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Tsz Him Lo

University of Nebraska-Lincoln

Derek M. Heeren

University of Nebraska-Lincoln, derek.heeren@unl.edu

Derrel Martin

University of Nebraska-Lincoln, derrel.martin@unl.edu

Luciano Mateos

Instituto de Agricultura Sostenible, ag1mainl@uco.es

Joe D. Luck

UNL, jluck2@unl.edu

See next page for additional authors

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Authors

Tsz Him Lo, Derek M. Heeren, Derrel Martin, Luciano Mateos, Joe D. Luck, and Dean E. Eisenhauer

PUMPAGE REDUCTION BY USING VARIABLE-RATE IRRIGATION TO MINE UNDEPLETED SOIL WATER

T. Lo, D. M. Heeren, D. L. Martin, L. Mateos, J. D. Luck, D. E. Eisenhauer

ABSTRACT. *Conventional irrigation schedules are typically based on portions of the field where root zones hold the least available soil water. This leaves undepleted available water in areas with larger water holding capacities. The undepleted water could be used through variable-rate irrigation (VRI) management; however, the benefits of VRI without in-field mapping are unexamined. In this research, the field-averaged amount of undepleted available soil water in the root zone was calculated from the NRCS Soil Survey Geographic database for 49,224 center-pivot irrigated fields in Nebraska. Potential reductions in pumpage from mining undepleted available water were then estimated. Results of the analysis show that widespread adoption of zone control VRI technology based only on the pumping savings from mining undepleted available water may be unwarranted for current VRI costs and average pumping energy expenses in the Central Plains (\$0.0026 m⁻³ to \$0.0947 m⁻³). Pumpage reductions exceeded 51 mm year⁻¹ for only 2% of the fields and exceeded 25 mm year⁻¹ for 13% of the fields; thus, reductions may be small compared to annual pumpage requirements. If VRI were implemented on all fields with a potential pumpage reduction greater than 51 or 25 mm year⁻¹, the volume of pumpage reduction would be approximately 0.35% or 1.3%, respectively, of the total irrigation pumpage in Nebraska. These data may be a conservative estimate of pumpage reduction in fields where the measured variability in soil properties exceeds that described by the NRCS Soil Survey, or if undepleted water is mined early in the season and the soil water profile is refilled by precipitation, allowing undepleted water to be mined again. Adoption of zone control VRI for mining undepleted available water is most feasible for fields where the pumpage reduction from VRI is large and pumping costs are above normal. Pivot fields with high undepleted water were sparsely distributed across Nebraska and were often located along streams and or in associated alluvial areas. The prevalence of fields with large quantities of undepleted water differed among and within soil associations. We were unable to assign feasibility of VRI based on the soil association, as the occurrence of undepleted water varied significantly within a soil association. These findings should assist producers and other entities interested in VRI technology; however, pumpage reduction through use of undepleted soil water is only one benefit of VRI technology and management. Producers are encouraged to consider all potential benefits when analyzing VRI investments.*

Keywords. *Center-pivot, Economics, Energy conservation, GIS, Pumpage, Site-specific, Variable-rate irrigation, Soil water holding capacity.*

According to Evans et al. (2013), variable-rate irrigation (VRI) is “the ability to spatially vary water application depths across a field to address specific soil, crop, and/or other conditions.” Like other precision agricultural technologies, VRI facilitates management of field heterogeneity to improve profitability and environmental stewardship. Potential activities include:

- Satisfaction of diverse in-field water requirements caused by microclimate, plant health, planting date, plant population, crop variety, or crop species variability.
- Application of profit-maximizing season irrigation that is spatially heterogeneous, which has the greatest impact on crops for which yield quantity (e.g., cotton; Grimes et al., 1969) or quality (e.g., wine grape; Matthews and Anderson, 1988) is maximized under mild deficit irrigation and is reduced under full irrigation even when soils are unsaturated.
- Compensation for spatial differences in water added to the root zone by hydrological processes such as capillary rise, subsurface lateral flow, and infiltration of direct rainfall and runoff.
- Variable chemigation rates of fertilizer and pesticide (Sadler et al., 2005).
- Reduction of application intensities over areas with high runoff potential when enlarging the wetted diameters of sprinklers is impractical or undesirable.
- Alleviation of the extent and severity of waterlogging, which can accelerate denitrification, reduce crop

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The authors are **Tsz Him Lo**, ASABE Member, Graduate Research Assistant, **Derek M. Heeren**, ASABE Member, Assistant Professor and Water for Food Global Institute Faculty Fellow, and **Derrel L. Martin**, ASABE Fellow, Professor, Department of Biological Systems Engineering, University of Nebraska-Lincoln, Lincoln, Nebraska; **Luciano Mateos**, Research Scientist, Instituto de Agricultura Sostenible, CSIC, Córdoba, Spain; **Joe D. Luck**, ASABE Member, Assistant Professor, and **Dean E. Eisenhauer**, ASABE Member, Professor Emeritus, Department of Biological Systems Engineering, University of Nebraska-Lincoln, Lincoln, Nebraska. **Corresponding author:** Derek M. Heeren, 241 L. W. Chase Hall, Lincoln, NE 68583-0726; phone: 402-472-8577; e-mail: derek.heeren@unl.edu.

yields by limiting soil aeration (Kanwar et al., 1988), and disrupt center-pivot or farm machinery operation (Sadler et al., 2005; W. L. Kranz, personal communication, 2015).

- Transferring excess irrigation from overwatered areas to water-stressed areas for yield-increasing transpiration when the water supply is inadequate for full yield throughout the field if the center-pivot irrigated uniformly.

Although VRI offers significant potential, a comprehensive method to predict the magnitude of benefits has not been developed. Previous research quantified some benefits from a small number of intensely studied fields using simulation (Nijbroek et al., 2003; DeJonge et al., 2007; Hedley and Yule, 2009) or experimentation (King et al., 2006; Khalilian et al., 2008; Hillyer and Higgins, 2014). It is unclear how field-specific research from the small number of fields studied can be extrapolated to assist VRI investment decisions for the spatial variability found in the larger set of farmer fields.

This article describes a method to estimate irrigation pumpage reduction from mining root zone water holding capacity (R) that is undepleted by conventional irrigation (CI; i.e., uniform irrigation). Scheduling irrigation for CI traditionally focuses on maintaining soil water in the root zone above an allowable depletion. Woodruff et al. (1972) scheduled irrigation using a larger allowable depletion at the end of the growing season than during the middle of the season. Their strategy, called “planned soil water depletion,” more thoroughly depletes water in the root zone and provides more opportunity to capture off-season precipitation (Lamm et al., 1994). The strategy also relies on using off-season precipitation to replenish soil water depletion prior to the following season. In comparison to an irrigation strategy using a constant allowable depletion, planned soil moisture depletion reduces pumpage and nitrate leaching. Planned soil moisture depletion cannot be fully implemented with CI on variable fields because the percent depletion of R at the end of the season varies spatially. Conventional irrigation is typically managed to avoid water stress in the most sensitive portions of the field, which produces a small, uniform, end-of-season depletion. However, a variable amount of soil water remaining above the ideal depletion would be left across the field. In other words, CI would treat the entire field as having a small R , so the soils with larger R would have undepleted available soil water.

Variable-rate irrigation could use the undepleted R by applying less irrigation to soils with large R values, enhancing extraction of more stored soil water than in areas with smaller allowable depletions. Therefore, VRI would empower farmers to reduce pumping energy use and decrease nitrogen leaching beyond that achieved with a CI strategy using planned soil moisture depletion. Reducing nitrate leaching is an important public benefit of VRI where nitrate concentrations in the groundwater have become a threat to drinking water supplies. These benefits exist annually for regions where off-season precipitation replenishes the root zone to field capacity before the irrigation season. In the Central Plains, average precipitation between April and June ranges from 175 mm at Scottsbluff, Nebraska, in the semi-

arid west to 320 mm at Falls City, Nebraska, in the sub-humid east (PRISM, 2012). Consequently, the managed root zone would generally refill in the spring prior to irrigation across the Great Plains.

Once the spatial distribution of R within a field is characterized, the generation of prescription maps to use undepleted R with VRI is straightforward; therefore, this application of VRI is readily adoptable to benefit farmers and the public. The method introduced here is applicable for fields not extensively sampled in research experiments. The method was applied to 49,224 center-pivot irrigated fields in Nebraska to:

1. Describe the statistical distribution of field-average undepleted R under CI for center-pivot irrigated fields.
2. Analyze the geographical distribution of fields with large field-average undepleted R relative to soil associations.
3. Assess the potential regional impact of pumpage reductions from mining undepleted R with VRI.
4. Quantify the pumping cost savings from mining undepleted R using VRI management.

