Variable Rate Irrigation
UNIVERSITY OF NEBRASKA-LINCOLN
Biological Systems Engineering

Water for Food
ROBERT B. DAUGHERTY INSTITUTE
University of Nebraska

Water, Energy and Agriculture Initiative
WEAI

Variable Rate Irrigation (VRI): Principles and Lab Setup

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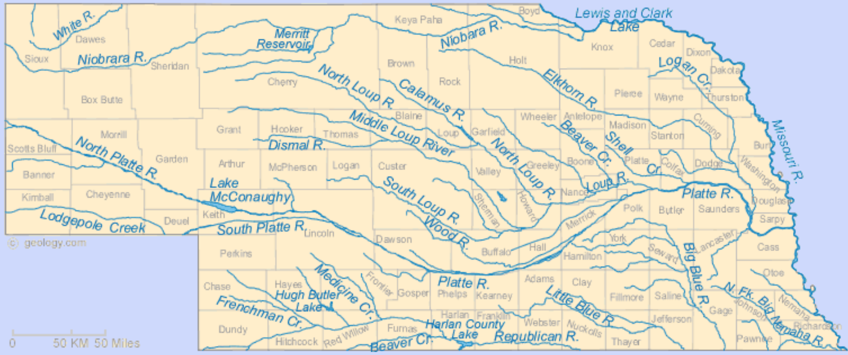
MSYM/AGRO/HORT 452/852, November 16, 2015

Watershed Scale Management

- **Water quality**
  - **Over-irrigation results in contamination of groundwater and surface water**



- **Consumptive use (ET)**
  - **Long term streamflow = precipitation – consumptive use**
  - **Allocations**
  - **VRI probably doesn't change consumptive use, but may help farmers optimize production with limited water**

Farm Scale Management

- **Maximize profits**
- **React to water shortages:**
  - **Water allocations**
  - **Limited pumping rate or load control**

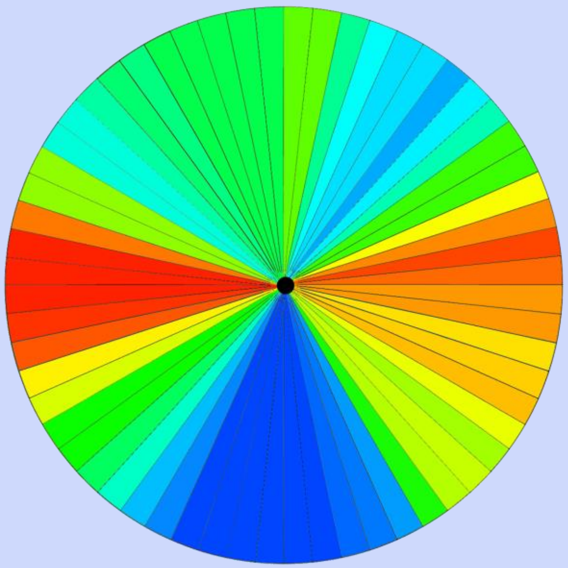
- **Response**
  - **Increase water use efficiency (WUE) or water productivity**
  - **What tools might help?**

Should Water be Managed Spatially?

- Irrigation related variables that vary spatially:
  - Soils
  - Topography
  - Yield
- Crop inputs which can vary spatially:
  - Nutrients
  - Population
  - Hybrid
- So, does the irrigation requirement vary spatially?
- Goal: avoid over-watering and under-watering

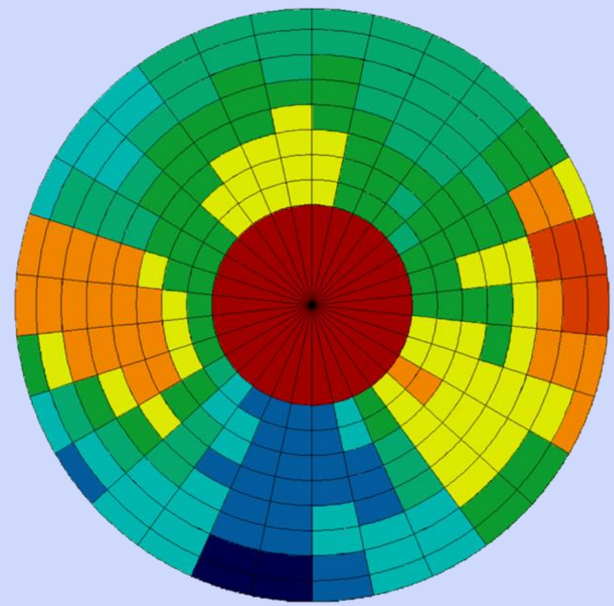
What is Variable Rate Irrigation (VRI)?

Sector/speed control:



Total Cost: ~$3,000
(free with some new panels)

Zone control:



Total Cost: ~$16,000+

Video Demonstration:
https://www.youtube.com/watch?v=u831kWRGVUk

Credit: Valmont

Disclaimer: UNL doesn't endorse any particular brand of irrigation equipment.

Variable Rate Irrigation

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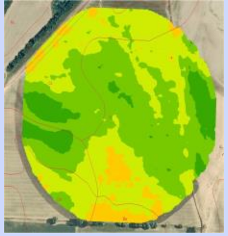
Common data layers:

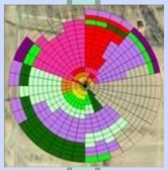
- Soils maps (including EC/EM)
- Grid sampling data
- Yield map
- Aerial image
- Elevation (DEM)

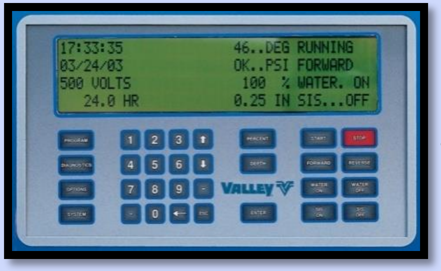


VRI-Zone Control

VRI Rx Generation

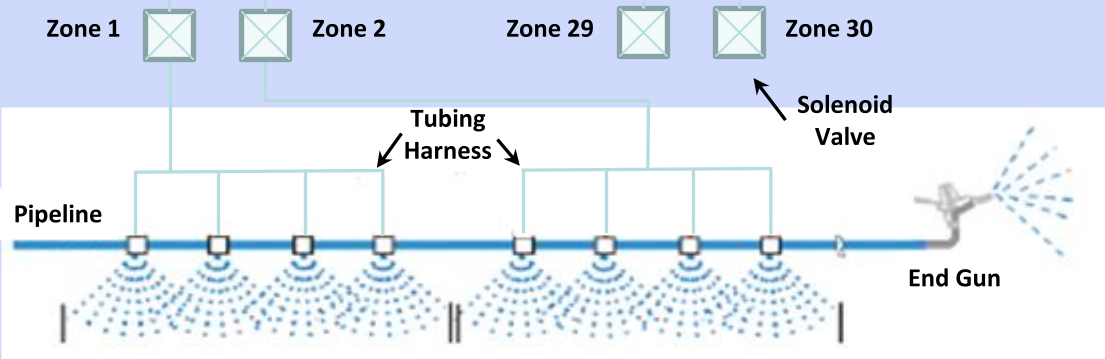
VRI Map Download





PRO2 Panel

Existing Span Cable



- On/off control for non-cropping areas and/or pulse control
- Simple design utilizing existing, already installed components
- No additional wiring (plug-and-play connection to existing span cable)

Credit: Jake LaRue

Variable Rate Irrigation

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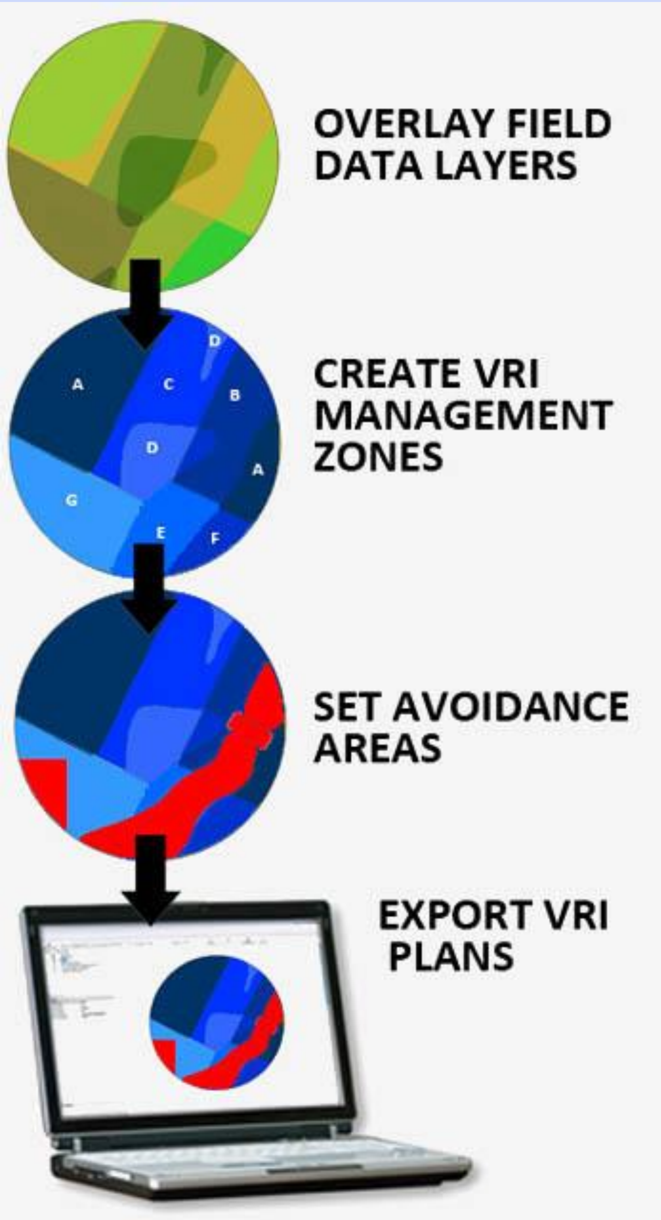
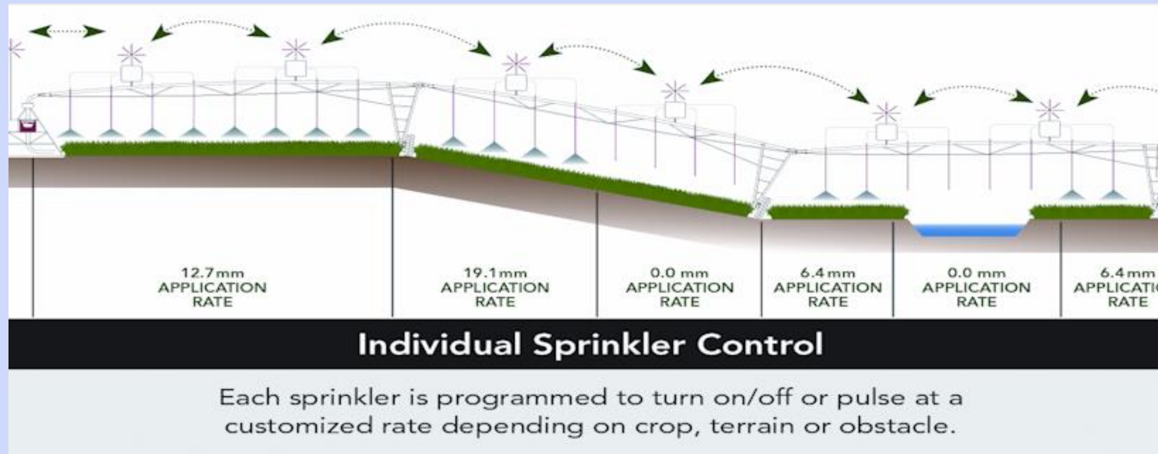
FieldMAP Software





Credit: Precision Irrigation, Lindsay Corporation

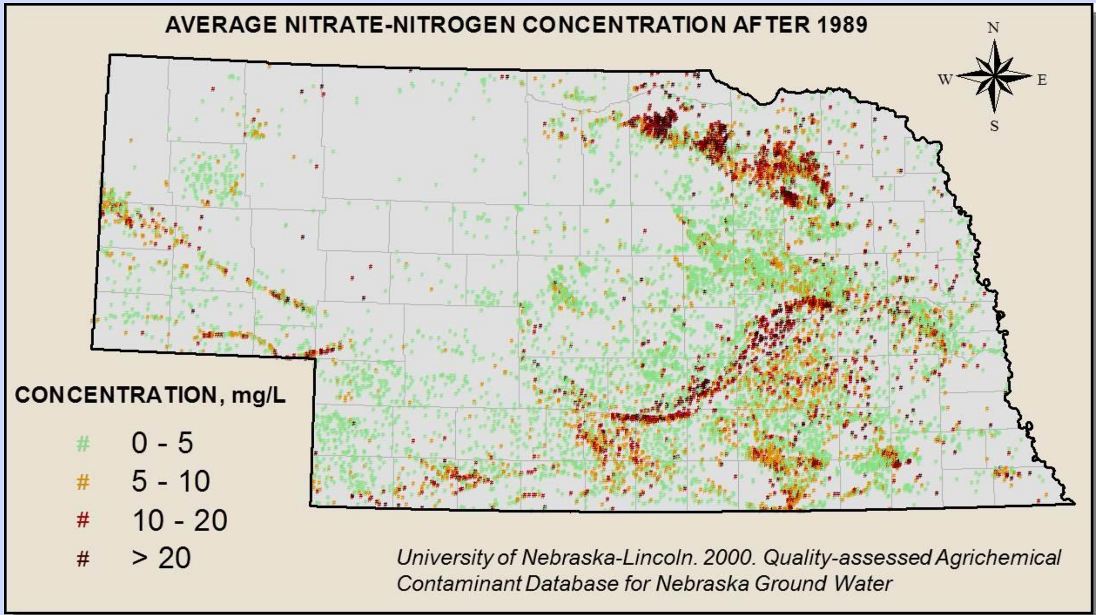
Potential Benefits of VRI

- Avoid putting chemical/liquid manure on waterways (create an “avoidance area”)
- Reduce pumping
  - Energy savings
  - Reduce nitrate leaching
- Prevent pivot from getting stuck
- Reduce yield losses due to over-irrigation
- Reduce water application rates on steep slopes (reduce runoff/erosion)
- More yield with given water allocation

Reduced Nitrate Leaching

- **Hypothesis:**
  - **Well managed VRI reduces over irrigation and deep percolation**

- **Reductions in N leaching have been estimated but not yet measured**



University of Nebraska-Lincoln. 2000. Quality-assessed Agrichemical Contaminant Database for Nebraska Ground Water

Manage N and Water Together?

- Research at UNL (Ferguson, Irmak et al.) investigated the science behind this
- They observed interactions between applied N and crop water use
- Future research will investigate management practices

Rudnick & Irmak (2014a)

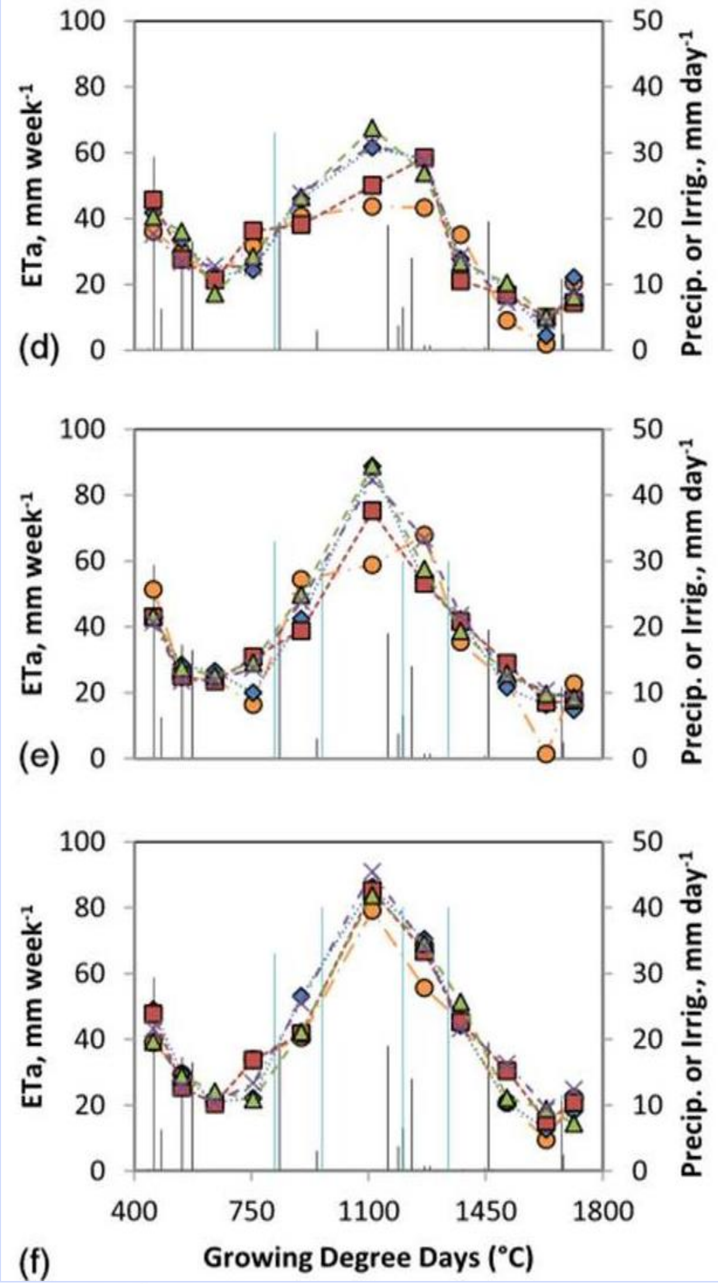
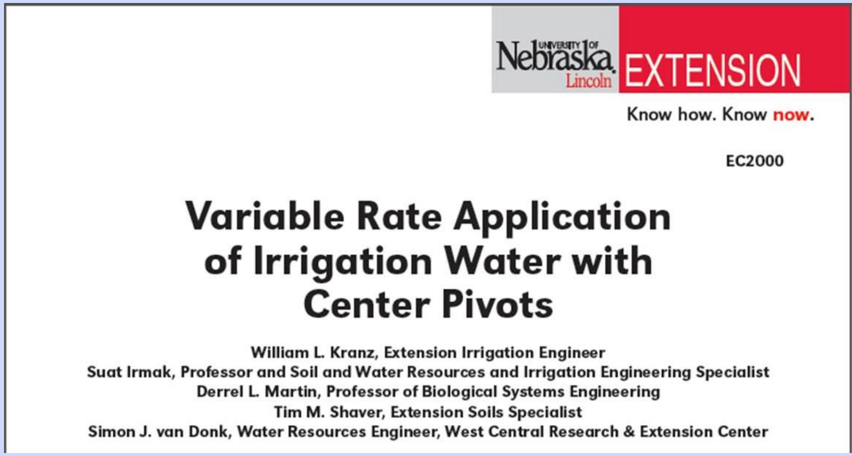


