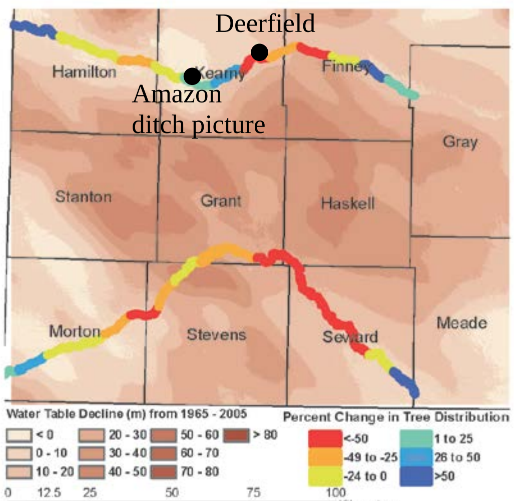
1) Title: Extending the usable lifetime of the Ogallala Aquifer by filling it through riverbeds.

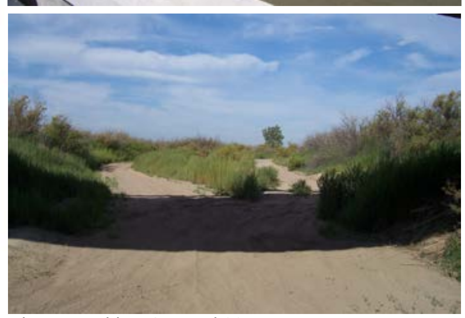
2) Investigators and Institutional Affiliations: David Steward (groundwater: KSU), Stacey Tucker-Kulesza (near surface geophysics: KSU), and Stephen M. Welch (uncertainty analysis: KSU), Groundwater Management District #3.

3) Summary/Abstract: The locations with the highest potential to quickly recharge groundwater to the Ogallala Aquifer are through riverbeds. Previously funded OAP research measured properties of riverbed sediments using infiltrometers coupled with remote sensing to establish transmission losses from the Arkansas River to the Ogallala Aquifer. Proposed work will investigate properties of the near surface geologic deposits beneath the rivers and develop models of groundwater recharge processes. The novel methods will employ electrical resistivity tomography (ERT) and ground penetrating radar (GPR) to quantify water content and identify regions of enhanced recharge through geological inclusions, coupled with vadose zone models and uncertainty analysis of the groundwater parameters necessary to match models with data. The methodology will be used to quantify the rates of filling the aquifer through riverbeds. We currently do not know how much water exists in the wetted regions beneath rivers, or how quickly river water is transported downward through these deposits to the Ogallala.

Rivers in SW Kansas GMD3 where declining groundwater levels have led to tree die-off are good potential recharge sites (Ahring and Steward, 2012).



The Amazon ditch controls surface water (located on the Arkansas River in Kearney County, as shown by dot on map to left).



Photos David R. Steward 2014

The Deerfield bridge (near the Kearney/ Finney county line about 20 mi downstream) had no river flow, with both pictures taken in August 2014.

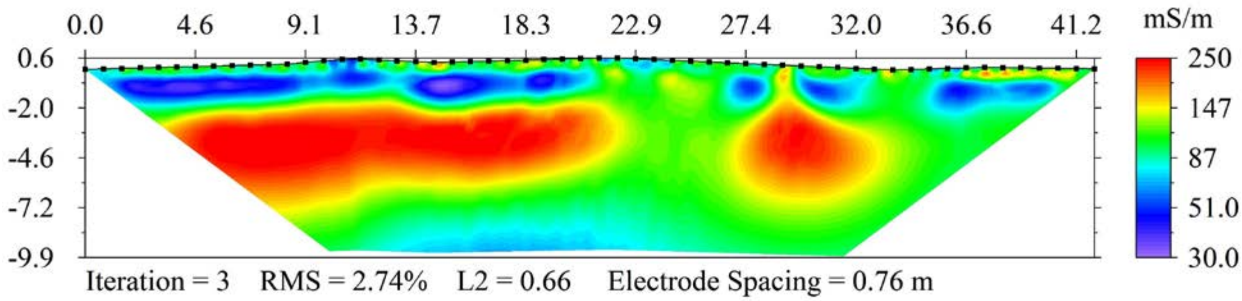
4) Project narrative: a) Objective(s)

