BEFORE THE OFFICE OF ADMINISTRATIVE HEARINGS

STATE OF KANSAS

IN THE MATTER OF

THE APPLICATION OF THE CITIES OF	)	
HAYS, KANSAS AND RUSSELL, KANSAS	)	
FOR APPROVAL TO TRANSFER WATER	)	**OAH NO. 23AG0003 AG**
FROM EDWARDS COUNTY, KANSAS	)	
PURSUANT TO THE KANSAS WATER	)	
TRANSFER ACT.	)	
	)	

Pursuant to K.S.A. Chapter 77.

DIRECT TESTIMONY OF ANTHONY L. LAYZELL, Ph.D.

ON BEHALF OF

THE CITIES OF HAYS AND RUSSELL, KANSAS

RELATING TO

KANSAS DROUGHTS: CLIMATIC TRENDS OVER THE PAST 1,000 YEARS

Q. Please state your name and present position.

A. Anthony L. Layzell, Ph.D.

Q. On whose behalf are you submitting testimony?

A. The City of Hays, Kansas and the City of Russell, Kansas (the "Cities") .

Q. Please describe your educational background and employment experience.

A. I obtained a B.Sc. degree in Geography from the University of Nottingham, United Kingdom, in 2001. In 2010, I earned a Masters in Earth Science from the University of North Carolina, Charlotte. I earned a Ph.D. in Geography from the University of Kansas in 2015. I was a recipient of the National Science Foundation IGERT Fellowship from 2011–2015.

I have worked for the Kansas Geological Survey at the University of Kansas since 2011, beginning as a Research Assistant (2011–2015) before being promoted to a Post-Doctoral Research Fellow (2015–2016), and then an Assistant Research Professor (2016–2017), before being hired as an Assistant Scientist in 2017, a position that I hold to the present time. At the Kansas Geological Survey, my job is devoted to research and publishing the results of fundamental and applied research in Quaternary geology in Kansas, participating in geologic mapping program as a lead mapper, and conducting geochemical research on the chronostratigraphy and paleoclimatology of Cenozoic deposits in Kansas.

To date, I have secured grants and contracts totaling just under $2.5 million to fund my research from a variety of federal and state agencies and private foundations, including the U.S. Geological Survey, the U.S. Army Corps of Engineers, the Environmental Protection Agency, the National Park Service, the Kansas Water Office, the Kansas Historical Society, and others. I have authored or co-authored more than 60 articles on various geological issues, and have been the primary or co-presenter of more than 75 presentations at numerous conferences. I have also served as Editor-in-chief of *Midcontinent Geoscience*, an open-access, peer-reviewed publication of the Kansas Geological Survey since 2018.

My educational background and employment experience is set out in more detail in my CV, which is attached as Exhibit ALL-01, and incorporated into my Pre-Filed Testimony as if set forth in full in this document.

Q. Has this direct testimony been prepared by you or under your direct supervision?

A. Yes, it has.

Q. Have you previously testified before the Kansas Department of Agriculture–Division of Water Resources or any other regulatory commission?

A. No, I have not.

Q. Have you testified in any litigation in the prior four years?

A. No, I have not.

Q. Are you sponsoring any exhibits with your direct testimony?

A. Yes. In addition, to ALL-01, I Sponsor Exhibit ALL-02, which is an article I authored published by the Kansas Geological Survey titled "A thousand years of drought and climatic variability in Kansas: Implications for water resources management." I also sponsor Exhibit ALL-03, an article I co-authored with Catherine S. Evans, also published by the Kansas Geological Survey, titled: "Kansas Droughts: Climatic Trends Over 1,000 Years." Both ALL-02 and ALL-03 are incorporated into my Pre-Filed Testimony as if set forth in full in this document.

Q. What is the purpose of your direct testimony?

A. My conclusions are set forth in detail in ALL-02 and ALL-03, but in general, my testimony relates to the frequency, duration, and intensity of drought occurrences over the last 1,000 years, adduced from the paleoclimatic record.

Q. In summary, what did you conclude?

A. PDSI data indicate that western Kansas has experienced more severe droughts than eastern Kansas and northern Kansas has typically experienced more severe drought than southern

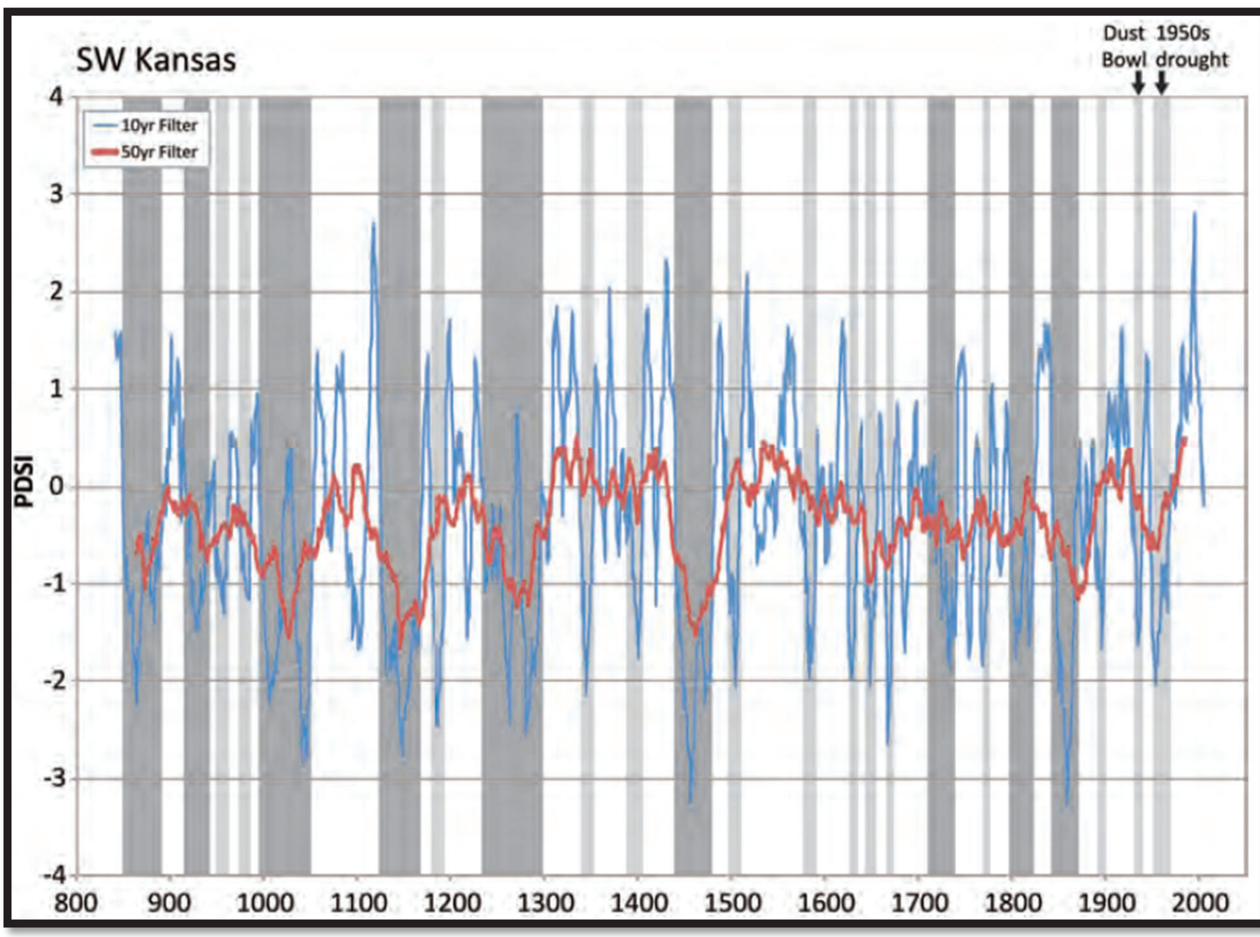
Kansas over the past 1,000 years. Several past drought episodes in Kansas have exceeded those of the 1930s and the 1950s in severity, extent, and duration, including several droughts spanning 50+ years and one drought lasting 110 years. Though ALL-02 and ALL-03 were published in 2012 and 2013, respectively, the content and conclusions of those documents remain valid.