Fig. 2. Weekly to biweekly actual evapotranspiration (ET_a) trends for 0, 84, 140, 196, and 252 kg ha^{-1} nitrogen (N) treatments under (a) rainfed; (b) limited irrigation (75% FIT); (c) FIT conditions as measured by the soil water balance method in 2011 and under (d) rainfed; (e) 75% FIT; (f) FIT conditions as measured by the soil water balance method in 2012; in addition, daily precipitation and irrigation events are included

UNL Extension Publication

- **How the technology works**
- **Block v. sprinkler control**
- **Transition zones**
- **Pump efficiency & VFD**
- **Potential for water and energy conservation**


University of Nebraska Lincoln EXTENSION
Know how. Know now.
EC2000

Variable Rate Application of Irrigation Water with Center Pivots

William L. Kranz, Extension Irrigation Engineer
Suat Irmak, Professor and Soil and Water Resources and Irrigation Engineering Specialist
Derrel L. Martin, Professor of Biological Systems Engineering
Tim M. Shaver, Extension Soils Specialist
Simon J. van Donk, Water Resources Engineer, West Central Research & Extension Center

Kranz et al. (2014)

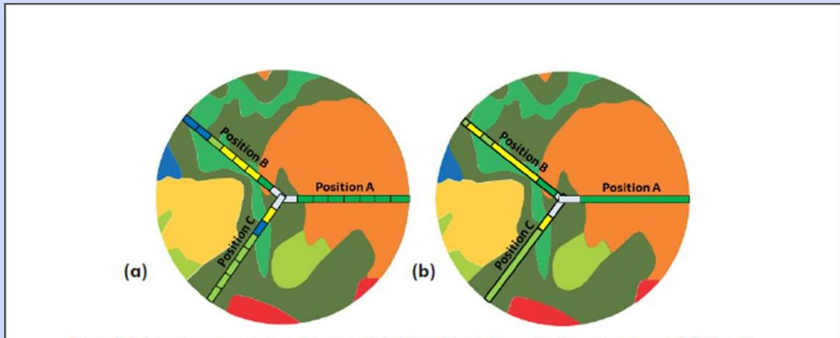
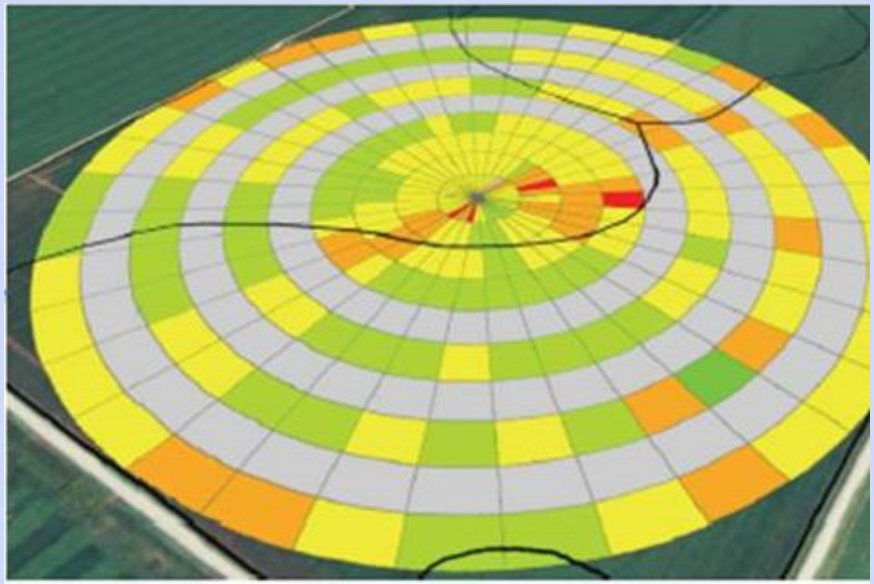


Figure 3. Schematic representation of the potential ability of the water application system to match field conditions when using the block of sprinklers (a) and individual sprinkler (b) control approach to VRI.

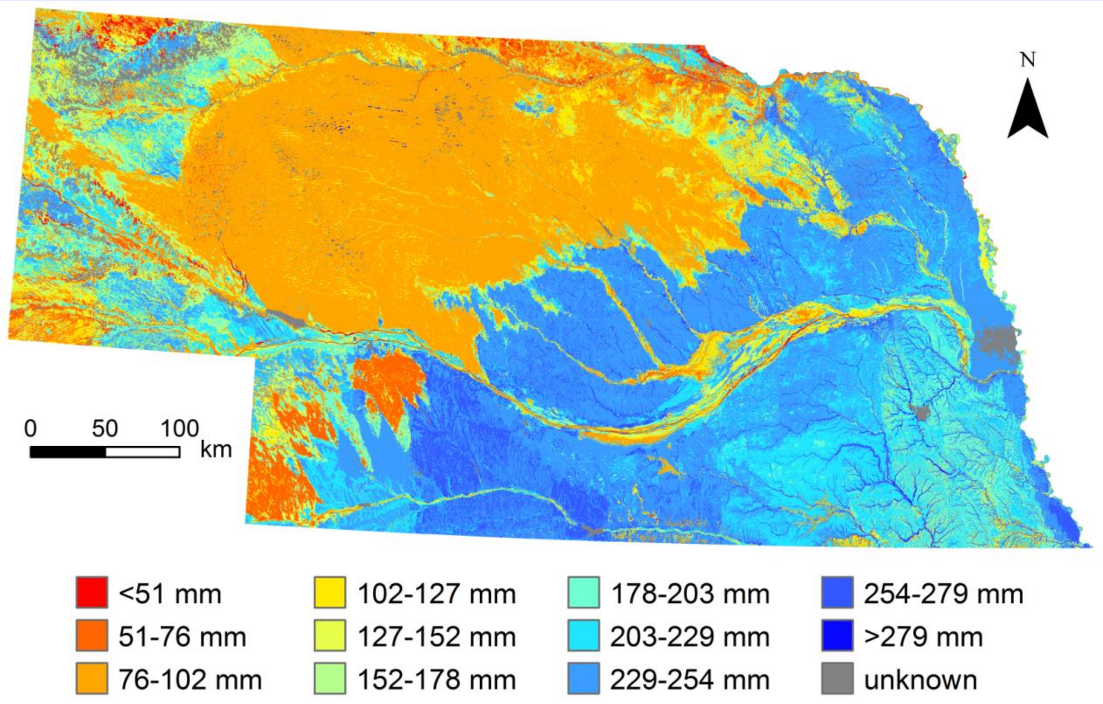
Producers Can Compare Yields

- **Utilize yield monitor data**
- **Keep part of field in uniform irrigation (gray)**
  - Rings or sectors
- **Compare yields and water use**
- **Then decide whether to invest in additional VRI systems**



Which Fields Might Benefit from VRI?

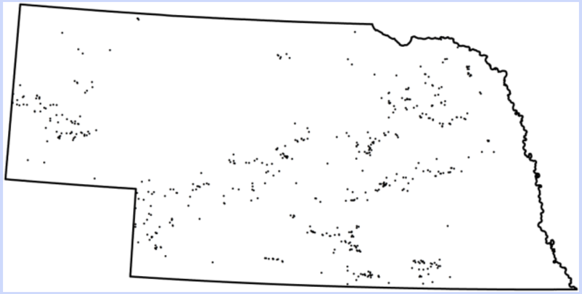
- GIS analysis using NRCS SSURGO data shows regional differences in ‘R’ variability across the state



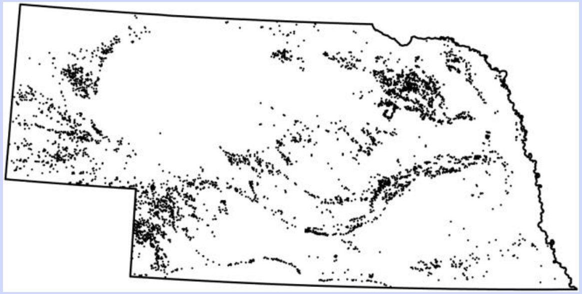
T. H. Lo thesis (2015)

How many pivots in Nebraska could be affected?

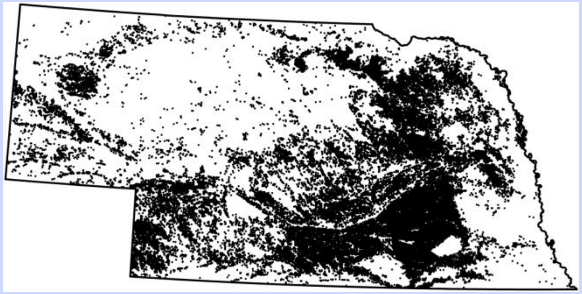
- 49,224 center pivots analyzed,
- Variability in ‘R’ was classified



High (1%), unutilized ‘R’ >4 in



Medium (10%), unutilized ‘R’ >2 in and <4 in

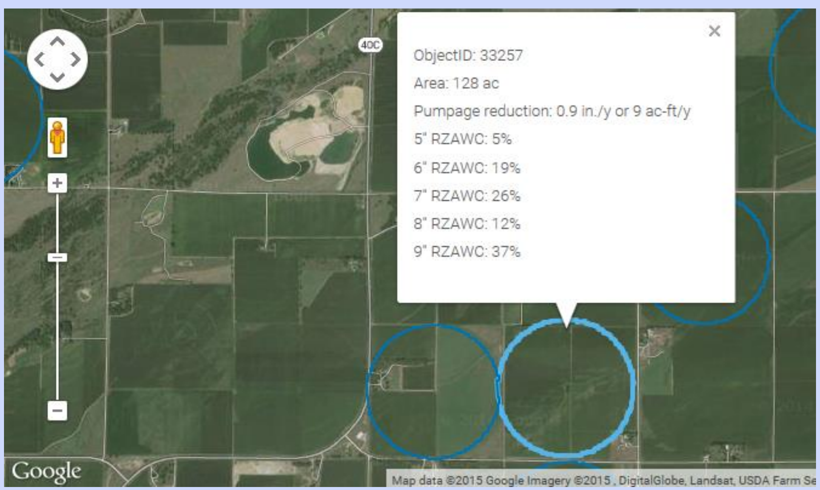


Low (89%), unutilized ‘R’ <2 in

T. H. Lo thesis (2015)

Developing a Tool for Public Use

- Statewide website for field-specific economic support of VRI pumping savings



T. H. Lo thesis (2015)

5000
Annual Total Variable Cost of Pumping ($)

120
Annual Total Volume of Pumping (ac-ft)

120
Irrigated Area (ac)

2
Annual Pumpage Reduction from Mining Unutilized RZAWC According to Map (in.)

5
Annual Interest Rate (%)

10
Amortization Period (years)

CALCULATE

Another online VRI savings calculator:

https://www.precisionirrigation.co.nz/save

By Precision Irrigation

VRI Investment/Affordability

- Compare present value of VRI benefits with VRI total cost
- If VRI for 124 ac costs $20,000 and is paid for entirely by one benefit:

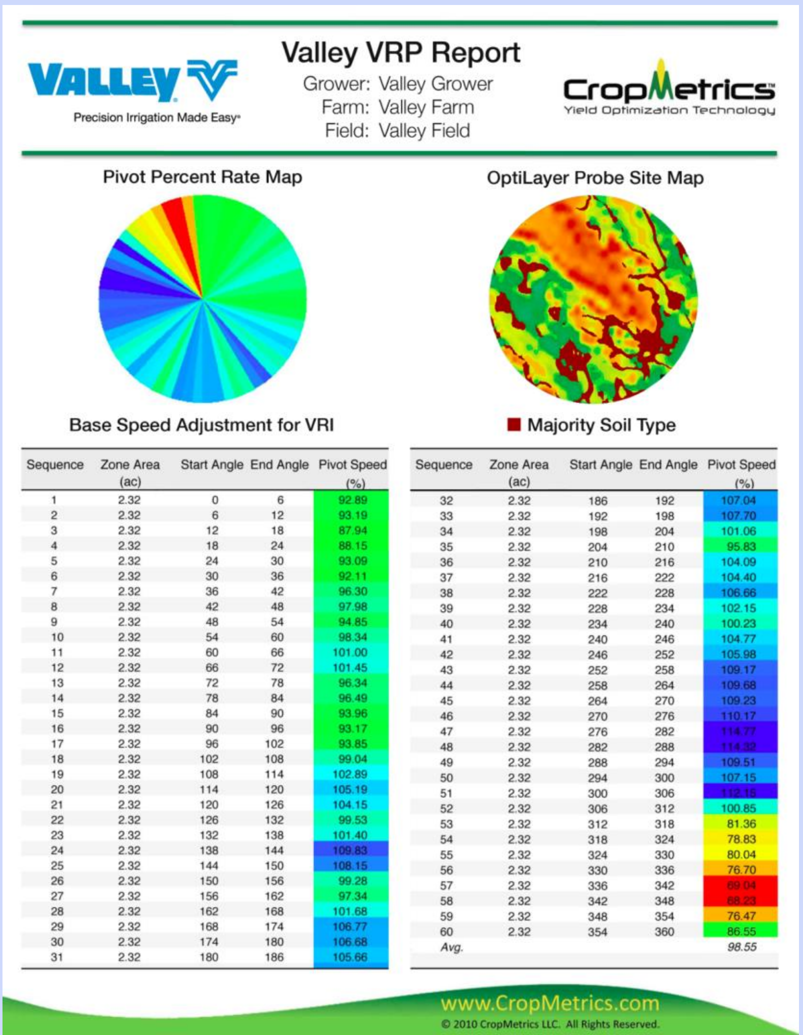
Category of VRI benefit	Example price	Annual field-average change at breakeven
irrigation cost reduction	$3/ac-ft of gross irrigation	-78” of gross irrigation
	$117/ac-ft of gross irrigation	-2” of gross irrigation
agrochemical cost reduction	47¢/lb of N	-44 lb/ac of N
	66¢/lb of N	-32 lb/ac of N
yield benefit increase	$5.30/bu of corn at 15.5% moisture	+4 bu/ac of corn at 15.5% moisture

(interest rate of 5% and amortization period of 10 years)

Based on economics at the farm gate, increasing yield is the most likely way to pay for a zone control VRI system

T. H. Lo thesis (2015)

Prescription Maps



Valley VRP Report

VALLEY Precision Irrigation Made Easy

Grower: Valley Grower
Farm: Valley Farm
Field: Valley Field

CropMetrics Yield Optimization Technology

Pivot Percent Rate Map

OptiLayer Probe Site Map

Base Speed Adjustment for VRI

Majority Soil Type

Sequence	Zone Area (ac)	Start Angle	End Angle	Pivot Speed (%)
1	2.32	0	6	92.89
2	2.32	6	12	93.19
3	2.32	12	18	87.94
4	2.32	18	24	88.15
5	2.32	24	30	93.09
6	2.32	30	36	92.11
7	2.32	36	42	96.30
8	2.32	42	48	97.98
9	2.32	48	54	94.85
10	2.32	54	60	98.34
11	2.32	60	66	101.00
12	2.32	66	72	101.45
13	2.32	72	78	96.34
14	2.32	78	84	96.49
15	2.32	84	90	93.96
16	2.32	90	96	93.17
17	2.32	96	102	93.85
18	2.32	102	108	99.04
19	2.32	108	114	102.89
20	2.32	114	120	105.19
21	2.32	120	126	104.15
22	2.32	126	132	99.53
23	2.32	132	138	101.40
24	2.32	138	144	109.83
25	2.32	144	150	108.15
26	2.32	150	156	99.28
27	2.32	156	162	97.34
28	2.32	162	168	101.68
29	2.32	168	174	106.77
30	2.32	174	180	106.68
31	2.32	180	186	105.66

Sequence	Zone Area (ac)	Start Angle	End Angle	Pivot Speed (%)
32	2.32	186	192	107.04
33	2.32	192	198	107.70
34	2.32	198	204	101.06
35	2.32	204	210	95.83
36	2.32	210	216	104.09
37	2.32	216	222	104.40
38	2.32	222	228	106.66
39	2.32	228	234	102.15
40	2.32	234	240	100.23
41	2.32	240	246	104.77
42	2.32	246	252	105.98
43	2.32	252	258	109.17
44	2.32	258	264	109.68
45	2.32	264	270	109.23
46	2.32	270	276	110.17
47	2.32	276	282	114.77
48	2.32	282	288	114.32
49	2.32	288	294	109.51
50	2.32	294	300	107.15
51	2.32	300	306	112.16
52	2.32	306	312	100.85
53	2.32	312	318	81.36
54	2.32	318	324	78.83
55	2.32	324	330	80.04
56	2.32	330	336	76.70
57	2.32	336	342	69.04
58	2.32	342	348	68.23
59	2.32	348	354	76.47
60	2.32	354	360	86.55
Avg.				*98.55*

www.CropMetrics.com

How do we develop dynamic prescription maps?

CropMetrics, North Bend, NE

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Unmanned Aircraft Systems (UAS)

- **Tempest fixed-wing aircraft**
- **On board sensing**
  - **Visual images**
  - **Thermal for crop water stress**
  - **Multispectral for crop coefficient**
  - **i.e. calculate ET spatially**

In collaboration with Burdette Barker, Wayne Woldt, Christopher Neale, George Meyer, Yufeng Ge, et al.

Figure 2. The Tempest unmanned aircraft system ready for agricultural research.

Figure 3. Preparing the Tempest for an agricultural test flight.