METHODS

A spatial map of R based on the NRCS Soil Survey Geographic database was created for the entire state of Nebraska. The field-averaged amount of undepleted R (U) was calculated for the 49,224 center-pivot irrigated fields that were considered to be viable (based on field size and data availability) for this VRI analysis. Finally, potential reductions in pumpage (and the associated cost savings) from mining U were estimated.

EXTRACTING SOIL PARAMETERS FROM SOIL SURVEY DATABASE

The primary source of data was the gridded Soil Survey Geographic database (gSSURGO; NRCS, 2014). Unlike the vector-formatted version of gSSURGO used by Lo et al. (2014), the raster-formatted gSSURGO conveniently incorporates spatial and tabular soil information for Nebraska into one database. The gSSURGO raster is composed of 10 m × 10 m grid cells in the North American Datum of 1983 Universal Transverse Mercator Zone 14N projection. In gSSURGO, contiguous areas with similar soils have been delineated as a map unit (fig. 1). Each soil within a map unit is designated as a component that composes a percentage of the map unit. In turn, the soil profile of each component has been divided into horizons, with a top depth, a bottom depth, and soil horizon water holding capacity (WHC) defined as the difference between field capacity and wilting point for that horizon. The “representative” values from the gSSURGO database (NRCS, 2014) were used for all soil properties (i.e., percent composition, top depth, bottom depth, and WHC).

The core calculations were completed using a Python script (Python, 2012; Lo, 2015) in ArcGIS (ArcGIS Desktop 10.2, ESRI, Redlands, Cal.). Horizons, components, and map units were excluded from calculations for the criteria listed in table 1. The value for a map unit was weighted by

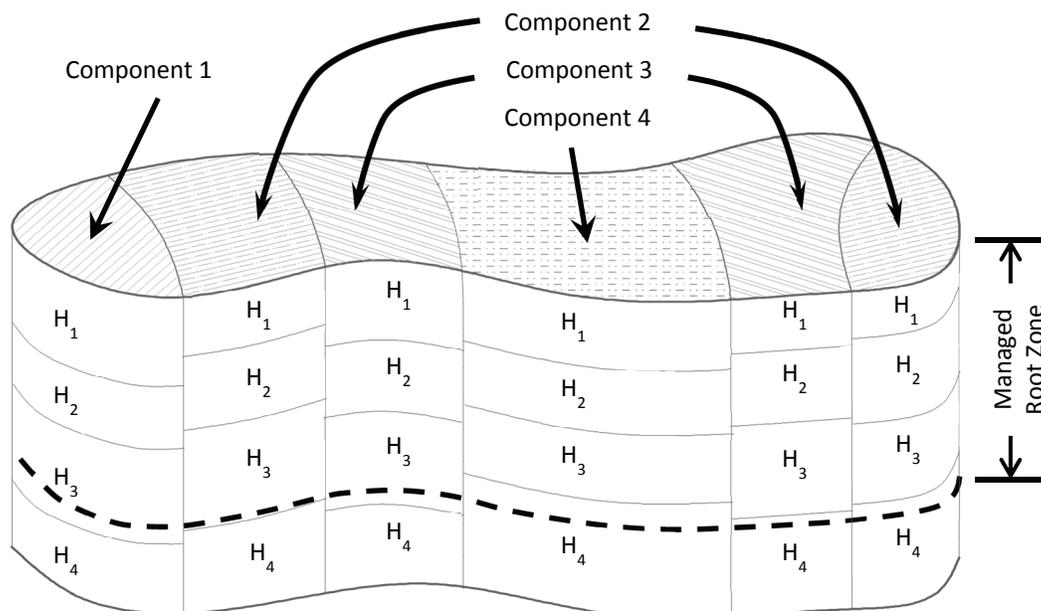


Figure 1. Diagram of a soil map unit in the gridded Soil Survey Geographic database (gSSURGO; NRCS, 2014). The l th soil horizon from the soil surface is labeled H_l .

Table 1. Criteria for excluding horizons, components, and map units from the calculations of R for each component and map unit in Nebraska.

	If WHC or R is...		Also excluded if:
	Zero	Negative	
Horizon	-	Excluded, except assumed zero for rock horizon	<ul style="list-style-type: none"> • Missing top depth or bottom depth; • Missing WHC, except assumed zero for rock horizon; or • Horizons were discontinuous.
Component	Excluded	Excluded	<ul style="list-style-type: none"> • Managed root zone not entirely covered by included horizons; or • Percent composition was negative or over 100%.
Map Unit	Excluded	Excluded	<ul style="list-style-type: none"> • The sum of the percent compositions of excluded and missing/excess components was at least 10%.

the included quantities when some elements were excluded.

Initially, the R of every component was determined. Starting at the soil surface, the WHC for each horizon was multiplied by the horizon thickness and summed as shown in equation 1. This computation concluded at the bottom of the managed root zone, which is assumed to occur at a depth of 120 cm (for typical irrigated crops in the Central Plains, i.e., corn and soybeans) or at the top depth of the first “lithic bedrock” or “paralithic bedrock” restrictive layer (NRCS, 2014), whichever was shallower:

$$R_k = \sum_1^d \{ [\min(z_{B,l}, z_k) - z_{T,l}] \times \text{WHC}_l \} \quad (1)$$

where

k = index for the included components within a map unit

R_k = R of component k (mm)

l = index for the included horizons in component k

d = number of included horizons at least partially within the managed root zone of component k

$z_{B,l}$ = bottom depth of horizon l (mm)

z_k = depth of the managed root zone in component k (mm)

$z_{T,l}$ = top depth of horizon l (mm)

WHC_l = WHC of horizon l ($\text{m}^3 \text{m}^{-3}$).

Subsequently, the value of R for each component was weighted by the percentage composition of the component and then averaged to obtain the expected value of R for the

map unit (eq. 2). Whenever the cumulative percent of included components was less than 100% in a map unit, the component percentage was normalized to 100%. The resulting R raster for the entire state of Nebraska is available from the process:

$$R_j = \frac{\sum_k^s (q_k R_k)}{\sum_k^s q_k} \quad (2)$$

where

j = index for the included map units within a field

R_j = R of map unit j (mm)

s = number of included components in map unit j

q_k = percent composition of component k (%).

Another data source was the 2005 Nebraska center-pivot data layer (CALMIT, 2007), which includes a mapping of center-pivots that were “active” in Nebraska during the 2005 growing season. Center-pivot fields were identified from satellite and aerial imagery analysis (CALMIT, 2007). The original 52,127 center-pivot polygons underwent four filtering steps. First, polygons were clipped to the borders of Nebraska (NRCS, 2009). Twelve polygons that were erroneously located outside of the state were removed.

Second, center-pivot polygons were converted to a raster matching the datum, grid size, and projection of the gSSURGO database. This step paired center-pivot raster cells (10 m × 10 m) with gSSURGO cells. Circular center-pivot polygons do not perfectly align with rectangular raster grid cells. A pivot polygon may include a portion of a raster cell, and multiple pivot polygons could intersect an individual raster cell. Procedures were required to avoid duplication of cells. Center-pivot cells were not shared by polygons and were assigned to the largest pivot polygon that at least partially overlapped the center-pivot cell. If a tie occurred, the polygon with the larger feature identification number (FID) was given priority. Twenty-seven polygons were eliminated because no center-pivot cells were assigned to those polygons.

Third, small polygons were removed from the analysis. This resulted in removal of 2,728 polygons with less than 2,024 10 m × 10 m cells (20 ha). This removed artifacts from the mapping process and fields that were unsuited to VRI due to their small size (<20 ha). Fourth, 136 polygons were omitted because less than 90% of the pivot cells corresponded to gSSURGO cells that included soil map units. The remaining 49,224 center-pivot fields were considered viable for VRI systems in this analysis.

Although additional center-pivots have been installed in the state since 2005, the 49,224 final polygons (94% of the original number) adequately represent center-pivot irrigated fields in Nebraska. For each field, only R values from the corresponding gSSURGO cells that belonged to included map units were accepted for the field. The total cell area of the field was modified to preserve the area of the center-pivot field determined from the pivot polygons.

The following procedures common to one-dimensional soil water balance modeling were used with a planned soil water depletion strategy. Soils were assumed to reach field capacity throughout the root zone before the irrigation season. Water fluxes, including rainfall infiltration, evapotranspiration, lateral flow, capillary rise, and deep percolation, were assumed to be the same across the field. The irrigation application and infiltration for CI were uniform within the field, whereas the application and infiltration of VRI were uniform within soil map units.

