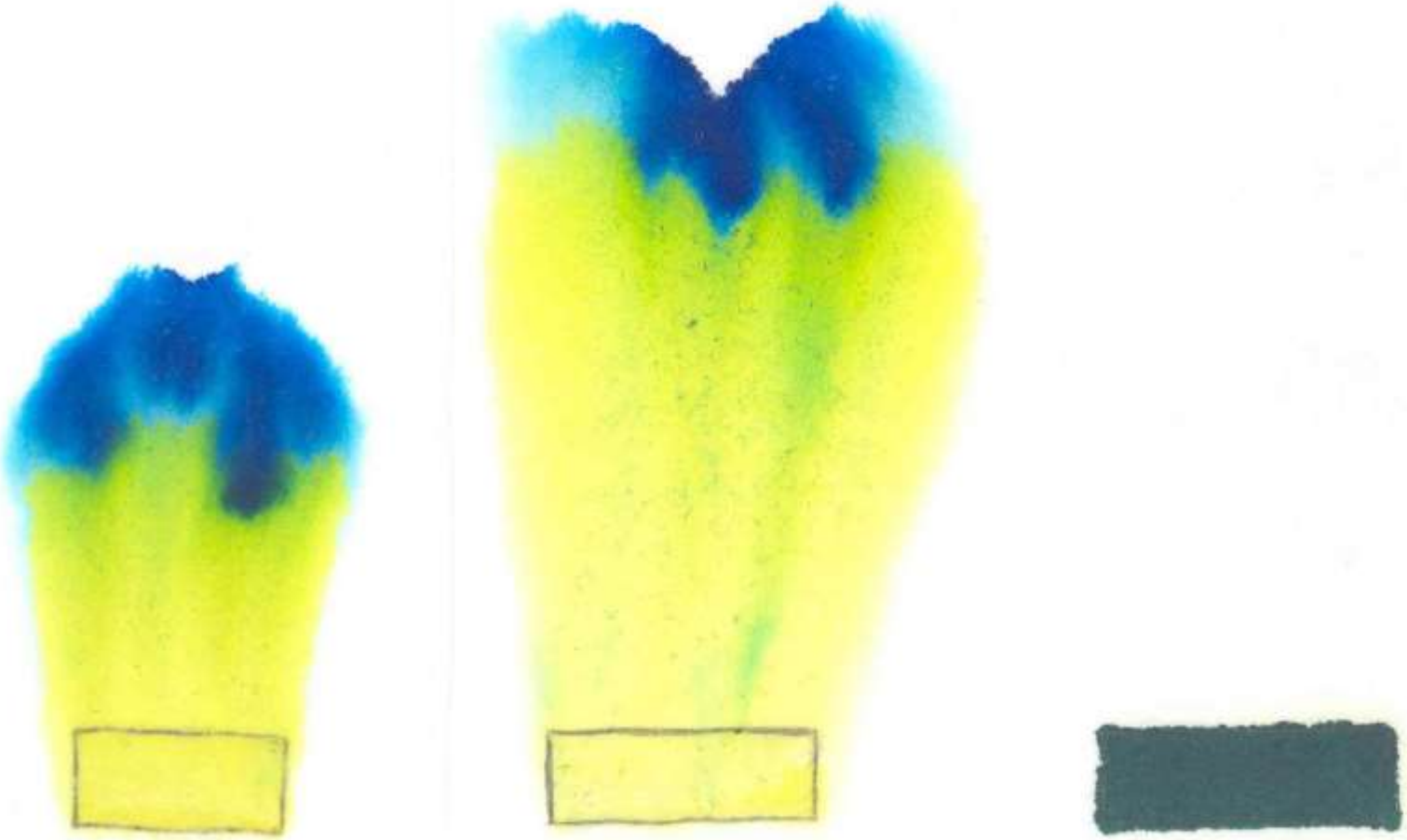
1) How much Oil was “Recovered “ (drained from the cup)?

2) What was the “fate” of our contaminant plume?

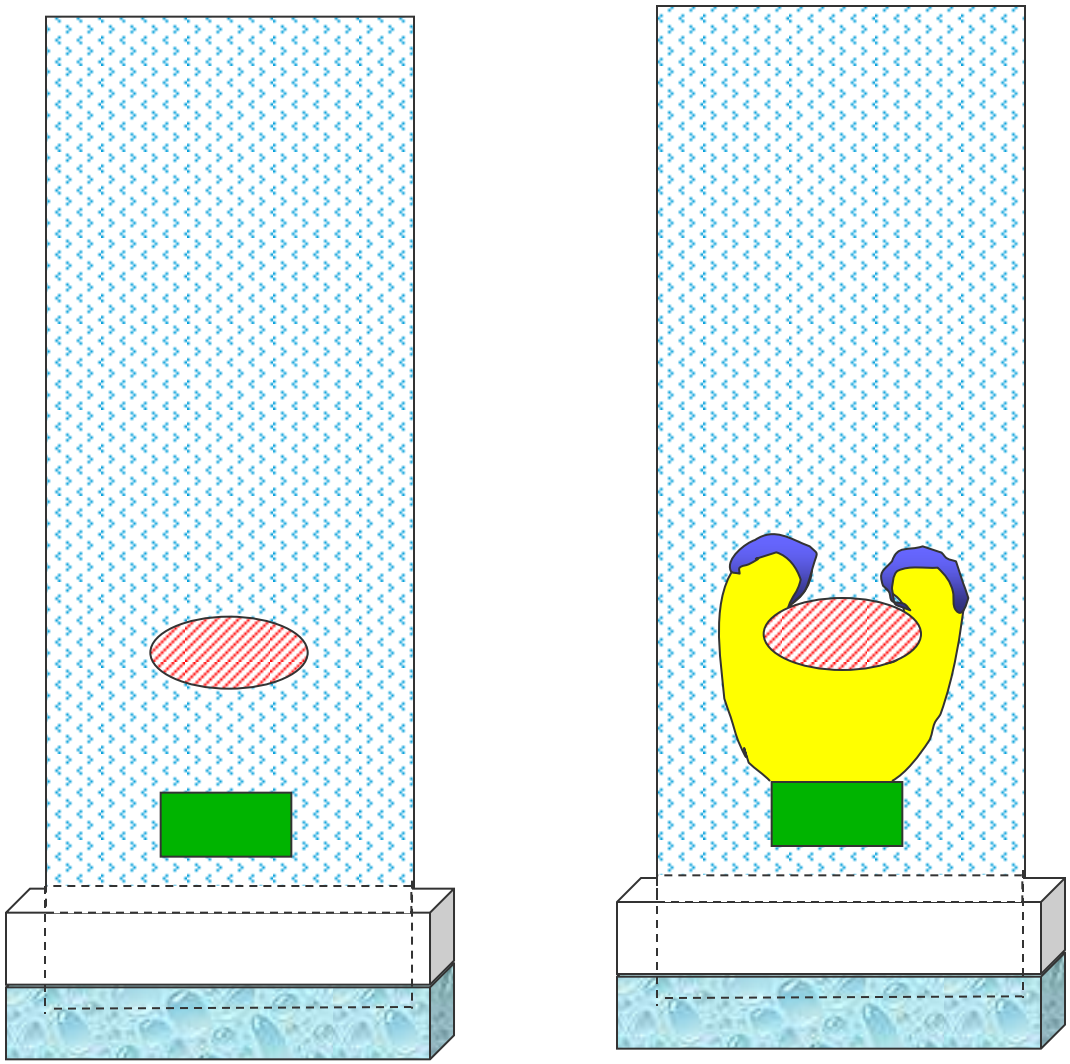





Paper Towel
"Source Area"
A
Container
Of Water
"Dissolved Phase
Plume"
"Advective Ground Water Flow"
B
C