Cosmic Ray Probes (CRP)

- **Measures volumetric water content (VWC) in top ~1 ft**
- **About 1000 ft diameter footprint**
- **Phase 1:**
  - **Mounted on the pivot lateral**

In collaboration with
Trenton Franz

Cosmic Ray Probes (CRP)

- **Phase 2:**
  - **Stationary & mobile CRPs**
- **Spatial VWC**
- **Then create prescription maps**

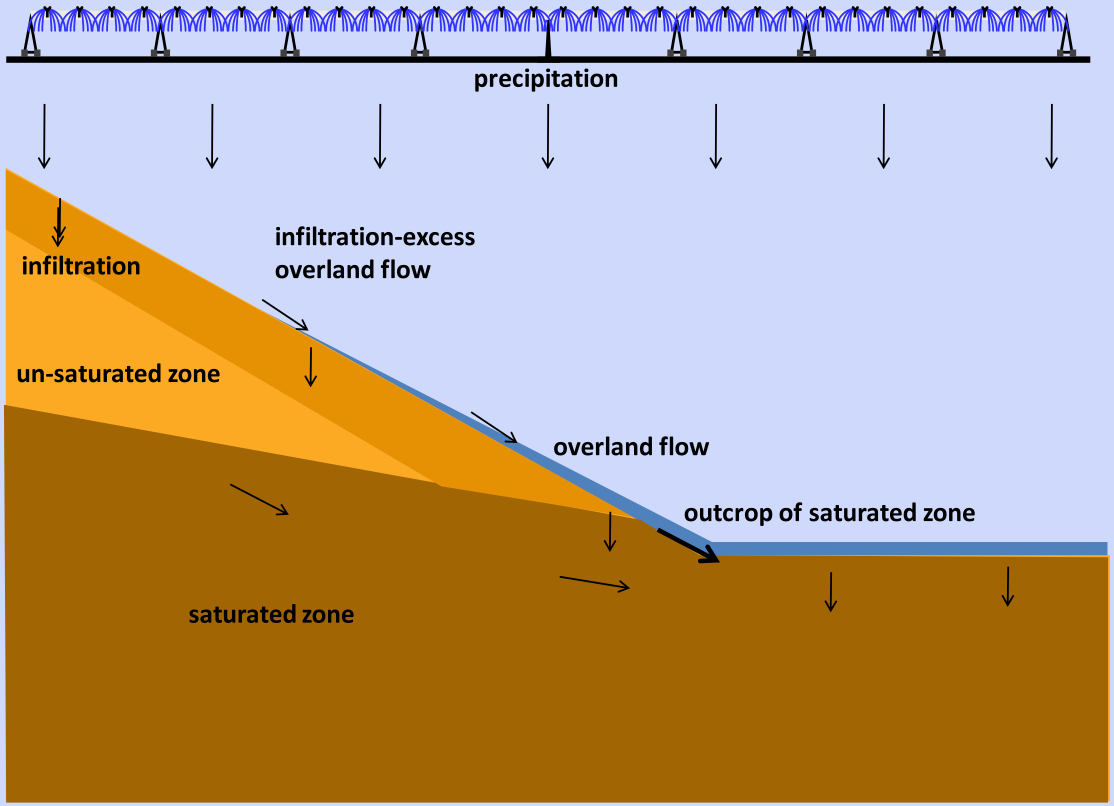
ARDC VWC Movie.avi

In collaboration with
Trenton Franz

Side-by-side with CRP rover.
Also towing a Dualem 21S for EM.

Account for topography?

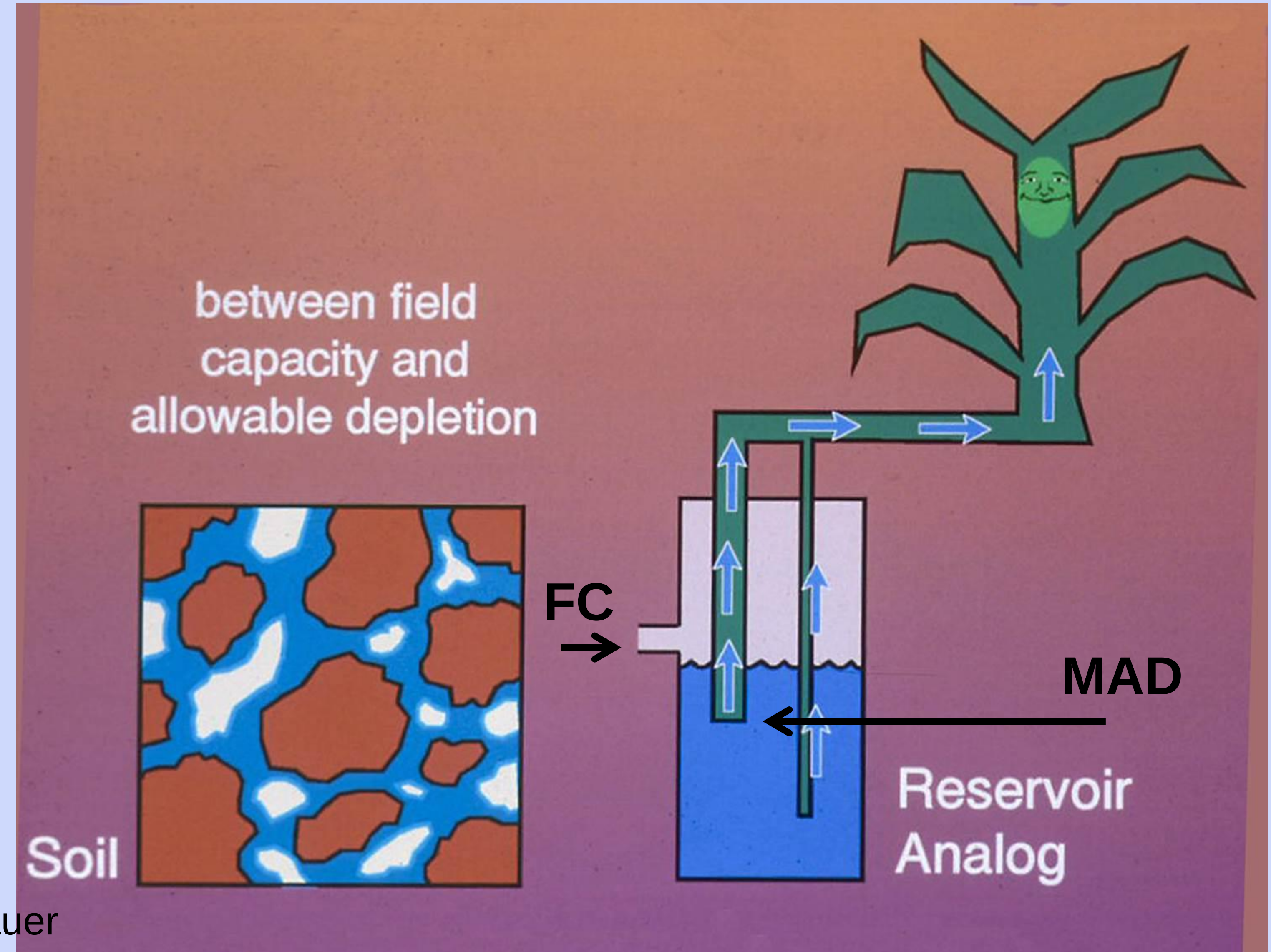
- Infiltration, runoff, runon, infiltration



Difficult to model these hydrological processes with sufficient accuracy for prescription maps

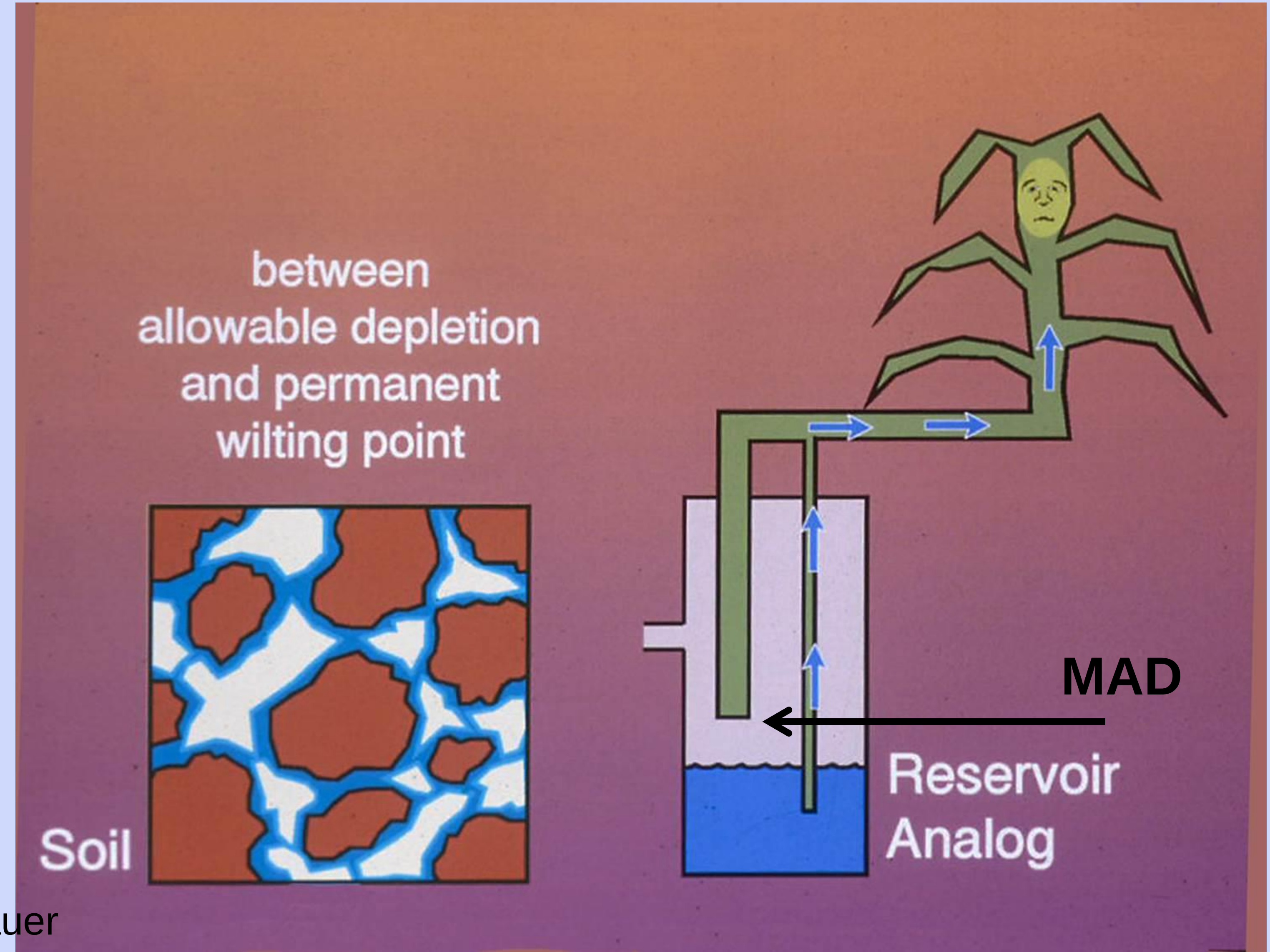
Luciano Mateos

A Quick Review: FC



Eisenhauer

A Quick Review: MAD



Eisenhauer

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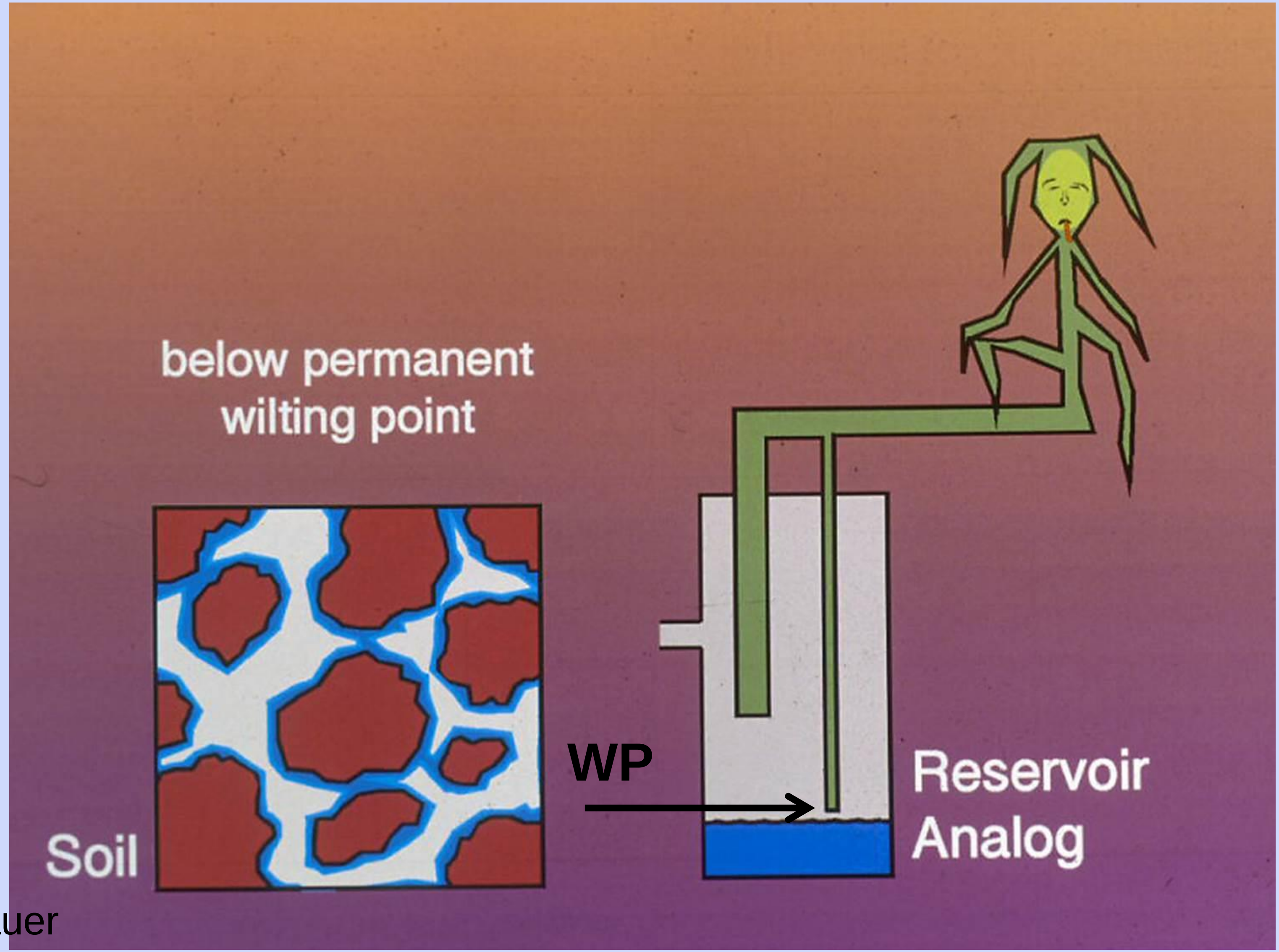
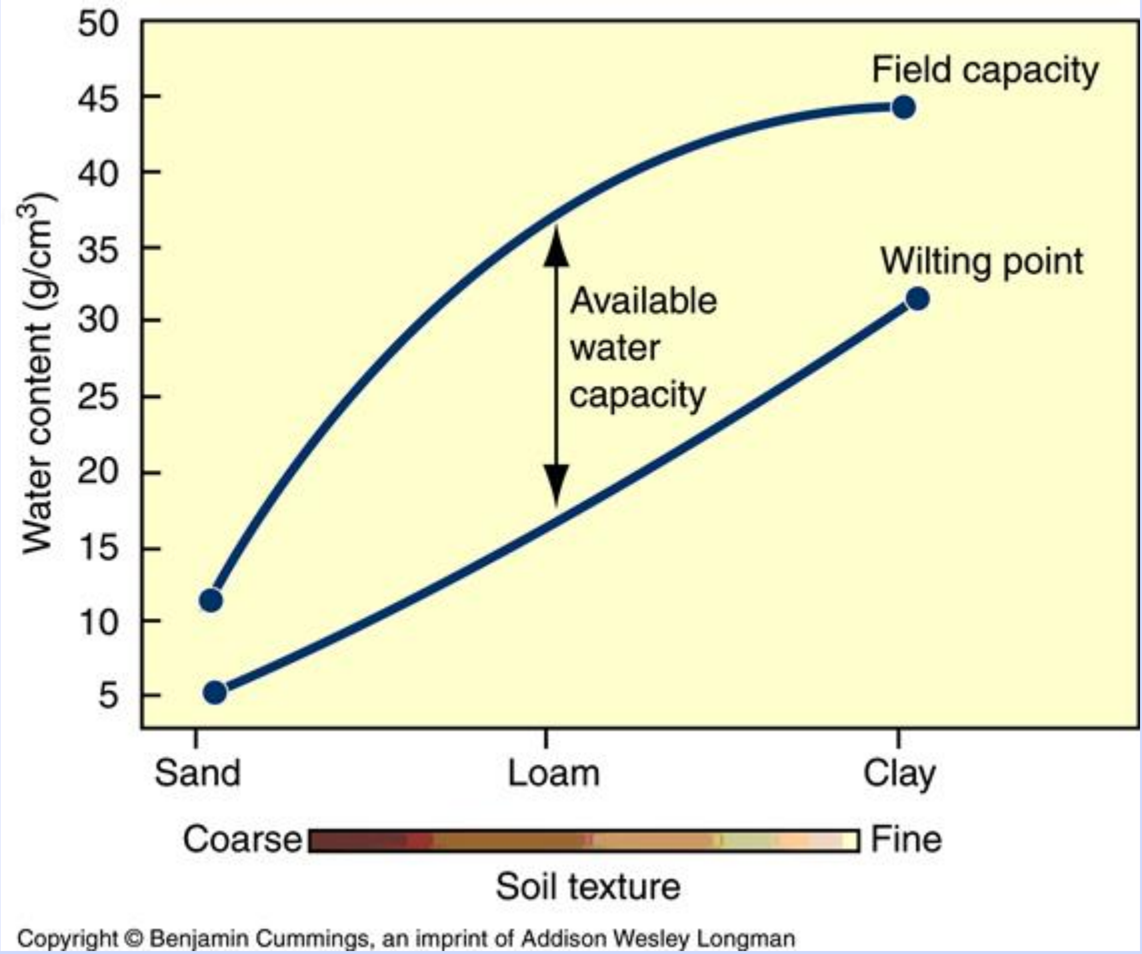
A Quick Review: WP



Eisenhauer

Root Zone Water Holding Capacity (R)

- Depends on soil type
- A critical variable for irrigation scheduling
- Field observed FC may be higher due to:
  - Layering
  - Compacted layers
  - WT



Electrical Conductivity (EC)