Q. Please describe how you arrived at your conclusions.

A. As explained in more detail in ALL-02 and ALL-03, the Palmer Drought Severity Index (PDSI) is one of the most widely used indices in North America to measure the severity of drought occurrence for a specified period. PDSI values are based on weather data; it can also be calculated using paleoclimate data reconstructed from tree rings and other proxy evidence. Scientists have been collecting and analyzing data to reconstruct "paleoclimates" (past climates dating back thousands of years) by studying tree rings, sediments, and other proxies in combination with more than a century of instrumental data.

Annual growth rings in living trees and preserved wood are measured to reconstruct climatic patterns over extensive areas. Wide tree rings in highly drought-sensitive trees typically indicate a long growing season with adequate moisture, and very narrow rings usually signify drought conditions. The exact calendar year a tree ring was formed can be determined by crossdating, a technique that statistically matches the patterns in tree-ring characteristics among several living or dead trees in a region. Data collected on crossdated trees in a given area form a tree-ring chronology, which can then be used to identify wide-ranging climatic trends. Synthesized data from hundreds of interlinking chronologies have been used to re-create annual climate patterns dating back at least a thousand years throughout most of North America. An extensive and ever-expanding network of annual tree-ring chronologies is accessible through the International Tree-Ring Data Bank (http://www.ncdc.noaa.gov/paleo/treering.html). A diverse variety of other proxies, derived from sand dunes, lake sediment, coral reefs, ice sheets, rock formations, microfossils, cave deposits, archaeological discoveries, and historical records help verify past droughts identified in tree-ring studies. For example, evidence from once-active sand dunes in Kansas provides evidence of periodic droughts that occurred in the state over several centuries.

Reconstructed PDSI values based on tree-ring chronologies are available for as far back as 837 AD in western Kansas and the whole state to 1,000 AD. For my research, I calculated the durations of drought episodes in Kansas by smoothing PDSI values—that is, filtering out the extreme high and low values by averaging over a 10- or 50- year periods—to identify long-term patterns of drought duration. The beginning and end of each drought period are demarcated by periods of more than two consecutive years of positive (wet) PDSI values. In the below figure, smoothed PDSI values were plotted to show the duration of droughts in southwestern Kansas.



The PDSI values in the above figure demonstrate that droughts of longer duration than the Dust Bowl and 1950s droughts in Kansas have occurred on multiple occasions over the past 1,000 years, including several droughts of 50+ years and one drought lasting for 110 years. These droughts of unusually long duration are commonly referred to as "megadroughts," generally considered to be a drought lasting 20 years or more.

Q. Does that concludes your testimony?

A. Yes, it does.

VERIFICATION

STATE OF KANSAS)
)
COUNTY OF JOHNSON)

I Anthony L. Layzell, being duly sworn, on oath state that I have read the foregoing and know the contents thereof, and that the facts set forth therein are true and correct to the best of my knowledge and belief.

By: [signature]
Anthony L. Layzell, Ph.D.

The foregoing was subscribed and sworn to before me this 25 day of MAY 2023, 2023.

STATE OF NOTARY PUBLIC KANSAS
KIRK ALLAN AADLAND
My Appointment Expires
October 15, 2024

Notary Public
[signature]

My Commission Expires:

OCTOBER 15, 2024

STATE OF NOTARY PUBLIC KANSAS
KIRK ALLAN AADLAND
My Appointment Expires
October 15, 2024

EXHIBIT
ALL-01

Curriculum Vitae (2023)

NAME **Layzell, Anthony L.**

EDUCATION

Ph.D. Geography, University of Kansas, 2015
Graduate Certificate in Environmental Studies, University of Kansas, 2012
National Science Foundation IGERT Fellowship, 2011-2015
M.S. Earth Science, University of North Carolina – Charlotte, 2010
B.Sc. (Honors) Geography, University of Nottingham, United Kingdom, 2001

EMPLOYMENT HISTORY

1. **Assistant Scientist**, Kansas Geological Survey, University of Kansas, 2017-present
2. **Assistant Research Professor**, Kansas Geological Survey, University of Kansas, 2016-2017
3. **Post-Doctoral Research Fellow**, Kansas Geological Survey, University of Kansas, 2015-2016
4. **Research Assistant**, Kansas Geological Survey, University of Kansas, 2011-2015

KU PROFESSIONAL PERFORMANCE RECORD

Job Responsibilities

1. 85% Research: Conduct and publish the results of fundamental and applied research in Quaternary geology that is of national stature and relevant to Kansas. Develop externally funded individual and cooperative research programs in Quaternary deposits and environments focused on their paleoenvironmental and environmental applications to Kansas. Participate in KGS geologic mapping program as a lead mapper, in KGS geoarchaeological research program, and in collaborative geochemical research on the chronostratigraphy and paleoclimatology of Cenozoic deposits in Kansas.
2. 15% Service: Participate in and serve in leadership roles in professional and scientific organizations. Serve on University and KGS committees and organizations as assigned or in response to opportunities. Provide technical assistance to KGS and KU staff in areas of scientific expertise. Provide external professional peer reviews of journal manuscripts and grant proposals. Oversee laboratory spaces operated by the Stratigraphic Research Section and supervise KU student laboratory workers in Parker 18, Moore 101, and Moore 105.

RESEARCH RECORD

A. Grants and Contracts

To date (March 2023) I have secured grants and contracts totaling **$2,466,871** to fund my research from both federal and state agencies and private foundations, including the US Geological Survey, US Army Corps of Engineers, Environmental Protection Agency, National Park Service, Kansas Water Office, Nebraska Department of Transportation, History Nebraska, Kansas Historical Society, and the International Continental Scientific Drilling Program.