“Kd scan 1”

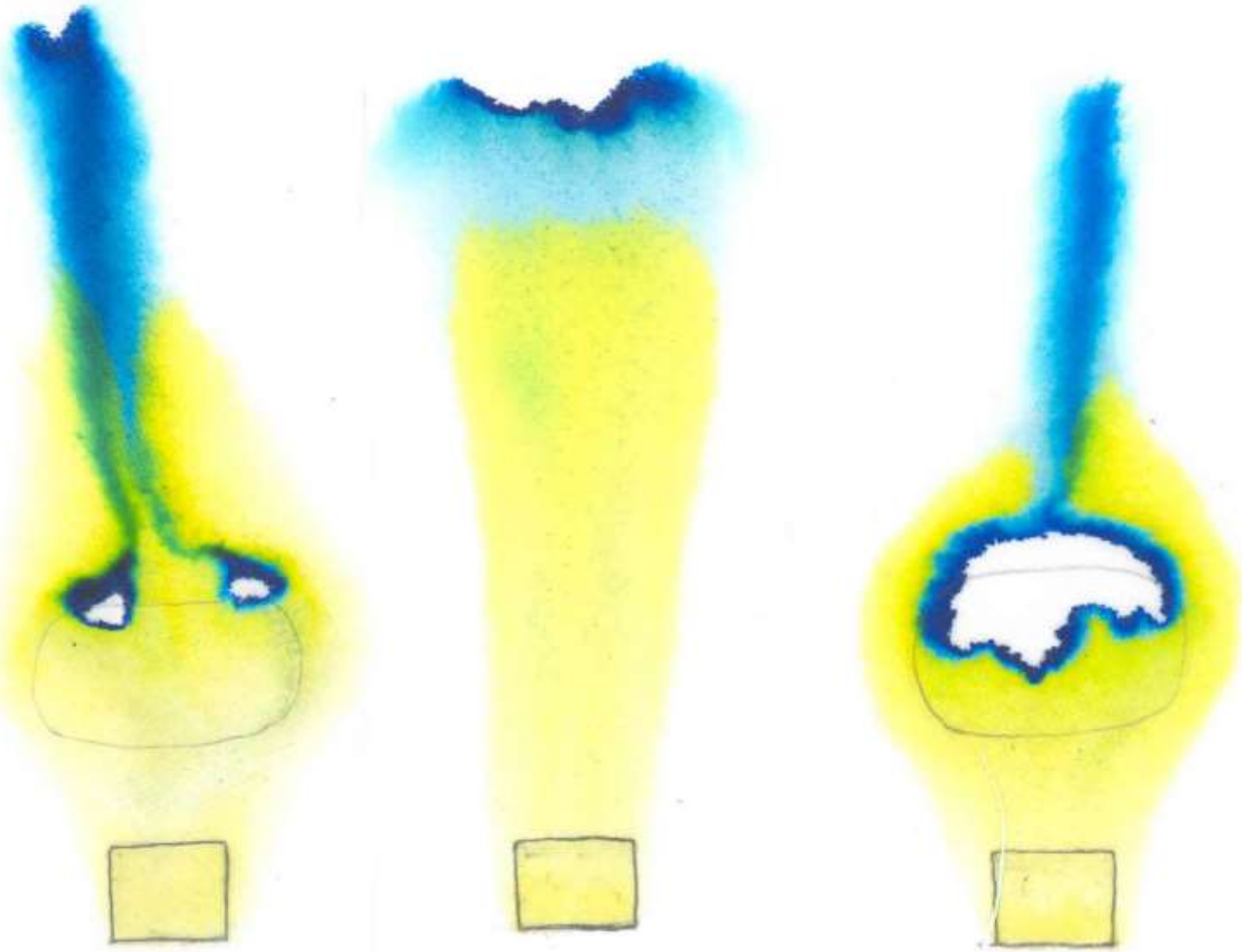


A **B**

Legend

"Low Permeability Zone"

Water



“Low Perm. Scan 3”

Outline

- Summary and Key Points
- Introduction / Background
- Processes governing LNAPL behavior in "normal" (i.e. inland, Non-Tidal) aquifers
- **Processes governing LNAPL behavior in coastal, Tidally Influenced Aquifers**

Processes governing LNAPL behavior in Tidal aquifers

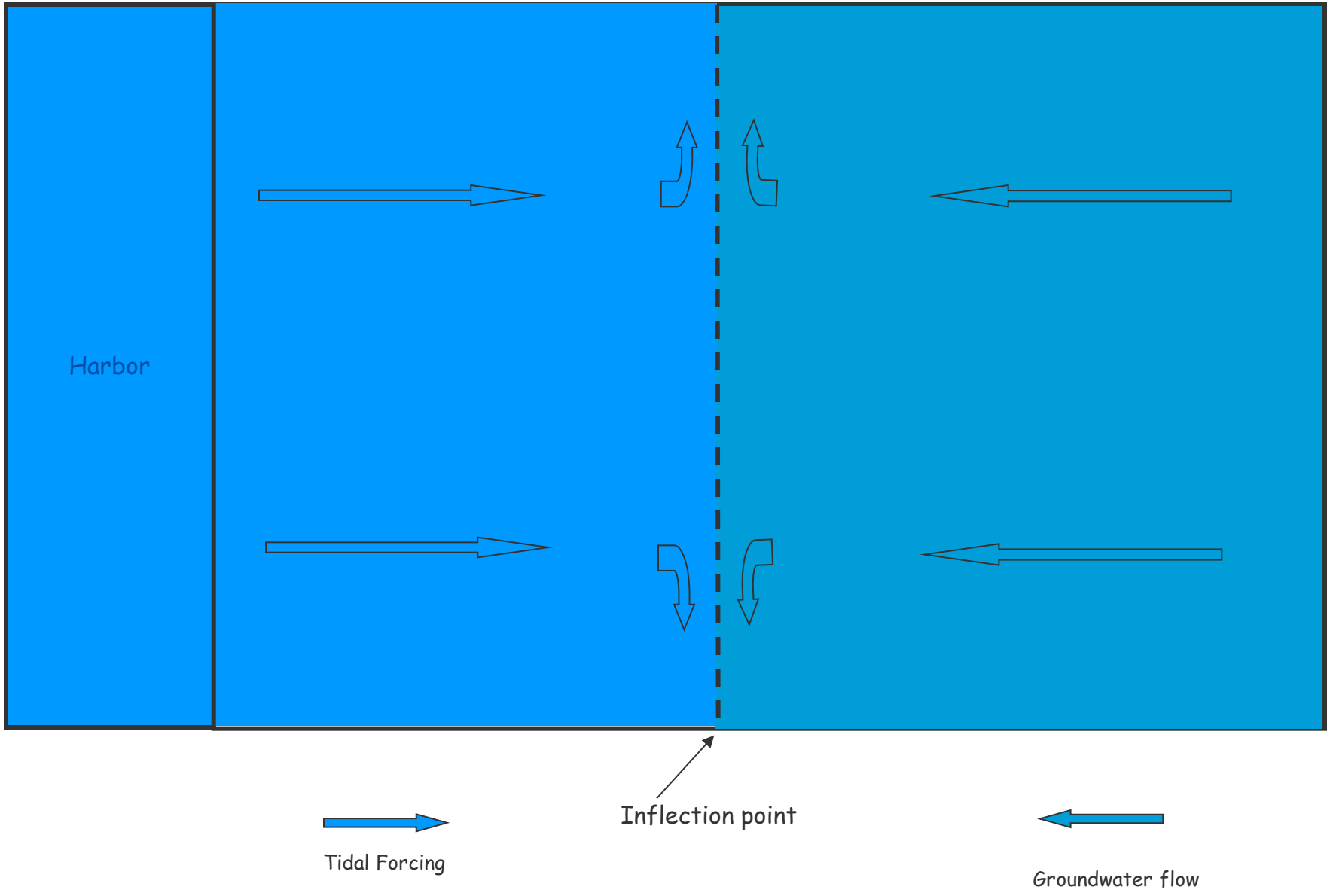
All of these processes for Non-Tidal Aquifers still apply:

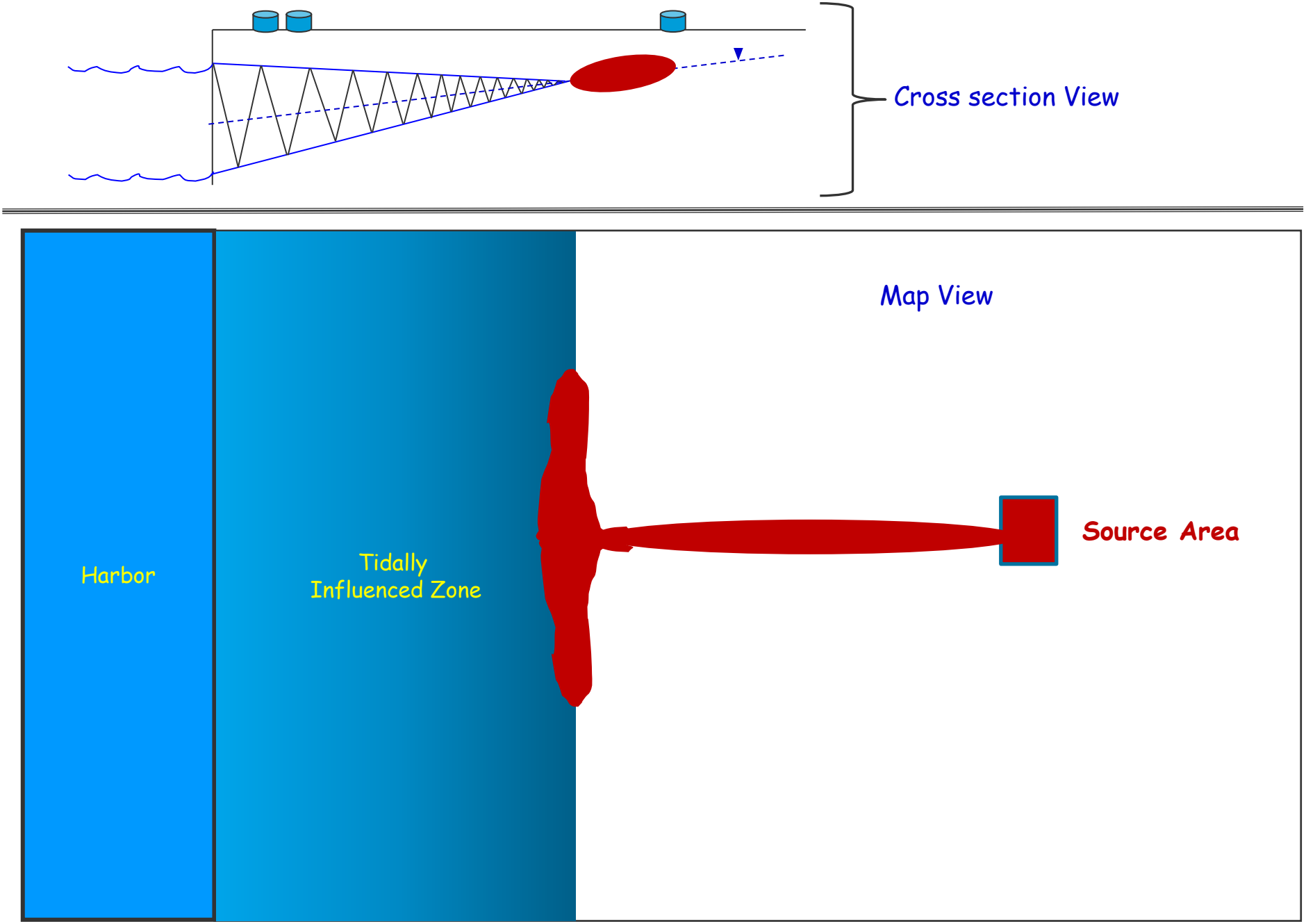
1) Aquifer materials have a pore entry pressure; non-wetting fluids (like NAPL) cannot intrude into adjacent pores without a sufficient pressure.
2) The NAPL saturation – and hence, the effective conductivity (K_N) – diminishes through time, as the finite volume of oil is spread over larger volumes of the aquifer.
3) The NAPL gradient (i_N) also diminishes through time, as the NAPL head cannot be sustained without an ongoing release.
4) Soil has a capacity to hold oil against drainage / movement as residual oil. This means that an entire finite NAPL release will theoretically be retained as residual oil, at some maximum spreading distance.