- **EC can be correlated to FC, PWP, or R**
- **Doesn't work in all fields**

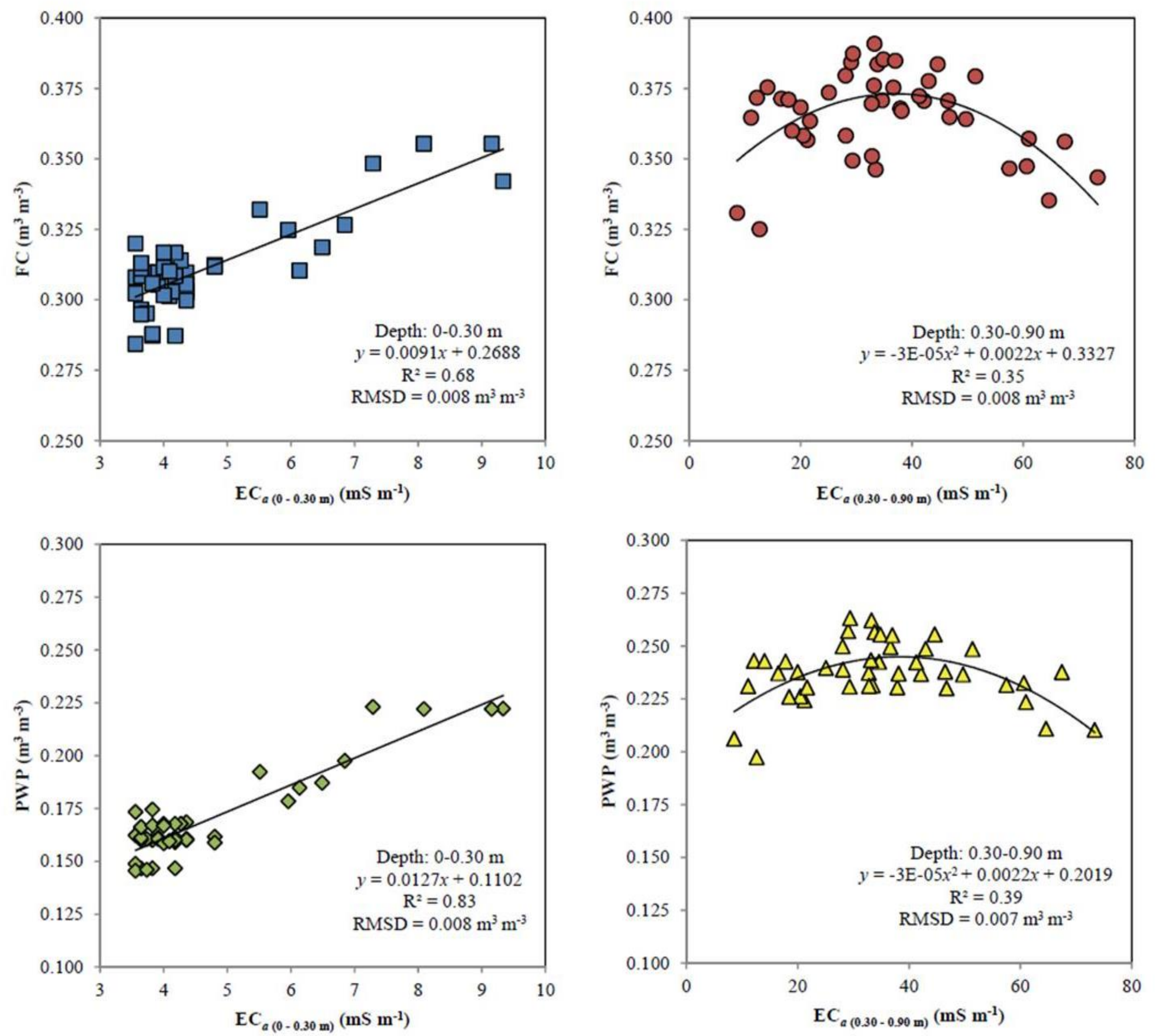
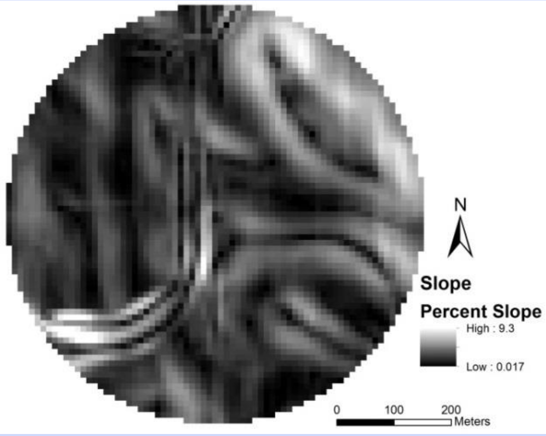


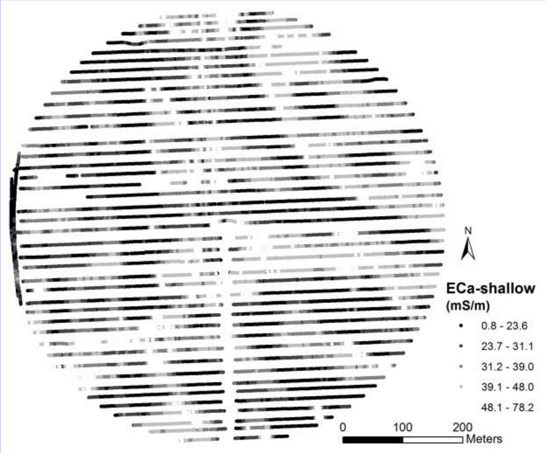
Figure 5. Relationships between EC$_{a(0-0.30m)}$ and FC at 0 to 0.30 m and between EC$_{a(0.30-0.90m)}$ and FC averaged between 0.30 and 0.90 m depth at SCAL in 2012.

Rudnick & Irmak (2014b)

WEAI Project: Field Data Collection

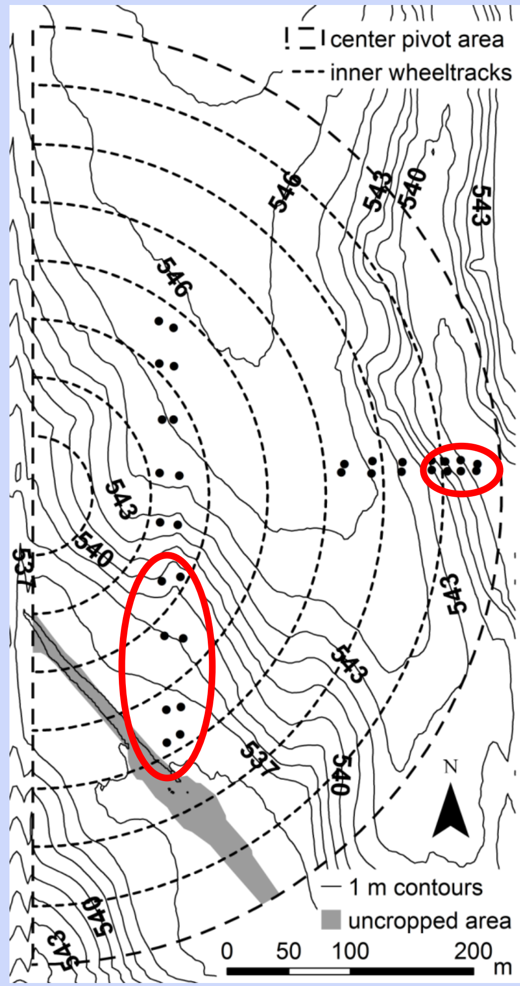
- Multiple spatial data layers were used to quantify variation across study fields
- Electrical Conductivity (EC)
- Digital Elevation Model (DEM) from LiDAR
- Field Observed Root Zone Water Holding Capacity (R)

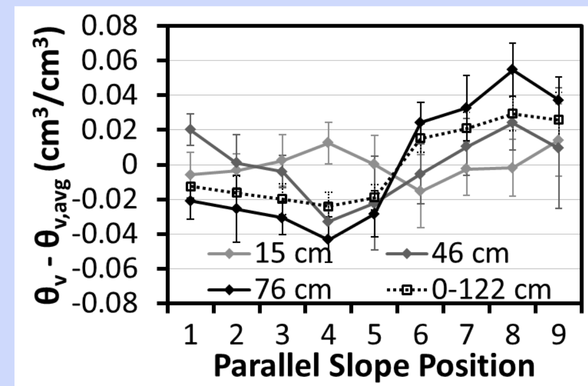


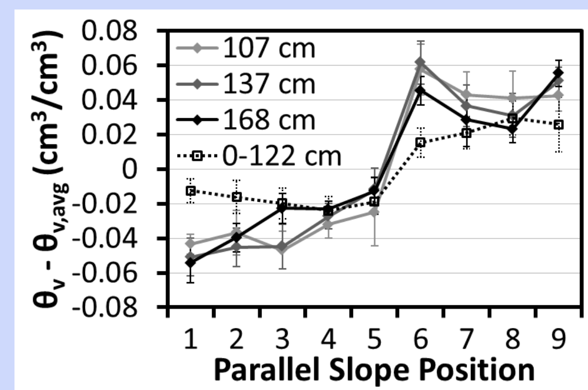


Wiper pivot near Aurora, NE

- Subsoil ‘R’ measurements were higher in concave slope locations
- This showed that variability in ‘R’ could be utilized



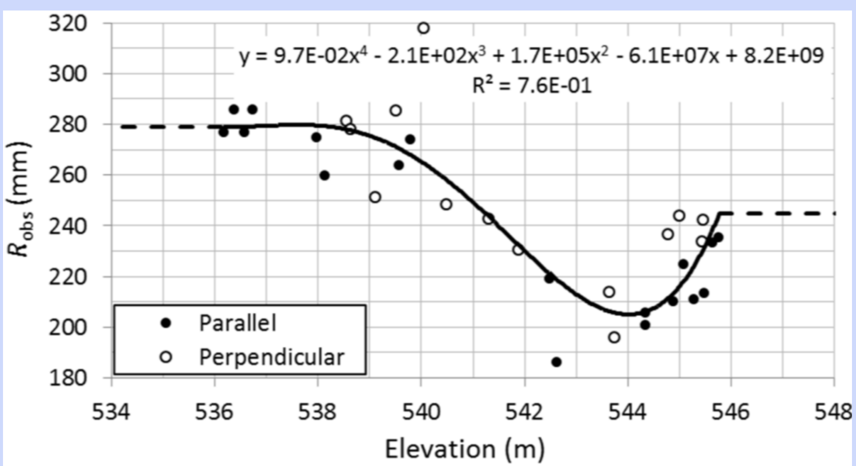


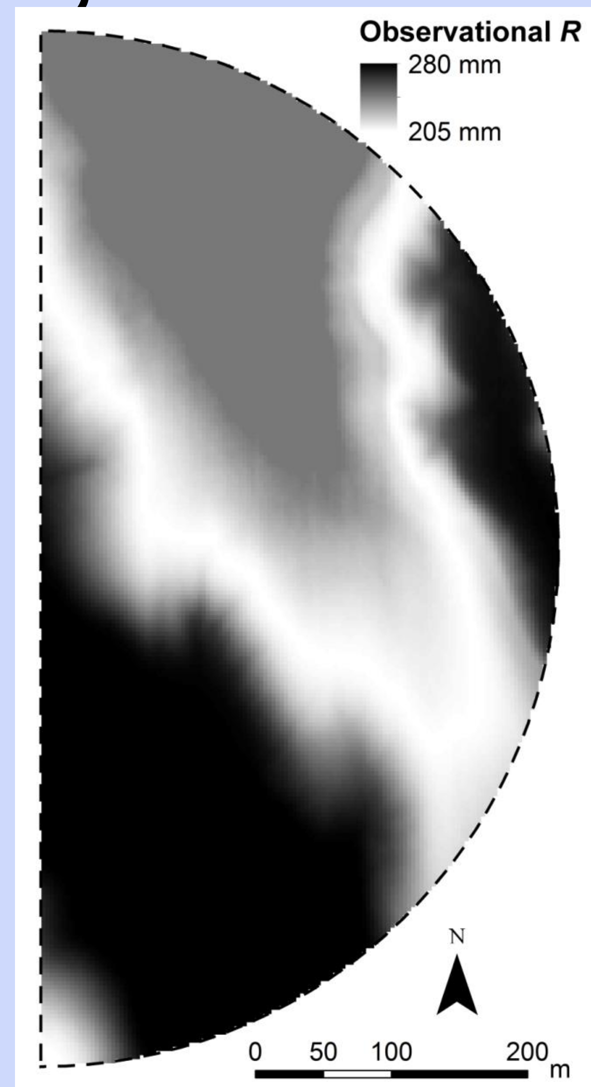


T. H. Lo thesis (2015)

Wiper pivot near Aurora, NE

- For this field, a strong relationship with elevation was noted
- ‘R’ versus piecewise elevation was used to generate a map
- Will be used to inform prescription maps in the VRI lab

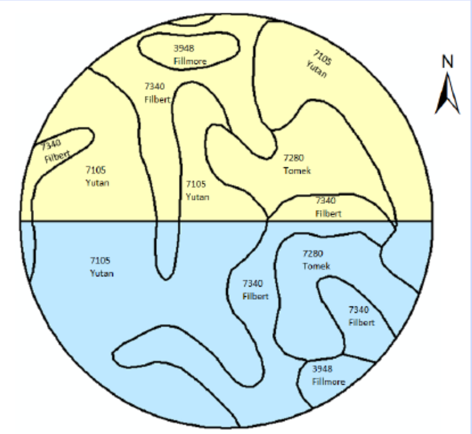


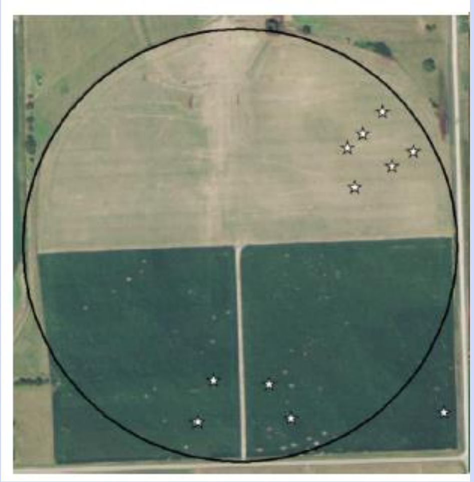


Lo (2015)

ARDC Study Site

- Three methods of estimating ‘R’ were studied:
  - SSURGO
  - EC w/ PTF
  - Terrain/EC regression with ‘R’ from Neutron Probe
- Spatial analysis of different VRI control zone scenarios were applied to estimate potential savings

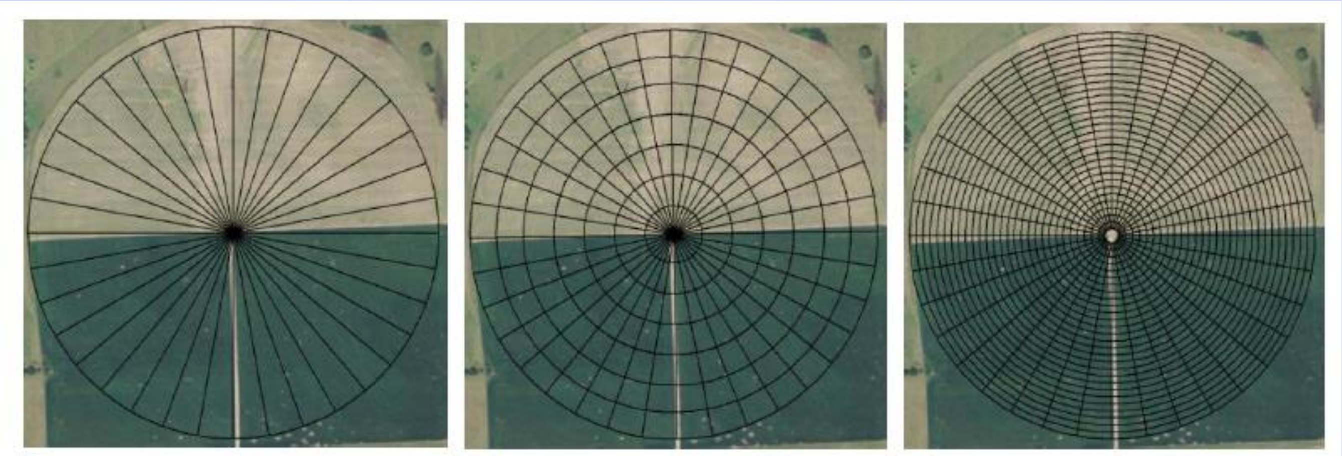




Keith Miller thesis (2015)

VRI Pivot Control Scenarios

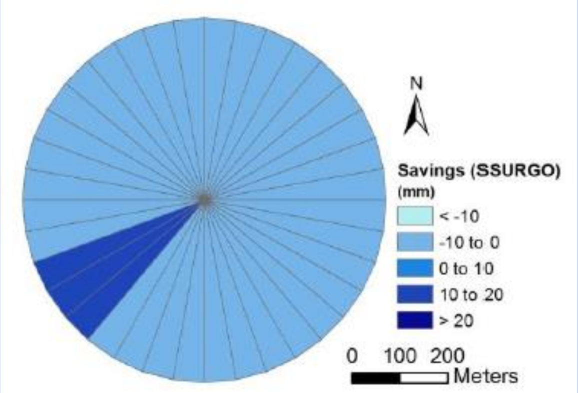
- Applied to different spatial data layer maps of ‘R’
- Simulated irrigation depths were applied to each zone considering MAD based on ‘R’
- Differences in irrigation depth required represented potential savings from reduced pumping

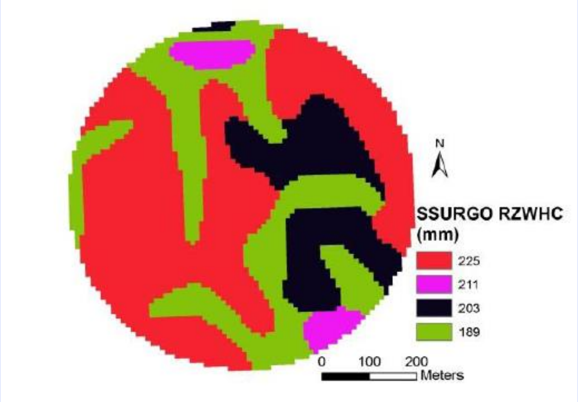


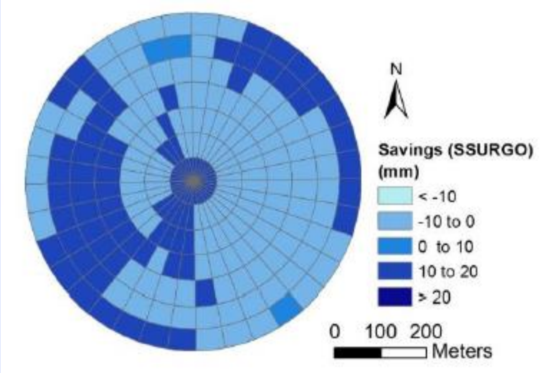
Keith Miller thesis (2015)