This workplan addresses OAP priority area 3) Improve the understanding of hydrological and climatic factors that affects water use and economic profitability, and provide estimates of the climatic, hydrologic, cropping, and profitability conditions that are likely to occur on the southern High Plains over the next 50 years. We know that the recharge rate beneath agriculture fields is only a fraction of the rate of groundwater decline, and this recharge will take decades to centuries to refill the Ogallala Aquifer (Steward et al. 2013). We also know that the streams used to be fed by groundwater (Allen, 2016) but they are now acting as zones of enhanced recharge (Ahring and Steward, 2012), and we know groundwater mounds are forming beneath rivers (Bulatewicz et al. 2014). What we don't know is the quantity of enhanced recharge occurring beneath riverbeds nor the hydrologic controls of this water balance. River corridors provide the best possible conduit between surface waters and groundwater, and this plan addresses the challenge of finding good recharge zones to effectively refill the aquifer for economic benefit.

b) Rationale/Literature Review/Conceptual framework

Previously funded OAP research has led to quantification of riverbed properties, such as saturated conductivity and porosity, which is important for understanding the recharge processes occurring from rivers to the Ogallala. The locations of significant recharge have also been identified from Landsat imagery, as occurring in the ditches and the Arkansas River, primarily in Kearney and western Finney Counties, just downstream of the Bear Creek Fault. Preliminary analysis was performed in this area along a section of the river that had recently received streamflow from a dam release in Colorado.

The preliminary results (below) show that recharge from a river to the Ogallala can be identified by changes in the conductivity of soils with increasing moisture content. We are encouraged that these results not only show the descending plume of recharge water, but also identify the role of invasive species like the salt cedar in limiting groundwater capacity (see figure at approx. 29m). We plan on conducting a series of surveys at different times to establish the movement of water to the Ogallala. Modeling tools have been developed from previous OAP work to quantify the distribution of pressure head in the vadose zone below a recharging source. The team also has expertise in utilizing such modeling tools with the type of data we will collect to study recharge problems.



Preliminary proof-of-concept ERT data (shown as conductivity) on Arkansas River, May 2015 east of the Bear Creek Fault in central Kearney County, KS. The black squares at the top are electrodes which were aligned parallel to the river. The highly conductive red zone from the start of the line to the midpoint (~20 m) is a descending plume of groundwater. The surrounding soil (green) is partially saturated sandy soil which is drier at the surface (blue). The red plume at ~29 m is beneath a salt cedar that is pulling water upward. We seek to develop such data images along the Arkansas River where recharge is occurring and at different times to study recharge events.

c) How the objective will be met

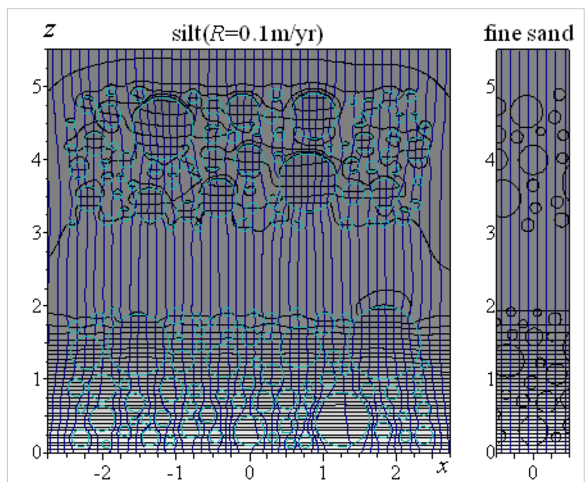
This workplan includes four interrelated activities: site investigation using near surface geophysical methods to locate soil inclusions where enhanced recharge processes occur, vadose zone model development to quantify seepage, uncertainty analysis to use the site investigation data with vadose zone models, and quantification of discharges available for future economic activities. This will give a calibrated model capable of reproducing observed flow from rivers to the Ogallala. Future endeavors could use this calibrated model to evaluate the capacity of rivers to fill the Ogallala over changes in river flow management.