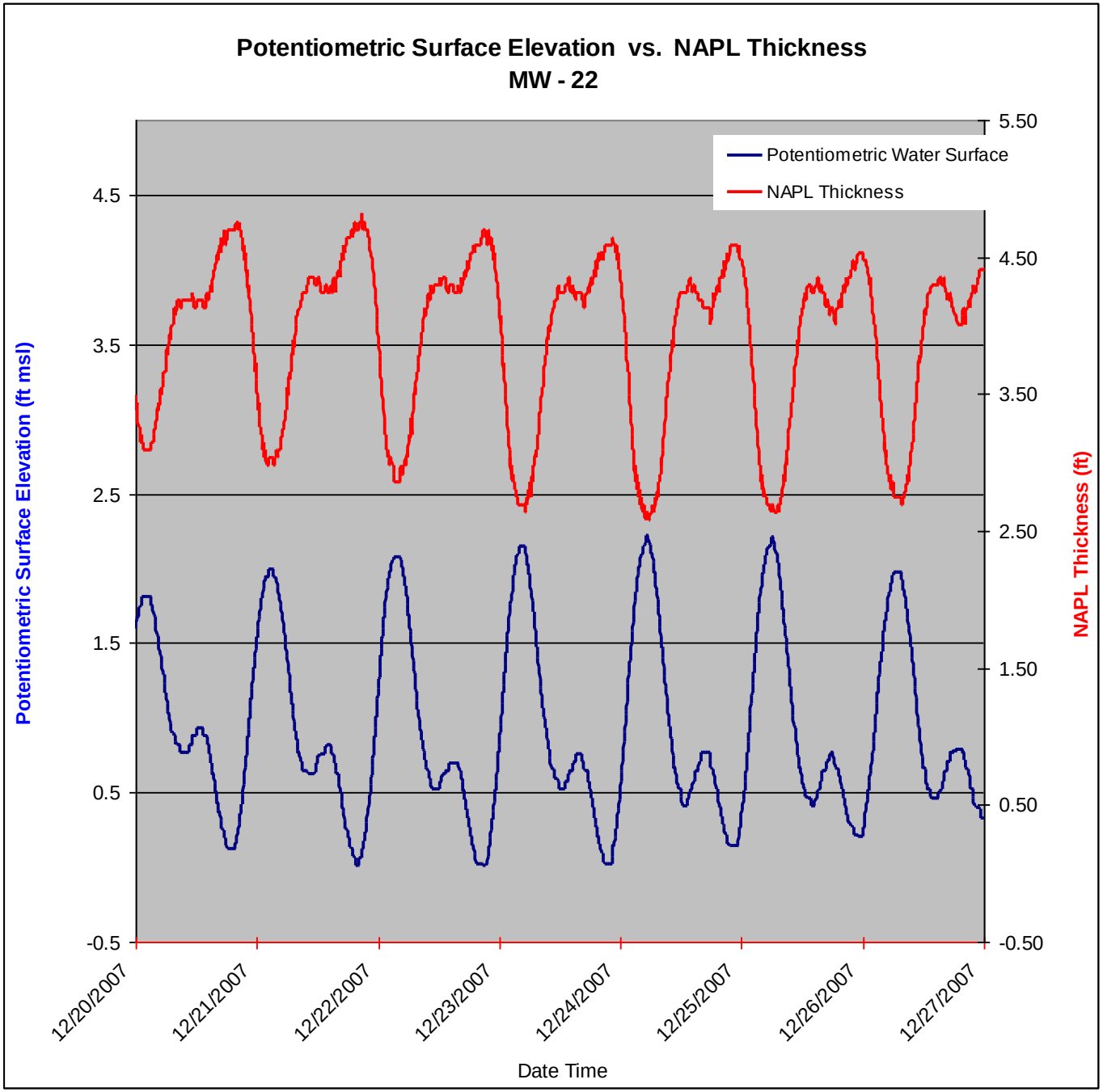
$$q_n = (k_n)\ (i_n)$$

Additional processes governing LNAPL behavior in Tidal aquifers

1) Both the k_n and the i_n terms are continually changing in response to the tidal fluctuations.

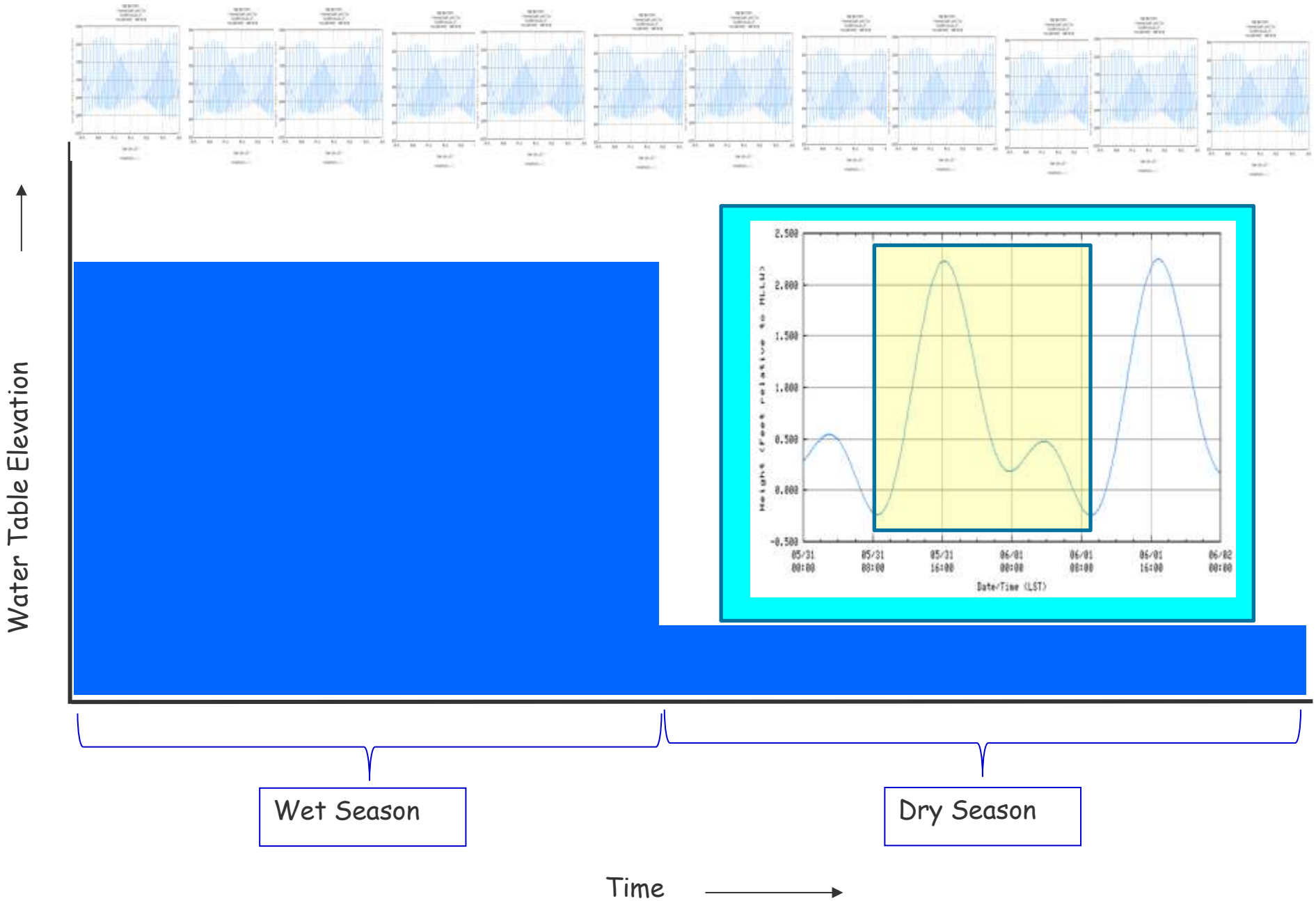

Harbor
Inflection point
Tidal Forcing
Groundwater flow


Cross section View
Map View
Harbor
Tidally
Influenced Zone
Source Area


Potentiometric Surface Elevation vs. NAPL Thickness
MW - 22
Potentiometric Water Surface
NAPL Thickness
Potentiometric Surface Elevation (ft msl)
NAPL Thickness (ft)
4.5
3.5
2.5
1.5
0.5
-0.5
5.50
4.50
3.50
2.50
1.50
0.50
-0.50
12/20/2007
12/21/2007
12/22/2007
12/23/2007
12/24/2007
12/25/2007
12/26/2007
12/27/2007
Date Time

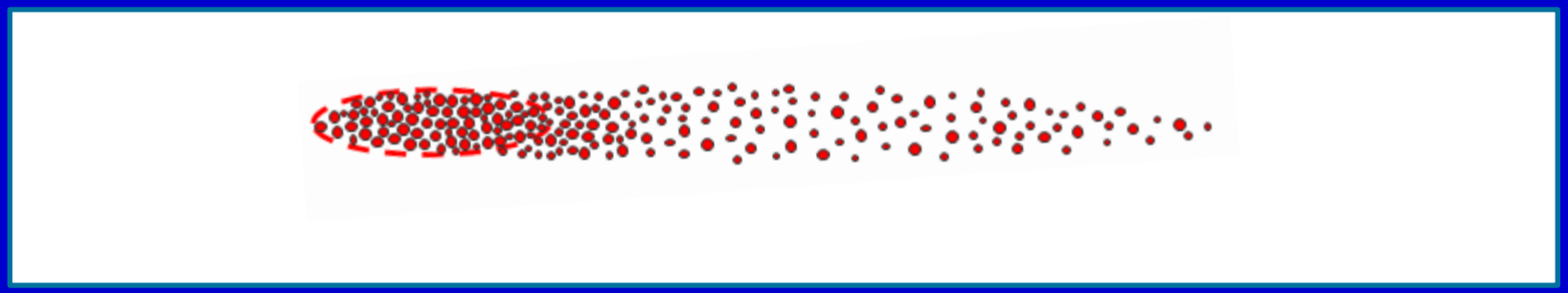
Additional Processes governing LNAPL behavior in Tidal aquifers