DETERMINATION OF UNDEPLETED WATER

Several parameters are required to determine the potential pumpage savings when converting from CI to VRI when employing a planned soil moisture depletion strategy. The procedure is illustrated in figure 2 for a field that contains eight soil map units with unique R . The distribution shows R versus the fraction of the field represented by the map unit. The first parameter required for a CI system is the value of R (R_p) that is used to determine the amount of depletable soil water at the end of the growing season for the field. The R_p value is usually based on a significant percentage (p) of the field that has a low R (map unit 7 in fig. 2). Some map units will have R (R_i) greater than R_p (map units 1 to 6 in fig. 2). Some fields may contain map unit areas with R_i less than R_p (map unit 8 in fig. 2); therefore, crop water stress may occur if too much of the available water is extracted from such areas. The U for the field is the summation of $(R_i - R_p)$. It should be

noted that R_p is not an independent variable; it depends on the selection of the percentage p and the distribution of R in the field.

The fraction (F) of R_p that can be depleted at the end of the growing season is essential for irrigation management and must be defined. The permissible end-of-season depletion for managing CI systems is $F \times R_p$. Simultaneously, the amount of water [$F \times (R_i - R_p)$] would be undepleted in the i th map unit area and would ultimately be lost to deep percolation before the next irrigation season for a CI system in regions where off-season precipitation replenishes the root zone to field capacity. (In regions where the root zone is not replenished by precipitation, such as parts of the western U.S., this approach could not be used to mine undepleted water on an annual basis.) The end-of-season depletion fraction F is not necessarily the same value as the management-allowed depletion (Merriam, 1966). The management-allowed depletion represents the amount of depletion prior to irrigation and would vary throughout the growing season for planned soil water depletion. The value of F represents how much water may be depleted without undue stress at the end of the growing season. With this approach, U would be mined once during the course of the growing season, using a zone control VRI prescription map for one to four irrigation events (depending on the range of R in the field). This may be scheduled to occur during peak evapotranspiration demand if well capacity is limited, or late in the season when crops are less sensitive to low soil water levels (i.e., the management-allowed depletion is higher). A more aggressive, although risky, approach (not simulated here) would be to mine U early in the season, with the potential to mine U a second time if all soil map units are refilled to field capacity from precipitation during the irrigation season.

Implementing a VRI system allows depletion of a larger amount of available water than for CI systems. If the value of F is constant across the field, then the additional soil water depletion possible for a map unit would be [$F \times (R_i - R_p)$]. The additional amount of soil water that can be depleted with VRI is shown as the net pumpage reduction (hatched area) in figure 2. More water could be applied in map unit areas with holding capacities smaller than R_p (such as the narrowly hatched region for map unit area 8 in fig. 2).

Selection of the percentage (p) of the field to define the critical R (R_p) is a management criterion. The quantity $(1 - p)$ is comparable to the irrigation adequacy concept of Clemmens (1991). The difference is that adequacy pertains to the variation of water application, while p relates to soil variability. For irrigation adequacy, R would be considered to be uniform, but a large fraction of the field would receive more water than required because irrigation applications varied across the field. For this study, irrigation applications were considered to be uniform, but $(1 - p)$ of the field would end the growing season with depletion fractions smaller than F because R is nonuniform. The target value of p was chosen to be 10% for this study. The distribution of R within a field was discrete because every field contained a discrete number of map units, each with a single value of R . When the actual p could not equal 10%, calculations favored yield protection; hence, R_p was chosen as the largest R within the field that

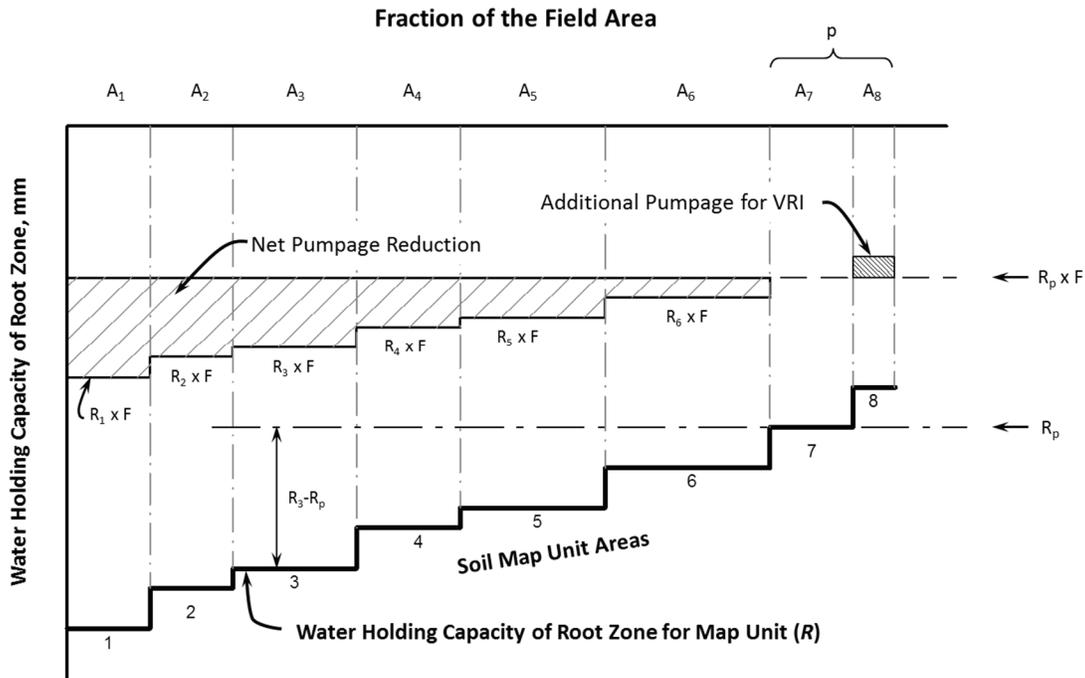


Figure 2. Cumulative distribution of R variability in a field. The area below the horizontal R_p line is undepleted with conventional irrigation.

was greater than at most 10% of R values for the map units in the field. The choice of p is important for comparing CI and VRI systems because U could be overestimated if p is too low and underestimated if p is too high. Selecting the target p of 10% for this research assumed that, under CI management, at most 10% of each field may be at risk of water stress, while at least 90% of each field would have some deep percolation.

The quantity U was defined as the field-average undepleted R with a CI system when using a planned soil moisture depletion strategy. In figure 2, U is essentially the area under the horizontal R_p line. More specifically, U has the dimension of depth and was computed as:

$$U = \sum_{j=1}^m \left[(R_j - R_p) \left(\frac{A_j}{A_{inc}} \right) \right] = R_a - R_p \quad (3)$$

where

- j = index for the map units within the field
- m = number of map units within the field
- A_j = field area that belonged to map unit j
- A_{inc} = total field area that belonged to included map units
- R_a = area-weighted average R within the field.

When U increases, the potential for pumpage reduction from mining R with VRI systems rises. To discover how the occurrence of large U values might differ between subregions of Nebraska, the fields were grouped by soil associations (UNL, 2009) based on the centroids of the center-pivot polygons. The number and fraction of fields within various ranges of U were then calculated for each soil association.

DETERMINATION OF PUMPAGE REDUCTION

Potential methods to reduce pumpage with VRI include reducing irrigation application by mining U , eliminating application over uncropped areas, reducing application on

hillslopes where runoff is high, reducing application in depressional areas with high infiltration due to runoff, etc. This analysis quantified pumpage reduction from mining U . For each map unit, the seasonal net irrigation could be reduced by $[(R_j - R_p) \times F]$. Consequently, the field-average potential depth of seasonal pumpage (i.e., gross irrigation) reductions from mining U with VRI systems (Δd_r) was estimated as follows:

$$\Delta d_r = \sum_{j=1}^m \left[\frac{(R_j - R_p) F}{E_a} \left(\frac{A_j}{A_{inc}} \right) \right] = \frac{U \times F}{E_a} \quad (4)$$

where E_a is the application efficiency as a decimal fraction.

The pumpage reduction is proportional to U . Once the distribution of U is calculated for center-pivot fields in Nebraska, the distribution of pumpage reduction can be determined using F and E_a . Typical values for parameters F and E_a are 0.5 (Kranz et al., 2008a) and 0.85 (Kranz et al., 2008b), respectively, for both CI and VRI. The 15% inefficiency accounted for irrigation water that was pumped but not stored in the managed root zone during the irrigation season (due to droplet evaporation, drift, surface runoff, etc.). If higher application efficiencies could be achieved with VRI systems than with CI systems, then pumpage reductions could be greater. The R distribution and Δd_r for each field were made available through an online map tool (<http://heeren.unl.edu/map>).