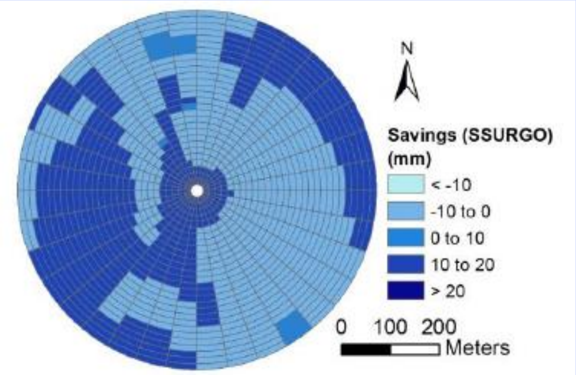
Predicted Pumping Reduction

- Harvesting root zone water based on SSURGO-derived 'R'
- Decreasing zone size allows for more precise application; potential for more pumping reduction









Keith Miller thesis (2015)

Predicted Energy Savings

- Additional spatial data layers were used as a proxy; attempted to relate these to 'R' (EC, TWI, Slope, etc.)
- Difficult to determine a solid relationship
- VRI applications were compared to field average values; some scenarios indicated the potential for energy savings from reduced pumping

Pivot Scenario	gSSURGO				PTF & $EC_{a\text{-}shallow}$ Regression				Slope regression (+/-25.4 mm)				Slope regression (+/-12.7 mm)			
	field depth (mm)	Volume (m^3)	kWh	Cost ($)	field depth (mm)	Volume (m^3)	kWh	Cost ($)	field depth (mm)	Volume (m^3)	kWh	Cost ($)	field depth (mm)	Volume (m^3)	kWh	Cost ($)
2 deg Sector	-5.0	-2117	-499	**-49.91**	-4.59	-1929	-455	**-45.46**	6.4	2670	629	**62.93**	6.5	2723	642	**64.20**
2 deg x Span	0.5	230	54	**5.41**	-4.30	-1806	-426	**-42.57**	9.8	4107	968	**96.80**	9.9	4152	979	**97.86**
2 deg x 12.5 m	2.0	860	203	**20.27**	-4.08	-1712	-403	**-40.35**	11.8	4974	1172	**117.24**	11.9	4999	1178	**117.85**
5 deg Sector	-4.9	-2056	-485	**-48.46**	-4.60	-1933	-456	**-45.57**	6.2	2615	616	**61.65**	6.4	2679	631	**63.15**
5 deg x Span	0.2	91	21	**2.13**	-4.34	-1821	-429	**-42.93**	9.5	3991	941	**94.08**	9.6	4026	949	**94.90**
5 deg x 12.5 m	1.7	711	168	**16.75**	-4.16	-1748	-412	**-41.21**	11.1	4659	1098	**109.83**	11.2	4686	1105	**110.47**
10 deg Sector	-5.1	-2160	-509	**-50.92**	-4.62	-1939	-457	**-45.70**	6.2	2623	618	**61.83**	6.3	2657	626	**62.64**
10 deg x Span	0.1	46	11	**1.08**	-4.40	-1849	-436	**-43.59**	8.8	3688	869	**86.93**	8.9	3741	882	**88.18**
10 deg x 12.5 m	1.0	402	95	**9.48**	-4.28	-1798	-424	**-42.39**	10.1	4225	996	**99.59**	10.2	4269	1006	**100.63**

Keith Miller thesis (2015)

Building Prescription Maps for the VRI Lab (MSYM 452)

Objective: Understand the capabilities of VRI and demonstrate one particular application of VRI

#1. Philosophy: use VRI to mine water from high Total Available Water (TAW, i.e. FC – WP) soils that would be unutilized with conventional irrigation

#2. Logistics of irrigation scheduling applied to prescription maps

A field with variable TAW

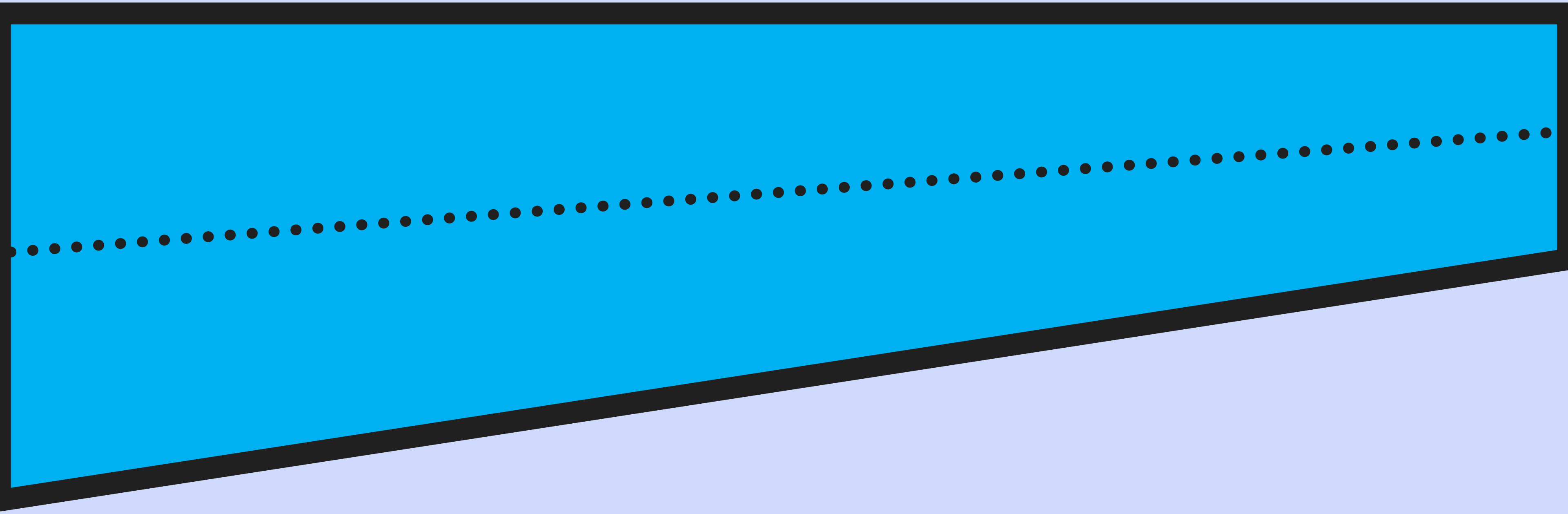
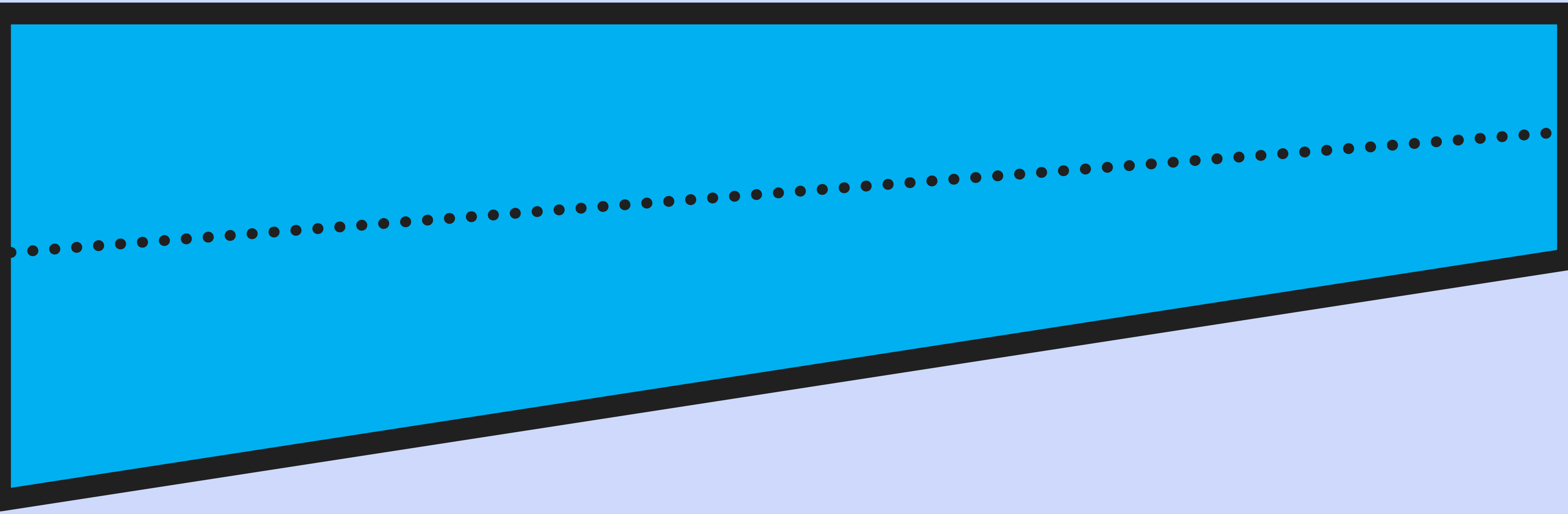
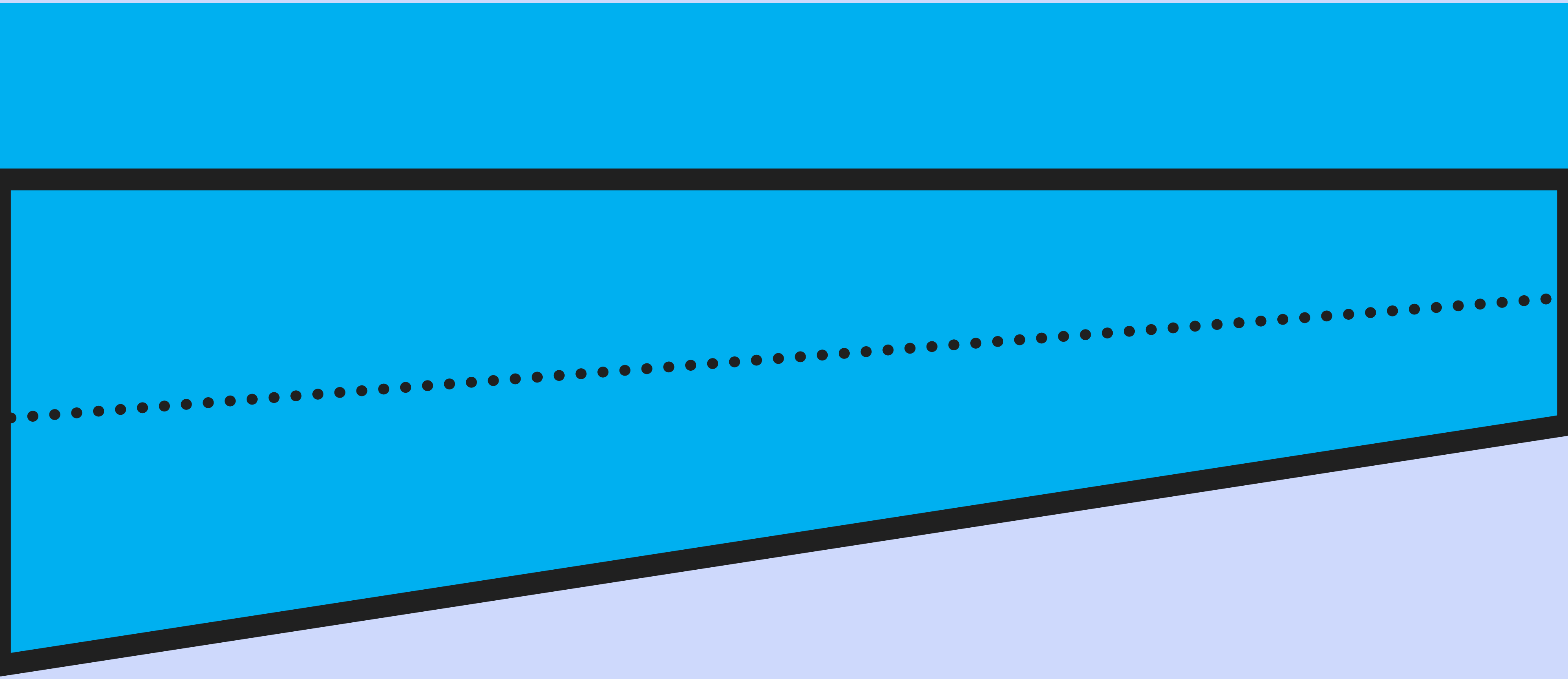