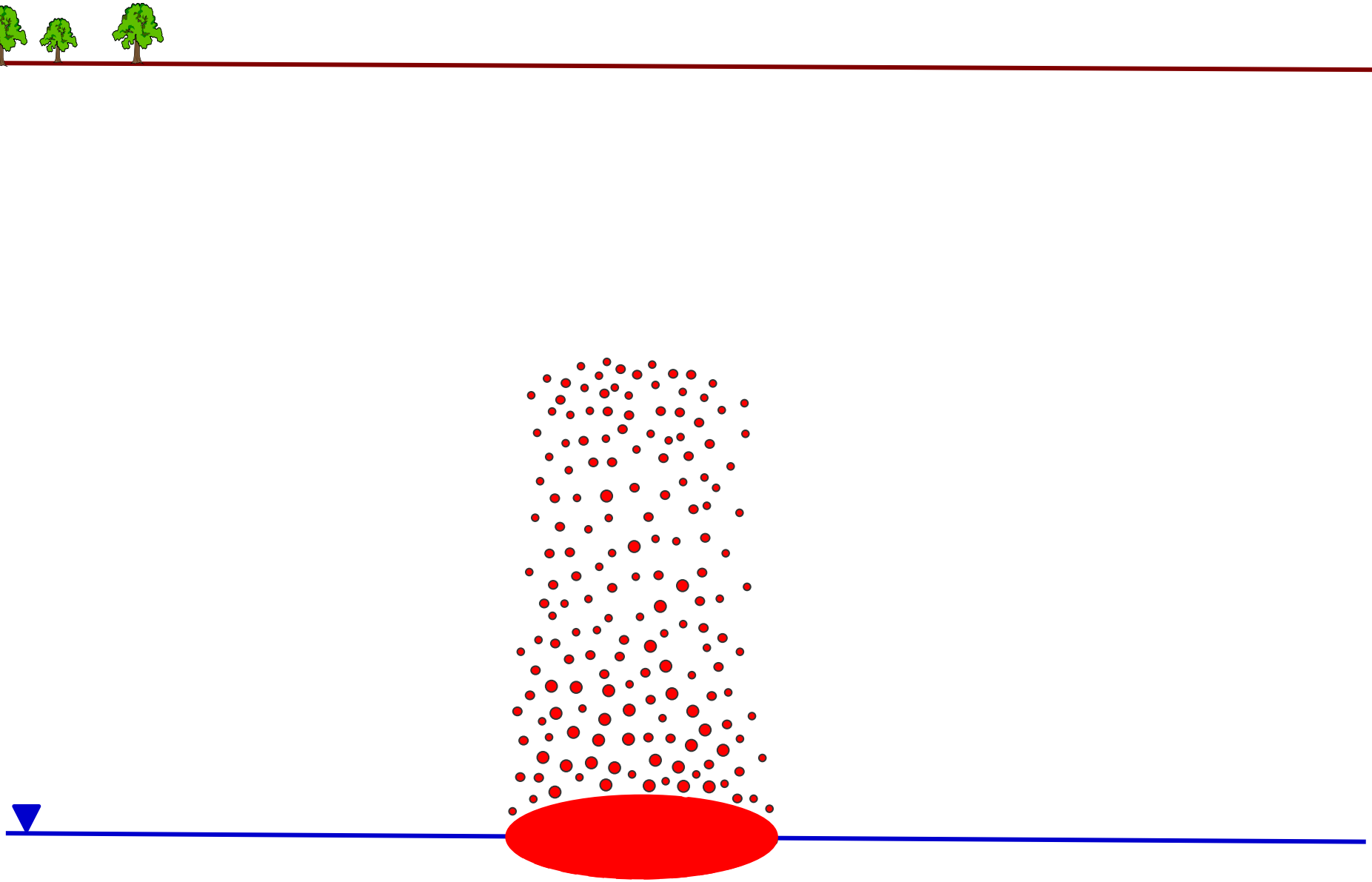
1) Both the k_n and the i_n terms are continually changing in response to the tidal fluctuations.
2) These changes are rapid enough that the aquifer never reaches equilibrium conditions.

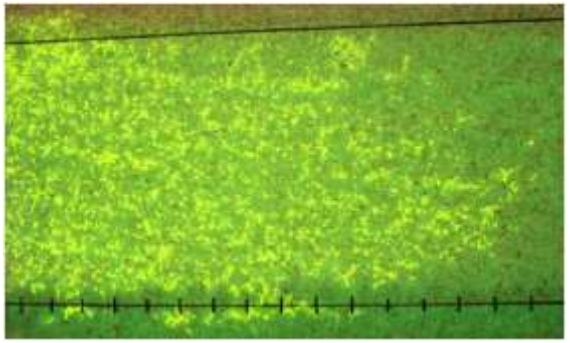

Water Table Elevation
2.500
2.000
1.500
1.000
0.500
0.000
-0.500
05/31 00:00
05/31 08:00
05/31 16:00
06/01 00:00
06/01 08:00
06/01 16:00
06/02 00:00
Date/Time (LST)
Wet Season
Dry Season
Time

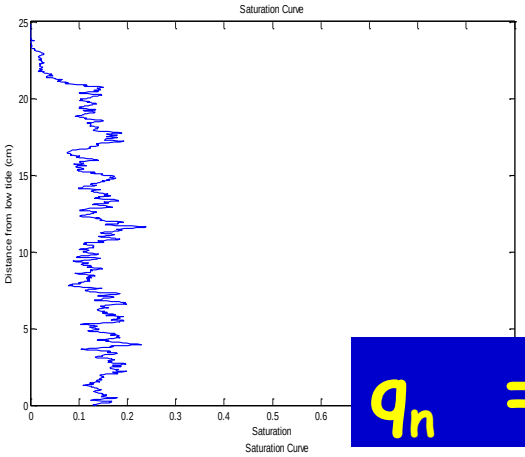
Additional Processes governing LNAPL behavior in Tidal aquifers

1) Both the k_n and the i_n terms are continually changing in response to the tidal fluctuations .
2) These changes are rapid enough that the aquifer never reaches equilibrium conditions.
3) In addition to the "horizontal smearing" that we see with LNAPL plumes in Non-Tidal aquifers, we now **also** have "vertical smearing", in Tidal aquifers.