Annual water supplies may be limited by pumping capacity and/or by water use regulations from state agencies. Thus, supplies may be inadequate to meet seasonal irrigation requirements for the whole field. In these cases, producers would not reduce pumpage with VRI because water could be shifted to water-short areas of the field. Current economic conditions encourage pumping enough irrigation water to

maximize yield, whether with CI or VRI systems. The available water supply for each center-pivot polygon was not determined. Instead, pumpage reductions were not considered for fields where the centroid of a center-pivot polygon fell within the four Natural Resources Districts, or NRDs (Nebraska DNR, 2011), that enforce NRD-wide groundwater quantity allocations. The economic advantages of VRI in water-short areas would require determination of yield enhancement resulting from improved water distribution. That benefit was not analyzed for this investigation, and the economic benefits of VRI in NRDs with seasonal allocations were not included. The center-pivot fields that were eliminated for the NRDs were subtracted from the viable fields for analysis.

DETERMINATION OF PUMPING COST SAVINGS

Estimates of pumpage reductions from mining U can provide valuable financial information regarding VRI purchases, as pumping cost savings contribute to profitability. The potential volume of seasonal pumpage reduction from mining U with VRI (ΔV_r) is computed as Δd_r multiplied by the total area for the field (A_f):

$$\Delta V_r = \frac{F}{E_a} U A_f \quad (5)$$

The present value (PV) of pumping cost savings (computed as a uniform annual series) accumulated over a payback period of n years was calculated from ΔV_r (eq. 6). Both the marginal pumping cost savings per unit of ΔV_r (C_w) and the annual discount rate (i , also called “interest rate”) were assumed to be fixed during the payback period. Adoption of VRI would be financially justified solely for pumping cost savings from mining U when PV exceeded the total cost of a VRI system:

$$PV = \sum_{t=1}^n \left[\frac{C_w \times \Delta V_r}{(1+i)^t} \right] = C_w \times \Delta V_r \times \frac{(1+i)^n - 1}{i(1+i)^n} \quad (6)$$

where t is the time in years since the VRI system began operation.

Pumping cost savings from mining U with VRI may be different from the marginal pumping cost savings from the improvement of CI management. With a well-selected and well-maintained pump, CI pumpage reductions would result from reductions in pumping time while operating near the maximum efficiency of the pump. The CI marginal pumping cost savings would be constant because system flow rate and total dynamic head would be unaltered. In contrast, VRI pumping reductions could result from reductions in system flow rate, which may shift the pump efficiency and increase the total dynamic head due to energy loss in pressure regulators. If a variable-frequency drive were used for the pump, energy loss in the pressure regulators would be reduced but the efficiency would still shift away from optimum efficiency during reduced flow rates. Therefore, the VRI marginal pumping cost savings would be variable and dependent on the pump performance curve and the system flow rate. For simplification, VRI marginal pumping cost savings (C_w) were assumed to equal CI marginal pumping cost savings,

with the understanding that annual pumping cost savings from this application of VRI may be overestimated.

Pumping costs can vary drastically between fields due to differences in energy requirements and energy prices. A low pumping cost may be exemplified by an electrically powered pump providing 0 m of lift (i.e., surface water source) and 100 kPa of pressure while consuming anytime interruptible electricity at $\$0.0624 \text{ kWh}^{-1}$ (NPPD, 2014). On the other hand, a high pumping cost may be exemplified by a diesel engine providing 60 m of lift and 400 kPa of pressure while consuming farm diesel at $\$0.851 \text{ L}^{-1}$. This diesel price is the 2011-2015 average of farm diesel prices in Iowa (AMS, 2015). For simplicity, both irrigation pumps were assumed to operate at 100% of the Nebraska Pumping Plant Performance Criteria (NPPPC) (Kranz, 2010). Less efficient pumping plants would result in a greater cost savings than reported in this analysis. The two CI marginal pumping costs, calculated to be $\$0.0026 \text{ m}^{-3}$ and $\$0.0947 \text{ m}^{-3}$, were assumed to represent low and high C_w (eq. 6) values for the Central Plains.

RESULTS AND DISCUSSION

DISTRIBUTION OF UNDEPLETED WATER

The quantity U is soil water that cannot be depleted with CI irrigation systems because of soil variability within a field. The variables defining U (R_a and R_p) ranged from 26 to 276 mm (fig. 3). The distribution of R_a was left-skewed, with values of R_a for 61% of the fields ranging between 203 and 254 mm. The distribution of R_p was slightly bimodal but was also left-skewed, loosely following the shape of the R_a with two exceptions. More R_p values fell in the 76 to 102 mm range, whereas more R_a values fell in the 229 to 254 mm range.

In contrast, the distribution of U was right-skewed, ranging from -16 to 164 mm (fig. 4). About 6% of the U values were negative, while 83% were between 0 and 51 mm. An additional 10% of the fields had U between 51 and 102 mm, while only 1% of the fields would provide more than 102 mm. Negative U values occur when the average R is less than the critical value R_p . This could occur for a nearly uniform field with a small area where the R is much smaller than the majority of the field. In figure 2, this would be equivalent to map unit areas 1 to 6 being nearly identical to map unit area 7 while map

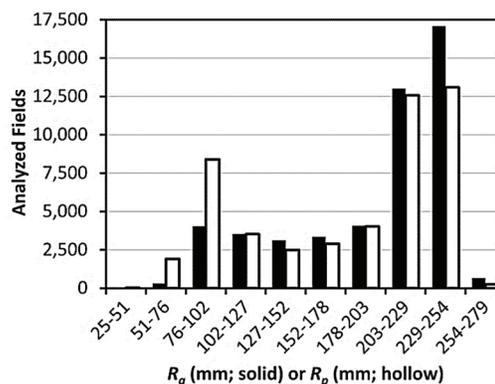


Figure 3. Distributions of R_a (solid bars) and the 10th percentile R (R_p ; hollow bars) for viable fields in Nebraska.

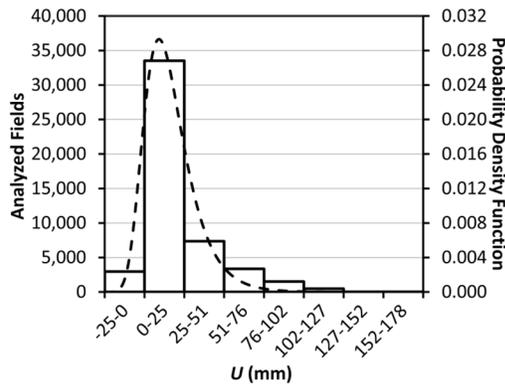


Figure 4. Empirical histogram (hollow bars; left axis) and fitted probability density function (dashed line; right axis) of U for viable fields in Nebraska.

unit area 8 has a much smaller R . Negative U values indicate that depletable water is larger for CI than VRI.

A Gumbel distribution with mean of $a + 0.5772b$ and standard deviation of $b\pi/\sqrt{6}$ was fitted to the U data (eq. 7). The “fitdistrplus” package (Delignette-Muller and Dutang, 2015) in the statistical software R (R Core Team, 2015) was used to maximize goodness of fit as described by the Cramér-von Mises distance criterion. The location parameter (a) was 9.25 mm, and the scale parameter (b) was 12.55 mm. The mean and standard deviation were 16.5 and 16.1 mm, respectively, using parameters for the fitted distribution, compared to 19.5 and 23.4 mm from direct computation:

$$g(U) = \frac{1}{b} \exp\left(\frac{a-U}{b}\right) \exp\left[-\exp\left(\frac{a-U}{b}\right)\right] \quad (7)$$

where

g = fitted probability density function of undepleted water (U)

a = location parameter of a Gumbel distribution

b = scale parameter of a Gumbel distribution.

The cumulative density function (G) represents the fraction of the fields that have U less than or equal to a specified value of U . The cumulative density is given by:

$$G(U) = \int_{-\infty}^U g(x) dx = \exp\left[-\exp\left(\frac{a-U}{b}\right)\right] \quad (8)$$

The density and cumulative probability functions for U are displayed in figure 5.