C1. Site investigation: ERT and GPR are near surface geophysical techniques used for mapping hydro-geology characteristics. ERT depends on subsurface characteristics such as geological layering and subsurface moisture (and requires analysis to delineate desired information about depth to groundwater), for example, see figure above. ERT surveys utilize stainless steel stakes, or electrodes, driven into the ground surface. Bulk electrical resistivity measurements are taken by injecting current through two electrodes and simultaneously measuring the voltage potential using two additional electrodes. A resistivity meter records injected current and measured voltage, from which we can determine the bulk electrical resistivity of the subsurface. The distance between current injecting electrodes and potential measuring electrodes governs the depth and location of the resistivity measurement. The KSU ERT system can use up to 84 electrodes per survey to allow for deeper measurements and measures voltage potentials across eight channels to speed up data acquisition. ERT surveys take hundreds of measurements to create a subsurface distribution of electrical resistivity or electrical conductivity, the inverse of resistivity, as shown in the proof of concept above.

The critical property that controls the electrical resistivity of the subsurface is the spatial distribution of pore-fluid electrolytes. Specifically in soils, the bulk electrical resistivity is a function of volumetric water content, the resistivity of fluid in the pore space, and porosity of the soil structure (Snapp and Tucker-Kulesza, in review). As such, ERT can be used to monitor the distribution of soil water content and to calculate soil water content using Archie's Law (Archie, 1942). In this study, we propose taking repeated measurements over several months in Kearney and Finney Counties where greatest interchanges are occurring. We anticipate taking measurements at a minimum of three sites, starting after the spring thaw in 2017.

GPR is an electromagnetic geophysical method which sends high frequency electromagnetic waves into the subsurface and measures the corresponding reflection. Wave reflections result from changes in material properties, specifically the dielectric permittivity which is a function of water content. The KSU GPR system uses a shielded antenna, meaning the transmitter and receiver are housed in a single unit that is moved along the surface as it transmits/receives the electromagnetic waves. An advantage of GPR over ERT is that continuous data are collected as the unit is moved along the surface providing dense spatial coverage and a means to identify the geologic inclusions rapidly and noninvasively. GPR will be used to identify regions for more detailed ERT surveys and to enhance hydrogeological features for the vadose zone model.

C2. Vadose zone modeling: A computer tool to investigate the flow of water beneath a riverbed to groundwater has been developed by PI Steward. This vadose zone model utilizes soil properties (conductivity, sorptive number) in the quasi-linear approximation of Philip (1969). Results enable predictions of increases in moisture content observed as recharge events flow downward to fill an aquifer (see figure). For this work plan, we will use the soil properties obtained from riverbeds (as part of previously funded OAP work) to develop preliminary estimates of the advancement of a wetting front beneath a river. This will enable estimates of how deep water from riverflow events will be in the soil column, and help design the ERT survey.



Vadose zone pressure head for silt embedded within fine sand (manuscript in preparation)

The quasi-linear approximation will be utilized for two reasons. First, Steward has developed the mathematical and computational capacity to perform this analysis (see figure). The quasi-linear approximation has seen several recent publications (Warrick, Knight, Nieber and others), and we believe we can utilize what we do here to develop highly publishable, highly citable publications. This model has the capacity to study changes in the moisture profile from recharge events.

C3. Uncertainty analysis to use ERT and GPR data with vadose zone models.

The vadose zone model we develop in C2 using estimates of soil properties from data collected in the riverbeds will be refined based upon the ERT and GPR data. We expect soil properties may be different deeper in the soil column than at the surface, and so the vadose zone model will be used to evaluate the impacts of a wide range of soil properties and layering on the movement of water through soils from a river to groundwater. Coupled with the GPR, this information will be used to estimate the location and depth of water to plan ERT surveys (electrode spacing, etc).

The vadose zone model and geophysical data will be used collectively to develop estimates of soil properties and geological soil distributions in the vadose zone model that most closely match the observed ERT wetted regions. Preliminary results identify that fine grained inclusions respond differently to changes in recharge than coarse grained material. And so, changes in the ERT profile due to changes in wetted soil have the capacity to provide parameter estimation of the vadose zone model necessary to achieve these observations. These, in term, are a function of the recharge rate, which we will be able to estimate. Through analysis of ERT and vadose zone models across sites we will be able to estimate how recharge processes change along a river transect.

C4. Extending the economic lifetime of the Ogallala: We will develop estimates of recharge occurring to the Ogallala Aquifer through the riverbeds across study sites. This discharge provides a direct source to support the economic vitality of the region, and provides the most likely future sources of recharged groundwater.