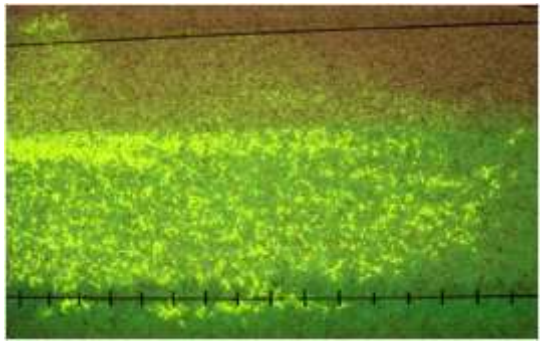


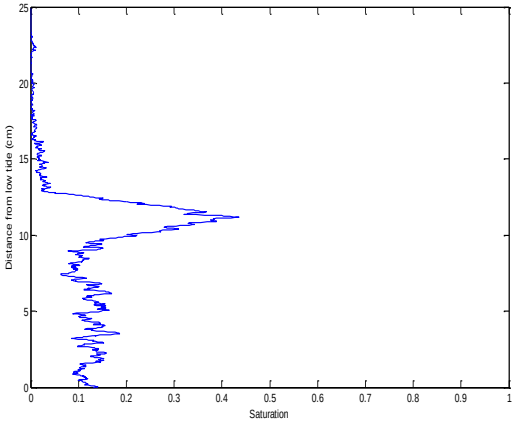




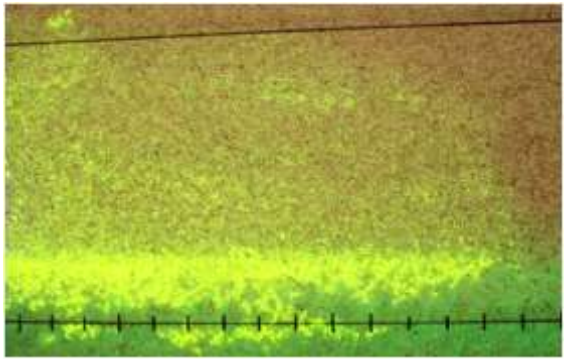
High Tide

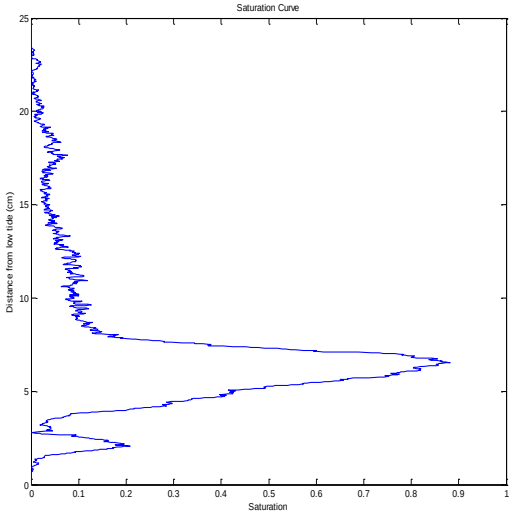
$$q_n = (k_n)\ (i_n)$$



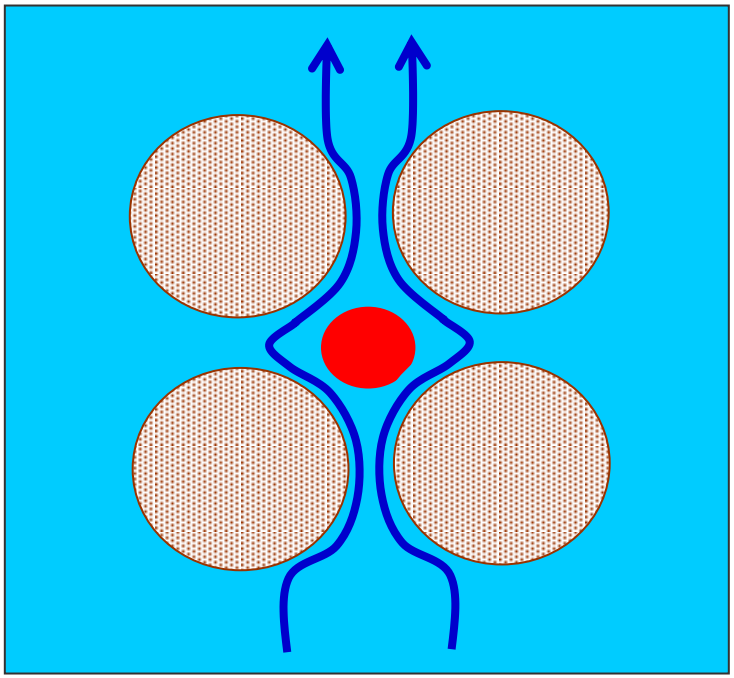


Rising (mid) Tide





Low Tide



Soil Particle

Air

Water

Oil

Groundwater flow

Additional Processes governing LNAPL behavior in Tidal aquifers

1) Both the k_n and the i_n terms are continually changing in response to the tidal fluctuations .
2) These changes are rapid enough that the aquifer never reaches equilibrium conditions.
3) In addition to the "horizontal smearing" that we see with LNAPL plumes in Non-Tidal aquifers, we now **also** have "vertical smearing", in Tidal aquifers.
4) [Soil has a capacity to hold oil against drainage / movement as residual oil. This means that an entire finite NAPL release will theoretically be retained as residual oil, at some maximum spreading distance.]

The combined effect of these additional processes means that in a Tidal aquifer we would expect that the maximum spreading distance where the entire plume could be theoretically retained as residual oil, would be reached more quickly.

Some practical bits for folks who have to manage NAPL plumes:

Some Talking Points

The presence of NAPL in a monitoring well MAY or MAY NOT indicate the presence of some "locally mobile" NAPL <u>in the vicinity</u> of that well.

Even if there is no measurable NAPL in a monitoring well, it is possible (and probably not uncommon), for there to be some NAPL in some of the pore spaces in the aquifer outside of that well bore:

- Capillary oil (< 1 atmosphere of pressure)
- NAPL at residual saturations (immobile)

Some Talking Points (continued):

While NAPL at the center of a plume may be able to move around within a narrow horizontal range, the edges of the plume are frequently immobile, and therefore, the plume as a whole can be considered stable.

One of the keys to determining the stability of the overall NAPL plume, therefore, is to focus on monitoring the **edges** of the plume.

Some Talking Points (continued):

As the potentiometric surface (PS) in an area changes (either rises or falls), the apparent NAPL thickness in a monitoring well will generally change in an inverse manner [i.e. increase as the PS falls, and decrease as the PS rises].

Removing mobile NAPL from monitoring wells does not <u>necessarily</u> reduce the <u>Magnitude</u> of the risk generated by the NAPL plume [though it may reduce the <u>Longevity</u> of the risk.]

Some Talking Points (continued):

The same factors that act to reduce the recoverability of a plume, also reduce the potential mobility of both the NAPL and dissolved phase components of that plume.

Some Talking Points (continued):

The issues related to the concepts of Risk, Mobility and Recoverability are all linked.

For example:

If the bulk of a NAPL plume is <u>not</u> recoverable, it is likely that the plume is immobile.

Some Practical Issues for Project Managers

1) The problem with Monitoring Wells:

"Monitoring wells are holes in the ground,
whose main purpose in life, is to lie to us!"
(John Wilson, EPA)

Some Practical Issues for Project Managers

2) In tidally influenced costal settings, the continually fluctuating water levels can have a significant effect on the movement of an LNAPL plume.

$$q_N = (K_N)\ (i_N)$$

Here are Some Things You Can Do with a Monitoring Well:

- You can measure the potentiometric surface.
- You can monitor for the presence of NAPL, ground water or vapor impacts.
- You can sample the NAPL, ground water or vapors.
- You can recover some of the NAPL, ground water or vapors.

Here are some things you Can't do with the measured apparent LNAPL thickness in a monitoring well:

You cannot use the measured thickness to calculate the "volume" of NAPL in the plume.

In the vast majority of cases, you cannot compare the measured NAPL thicknesses in different wells, and use those differences to draw conclusions about either which areas are more heavily impacted or which wells will yield more NAPL.