DISTRIBUTION OF PUMPAGE REDUCTION

Pumpage reduction (Δd_r) is proportional to U with the ratio F/E_a as a scalar multiple (eq. 4). Therefore, if the distribution of U is known, then the distribution of Δd_r is known. The inverse cumulative density function of U is expressed as:

$$U = a - b \ln[-\ln(G)] \quad (9)$$

The inverse cumulative density function allows for the computation of U for a selected probability. Substituting $\Delta d_r \times (E_a/F)$ (from eq. 4) for U provides an inverse distribution for Δd_r (fig. 6):

$$\Delta d_r = \left(\frac{F}{E_a}\right) (a - b \ln[-\ln(G)]) \quad (10)$$

The ratio F/E_a for typical conditions was approximately 0.6 (i.e., 0.5/0.85). The median Δd_r for that ratio would be approximately 8.3 mm, while 75% of the fields would produce Δd_r less than about 15 mm (i.e., only 25% would produce Δd_r greater than 15 mm) (fig. 6). Some crops may withstand drier end-of-season soils, which would increase Δd_r . For example, allowing an F of 0.7 with an E_a of 85% ($F/E_a = 0.82$) would provide a median Δd_r of about 11 mm, and 25% of the fields would provide more than 20 mm of Δd_r . The potential pumpage reductions represent a small percentage of the annual pumpage for the large majority of fields in Nebraska.

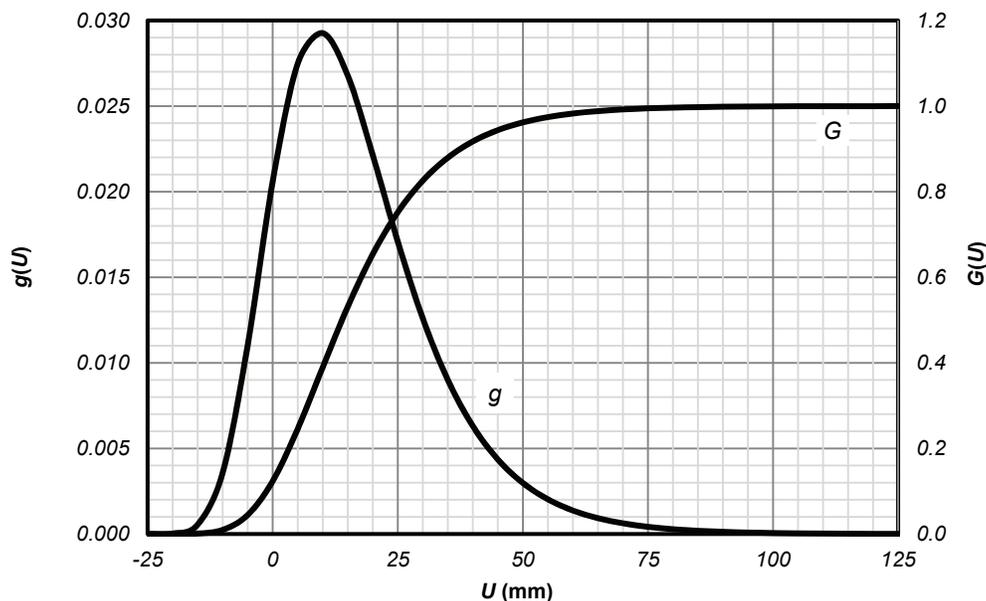


Figure 5. Density and cumulative probability functions for U for viable fields in Nebraska.

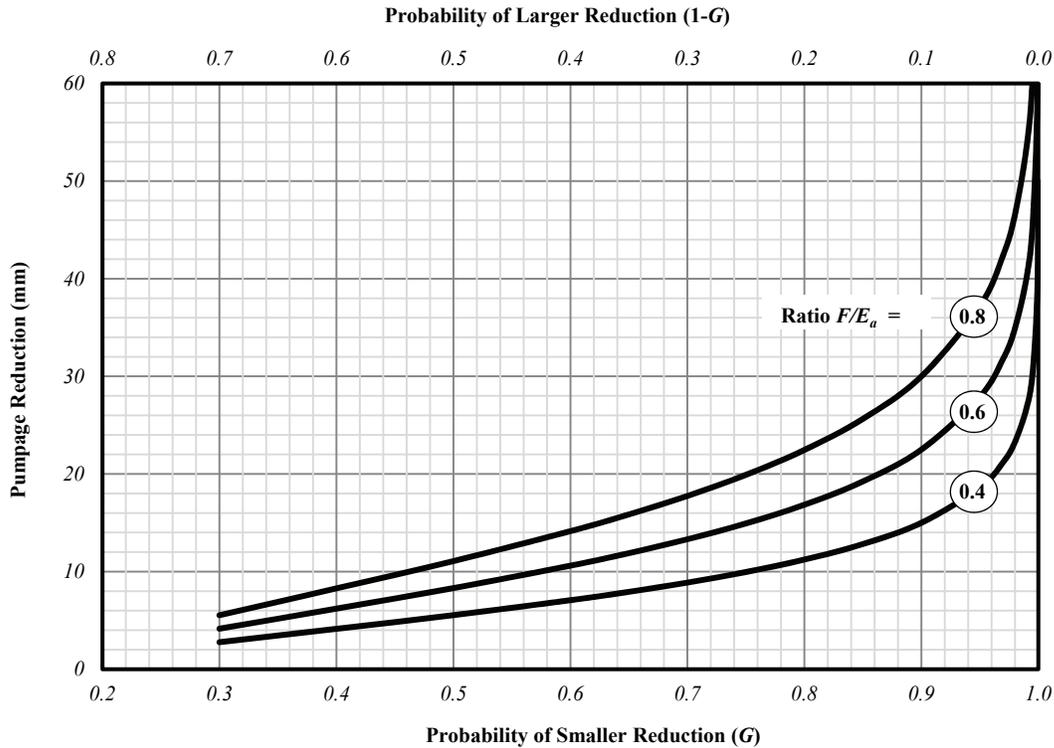


Figure 6. Inverse distribution for pumpage reduction (Δd) for viable center-pivot irrigated fields in Nebraska. The top horizontal axis can be used to determine the percentage of fields with Δd greater than a specified value (vertical axis).

SENSITIVITY OF UNDEPLETABLE WATER

The amount U depends on the distribution of R in a field and the selected value of p , i.e., the percent of the field where $R \leq R_p$. Irrigators only have control over the value of p . The distribution of R within a field is unique; thus, modifying p could create sizable changes in R_p in some fields. To examine this sensitivity, R_p and U were calculated using target p values of 5%, 10%, and 15%. The distributions of R_p and U were similar for the values of p (table 2). Eighty percent of the U values remained the same when using p equal to 5% instead of 10%, while 83% of the U values remained the same when using a p value of 15%. A target p of 5% led to an average increase of 20 mm in U , whereas a p of 15% led to an average decrease of 19 mm. In one field, U changed by 220 mm. The number of fields with a negative U value was

clearly affected when p was altered. Overall, U was insensitive to values for p between 5% and 15% on most fields; however, it was sensitive on a minority of the fields.

SPATIAL DISTRIBUTION OF UNDEPLETED WATER

The distribution of center-pivot fields in Nebraska for three ranges of U is shown in figure 7. Fields with small values of U are dispersed across the irrigated regions of the state. Areas without fields with small U values are regions with little irrigated land (fig. 7a). Fields with medium U values are scattered throughout the state as well but are concentrated along streams and/or along breaks between soil type areas. Moderate U pivots are less common on tablelands where many pivots are found (fig. 7b). Pivot fields with high U values are quite sparse and are often located along streams and or in associated alluvial areas (fig. 7c).

Table 2. Distribution of R_p and U for conventional irrigation with R_p from $p = 5\%$, 10% , and 15% .