Timeline: winter/spring 2017: development of vadose zone estimates, conduct GPR surveys, and design ERT survey; spring/fall 2017: ERT survey/ vadose zone model interpretation/ refinement of survey as results are interpreted; fall 2017/summer2018: result interpretation/ publication development/ presentation at OAP workshop.

d) Expected outcomes: This plan targets hydrologic understanding of recharge through riverbeds and diversion ditches through application of geophysical methods and vadose zone modeling, recharge needed for future economic activities. Given the novelty of this integrated approach, and the fact that it has not yet been applied to the study region, we anticipate being able to publish findings in high impact journals. The team members individually have strong publication histories, which will contribute towards successful dissemination. This project will provide funding contributing towards the interdisciplinary understanding necessary to resolve the important problem of Ogallala Aquifer recharge, and estimates of future discharges necessary to support regional agriculture.

We will quantify the volume of groundwater that is currently being filled by natural processes, and work with local stakeholders (through collaborator GMD3) to identify means to enhance these natural processes to provide more water to the best areas for recharge. This provides a significant potential to slow or reverse declining aquifer trends in regions near dry streambeds and extend the long-term usable lifetime of the aquifer. Water means livelihood and a better understanding of recharge processes will contribute towards economic assessment and enhancing long-term prospects Results will lead to knowledge of where rivers are effectively recharging as well as their recharge rates. Technology transfer activities will discussion findings with stakeholders to lead to future proposed diversion projects to enhance filling the Ogallala and future studies of their effectiveness.

5) Relevant publications: This brief list of publications authored by team members addresses their ability to complete the proposed activities and to disseminate findings.

Ahring, T. S. and D. R. Steward, *Groundwater surface water interactions and the role of phreatophytes in identifying recharge zones*, Hydrology and Earth System Sciences, 16, 4133-4142, 2012.

Allen, A. J. and D. R. Steward, *A hybrid non-linear optimization model to assess groundwater/surface water interactions in the High Plains Aquifer*, Advances in Water Resources, in review, 2016.

Arjwech, R., Everett, M. E., Briaud, J.-L., Hurlebaus, S., Medina-Cetina, Z., Tucker, S., Yousefpour, N., *Electrical Resistivity Imaging of Unknown Bridge Foundations*, Near Surface Geophysics, 11(6), 591-598, 2013.

T. Bulatewicz, D. Andresen, S. Auvenshine, J. Peterson, D. R. Steward, *A distributed data component for the Open Modeling Interface*, Environmental Modelling & Software, 57, 138–151, July 2014.

Snapp, M. and Tucker-Kulesza, *Electrical Resistivity Imaging of Mechanically Stabilized Earth Wall Backfill*, Journal of Applied Geophysics. (in review).

Steward, D. R. and Ahring, T., *An analytic solution for groundwater uptake by phreatophytes spanning spatial scales from plant to field to regional*, Journal of Engineering Mathematics, 64(2), 85-103, 2009.

Steward, D. R. and A. J. Allen, *The Analytic Element Method for rectangular gridded domains and application to the Ogallala Aquifer*, Advances in Water Resources, 60, 89-99, 2013.

Steward, D. R., Bruss, P. J., Yang, X., Staggenborg, S. A., Welch, S. M. and M. D. Apley, *Tapping unsustainable groundwater stores for agricultural production in the High Plains Aquifer of Kansas, projections to 2110*, Proceedings of the National Academy of Sciences of the United States of America, 110(37) E3477-E3486, September 10, 2013.

Steward, D. R., *Analysis of discontinuities across thin inhomogeneities, groundwater/surface water interactions in river networks, and circulation about slender bodies using slit elements in the Analytic Element Method*, Water Resources Research, 51(11), 8684–8703, 2015.

Steward, D. R. and Allen, A. J., *Peak groundwater depletion in the High Plains Aquifer, projections from 1930 to 2110*, Agricultural Water Management, 170, 36-48, May 2016.

Tucker, S., Briaud, J.-L., Hurlebaus, S., Everett, M., Arjwech, R., *Electrical Resistivity and Induced Polarization Testing for Unknown Bridge Foundations*, J. Geotech. Geoenviron. Eng, 141(5), 04015008, 2015.

7) Literature Cited /References (those references not already listed in section 5)

Archie, G.E. (1942). *The electrical resistivity log as an aid in determining some reservoir characteristics*. Transactions of the American Institute of Minining, Metallurgical and Petroleum Engineers, 146, 54-61.