B. Research Publications

Major Publications

Entry No.	Peer-Reviewed	Publication
18	Yes	**Layzell, A.L.**, Ludvigson, G.A., Smith, J.J., Mandel, R.D., 2023. Using the factors of soil formation to assess stable carbon isotope disequilibrium in late Pleistocene (MIS 3) buried soils of the Great Plains. Palaeogeography, Palaeoclimatology, Palaeoecology. In revision
17	Yes	Oborny, S.C., Smith, J.J., **Layzell, A.L.**, Ludvigson, G., Hasiuk, F., 2022. Revision to Nomenclature of the Zarah Subgroup of the Kansas City Group (Pennsylvanian) in Kansas. Midcontinent Geoscience, 3, 27–34.
16	Yes	**Layzell, A.L.**, Peterson, A., Moore, T., Bigham, K., 2022. UAS-based assessment of streambank stabilization effectiveness in an incised river system. Geomorphology, 408, 108240. doi.org/10.1016/j.geomorph.2022.108240
15	Yes	**Layzell, A.L.**, Mandel, R.D., 2020. Late Quaternary Landscape Evolution and Bioclimatic Change in the Central Great Plains, USA. Geological Society of America Bulletin, 132 (11-12), 2553–2571. doi.org/10.1130/B35462.1
14	Yes	Brookfield, A.E., **Layzell, A.L.**, 2019. Simulating the effects of reservoir management strategies on fluvial erosion. Water Resources Management, 33 (15), 4983–4995.
13	Yes	Lukens, W.E., Fox, D.L., Snell, K.E., Wiest, L.A., **Layzell, A.L.**, Uno, K.T., Martin, R.A., Fox-Dobbs, K., Pelaez-Campomanes, P., 2019. Pliocene paleoenvironments in the Meade Basin, southwest Kansas, Journal of Sedimentary Research 89(5), 416–439.
12	Yes	**Layzell, A.L.**, Mandel, R.D., 2019. Using soil survey data as a predictive tool for locating deeply buried archaeological deposits in stream valleys of the Midwest, USA. Geoarchaeology 34(1), 80–99. doi.org/10.1002/gea.21707
11	Yes	**Layzell, A.L.**, Sawin, R.S., Franseen, E.K., Ludvigson, G.A., Watney, W.L., West, R.R., 2017. Quaternary stratigraphy and stratigraphic nomenclature revisions in Kansas. Current Research in Earth Sciences, Kansas Geological Survey Bulletin 263, 8 p.
10	Yes	Smith, J.J., Ludvigson, G.A., **Layzell, A.L.**, Möller, A., Harlow, R.H., Turner, E., Platt, B., Petronis, M., 2017. Discovery of Paleogene deposits of the central High Plains aquifer in the western Great Plains, USA. Journal of Sedimentary Research 87(8), 880–896.
9	Yes	**Layzell, A.L.**, Mandel, R.D., Rittenour, T., Smith, J.J., Harlow, R.H., Ludvigson, G.A., 2016. Stratigraphy, morphology, and geochemistry of late Quaternary buried soils on the High Plains of southwestern Kansas, USA. Catena 144, 45–55.

Entry No.	Peer-Reviewed	Publication
8	Yes	Smith, J.J., **Layzell, A.L.**, Lukens, W.E., Morgan, M.L., Keller, S.M., Martin, R.A., and Fox, D.L., 2016. Getting to the bottom of the High Plains aquifer: New insights into the depositional history, stratigraphy, and paleoecology of the Cenozoic High Plains, in Keller, S.M., and Morgan, M.L., eds., Unfolding the Geology of the West: Geological Society of America Field Guide 44, 93–124.
7	Yes	Johnson, B.G., **Layzell, A.L.**, Eppes, M.C., 2015. Chronosequence development and soil variability from a variety of sub-alpine, post-glacial landforms and deposits in the southeastern San Juan Mountains of Colorado. Catena 127, 222–239.
6	Yes	**Layzell, A.L.**, Mandel, R.D., Ludvigson, G.A., Rittenour, T., Smith, J.J., 2015. Forces driving late Pleistocene (ca. 77-12 ka) landscape evolution in the Cimarron River valley, southwestern Kansas. Quaternary Research 84, 106–117.
5	Yes	**Layzell, A.L.**, Mandel, R.D., 2014. An assessment of the erodibility of Holocene lithounits comprising streambanks in northeastern Kansas, USA. Geomorphology 213, 116–127.
4	Yes	**Layzell, A.L.**, Eppes, M.C., Johnson, B.G., Diemer, J.A., 2012. Post-glacial range of variability in the Conejos River Valley, Southern Colorado, USA: Fluvial response to climate change and sediment supply. Earth Surface Processes and Landforms 37(11), 1189–1202.
3	Yes	**Layzell, A.L.**, Eppes, M.C., Lewis, R.Q., 2012. A soil chronosequence study on terraces of the Catawba River near Charlotte, NC: Insights into the long-term evolution of a major Atlantic Piedmont drainage basin. Southeastern Geology 49 (1), 13–24.
2	Yes	**Layzell, A.L.**, Eppes, M.C., 2012. Holocene pedogenesis in fluvial deposits of the Conejos River Valley, southern Colorado. The Compass: Earth Science Journal of Sigma Gamma Epsilon, 84 (4), Article 4.
1	Yes	Johnson, B.G., Eppes, M.C., Diemer, J.A., Jimenez-Moreno, G., **Layzell, A.L.**, 2011. Post-glacial landscape response to climate variability in the southeastern San Juan Mountains of Colorado, USA. Quaternary Research 76 (3), 352–362.

Minor Publications

Entry No.	Peer-Reviewed	Publication
47	No	**Layzell, A.L.**, Brookfield, A.E., Seybold, E., 2022. Simulating the effects of reservoir management strategies on in-stream sediment load, streambank stability, and water quality. Report prepared for Kansas Water Resources Institute, Oct. 2022.