Range (mm)	No. of Fields with R_p in Range			No. of Fields with U in Range		
	Target $p = 5\%$	Target $p = 10\%$	Target $p = 15\%$	Target $p = 5\%$	Target $p = 10\%$	Target $p = 15\%$
-25 to 0	0	0	0	1,232	2,976	5,036
0 to 25	2	0	0	32,717	33,510	33,466
25 to 51	70	32	23	8,135	7,350	6,608
51 to 76	2,326	1,916	1,617	3,988	3,350	2,785
76 to 102	9,031	8,396	7,929	2,098	1,513	1,065
102 to 127	3,465	3,523	3,422	877	480	248
127 to 152	2,584	2,506	2,515	156	43	16
152 to 178	2,904	2,907	2,922	17	2	0
178 to 203	4,272	4,022	3,950	2	0	0
203 to 229	12,883	12,578	12,195	2	0	0
229 to 254	11,498	13,088	14,325	0	0	0
254 to 279	189	256	325	0	0	0
279 to 305	0	0	1	0	0	0

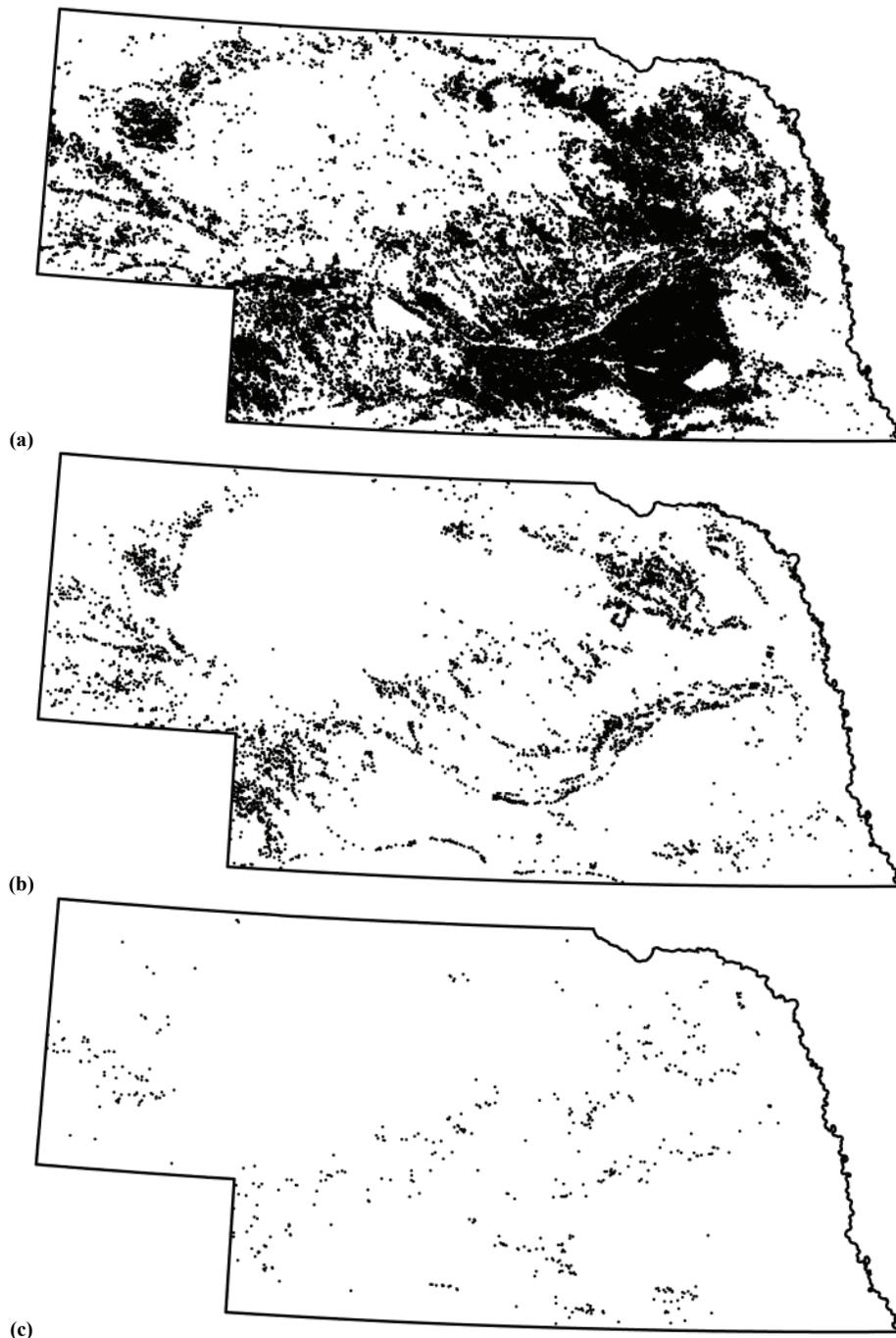


Figure 7. Centroids of center-pivot fields with (a) $U < 51$ mm, (b) $51 \text{ mm} < U \leq 102$ mm, and (c) $U > 102$ mm.

The percentages of U values that were ≥ 51 mm and ≥ 102 mm, respectively, were computed for all soil associations except those with less than 30 fields. The eight soil associations that ranked in the top 15 in terms of the percentages of U values for each range are shown in figure 8. These soil associations were Tripp-Mitchell-Alice (code 13), Thurman-Boelus-Nora (code 27), Hord-Cozad-Boel (code 30), Albaton-Haynie-Sarpy (code 38), Canyon-Alliance-Rosebud (code 46), Valent-Sarben-Otero (code 52), Moody-Thurman (code 54), and Nuckolls-Holdrege-Campus (code 69). These soil associations included coarser parent materials,

such as eolian sand or sandstone, combined with finer parent materials, such as loess (UNL, 2009). In addition, three soil associations (codes 13, 30, and 38) were affected by alluvial processes during formation (UNL, 2009). The large degree of spatial variability known to exist in alluvial soils (Iqbal et al., 2005; Heeren et al., 2015) may explain why center-pivots with large U values align with several rivers in Nebraska (figs. 7b and 7c). This suggests that the greater prevalence of fields with large U values in these associations may be explained by soil formation.

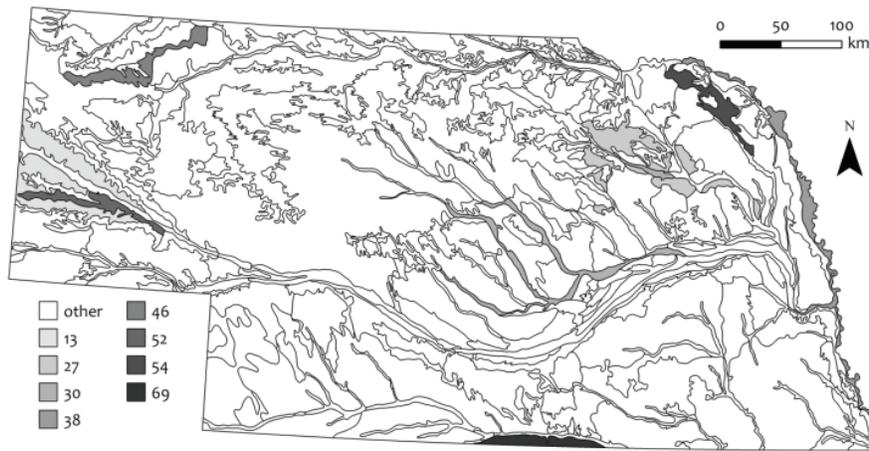


Figure 8. Soil associations in Nebraska (black outlines) and eight associations ranked in the top 15 in terms of percentages of U values ≥ 51 mm and ≥ 102 mm are colored in various shades of gray and listed in the text.

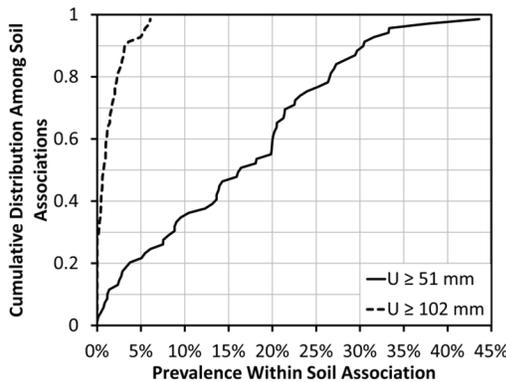


Figure 9. Cumulative distributions of the occurrence of large values of U in Nebraska using conventional irrigation systems (only includes associations with >30 viable fields).

Contrary to expectations, the statistical distributions of U values ≥ 51 mm and ≥ 102 mm among soil associations were not bimodal (fig. 9). The majority of U values were small, with few high U values, in most soil associations. Of the 68

soil associations with a minimum of 30 fields, 19 contained no U values ≥ 102 mm; however, none contained U values that were exclusively ≥ 51 mm. Thus, in the Central Plains, soil association information alone is inadequate to identify fields with potential for large pumpage reductions by mining U using VRI systems.

REGIONAL IMPACT OF PUMPAGE REDUCTION

Pumpage reductions from mining U with VRI systems were estimated for two levels of implementation. The smaller level of implementation included VRI systems used on viable fields with $\Delta d_r > 51$ mm. The larger implementation considered viable fields with $\Delta d_r > 25$ mm. For both levels, the percentage of implemented fields, the area-weighted average Δd_r for implemented fields, and the total ΔV_r were calculated for 19 NRDs without groundwater pumpage allocations (table 3). These pumpage reductions result from a shift in the source of evapotranspired water and not from a change in the quantity of evapotranspiration. Reductions in groundwater withdrawal through application of

Table 3. Each natural resources district's (NRD) percentage of implemented fields, Δd_r among implemented fields, and ΔV_r for two VRI implementation extents. Four NRDs were omitted due to NRD-wide groundwater quantity allocations.