Illustration created by L. Mateos and T. H. Lo

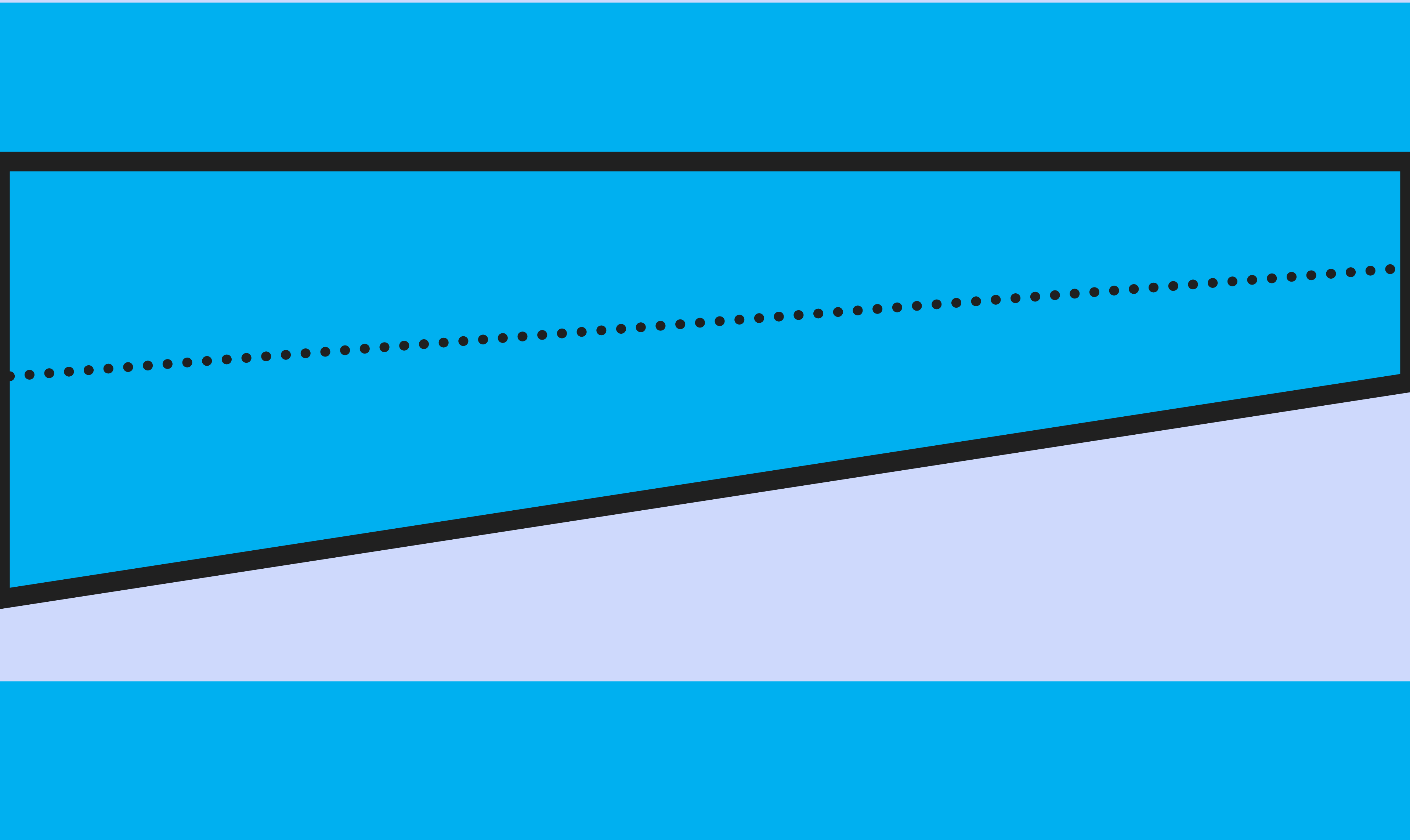
With ET, & conventional irrigation,



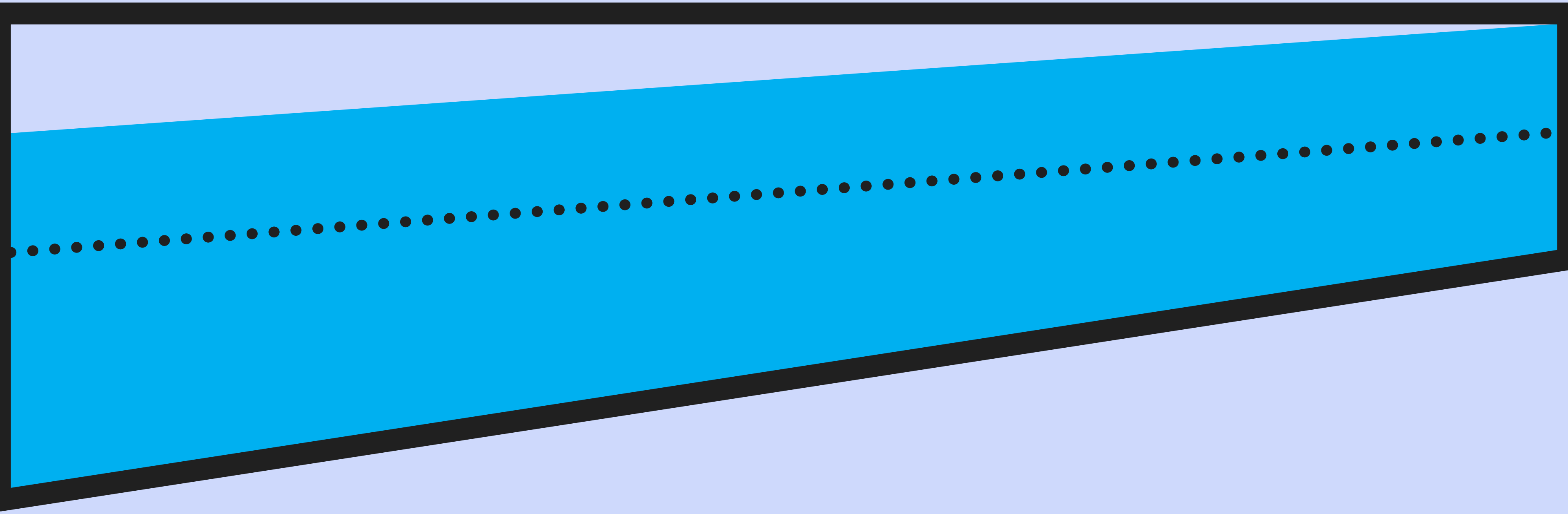
ET, and a large rain…



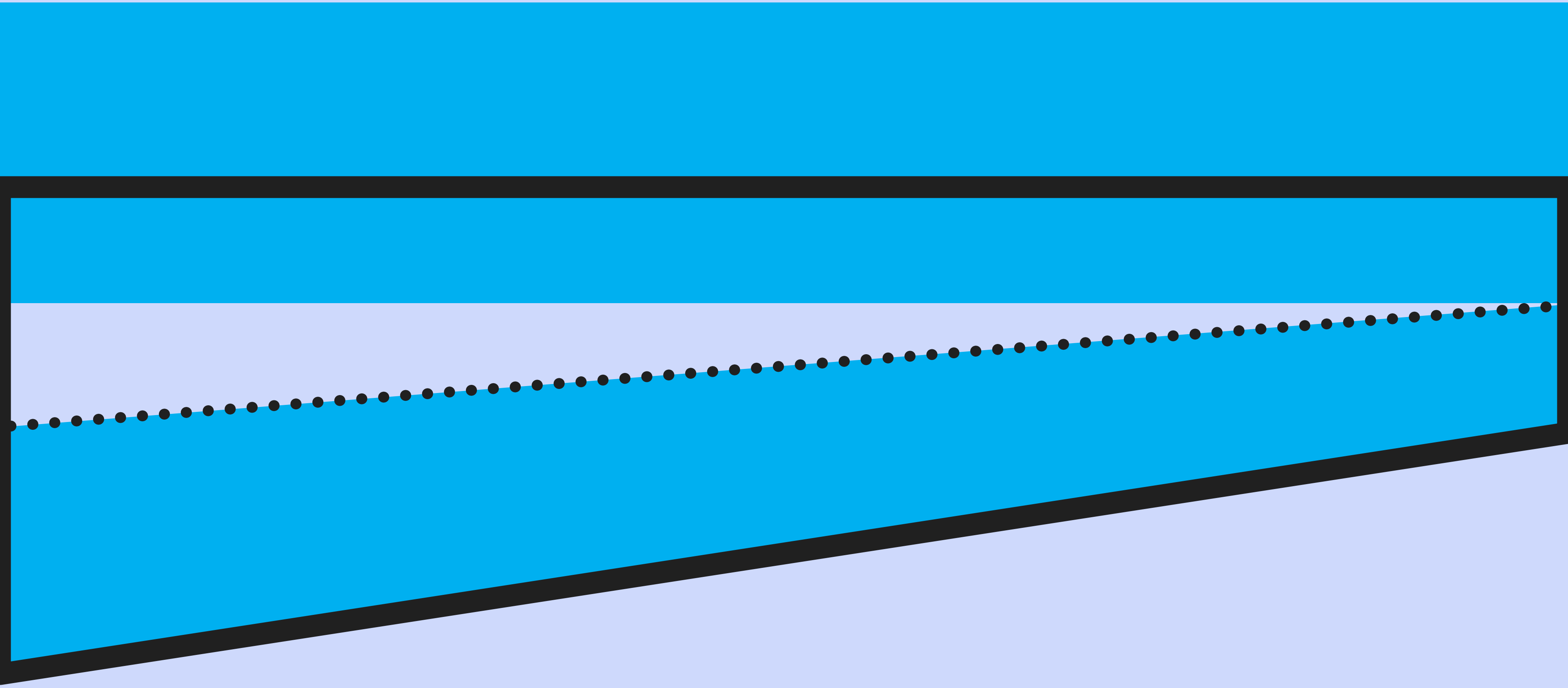
lots of deep percolation!

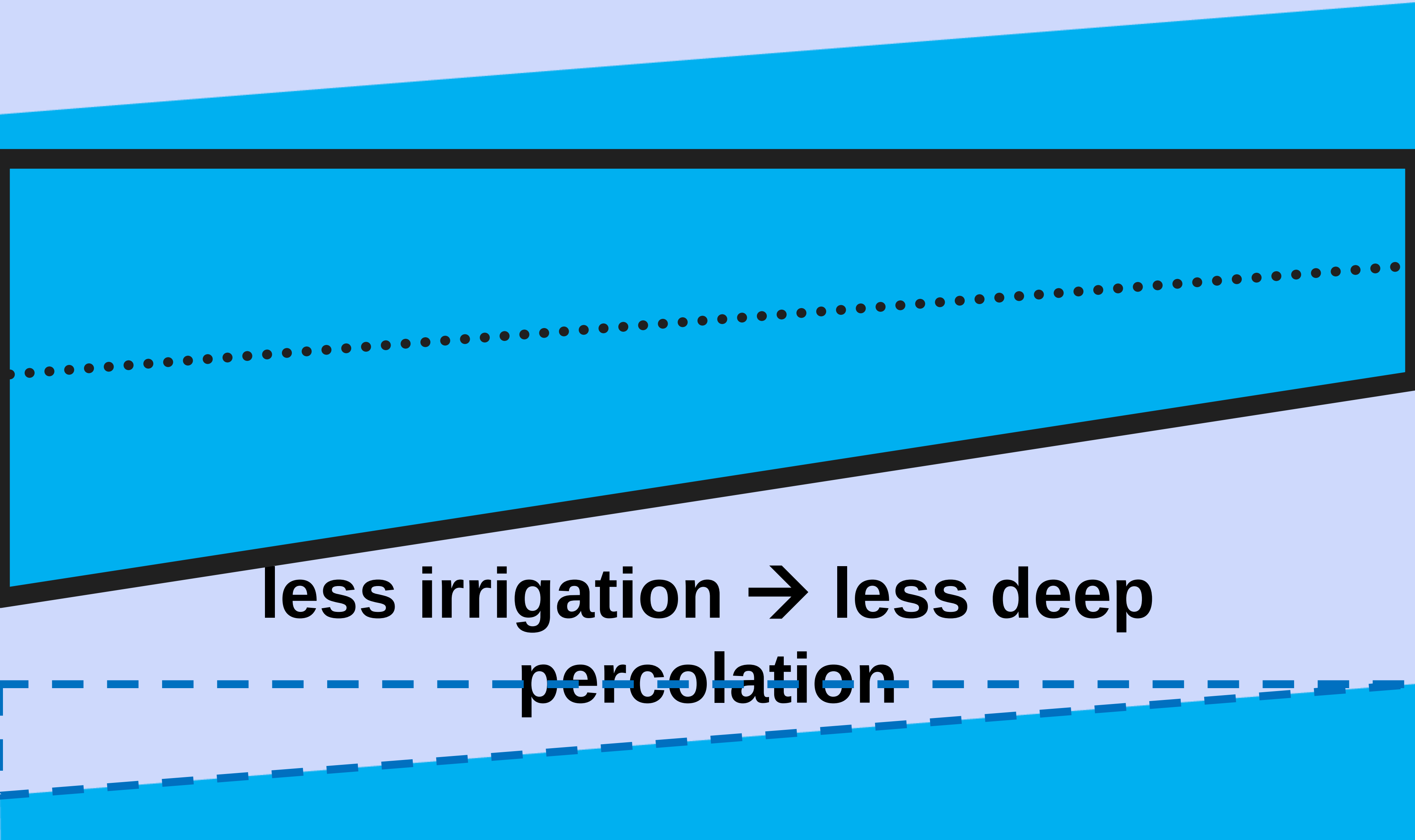


With ET, and VRI,



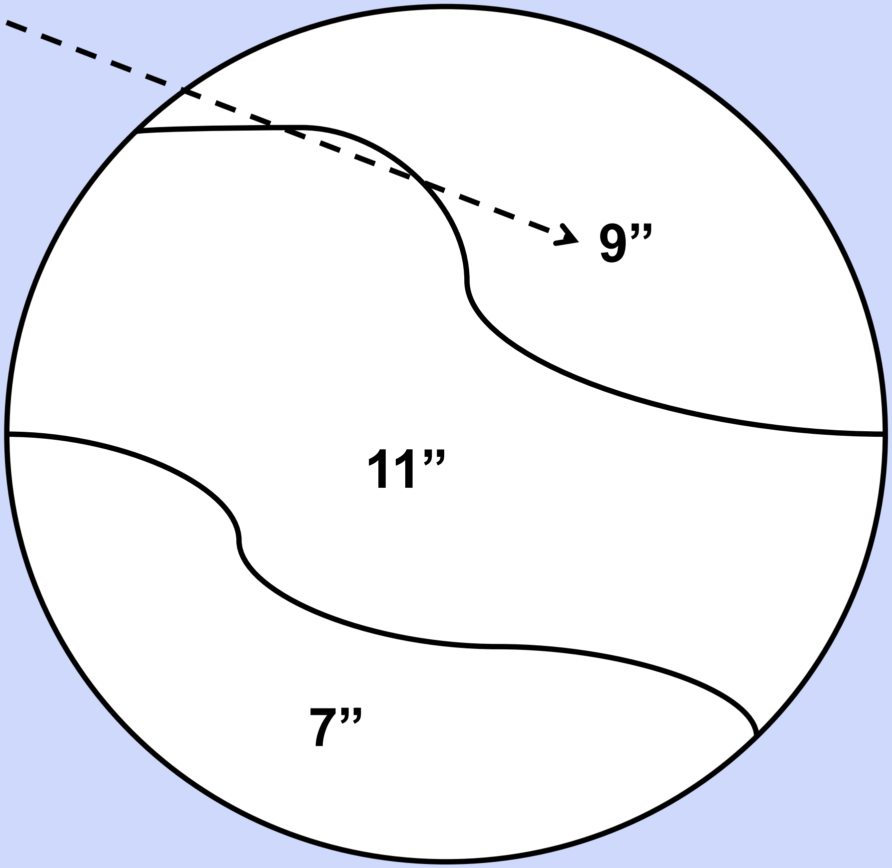
ET, and a large rain…




less irrigation → less deep percolation

Building Prescription Maps

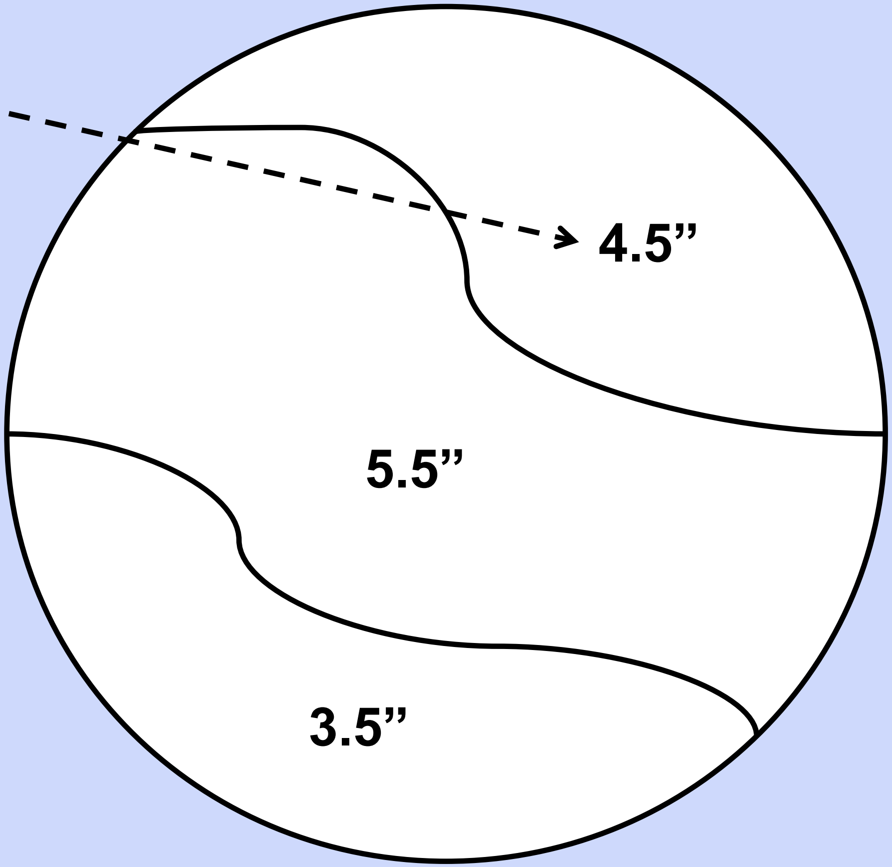
- **TAW (Total Available Water)**
- **Round to the nearest 1 in**
- **Example: 3 irrigation management zones (IMZs)**
- **An IMZ shouldn't be smaller than 2d_c (sprinkler diameter of coverage) in any direction**



Hypothetical field with variable TAW

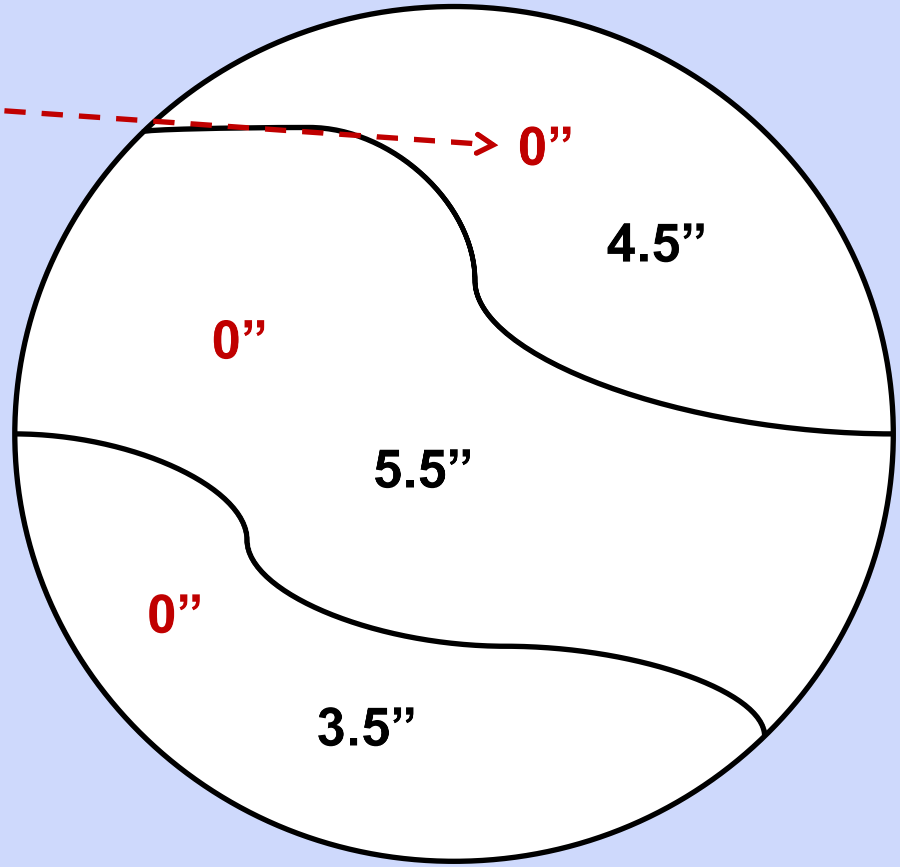
Management Allowed Depletion (MAD)

- MAD
  - TAW * f_{dc}
  - TAW * 0.5



Irrigation Scheduling: Day 0

- MAD
- SWD (Soil Water Depletion)
  - Start at FC
  - Assume ET = 0.25 in/d
  - Which IMZ will need water first?
  - Latest Date (LD) = 3.5/0.25 = 14 d

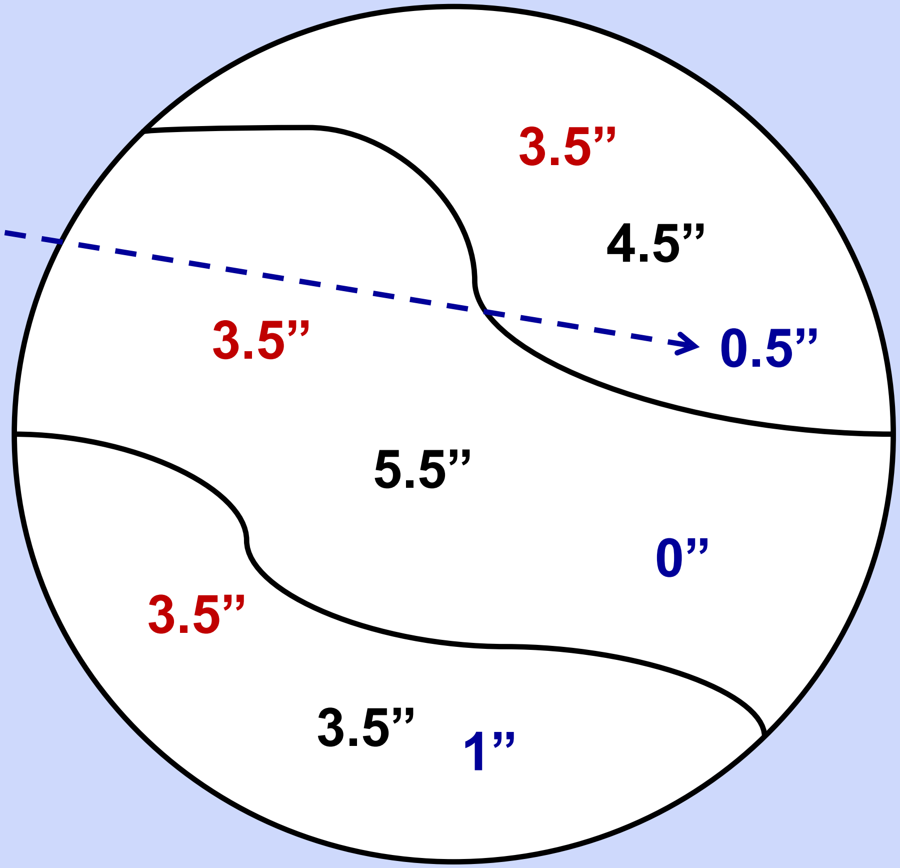


Irrigation Scheduling: Day 14

- MAD
- SWD
- Irrigation
  - Mine ½ of the extra water in high MAD soils

$$I_{IMZ} = \frac{1}{2}(MAD_{max} - MAD_{IMZ})$$

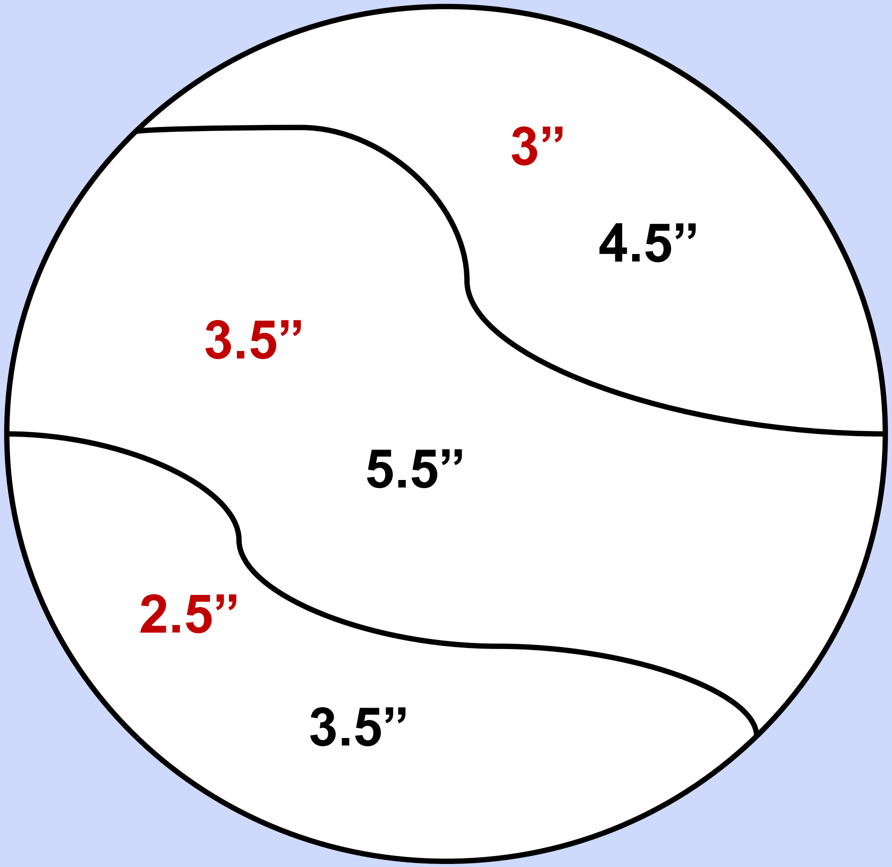
  - Complete the revolution before the end of day 14