Entry No.	Peer-Reviewed	Publication
46	Yes	**Layzell, A.L.**, Newell, K.D., Oborny, S.C., Mandel, R.D., and Dunham, J.W., 2022. Surficial Geology of Miami County, Kansas: Kansas Geological Survey, Map M-126, scale 1:50,000.
45	No	**Layzell, A.L.**, Dunham, J., 2022. Preliminary surficial geology of the Sumner County portion of the Wellington quadrangle, Kansas. Kansas Geological Survey, Open-file Report no. 2022-15, scale 1:24,000.
44	No	**Layzell, A.L.**, Dunham, J., 2022. Preliminary surficial geology of the Sumner County portion of the Millerton quadrangle, Kansas. Kansas Geological Survey, Open-file Report no. 2022-14, scale 1:24,000.
43	No	**Layzell, A.L.**, Dunham, J., 2022. Preliminary surficial geology of the Sumner County portion of the Mayfield quadrangle, Kansas. Kansas Geological Survey, Open-file Report no. 2022-13, scale 1:24,000.
42	No	Oborny, S.C., Hasiuk, F. **Layzell, A.L.**, Smith, J.J., 2022. Nomenclatural history of Upper Desmoinesian through Lower Virgilian (Pennsylvanian) strata in Kansas. Kansas Geological Survey, Open-file Report no. 2022-5.
41	No	Oborny, S.C., **Layzell, A.L.**, Newell, K.D., Mandel, R.D., Smith, J.J., 2022. Geologic details for 2021 Geological Mapping of Miami County, Kansas. Kansas Geological Survey, Open-file Report no. 2022-3.
40	No	Mandel, R.D., **Layzell, A.L.**, 2022. Geomorphological Investigation. Report prepared for Bear Creek Archeology, Inc., Feb. 2022.
39	No	**Layzell, A.L.**, Bigham, K., Moore, T., 2021. Streambank Evaluation of the Cottonwood and Neosho Rivers above John Redmond Reservoir: Final Report (21-110). Report submitted to Kansas Water Office, Dec. 2021.
38	No	Mandel, R.D., **Layzell, A.L.**, 2021. Geomorphological Investigation. In: *Phase I Archaeological Investigation for a Proposed Storm Water Project in the Hillview Recreation Area, Hungerford Township, Plymouth County, Iowa.* Langseth, J.A., Bear Creek Archeology, Inc., Report prepared for Plymouth County Conservation, Dec. 2021.
37	No	**Layzell, A.L.**, Mandel, R.D., Ziska, C.L., Bozell, J.R., 2021. A Statewide Geographic Information System (GIS) as a Predictive Tool for Locating Deeply Buried Archeological Deposits in Nebraska: Phase II. Final report submitted to Nebraska Department of Transportation, Sept. 2021.
36	No	**Layzell, A.L.**, Mandel, R.D., 2021. Creation of a GIS-based model for buried cultural resources in Kansas. Report submitted to Kansas Historical Society, Aug. 2021.
35	No	Mandel, R.D., **Layzell, A.L.**, 2021. Geomorphological Investigation. In: *Phase I Archaeological Investigation and Phase II Testing of Sites 13CF50 and 13CF131, Primary Roads Project BRFN-030-2(168)--39-2, a.k.a. PIN 18-24-030-010, Crawford County, Iowa,* Davis, W., Office of the State Archaeologist, Iowa. Report prepared for Iowa Department of Transportation, Mar. 2021.

Entry No.	Peer-Reviewed	Publication
34	No	Mandel, R.D., **Layzell, A.L.**, 2021. Geomorphological Investigation. In: *Phase I Cultural Resources Investigation for a proposed levee and well construction project, Washington Township, Fremont county, Iowa*, Langseth, J.A., Bear Creek Archeology, Inc. Report prepared for City of Hamburg, Jan. 2021.
33	No	**Layzell, A.L.**, Bigham, K., Moore, T., 2020. Streambank Evaluation of the Cottonwood and Neosho Rivers above John Redmond Reservoir: Final Report (20-108). Report submitted to Kansas Water Office, Dec. 2020.
32	No	**Layzell, A.L.**, Chao, H., 2020. Assessing the effectiveness of streambank stabilization projects on the Cottonwood River using Unmanned Aircraft Systems (drones). Report prepared for Kansas Water Resources Institute, Dec. 2020.
31	No	**Layzell, A.L.**, Peterson, A., 2020. Assessing the effectiveness of streambank stabilization projects on the Cottonwood River using Unmanned Aircraft Systems. Kansas Geological Survey, Open-file Report no. 2020-16.
30	No	**Layzell, A.L.**, 2020. Glaciers in Kansas (Revised). Kansas Geological Survey Public Information Circular, 28.
29	No	**Layzell, A.L.**, Dunham, J., 2020. Preliminary surficial geology of the Sumner County portion of the Zyba quadrangle, Kansas. Kansas Geological Survey, Open-file Report no. 2020-6, scale 1:24,000.
28	No	**Layzell, A.L.**, Dunham, J., 2020. Preliminary surficial geology of the Sumner County portion of the Belle Plaine quadrangle, Kansas. Kansas Geological Survey, Open-file Report no. 2020-5, scale 1:24,000.
27	No	**Layzell, A.L.**, Dunham, J., 2020. Preliminary surficial geology of the Dalton quadrangle, Sumner County, Kansas. Kansas Geological Survey, Open-file Report no. 2020-4, scale 1:24,000.
26	No	Mandel, R.D., **Layzell, A.L.**, McLean, J.A., Welch, G.A., Potter, A.R., 2020. Geoarchaeological investigations for three erosion repair projects (Peach Tree crossing, Beef Creek road, and Hairpin) on East Cache Creek, Fort Sill, Oklahoma. Report prepared for US Army Corps of Engineers, Fort Sill Environmental Quality Division, and ALL Consulting, Inc., April 2020.
25	Yes	Shelley, J., Kenney, M., **Layzell, A.L.**, Brown, T., 2020. Contribution of two eroding banks to multipurpose pool sedimentation at a Midwestern Reservoir. ERDC/TN RSM-20-6. U.S. Army Engineer Research and Development Center, Vicksburg, MS. http://dx.doi.org/10.21079/11681/37946
24	No	Mandel, R.D., **Layzell, A.L.**, 2019. Geomorphological Investigation. In: *Phase I archaeological investigation of the Eagle Crossing Business Park, Plattville Township, Mills County, Iowa*, Skeens, J., Mandel, R., Layzell, A., & Blikre, L. Report prepared for Terracon Consultants, Inc., Dec. 2019.

Entry No.	Peer-Reviewed	Publication
23	No	Smith, J.J., **Layzell, A.L.**, Peterson, A., 2019. A Report to the Calvert Corporation on the Thickness of Volcanic Ash and Overburden at the Calvert Volcanic Ash Mine, Kansas. Kansas Geological Survey, Open-file Report no. 2019-6.
22	No	**Layzell, A.L.**, Bigham, K., Moore, T., 2019. Streambank Evaluation of the Cottonwood and Neosho Rivers above John Redmond Reservoir: Final Report (19-105). Report submitted to Kansas Water Office, July 2019.
21	No	Dunham, J., **Layzell, A.L.**, Newell, K.D., Mandel, R.D., 2019. Preliminary Surficial Geology of Miami County, Kansas. ESRI Map Book 34, 10-11. https://www.esri.com/en-us/esri-map-book/maps#/details/2/1
20	No	**Layzell, A.L.**, Dunham, J., 2019. Preliminary Surficial Geology of the Perth quadrangle, Sumner county, Kansas. Kansas Geological Survey, Open-file Report no. 2019-10, scale 1:24,000.
19	No	**Layzell, A.L.**, Dunham, J., 2019. Preliminary Surficial Geology of the Caldwell NW quadrangle, Sumner county, Kansas. Kansas Geological Survey, Open-file Report no. 2019-9, scale 1:24,000.
18	No	**Layzell, A.L.**, Dunham, J., 2019. Preliminary Surficial Geology of the Caldwell quadrangle, Sumner county, Kansas. Kansas Geological Survey, Open-file Report no. 2019-8, scale 1:24,000.
17	No	Blikre, L., Mandel, R.D., **Layzell, A.L.**, Bond, E., 2019. Phase I archeological survey, US Highway 30 Missouri Valley bypass location study area, Harrison County, Iowa. Final report prepared for HDR Engineering, Inc. October 2019.
16	Yes	Mandel, R.D., **Layzell, A.L.**, 2019. Geoarchaeology of Harlan County Lake Project Area. In *Historic Properties Management Plan for Harlan County Lake, Nebraska*, Lopinot, N.H., Thompson, D.A., Rideout, J.A., Reid, S.J. Research Report No. 1605, Center for Archaeological Research, Missouri State University. Report prepared for US Army Corps of Engineers, Kansas City and St. Louis Districts. May, 2019.
15	Yes	Franseen, E.K., Sawin, R.S., Watney, W.L., West, R.R., **Layzell, A.L.**, Ludvigson, G.A., 2018. Mississippian Stratigraphic Nomenclature Revisions in Kansas. Current Research in Earth Sciences: Kansas Geological Survey, Bulletin 264, 4 p.
14	No	**Layzell, A.L.**, Dunham, J., 2018. Preliminary Surficial Geology of the Oxford quadrangle, Sumner and Cowley counties, Kansas. Kansas Geological Survey, Open-file Report no. 2018-9, scale 1:24,000.
13	No	**Layzell, A.L.**, Dunham, J., 2018. Preliminary Surficial Geology of the Adamsville quadrangle, Sumner and Cowley counties, Kansas. Kansas Geological Survey, Open-file Report no. 2018-8, scale 1:24,000.
12	No	**Layzell, A.L.**, Dunham, J., 2018. Preliminary Surficial Geology of the South Haven quadrangle, Sumner and Cowley counties, Kansas. Kansas Geological Survey, Open-file Report no. 2018-6, scale 1:24,000.