NRD	Viable Fields	$\Delta d_r \geq 51$ mm			$\Delta d_r \geq 25$ mm		
		Implemented Fields	Mean Δd_r (mm)	Total ΔV_r ($\times 10^6$ m 3)	Implemented Fields	Mean Δd_r (mm)	Total ΔV_r ($\times 10^6$ m 3)
Central Platte	3,666	3%	59	2.6	14%	40	9.8
Lewis & Clark	602	9%	58	1.5	34%	43	4.6
Little Blue	3,348	2%	62	2.4	4%	51	3.5
Lower Big Blue	1,079	0.09%	51	< 0.1	10%	30	1.5
Lower Elkhorn	3,700	3%	60	3.9	19%	41	13.6
Lower Loup	6,087	3%	61	5.3	11%	43	14.1
Lower Niobrara	1,443	0.9%	57	0.3	12%	35	3.1
Lower Platte North	1,989	1%	61	0.5	11%	37	3.8
Lower Platte South	104	0%	0	0	16%	34	0.3
Middle Niobrara	678	2%	59	0.3	20%	36	2.3
Nemaha	181	2%	65	0.2	25%	40	1.0
North Platte	1,652	8%	61	3.8	33%	42	11.2
Papio-Missouri River	436	5%	59	0.6	25%	41	2.6
Tri-Basin	2,563	2%	66	1.5	7%	43	3.8
Twin Platte	1,826	4%	60	2.2	20%	40	7.8
Upper Big Blue	6,841	0.04%	56	0.1	0.2%	34	0.2
Upper Elkhorn	3,059	3%	57	2.1	25%	37	14.0
Upper Loup	380	2%	57	0.2	21%	38	1.5
Upper Niobrara-White	1,763	3%	58	1.4	28%	37	9.4
Total	41,397	2%	60	29.0	13%	40	108.1

VRI will approximately equal the decrease in groundwater recharge by water percolating past the root zone. Therefore, the water supply for other users in the watershed should not increase due to these pumpage reductions.

A pumpage reduction trend emerged for the NRDs listed in table 3. As the Δd_r criteria decreased from 51 to 25 mm, implementation expanded from 2% to 13% of the fields in all NRDs. The volume of the pumpage reduction (ΔV_r) increased with the wider implementation because of the larger number of fields, even though the area-weighted depth decreased with more extensive implementation.

There were differences between NRDs. For instance, for both implementation levels, the Lewis & Clark and North Platte NRDs had much higher percentages of implemented fields than the Upper Big Blue and Little Blue NRDs. Two percent or less of the fields in ten NRDs would be included in the implementation for the 51 mm level. Three of the 19 NRDs involved $\geq 5\%$ of the viable fields in the NRD for the 51 mm level. Conversely, for the 25 mm level, 11 of the 19 NRDs included $\geq 15\%$ of the viable pivots in the NRDs.

The potential statewide pumpage reduction was compared to statewide pumpage. The USDA-NASS Farm and Ranch Irrigation Survey gathered self-reported irrigation data from farmers in 2013. The survey reported that 2,943,836 ha of land were irrigated with center-pivot systems in Nebraska (NASS, 2014). The total irrigated area for the viable fields in 2005 was 2,430,562 ha. If the results of this study are also representative of center-pivots installed after 2005, then the total volume of pumpage reduction (ΔV_r) in 2013 would be approximately 35 million m^3 for the 51 mm implementation level and 131 million m^3 for the 25 mm level of implementation. These volumes were 0.35% and 1.3%, respectively, of the 9,953 million m^3 of irrigation pumpage in Nebraska during 2013 as reported in the survey (NASS, 2014). Well-managed CI systems with a planned soil moisture depletion strategy were used as the baseline for pumpage reduction from mining U with VRI systems. A smaller volume would probably have been pumped during 2013 if well-managed CI systems with planned soil moisture depletion were operated on all irrigated fields. Nevertheless, the results suggest that mining U with VRI systems would not generate meaningful reductions in statewide pumpage.

These findings indicate that pumpage reductions from mining U with VRI systems might not significantly reduce energy consumption for center-pivot irrigation in Nebraska. Yet application of VRI may affect peak power demand. When applying a reduced depth of water onto soils with larger holding capacities, the system flow rate could be lowered, or the operation time would be shortened. The instantaneous power demand may decrease with system flow rate depending on the pump performance. In addition, some low-capacity systems might be switched from continuous to interruptible electricity service without incurring water stress.

From an environmental perspective, application of VRI technology could minimize nitrate leaching during the irrigation season and prior to the season when using a programmed soil water depletion strategy. Mining U with VRI would decrease deep percolation from soils with larger R . This decrease could be significant relative to the magnitude

of annual deep percolation from these soils, even though the associated pumpage reductions may be moderate relative to the magnitude of annual irrigation.

PUMPING COST SAVINGS

Regardless of the expected regional impact of pumpage reductions from mining U , pumping cost savings from application of VRI may justify investment for certain fields. The PV of pumping cost savings was calculated for the 41,937 viable fields in NRDs without NRD-wide groundwater pumpage allocations. Two C_w were combined with an annual discount rate of 5%, which was fixed in real terms (i.e., equal inflation rate) during a payback period of ten years. The exceedance distributions, computed using the Weibull formula, for the two sets of PV values are plotted in figure 10. In equation 6, PV was linear with respect to ΔV_r . Thus, the exceedance distributions of PV inherited the right-skewed distribution of ΔV_r . The quantity PV was also linear with respect to C_w (eq. 6). Because the high C_w of $\$0.0947 m^{-3}$ was 36 times larger than the low C_w of $\$0.0026 m^{-3}$, the PV for a given ΔV_r was 36 times larger with the high C_w than with the low C_w .

The exceedance distributions of PV were compared with the capital cost for zone control VRI capability, which provides the greatest flexibility for adapting to spatial heterogeneity. Adjusting the application rate and depth by pulsing valves that control individual sprinklers or banks of sprinklers is referred to as zone control. Such VRI systems have been reported to cost “about $\$200$ to $\$550 ha^{-1}$ ” for center-pivots (Evans et al., 2013). This capital cost would be $\$10,000$ to $\$27,500$ for a typical center-pivot in the Central Plains irrigating 50 ha. For the low pumping cost, PV was below this range of capital costs for all viable fields without NRD-wide allocations. For the high water cost scenario, PV exceeded $\$10,000$ on 10% of the fields and $\$27,500$ on only 0.4% of the fields. Based on this comparison, VRI adoption solely for pumping cost savings from mining U are limited to fields with large ΔV_r and high C_w values. Widespread adoption of VRI in the Central Plains for this benefit appears to be unlikely, unless VRI prices decrease relative to C_w . Sector control (also known as “speed control”) VRI capability, which adjusts application depth by altering the revolution speed of the outermost tower, is less expensive than zone control. However, because only sectors spanning the

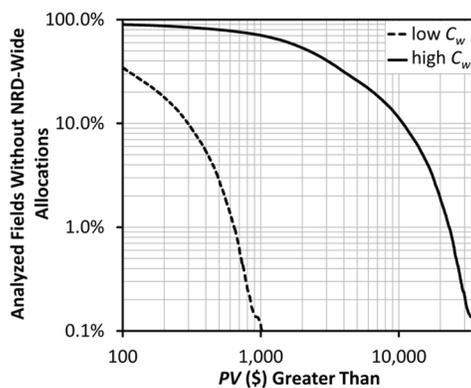


Figure 10. Distribution of the present value (PV) of pumping cost savings in Natural Resources Districts without groundwater pumpage allocations.

entire length of the pivot lateral can be independently managed with speed control, the effectiveness of VRI systems in matching spatial variability in R and achieving pumping cost savings may be lower with speed control than with zone control. Readers could refer to Miller (2015) and Haghverdi et al. (2015) for comparisons between these VRI control technologies.