Before irrigation

Irrigation Scheduling: Day 14

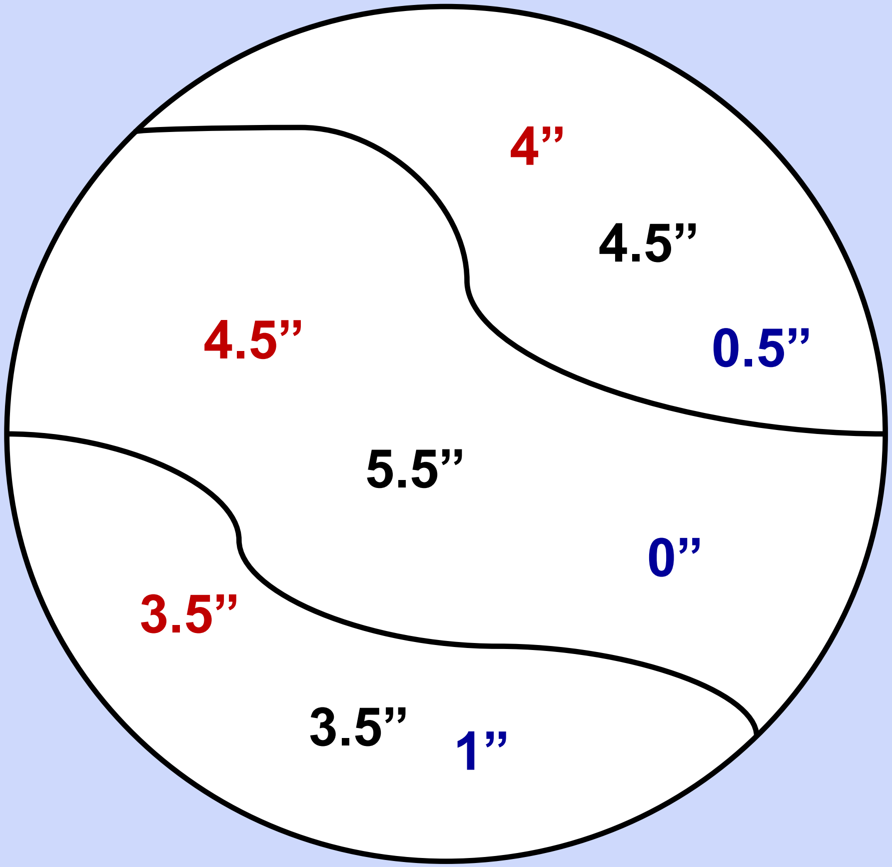
- MAD
- SWD
- Irrigation
  - LD = 1/0.25 = 4 d from today



After irrigation

Irrigation Scheduling: Day 18

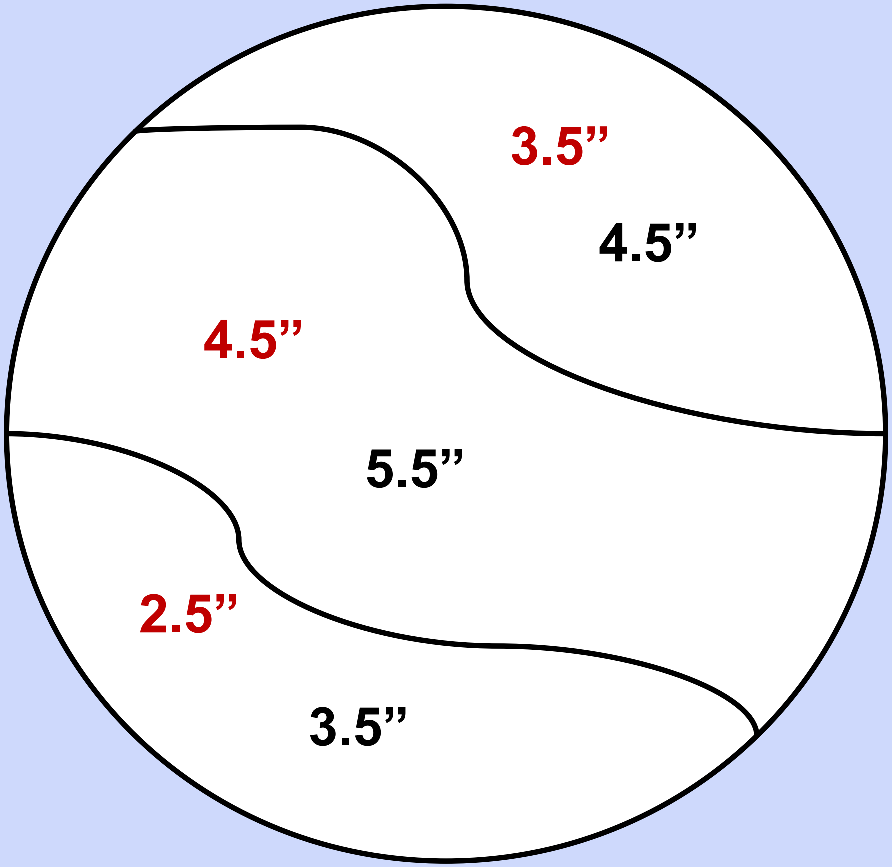
- MAD
- SWD
- Irrigation
  - Mine the second ½ of the extra water in high MAD soils (i.e. the same prescription map)
  - Complete the revolution before the end of day 18



Before irrigation

Irrigation Scheduling: Day 18

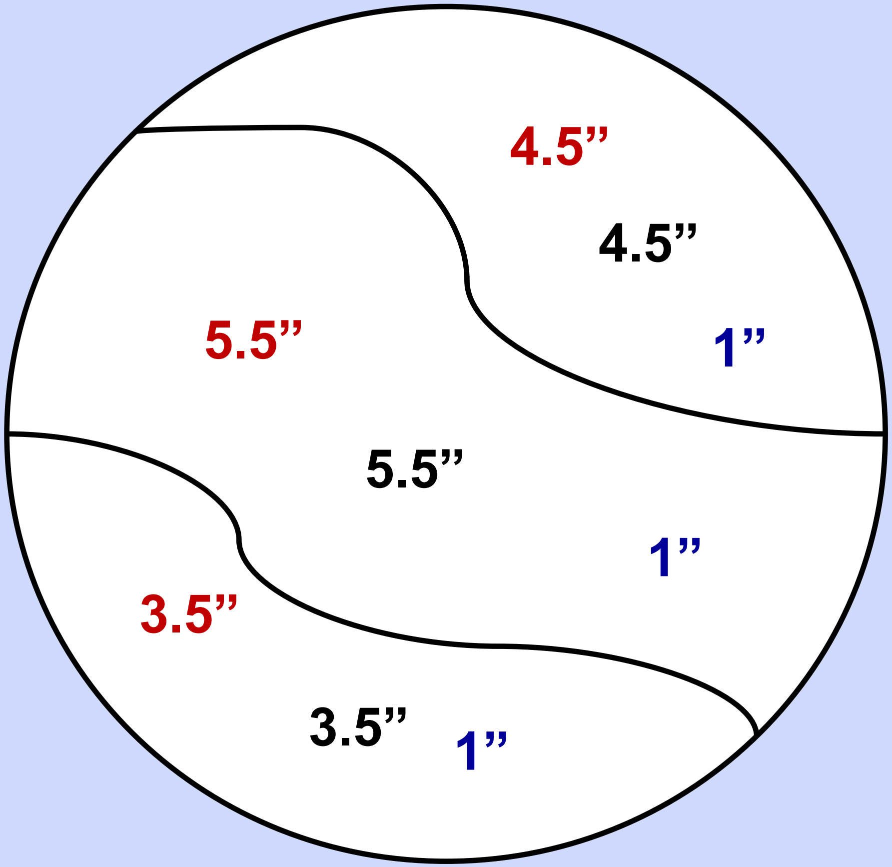
- MAD
- SWD
- Irrigation
  - Now, (MAD-SWD) is the same in all IMZs
  - LD = 1/0.25 = 4 d from today



After irrigation

Irrigation Scheduling: Day 22

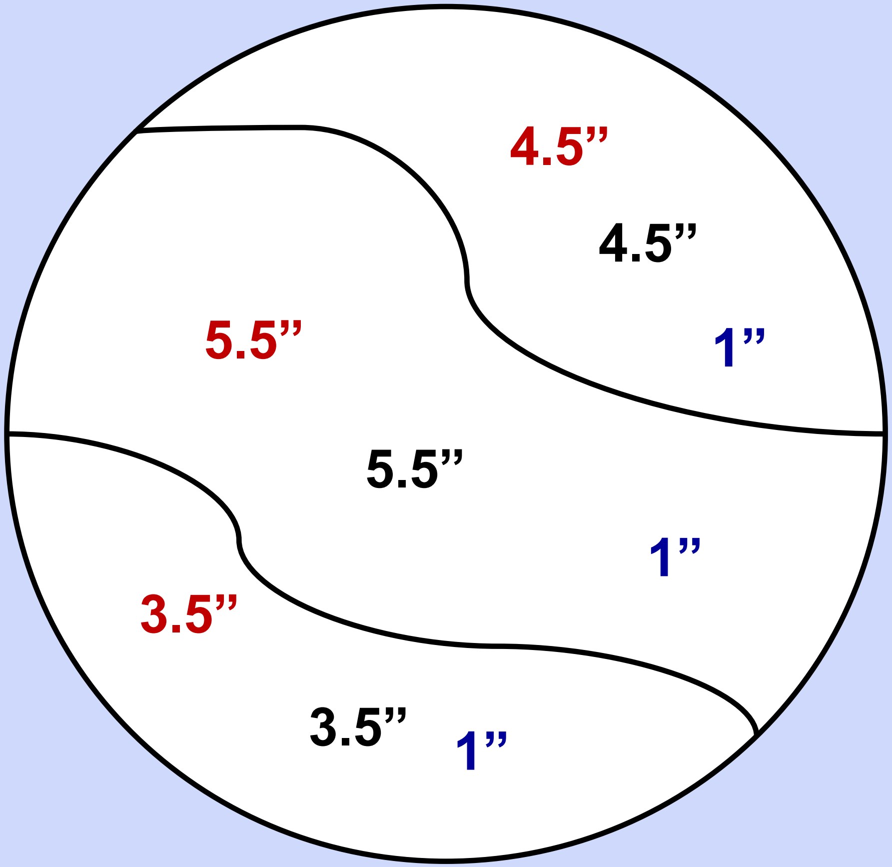
- MAD
- SWD
- Irrigation
  - Each part of the field is at MAD
  - Uniform irrigation for the rest of the season (simply replace ET)
  - Complete the revolution before the end of day 22



Before irrigation

Observations

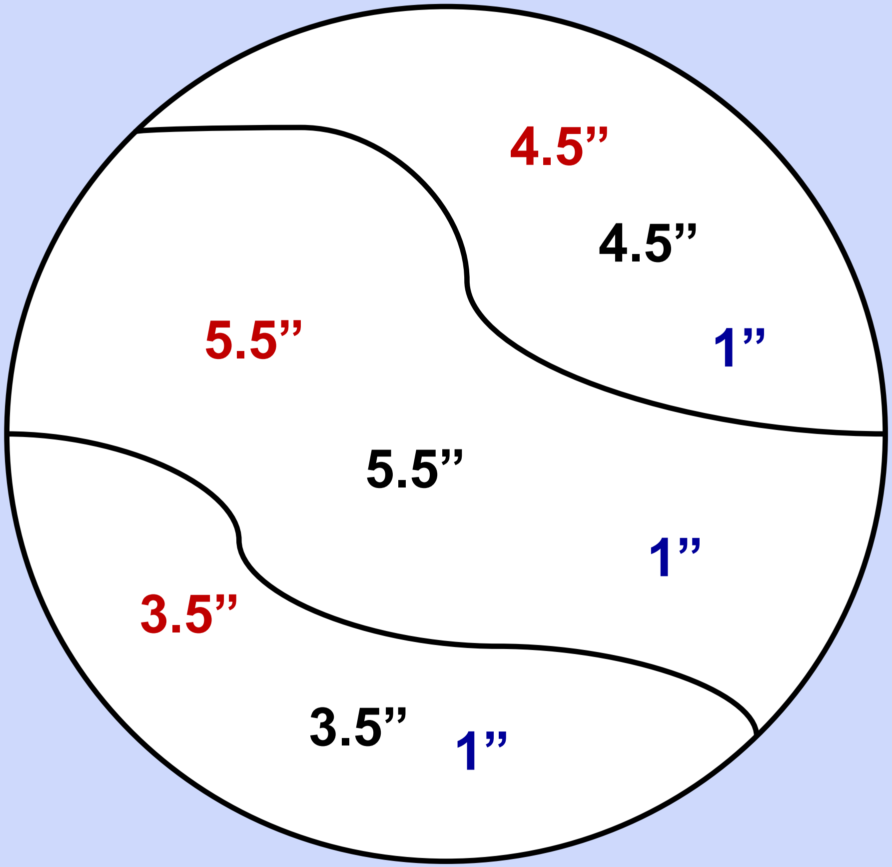
- Only needed 2 prescription maps
  - VRI map
  - Uniform map
- Scheduled irrigation events based on the IMZ with the lowest MAD
- Soil water sensor placement
  - 2 stations in the low MAD IMZ and 2 stations in the high MAD IMZ?



Before irrigation

Observations

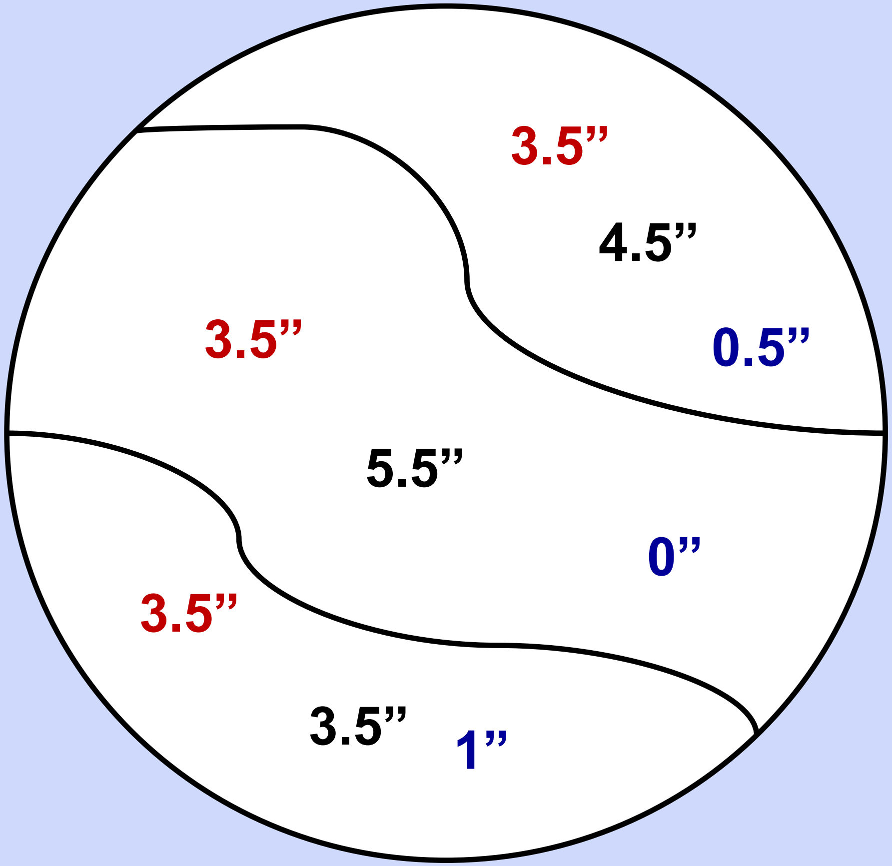
- This is d_{eff}, but the actual prescription map should be d_a
- $d_a = d_{eff} / E_{LQ}$
- You will also need to build an “avoidance area” for a waterway based on the aerial image



Before irrigation

When to use the VRI prescription map?