Entry No.	Peer-Reviewed	Publication
11	No	**Layzell, A.L.**, Mandel, R.D., 2017. Systematic approach to identifying deeply buried archeological deposits. Final report prepared for the Nebraska Department of Transportation.
10	No	Lueck, E.J., Buhta, A.A., Mandel, R.D., **Layzell, A.L.**, 2017. Phase I Archeological Survey and Geomorphic Evaluation of the Iowa and Cedar Rivers HDD Pipeline Replacement Project in Muscatine and Louisa Counties, Iowa. Report prepared for Natural Gas Pipeline Co. of America.
9	No	**Layzell, A.L.**, Newell, K.D., Mandel, R.D., Dunham, J., 2017. Preliminary Surficial Geology of Miami County, Kansas. Kansas Geological Survey, Open-file Report no. 2017-20, scale 1:50,000.
8	No	Alig, P., Mandel, R.D., **Layzell, A.L.**, Meade, T., Perkl, B., Keeney, K., Hall, S.M., 2016. Phase II intensive archaeological inventory survey of eight areas and the National Register of Historic Places site evaluation of two sites within the Fort Leavenworth, U.S. Army Garrison Command, Leavenworth County, Kansas. Report to U.S. Army Garrison Command, Fort Leavenworth, Kansas by the U.S., Army Corps of Engineers, Kansas City District. Report prepared for the U.S. Army Garrison Command, Fort Leavenworth, Kansas.
7	No	**Layzell, A.L.,** 2015. *Plio-Pleistocene landscape evolution on the High Plains of southwestern Kansas*. Ph.D. Dissertation, Department of Geography, The University of Kansas, Lawrence, KS.
6	No	Ludvigson, G.A., González, L.A., **Layzell, A.L**., 2014. Stable isotopic studies on core samples from the Cold Lake property. Report to Cold Lake Geoscience, Imperial, Canada and the Alberta Energy Regulator Core Research Centre.
5	Yes	**Layzell, A.L.**, Mandel, R.D., 2014. An Assessment of the Lithostratigraphy and Erodibility of Holocene Alluvial Fills in the Watersheds of Atchison County Lake, Banner Creek Lake and Centralia Lake. In *Assessment of Lake Sedimentation from Three Watersheds in Kansas*, Kansas State University, Special Publication.
4	Yes	**Layzell, A.L.**, Evans, C.S., 2013. Kansas Droughts: Climatic Trends Over 1,000 Years. Kansas Geological Survey Public Information Circular, 35.
3	No	**Layzell, A.L.**, 2012. A thousand years of drought and climate variability in Kansas: Implications for Water Resources Management. Kansas Geological Survey Open-File Report 2012-18.
2	No	**Layzell, A.L.**, 2010. *Soils and geomorphology of the Conejos River Valley, Colorado: Fluvial response to post-Last Glacial Maximum climatic variability and sediment supply*. M.S. Thesis, Department of Geography and Earth Sciences, University of North Carolina at Charlotte, Charlotte, NC.
1	No	**Layzell, A.L.**, Eppes, M.C., Diemer, J.A., 2010. Surficial geologic map of the Central Conejos River Valley, Southeastern San Juan Mountains, Colorado. United States Geologic Survey, EDMAP program.

Scholarly Presentations

Major Presentations (National/International)

Entry No.	Title of Presentation
52	Andrzejewski, K.A., **Layzell, A.L.**, Ludvigson, G.A., Ishman, S.E., Joeckel, R.M., Möller, A., Mandel, R.D., 2022. Unique insight to the Cretaceous OAE 1d, Mid-Cenomanian Event, and OAE2 from long-line drillcores along the eastern cratonic margin of the Western Interior Basin. SEPM Gulf Coast Section Perkins-Rosen Research Conference, Houston, TX, Dec. 5-7, 2022.
51	**Layzell, A.L.**, Peterson, A., Moore, T., Bigham, K.A., 2022. The use of Unmanned Aircraft Systems to monitor and assess the effectiveness of streambank stabilization projects in an incised river system. Geological Society of America, Abstracts with Programs, 54(5), doi: 10.1130/abs/2022AM-382717
50	Oborny, S., **Layzell, A.L.**, Smith, JJ., Hasiuk, F., Mulvany, P., Bridges, D., Joeckel, R.M., Stanley, T., Eichler, C.M., Bancroft, A.M., Clark, R., 2022. Reconciliation of Pennsylvanian stratigraphic nomenclature in the midcontinent, USA. Geological Society of America, Abstracts with Programs, 54(5), doi: 10.1130/abs/2022AM-382965
49	Wei, Q.*, Brookfield, A.E., **Layzell, A.L.**, 2022. Quantifying the effects of water management decisions on streambank stability. Geological Society of America, Abstracts with Programs, 54(5), doi: 10.1130/abs/2022AM-378200
48	Opalka, C.*, **Layzell, A.L.**, 2022. Quaternary stable carbon isotope signatures across the Great Plains of North America. Geological Society of America, Abstracts with Programs, 54(5), doi: 10.1130/abs/2022AM-383717
47	**Layzell, A.L.**, Mandel, R.D., 2022. Mid to Late Holocene bioclimatic change and fluvial geomorphic response in western Nebraska. Biennial Meeting of the American Quaternary Association, Madison, WI, Jun. 8-10, 2022.
46	Aldred, J., Eppes, M.C., Kayser, B., **Layzell, A.**, Deal, R., Johnson, B., 2022. A soil stratigraphic analysis: Linking tributary basins and alluvial fans in the San Juan Mountains, CO, USA. Geological Society of America, Abstracts with Programs, 54(2), doi: 10.1130/abs/2022CD-374380
45	Oborny, S., **Layzell, A.L.**, 2021. Pennsylvanian stratigraphic nomenclature reconciliation in the midcontinent. Digital Mapping Techniques-Lite. Virtual conference, Dec 6-7, 2021.
44	**Layzell, A.L.**, Mandel, R.D., 2021. The past 14,000 years: Evidence for periods of warming and aridity from river valleys of the central Great Plains. Geological Society of America, Abstracts with Programs, 53(6), doi: 10.1130/abs/2021AM-371122
43	Nerhus, K., Stotler, R., **Layzell, A.L.**, Kastens, J., Bowen, M.W., Baker, D., Brookfield, A., Zipper, S., 2021. Analyzing recharge through playas with various land uses to the Central High Plains Aquifer in western Kansas. Geological Society of America, Abstracts with Programs, 53(6), doi: 10.1130/abs/2021AM-366296