Other potential benefits of VRI need consideration during investment analysis to assess the feasibility of VRI systems. A brief economic analysis by Lo (2015) for the Central Plains revealed that using VRI to reduce yield losses associated with excessive water might have potential to justify investment in zone control VRI for fields where water supplies are adequate for full irrigation. Future research should quantify reductions in yield losses associated with excessive water as an economic benefit of VRI. For typical irrigated crops in the Central Plains (i.e., corn and soybeans), maximum yield is achieved by minimizing water stress. In other regions, VRI may be economical for crops that attain maximum yield quantity (e.g., cotton; Grimes et al., 1969) or quality (e.g., wine grape; Matthews and Anderson, 1988) under mild deficit irrigation. In addition, mining U and reducing pumpage with VRI may lower on-farm fertilizer costs (due to less nitrogen loss through denitrification and leaching). The public cost of purifying and/or protecting public drinking water supplies from nitrate contamination and/or the environmental cost of pumping energy generation and of fertilizer production and application could also be reduced. The magnitude of these benefits may be difficult to estimate, but their quantification would improve the viability of VRI systems compared to pumping cost savings alone.

CASE STUDY

Various factors can affect the reliability of this research. The accuracy of analytical results depends on the quality of the underlying data. Publicly available geospatial data were used without extensive adjustments; thus, database errors were inherited by this study. The center-pivot map contained a limited number of inaccuracies in the location and boundaries of center-pivot irrigated fields. Some issues were corrected, or center-pivot polygons were eliminated if corrections were not possible. Analysis of the data quality assured us that the data are reliable for the uses in the study. For example, spot checks by superimposing pivot coverage polygons over digital photographs showed that most pivot polygons are representative of center-pivot locations and characteristics in 2005. Imprecise delineation of soil map units as well as uncertainties and errors in soil properties could exist but were undetectable. The gSSURGO datasets have been extensively inspected, and thus we are confident that there are few actual errors in the database. However, soil surveys were not conducted with precision agriculture applications in mind (Brevik et al., 2003), so gSSURGO datasets lack detailed information about heterogeneities below the soil map unit level. Thus, small regions with characteristics that may benefit from VRI are homogenized within a map unit area; this would reduce the computed viability of VRI systems. Hedley and Yule (2009) found greater variability in soil water content within management zones than between management zones, although variability at a scale smaller than the

wetted diameter of sprinkler could not be addressed with sprinkler VRI. These issues somewhat constrain gSSURGO datasets for this application; however, the dataset is the only viable statewide resource and provides for high-level analysis of applicability.

The method included some simplifying assumptions that could cause predictions to deviate from actual pumpage reductions. If a substantial rain occurs after depletion of available water exceeds R_p , then soils with larger R may retain more infiltrated water than soils with smaller R , which may experience more deep percolation or runoff. Additionally, soils with large R typically occur in lower topographic positions where they may infiltrate more water due to longer opportunity times during runoff recession. In these instances, the potential pumpage reductions from mining U with VRI systems would be underestimated by this study because U could be mined more than once per season.

In other situations, pumpage reductions from mining U with VRI would be specious. In subhumid areas, like eastern Nebraska, years may occur in which the end-of-season depletion fraction in soils with large R never reaches the specified F because of initial soil moisture and abundant in-season rainfall. In semiarid regions, like western Nebraska, soils depleted to the specified F at the end of the previous growing season may not completely refill before the current season. There may be seasons in which only soils with small R refill due to off-season precipitation. Additionally, if an intense rain occurs, soils with larger R (which tend to be composed of finer textures and have lower infiltration rates) may capture less water than soils with smaller R . The E_a was the same for CI and VRI systems in this analysis. Future work can analyze how applied irrigation differs between CI and VRI systems to improve estimates of the E_a .

In order to address these concerns, the U from gSSURGO was compared to U based on actual field data (Lo, 2015) from a 26 ha center-pivot irrigated field near Aurora, Nebraska (latitude 40.832°, longitude -98.015°). The field consisted predominantly of upland loess-derived soils, with a hill that separated two ephemeral streams. Observational field capacity (FC_{obs}) measures field capacity *in situ* and captures the effect of soil layering and other obstructions to water flow that are not accounted for in laboratory-determined field capacity (Lo, 2015; Jiang et al., 2007; Martin et al., 1990). The FC_{obs} was determined at 32 locations in the field with neutron probe soil water measurements three days after a 19 mm rain near the end of a wet period. The correlating observational R (R_{obs}) was calculated as the difference between FC_{obs} and the wilting point determined with a pedo-transfer function. Finally, R_{obs} was predicted throughout the field by regression with another geospatial variable.

The R maps computed from gSSURGO shared similarities with the R_{obs} maps obtained from field measurements. According to both data sources, the top of the hill was identified as a zone of intermediate R values, the sideslopes of the two valleys (at least a stretch) as a zone of low R values, and the bottom of the wider valley as a zone of high R values. The two data sources also exhibited substantial differences. However, the overall agreement supported the use of gSSURGO for preliminary analyses in VRI investment decisions.

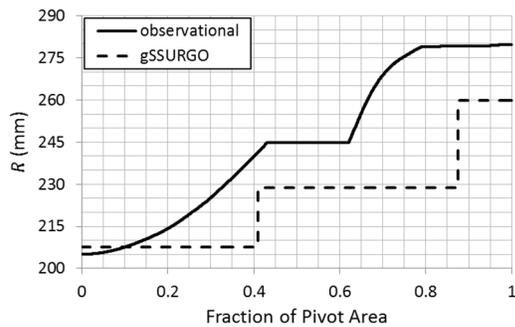


Figure 11. Cumulative distribution functions of R from the gridded Soil Survey Geographic database (gSSURGO) and field-measured observational R (R_{obs}) for a field site near Aurora, Nebraska.

Data were analyzed using the cumulative distribution functions of R_{obs} and the gSSURGO R (fig. 11). Interestingly, the 10th percentile values of R from both maps were within 0.1 mm of each other. One might expect that the difference between the 10th percentile value and the 5th or 15th percentile value would tend to be greater for gSSURGO R , with coarsely discretized map units, than for actual R . This expected outcome was not observed at this field site. The values of gSSURGO R between the 5th and 15th percentiles were equal. On the other hand, the 10th percentile value of R_{obs} was 2 mm larger than the 5th percentile value and 3 mm smaller than the 15th percentile value.

Assuming that CI planned soil moisture depletion (Woodruff et al., 1972, as cited by Lamm et al., 1994) was managed based on the 10th percentile value of R , the U would be 37 mm according to the R_{obs} map and 16 mm according to the gSSURGO R map. The difference in U is primarily due to the large range in R_{obs} , resulting from FC_{obs} having a larger range than field capacity estimated by gSSURGO. This analysis indicated that Δd_r may be a conservative estimate of pumpage reductions.

Notwithstanding issues with using gSSURGO data, the methodology and associated data were deemed reliable and adequate for providing a statewide assessment for application of VRI. Analysis of VRI application at the field level may require field data collection.

CONCLUSION

Few center-pivot irrigated fields in Nebraska were found to provide large values of U or Δd_r . It is expected that implementing VRI to reduce pumpage by mining U may decrease nitrate leaching and peak energy demand, but the regional impact on seasonal total pumping energy consumption is expected to be small. Pumpage savings alone may be insufficient to justify zone control VRI investment at prevailing prices for most fields. Pumpage savings occur in conjunction with other VRI benefits that should be considered when analyzing investments. Adoption of VRI would be enhanced if benefits from nitrogen fertilizer savings due to reduced leaching were included. The viability of VRI would be enhanced if public externalities and environmental benefits were internalized to producers. Lower VRI prices relative to the cost of pumping energy would also encourage adoption. Results revealed clear differences in the occurrence of large

amounts of U among soil associations in Nebraska. Notably, some soil associations contained many center-pivot irrigated fields but few fields with large values of U . Knowing the soil association of a field rarely provided adequate information of the magnitude of U for the field. Based on the components considered in the analysis, it appears that pumpage savings from VRI may be small for most center-pivot irrigated fields. Assessment of individual fields will require of field-specific surveys.

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NOMENCLATURE

- CI = conventional irrigation
VRI = variable-rate irrigation
WHC = soil horizon water holding capacity ($\text{cm}^3 \text{cm}^{-3}$)
 R = root zone water holding capacity (mm)
 R_a = area weighted average R within a field (mm)
 R_p = the p percentile of R within a field used for CI management (mm)
 U = undepleted R under CI (mm)
 F = fraction of R that can be depleted (-)
 E_a = application efficiency of the irrigation system (-)
 Δd_r = field-average potential depth of seasonal pumpage reductions (mm)
 ΔV_r = potential volume of seasonal pumpage reduction for a field (m^3)
 C_w = marginal pumping cost savings per unit of ΔV_r ($\text{\$ m}^{-3}$)
 PV = present value of pumping cost savings accumulated over a payback period ($\text{\$}$)