Here is a Complete List of the Things You Can Do with the Measured Apparent NAPL Thickness in a Monitoring Well:

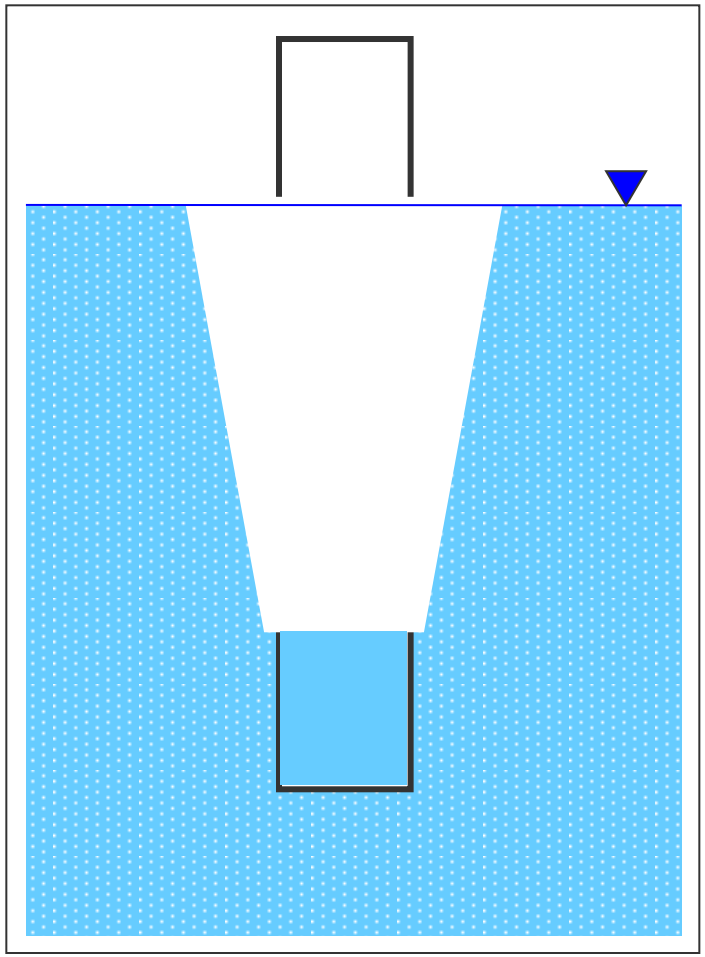
Any questions?

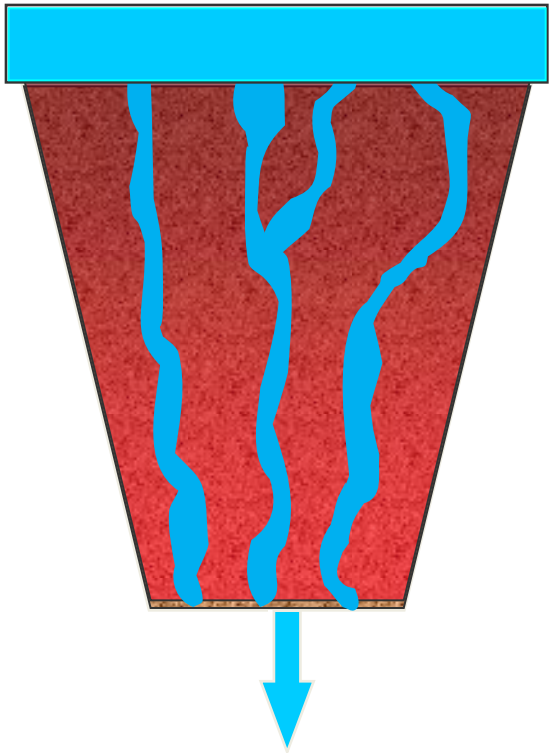
Check on the progress of our “Oil Spill” and Paper Towel Experiments

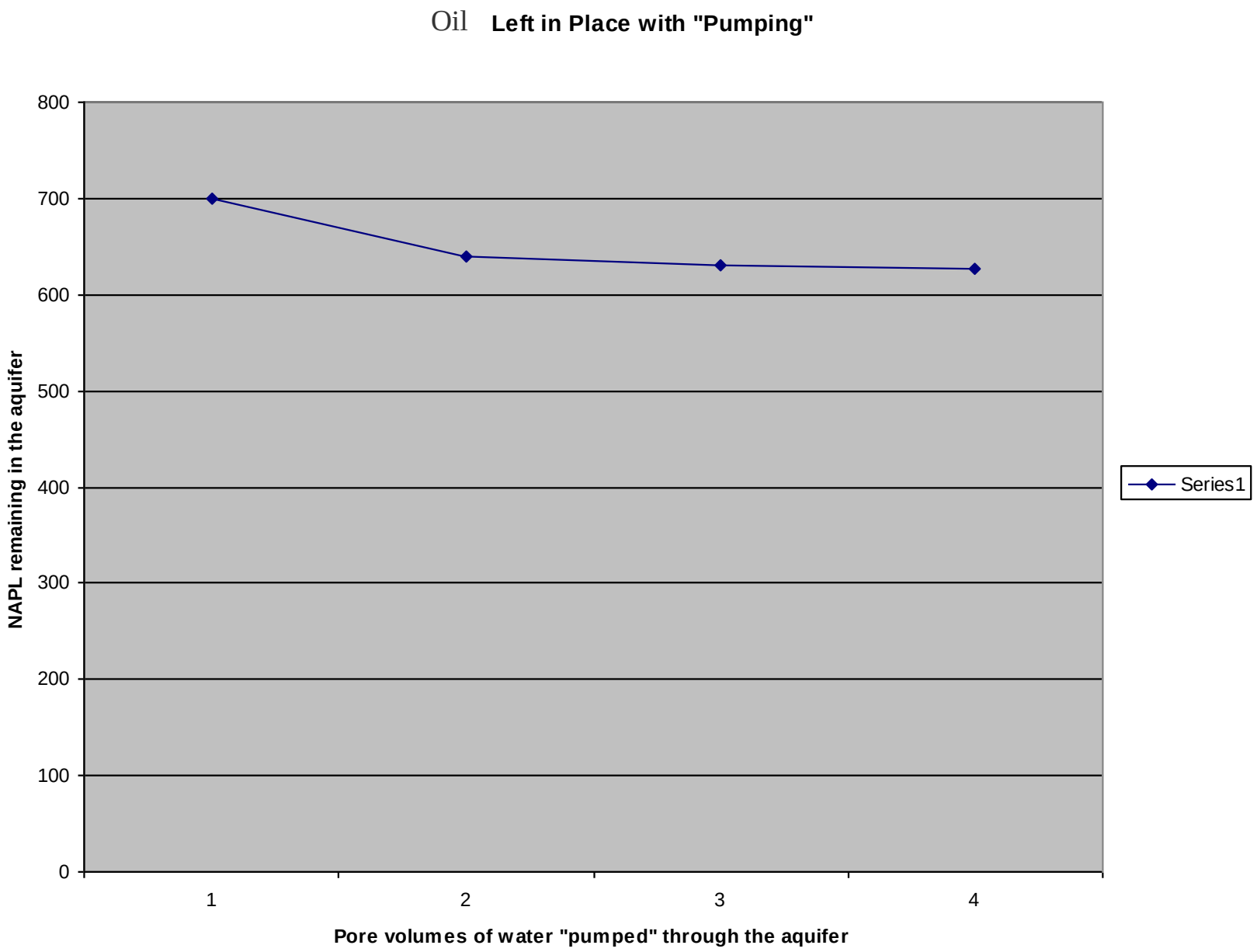
1) How much Oil was “Recovered “ (drained from the cup)?