Entry No.	Title of Presentation
42	Rasmussen, M.L., Eppes, M.C., Aldred, J., Cavender, J., Evans, S., Folz-Donahue, K., **Layzell, A.L.**, Smith, I., 2021. Quaternary Geology & Geomorphology Division J. Hoover Mackin Award: Chronosequences of mechanical weathering: the influence of rock type on time-dependent cracking in the Mojave Desert, California. Geological Society of America, Abstracts with Programs, 53 6), doi: 10.1130/abs/2021AM-365465
41	**Layzell, A.L.**, Ludvigson, G.A., Mandel, R.D., Smith, J.J., 2020. Using factors of soil formation to investigate stable carbon isotope disequilibrium in late Pleistocene (MIS 3) buried soils of the central Great Plains, USA. Geological Society of America, Abstracts with Programs, 52(6), doi: 10.1130/abs/2020AM-355553
40	Brookfield, A., Farmer, W., Hansen, A., Hill, M., **Layzell, A.L.**, Porter, M., Sullivan, P., Zipper, S., 2020. Untangling the implications of water management on hydrologic systems. Geological Society of America, Abstracts with Programs, 52(6), doi: 10.1130/abs/2020AM-355795
39	**Layzell, A.L.**, 2020. Assessing the effectiveness of streambank stabilization projects. Environmental Protection Agency Region 7 Nonpoint Source Virtual Annual Meeting. July 16, 2020.
38	**Layzell, A.L.**, Ludvigson, G.A., Smith, J.J., Mandel, R.D., 2020. Assessing stable carbon isotope disequilibrium in late Pleistocene buried soils of the Great Plains, USA, using a state factor approach. Goldschmidt, Virtual 2020. June 21-26.
38	Tomin, M., Smith, A.J., **Layzell, A.L.**, 2020. Ostracodes as hydrologic indicators in Plio-Pleistocene aquatic deposits in Meade County, Kansas. Geological Society of America, Abstracts with Programs, 51(1), doi: 10.1130/abs/2020SC-343188
37	**Layzell, A.L.**, Lukens, W.E., Fox, D.L., Snell, K.E., Gosse, J.C., Smith, JJ., 2019. Paleoenvironments across the Plio-Pleistocene transition in the Meade Basin, southwest Kansas. Geological Society of America, Abstracts with Programs, 51(5).
36	Brookfield, A.E., **Layzell, A.L.**, 2019. Water management multitasking: Managing reservoirs for more than water supply. Geological Society of America, Abstracts with Programs, 51(5).
35	Lukens, W.E., Fox, D.L., Snell, K.E., Wiest, L.A., **Layzell, A.L.**, Uno, K.T., Pollisar, P.J., Fox-Dobbs, K., Pelaez-Campomanes, P., 2019. Pliocene paleoenvironments in the Meade Basin, southwest Kansas. Geological Society of America, Abstracts with Programs, 51(5).
34	Snell, K.E., Uno, K.T., Lukens, W.E., Fetrow, A.C., Fox, D.L., **Layzell, A.L.**, Burgess, C.S., Fox-Dobbs, K., Haveles, A.W., Polissar, P.J., Martin, R.A., 2019. No change in clumped isotope temperatures during C4 grassland expansion in the Meade Basin, Kansas, during the Pliocene. Geological Society of America, Abstracts with Programs, 51(5).
33	Ludvigson, G.A., **Layzell, A.L.**, Joeckel, R.M., Moller, A., Mandel, R.D., 2019. Chemostratigraphic profiles of the Cretaceous OAE 1D, mid-Cenomanian event, and OAE2 from long-line drillcores, cratonic margin of the North American Western Interior Basin. Geological Society of America, Abstracts with Programs, 51(5).

Entry No.	Title of Presentation
32	Smith, A.J., Ito, E., Fritz, S.C., Hatfield, R., **Layzell, A.L.**, Lowenstein, T.K., McGee, D., Molnar, P., Stefanova, I., Valero-Garces, B.L., Werne, J.P., Williams, J.W., 2019. Exploring hydroclimatic connections between the Blythe Basin, Arizona and western Pliocene lakes of North America. Geological Society of America, Abstracts with Programs, 51(5)
31	**Layzell, A.L.**, and Mandel, R.D., 2019. Holocene river terraces and alluvial fans in the Republican River valley: Implications for geoarchaeology in the central Great Plains, USA. 20th Congress of the International Union for Quaternary Research (INQUA), P-2901, Dublin, Ireland, July 25th-31st.
30	**Layzell, A.L.**, and Mandel, R.D., 2019. The application of Holocene alluvial stratigraphy to address streambank erosion and reservoir sedimentation in the Midwestern U.S.A. 20th Congress of the International Union for Quaternary Research (INQUA), O-3217, Dublin, Ireland, July 25th-31st.
29	**Layzell, A.L.**, Newell, K.D., Mandel, R.D., and Dunham, J.W., 2019. Preliminary surficial geology of Miami County, Kansas. Geological Society of America, Abstracts with Programs, 51(2).
28	Ludvigson, G.A., Joeckel, R.M., **Layzell, A.L.**, Moller, A., Mandel, R.D., 2019. Expression of the Middle Cenomanian event along the cratonic margin of the Cretaceous Western Interior Seaway (WIS). Geological Society of America, Abstracts with Programs, 51(2).
27	**Layzell, A.L.**, Mandel, R.D., 2019. Holocene landscape evolution in the Republican River valley, south-central Nebraska. Geological Society of America, Abstracts with Programs, 51(2).
26	Peterson, A., Smith, J.J., **Layzell, A.L**., Ludvigson, G.A., 2019. Potential geomorphic indicators of structural deformation from lidar and high resolution imagery in east-central Kansas. Geological Society of America, Abstracts with Programs, 51(2).
25	Smith, J.J., Field, H.L., Joeckel, R.M., Ludvigson, G.A., Moller, A., Tucker, S.T., **Layzell, A.L.**, 2019. New approach to U-Pb zircon dating and carbon isotope geochemistry of paleosols in the Miocene Ogallala Group, north-central Nebraska, USA. Geological Society of America, Abstracts with Programs, 51(2).
24	Ludvigson, G.A., **Layzell, A.L**., Smith, J.J., Fox, D.L., Stotler, R.L., 2019. Paleohydrological evaluations of Cenozoic calcretes from the High Plains of western Kansas. Geological Society of America, Abstracts with Programs, 51(2).
23	Mandel, R.D., **Layzell, A.L.**, 2018. Advances in using soil survey data as a predictive tool for locating deeply buried archaeological deposits in stream valleys of the Midwest, USA. Geological Society of America, Abstracts with Programs, 50(6).
22	**Layzell, A.L**., Mandel, R.D., 2018. Holocene landscape evolution and bioclimatic change in the Republican River valley, south-central Nebraska: Implications for geoarchaeology in the central Great Plains. Geological Society of America, Abstracts with Programs, 50(6).