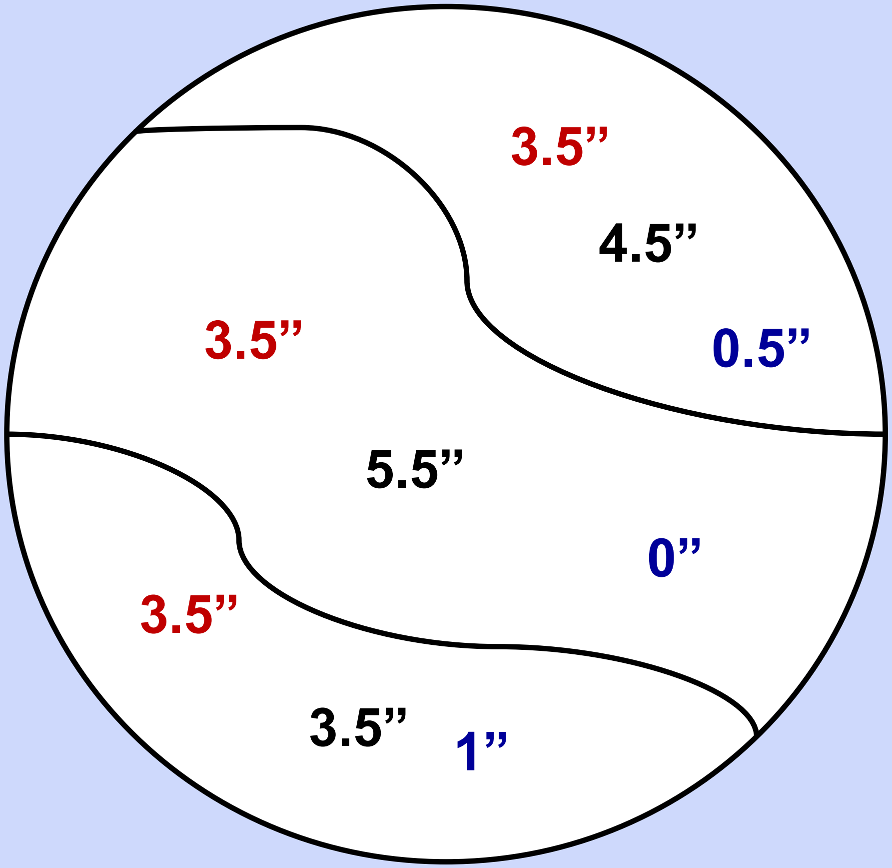
- Need to use it twice to mine all of the extra water in the high MAD soils
- Use it once for the first irrigation to increase the rain allowance (r_a)
- Use it the second time once maximum rooting depth has been reached



Before irrigation

When to use the VRI prescription map?

- **Alternately, save both VRI applications for peak ET if pumping rate is limited (assuming that VRI reduces cycle time, T_c)**
- **If the soil water profile is refilled mid-season, then use the VRI map another 2 times**

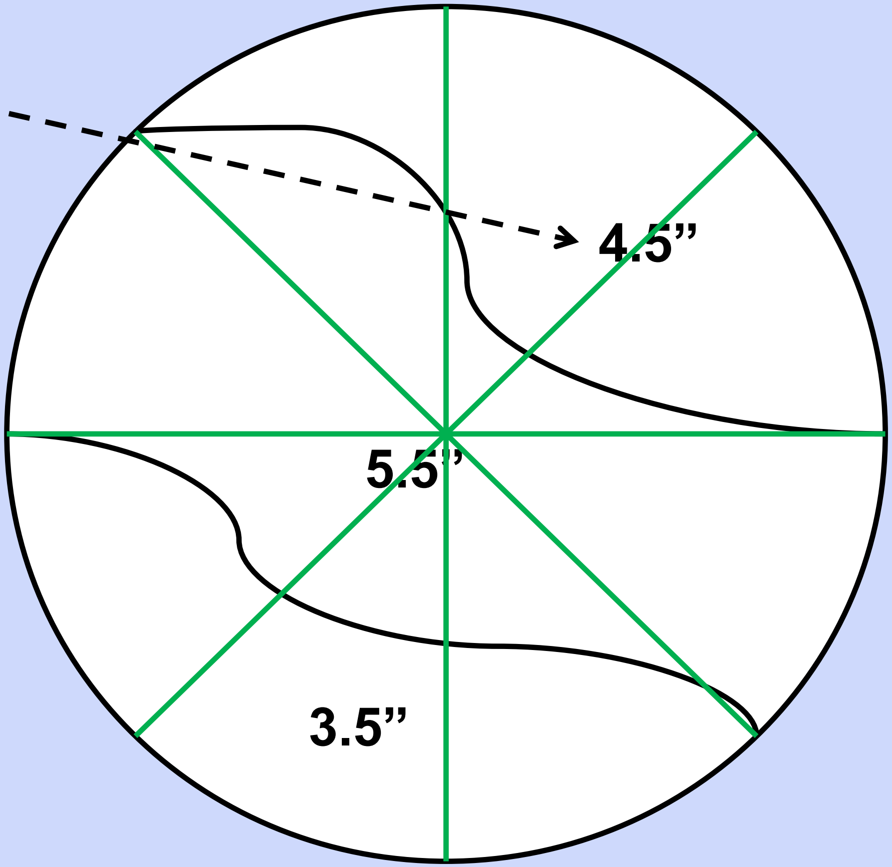


Before irrigation

Variable Rate Irrigation
UNIVERSITY OF NEBRASKA-LINCOLN
Biological Systems Engineering

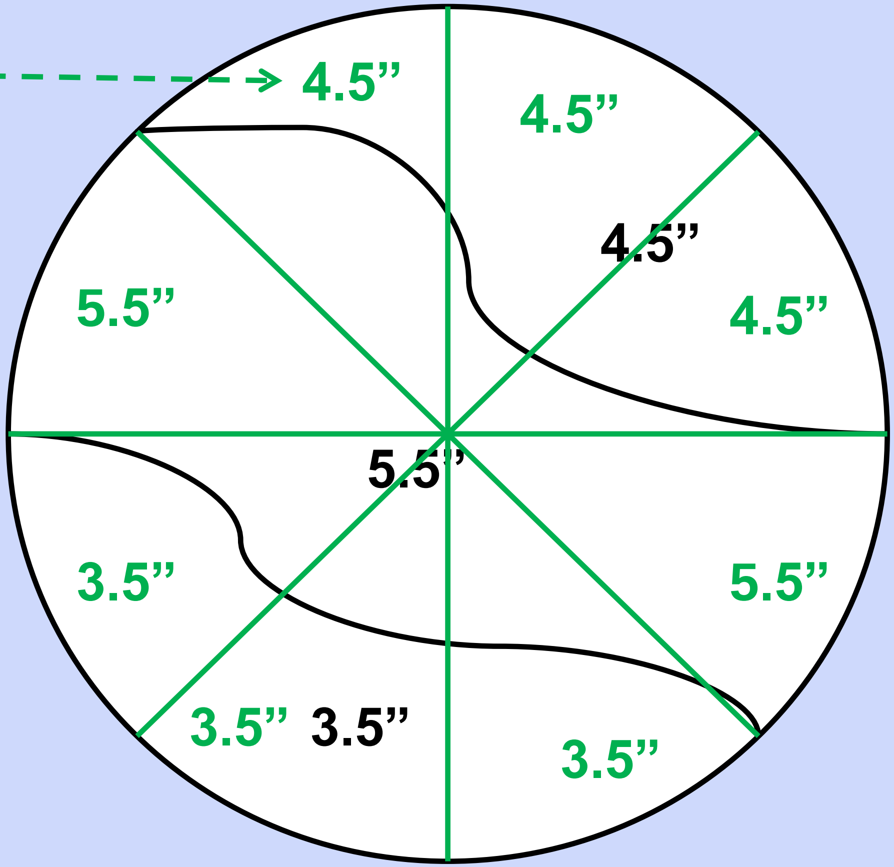
What about speed control?

- MAD
- 8 sectors (45°) for a simple example



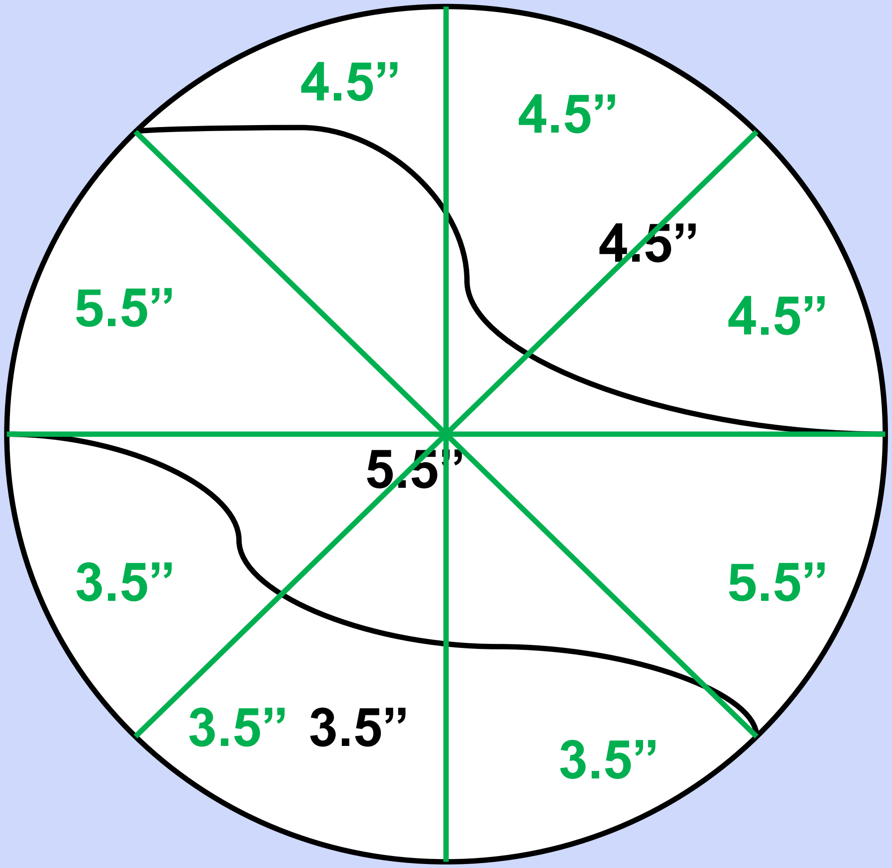
Speed control: MAD

- MAD
- MAD (Sector)
  - Err on the conservative side (low MAD)
  - 10th percentile of MAD values within that sector
    - 90% adequacy
  - I.e., pick the lowest MAD unless it is less than 10% of the area of that sector



Speed control: savings

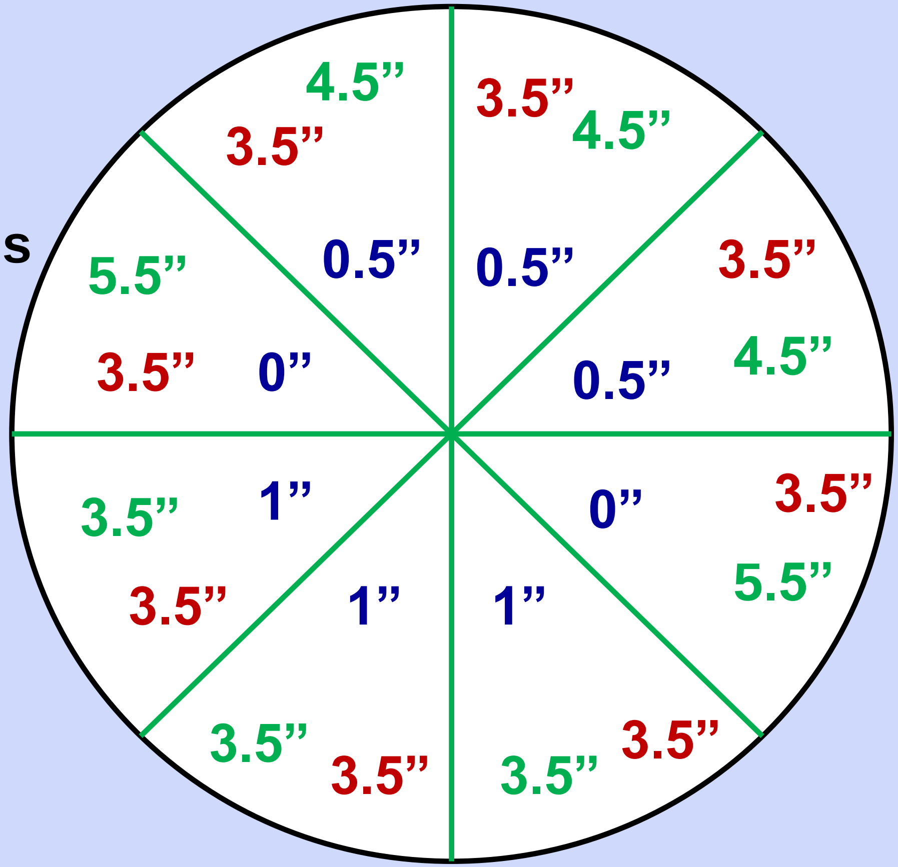
- MAD
- MAD (Sector)
  - Now only 25% of the field has a MAD of 5.5”
  - Less reduction in pumping (but cheaper than zone control)



Speed control: prescription maps

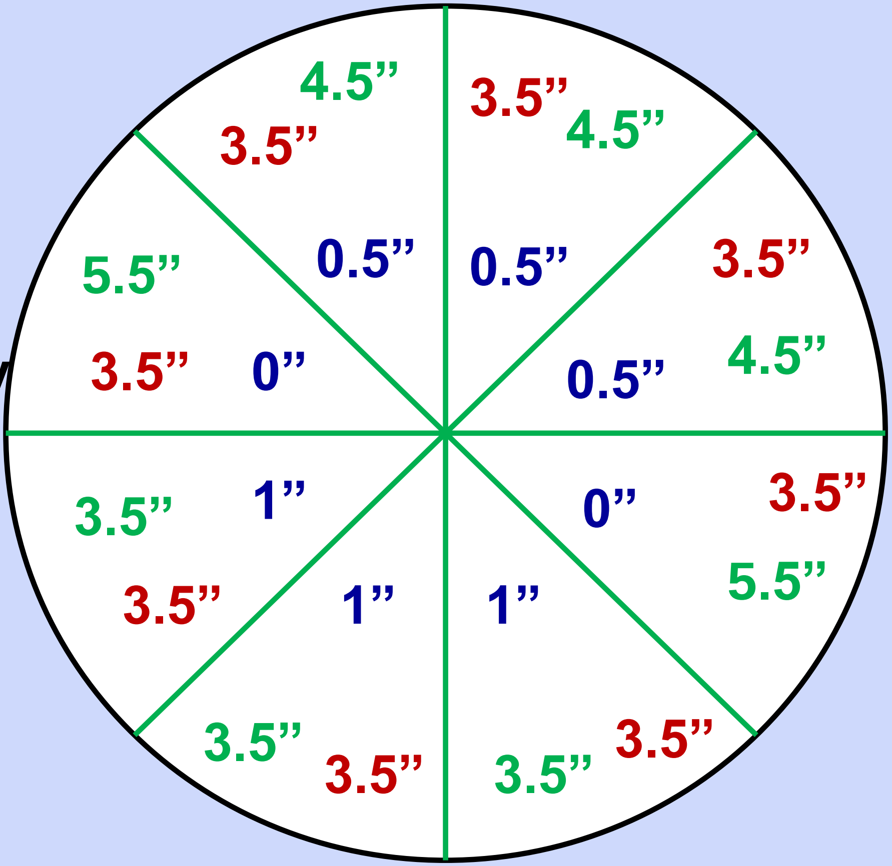
- MAD (Sector)
- SWD
- Irrigation
  - Develop prescription maps following the above protocol for zone control

$$I_{IMZ} = \frac{1}{2}(MAD_{max} - MAD_{IMZ})$$



Speed control: logistics

- MAD (Sector)
- SWD
- Irrigation
  - A 0” sector is okay for the lab, but in reality you would probably use a very small amount (0.1”) instead of shutting down the pump



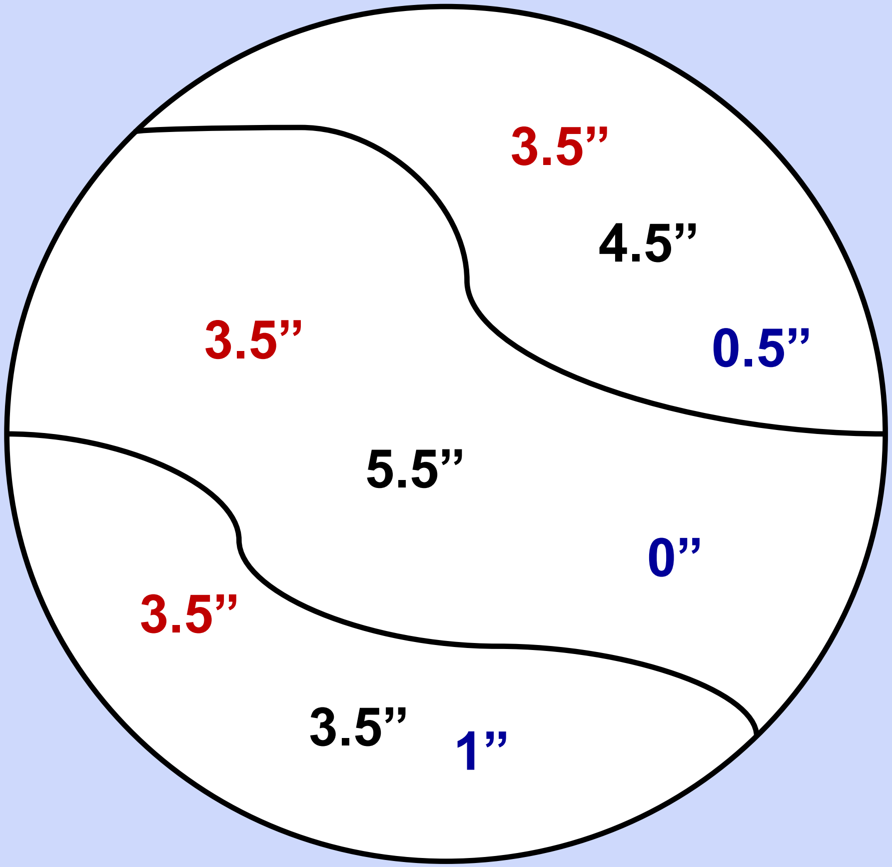
Number of VRI Events Required

- The number of VRI irrigations (N, rounded up to the nearest whole number) depends on the maximum desired net irrigation (I_{max}):

$$N = \left(\frac{MAD_{max} - MAD_{min}}{I_{max}}\right)$$

$$I_{IMZ} = \frac{1}{N}(MAD_{max} - MAD_{IMZ})$$

$$I_{IMZ,gross} = \frac{I_{IMZ}}{E_a}$$



Acknowledge:

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Additional VRI Resources:

http://engineering.unl.edu/bse/faculty/derek-heeren-0/