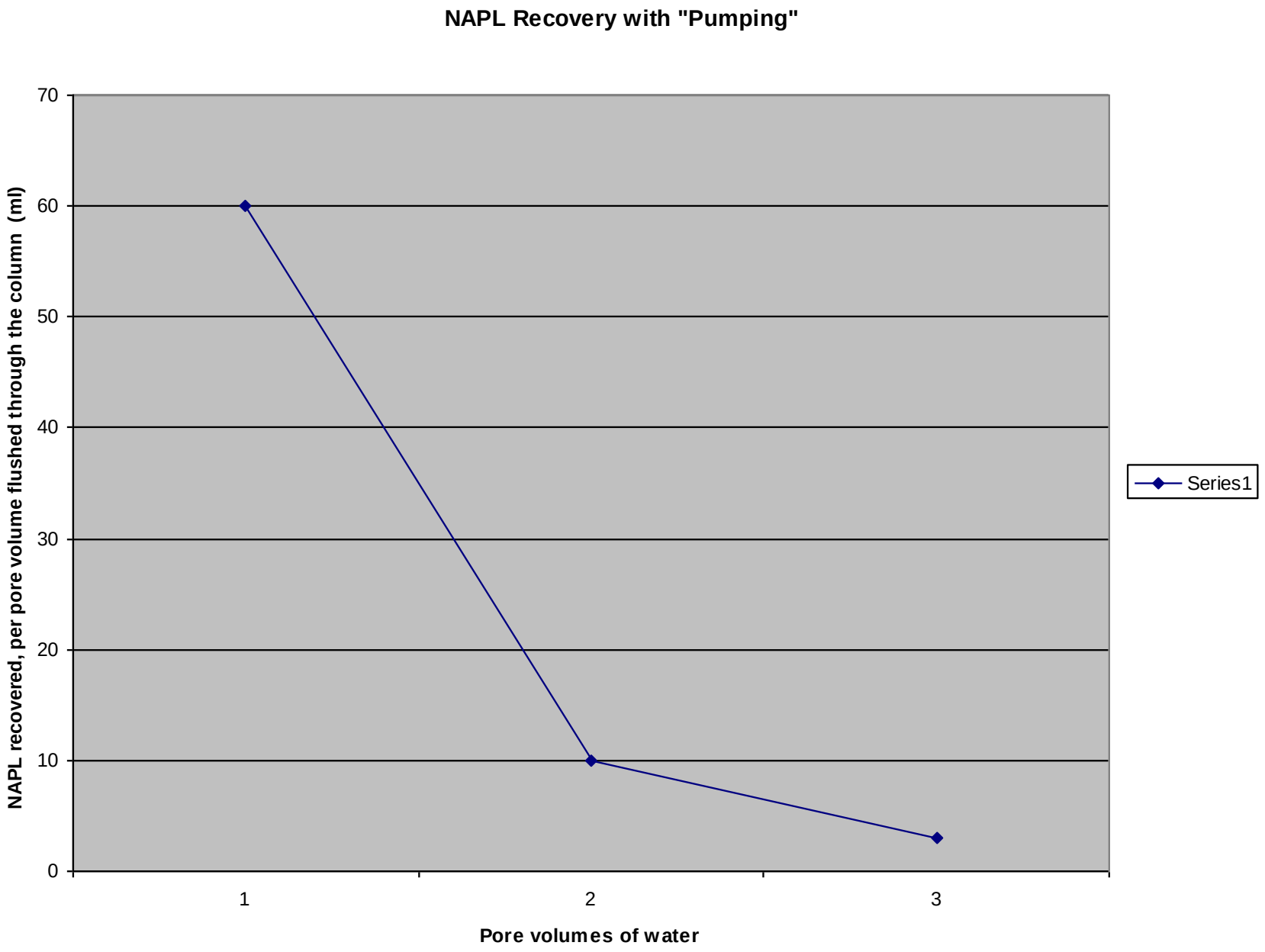
2) What was the “fate” of our contaminant plume?

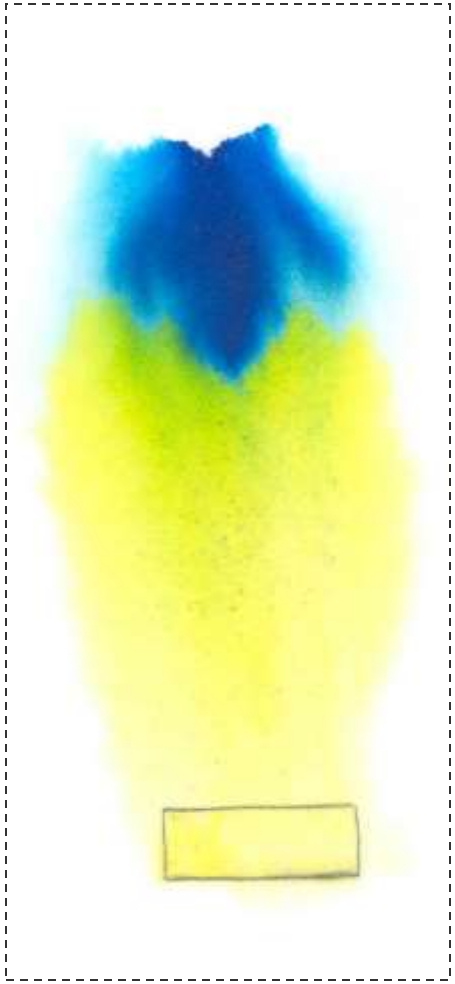
General Shape of a Drawdown Cone for a Pumping Well



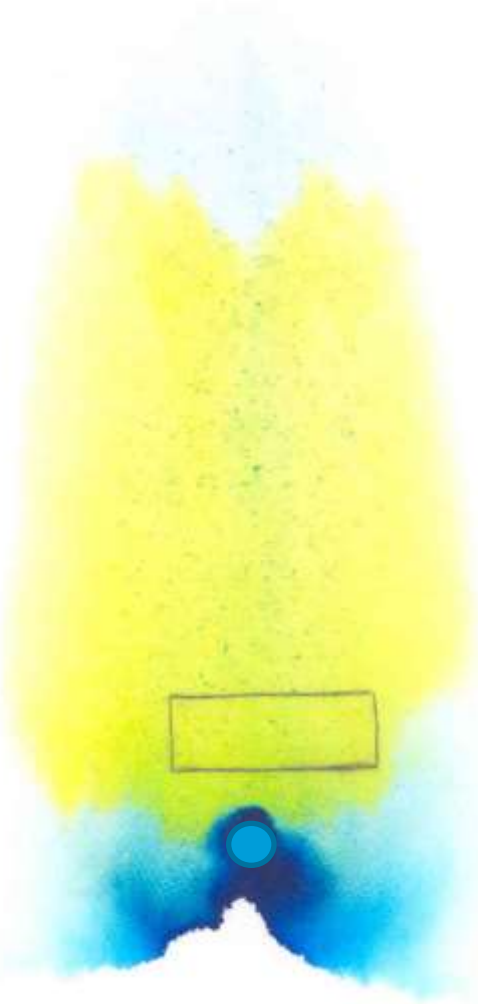








A



Quick Summary and Key Points

1) In the "Early Years", we stumbled quite a bit . . . But, as we've done more research on the movement of shallow NAPL plumes AND, as we have gathered more actual data in the field, then our understanding of how shallow NAPL plumes behave, has both evolved and improved.

Quick Summary and Key Points

2) We now have a body of both theoretical work and actual field data, which suggests that NAPL plumes generated by **finite** releases of NAPL, will stabilize over time (i.e. become immobile).

3) For NAPL plumes located in coastal (i.e. tidally influenced) areas, there are some additional factors that help to stabilize these even more quickly.

Quick Summary and Key Points

4) The same factors that cause NAPL plumes (from finite releases) to stabilize, also inhibit our ability to continue recovering the NAPL, once NAPL saturations in the plume have dropped below "residual" NAPL saturation" levels.

5) When thinking about the potential mobility of a NAPL plume, keep focused on this equation:

$$q_n = (k_n)\ (i_n)$$

Questions?