Entry No.	Title of Presentation
21	Peterson, A., Smith, J.J., **Layzell, A.L**., Ludvigson, G.A., 2018. Mapping potential surface expressions of structural features from lidar and high resolution imagery in east-central Kansas. Geological Society of America, Abstracts with Programs, 50(6).
20	Smith, J.J., Ludvigson, G.A., **Layzell, A.**, and Möller, A., 2018. Recent advances in developing a U-Pb zircon chronostratigraphy of Cenozoic strata in the High Plains of western U.S.A. 20th International Sedimentological Congress, Quebec City, Canada, August 13-17, 2018.
19	**Layzell, A.L.**, and Mandel, R.D., 2018. The application of Holocene alluvial stratigraphy to address streambank erosion and reservoir sedimentation in the Midwestern USA. Joint Meeting of the Canadian and American Quaternary Associations, Ottawa, Canada, Aug. 7-11, 2018.
18	Dunham, J.W., **Layzell, A.L.**, Mandel, R.D., and Newell, K.D., 2018. Preliminary surficial geology of Miami County, Kansas. ESRI User Conference, San Diego, July 9-13, 2018.
17	Smith, J.J., Ludvigson, G.A., **Layzell, A.L**., Dunham, J.W., 2018. Geologic mapping in Kansas: Overview of programmatic directions and current projects. Minnesota Geological Survey Open File Report OFR-18-1. Presentation at Geologic Mapping Forum in Minneapolis, MN.
16	**Layzell, A.L**., Newell, K.D., Oborny, S., Ludvigson, G.A., Dunham, J.., 2018. Geologic mapping in Miami County, Kansas. Minnesota Geological Survey Open File Report OFR-18-1. Presentation at Geologic Mapping Forum in Minneapolis, MN.
15	Smith, J.J., Ludvigson, G.A., **Layzell, A.L**., Möller, A., Turner, E., 2017. Scientific drilling in Cenozoic strata of the central High Plains aquifer: Developing U-Pb zircon chronostratigraphy in western Kansas. Geological Society of America Abstracts with Programs, 49 (1).
14	**Layzell, A.L**., Ludvigson, G.A., Fox, D.L., 2016. Stable isotopic paleohydrology of pedogenic carbonate nodules from Pliocene paleosols in the Meade Basin, southwestern Kansas. Geological Society of America Abstracts with Programs, 48 (7).
13	Smith, J.J., Ludvigson, G.A., **Layzell, A.L**., Möller, A., Stotler, R.L., Harlow, H.H., Petronis, M., Rittenour, T.M., Doveton, J.H., 2016. Maximum depositional age constraints and provenance of Cenozoic deposits of the Central High Plains in western Kansas. Geological Society of America Abstracts with Programs, 48 (7).
12	Stotler, R.L., Butler, J.J., Hirmas, D.R., Johnson, W.C., Katz, B., Knobbe, S.J., **Layzell, A.L**., Long, M.M., Ludvigson, G.A., Reboulet, E.C., Smith, J.J., Whittemore, D.O., 2016. Understanding the role of geology on recharge to and production from the High Plains aquifer in Kansas. Geological Society of America Abstracts with Programs, 48 (7).
11	**Layzell, A.L**., Harlow, R.H., Ludvigson, G.A., Mandel, R.D., Smith, J.J., 2015. Major element and isotope geochemistry from late Quaternary paleosols in southwestern Kansas: Assessing climate and parent material change. Geological Society of America Abstracts with Programs, 47 (7).

Entry No.	Title of Presentation
10	Turner, E., Smith, J.J., Ludvigson, G.A., **Layzell, A.L.**, Möller, A., 2015. Maximum depositional age constraints from U-Pb dating of zircons in Cenozoic deposits of the High Plains Aquifer, southwestern Kansas. Geological Society of America Abstracts with Programs, 47.
9	Mandel, R.D., Goldberg, P., **Layzell, A.L.**, Hass, J.R., 2015. Unraveling the Site Formation Process at Finch (47JE0902): A Multicomponent Habitation in Southeastern Wisconsin. 80th Annual Meeting of the Society for American Archaeology, San Francisco, California.
8	Smith, J.J., Ludvigson, G.A., Doveton, J., **Layzell, A.L.**, Stotler, R.L., Möller, A., Rittenour, T.M., 2015. A scientific drilling program in the Cenozoic strata of the High Plains Aquifer: Sedimentological and hydrostratigraphic characterization of cored sediments from the Ogallala Formation. International Conference on Novel Methods for Subsurface Characterization and Monitoring (NovCare), Lawrence, Kansas.
7	**Layzell, A.L.**, Mandel, R.D., Ludvigson, G.A., Smith, J.J., 2014. Late Pleistocene eolian sedimentation, soil development and climate change on the High Plains of southwestern Kansas. Geological Society of America Abstracts with Programs, 46(6), 151.
6	**Layzell, A.L.**, Mandel, R.D., 2014. Late Quaternary stratigraphy and paleoenvironmental change in the Cimarron River Valley, southwestern Kansas. American Quaternary Association 23rd Biennial Meeting, Seattle, WA.
5	**Layzell, A.L.**, Ludvigson, G.A., Mandel, R.D., Smith, J.J., 2014. Investigations of the litho- and soil-stratigraphy of Plio-Pleistocene strata in the Cimarron River valley, southwestern Kansas. Geological Society of America Abstracts with Programs, 46 (4), 57.
4	**Layzell, A.L.**, Mandel, R.D., 2013. An assessment of the lithostratigraphy and erodibility of Holocene alluvial fills (Deforest Formation) in northeastern Kansas, USA. Geological Society of America Abstracts with Programs, 45 (7), 120.
3	**Layzell, A.L.**, Eppes, M.C., 2012. The effect of remnant glacial topography on Holocene alluvial forms and processes in the San Juan Mountains, southern Colorado. American Quaternary Association 22nd Biennial Meeting, Duluth, MN.
2	Aquino, K., Eppes, M.C., Diemer, J., **Layzell, A.**, 2012. A chronosequence on the Catawba River near Charlotte, NC: Insights into the geomorphology and remediation of this heavily industrialized river. Geological Society of America Abstracts with Programs, 44 (4), 79.
1	**Layzell, A.L.**, Eppes, M.C., Johnson, B.G., 2011. Fluvial response to post Last Glacial Maximum climatic variability: The Conejos River Valley, Southern Colorado. Association of American Geographers Annual Meeting, Seattle, WA.

Minor Presentations (Regional/Local)

Entry No.	Title of Presentation
28	Wei, Q*., Brookfield, A.E., **Layzell, A.L**., Seybold, E., 2022. Quantifying the Effects of Water Management Decisions on Streambank Stability. Governor's Conference on the Future of Water in Kansas, Manhattan, KS. Nov 16-17.
27	**Layzell, A.L**., Kastens, J., 2022. Evaluating Playas in Western Kansas: Recharge to the High Plains aquifer and Economics of Cropping. Governor's Conference on the Future of Water in Kansas, Manhattan, KS. Nov 16-17.
26	Kastens, J., Baker, D., Huggins, D., Stotler, R., Peterson, D., **Layzell, A.L**., 2022. An Incomplete Overview of Recent Playa Research in Kansas. Platte River Basin Conference and 3rd Playa Research Symposium, Kearney, NE. Oct 24-26.
25	**Layzell, A.L.**, 2020. Streambank stabilization research in Kansas. Kansas Water Office Webinar, Virtual, August 25, 2020.
24	**Layzell, A.L.**, 2019. The use of Unmanned Aircraft Systems to assess streambank erosion and related engineering solutions. Governor's Conference on the Future of Water in Kansas, Wichita, KS. Nov 9-10.
23	Ziska, C., Johnson, N.L., **Layzell, A.L.**, 2019. The Nebraska Buried Sites GIS in Practice: Initial Results and Next Steps. 77th Plains Anthropological Conference, Bloomington, IN. Oct. 16-19.
22	Ludvigson, G.A., Joeckel, R.M., **Layzell, A.L.**, Moller, A., Doveton, J., Mandel, R.D., 2019. Record of the Middle Cenomanian Event from the Cretaceous Western Interior Seaway (WIS) in Kansas. AAPG Mid-continent Section Meeting, Wichita, KS. Oct. 7-8.
21	**Layzell, A.L**., 2018. Streambank stabilization effectiveness in the Cottonwood/Neosho River Basin. Governor's Conference on the Future of Water in Kansas, Manhattan, KS. Nov 13-14.
20	**Layzell, A.L.**, 2018. The role of the Kansas Geological Survey in the future of the National Geologic Map Database. Meeting of the Kansas Geological Survey Mapping Advisory Committee, Lawrence, KS.
19	Mandel, R.D., Butler, J., **Layzell, A.L.**, Holubnyak, E., Stover, S., Nelson, K., Potter, N., 2018. The Kansas Geological Survey. University of Kansas, Department of Geology Colloquium Series, Lawrence, KS.
18	**Layzell, A.L.**, 2018. Research related to assessing the effectiveness of streambank stabilization in Kansas. Meeting of the Kansas Geological Survey Advisory Council, Lawrence, KS.
17	Peterson, A., Smith, J.J., **Layzell, A.L**., Bidgoli, T., 2018. Structural mapping in the Humboldt Fault Zone using remote sensing, Chase County, Kansas. Transactions of the Kansas Academy of Science 121(1-2), 220-221. Presentation at the 150th Annual Meeting of the Kansas Academy of Science.
16	Smith, J.J., Ludvigson, G.A., **Layzell, A.L**., Dunham, J.W., 2018. Overview and direction of the geologic mapping projects at the Kansas Geological Survey. Transactions of the Kansas Academy of Science 121(1-2), 226. Presentation at the 150th Annual Meeting of the Kansas Academy of Science.

Entry No.	Title of Presentation
15	Smith, J.J., Ludvigson, G.A., **Layzell, A.L**., Möller, A., Turner, E., Hallman, J., Sitek, B., 2017. Recent advances toward developing a U-Pb zircon chronostratigraphy of Cenozoic strata in the central High Plains aquifer of Kansas. Governor's Conference on the Future of Water in Kansas, Manhattan, KS.
14	**Layzell, A.L**., 2017. Using soils and stratigraphy to help address important river management and cultural resource questions in Kansas. Transactions of the Kansas Academy of Science 120(1-2), 110. Presentation at the 149th Annual Meeting of the Kansas Academy of Science.
13	**Layzell, A.L.**, Mandel, R.D., Ziska, C., Bozell, J.R., 2017. Systematic approach to identifying deeply buried archaeological deposits. Nebraska Department of Transportation.
12	**Layzell, A.L.**, Peterson, A., 2017. The application of UAVs (drones) to Kansas Geological Survey research. Meeting of the Kansas Geological Survey Advisory Council, Lawrence, KS.
11	**Layzell, A.L.**, 2017. Holocene alluvial stratigraphy as a research tool in Kansas. University of Kansas, Department of Geology Colloquium Series, Lawrence, KS.
10	Smith, J.J., Ludvigson, G.A., **Layzell, A.L**., Möller, A., Turner, E., Hallman, J., Sitek, B., 2017. Recent advances toward developing a U-Pb zircon chronostratigraphy of Cenozoic strata in the central High Plains aquifer of Kansas. Transactions of the Kansas Academy of Science 120(1-2), 122. Presentation at the 149th Annual Meeting of the Kansas Academy of Science.
9	**Layzell, A.L.**, 2017. Systematic mapping of Holocene paleoliquefaction features in south-central Kansas. Meeting of the Kansas Geological Survey Mapping Advisory Committee, Lawrence, KS.
8	**Layzell, A.L.**, Mandel, R.D., Ziska, C., Bozell, R., 2016. Developing a Geographic Information System (GIS) as a Predictive Tool for Locating Deeply Buried Archaeological Deposits in Nebraska. 74th Plains Anthropological Conference, Lincoln, NE.
7	**Layzell, A.L.**, 2016. A stratigraphic assessment of streambank erodibility in northeastern Kansas. Meeting of the Kansas Geological Survey Advisory Council, Lawrence, KS.
6	**Layzell, A.L**., Mandel, R.D., 2016. Variability of streambank erosion in northeast Kansas: The importance of litho- and soil-stratigraphy. Transactions of the Kansas Academy of Science 119(2), 252. Presentation at the 148th Annual Meeting of the Kansas Academy of Science.
5	Smith, J.J., Ludvigson, G.A., **Layzell, A.L**., Stotler, R., Möller, A., 2016. Scientific drilling in the Cenozoic strata of the High Plains of western Kansas. Transactions of the Kansas Academy of Science 119(2), 261. Presentation at the 148th Annual Meeting of the Kansas Academy of Science.
4	Ludvigson, G.A., Smith, J.J., Doveton, J.D., Mandel, R., Murphy, L., **Layzell, A.**, Stotler, R.L., and Sleezer, R., 2014. Sedimentologic and stratigraphic characterization of cored sediments from the High Plains Aquifer system of western Kansas. Governor's Conference on the Future of Water in Kansas, Manhattan, KS.

Entry No.	Title of Presentation
3	**Layzell, A.L.**, Mandel, R.D., Ludvigson, G.A., 2014. Pedogenic and isotopic evidence for Pleistocene paleoenvironmental change in southwestern Kansas. Transactions of the Kansas Academy of Science 117(1-2), 128. Presentation at the 146th Annual Meeting of the Kansas Academy of Science.
2	**Layzell, A.L.**, 2012. Long-term drought and climatic variability in Kansas. Governor's Conference on the Future of Water in Kansas, Manhattan, KS.
1	**Layzell, A.L.**, 2012. 1000 years of Drought Variability in Kansas. Meeting of the Kansas Geological Survey Advisory Council, Lawrence, KS.

C. Honors and Awards for Research

1. ICA and IMIA Recognition of Excellence in Cartography Award. Surficial Geology of Miami County, Kansas. ESRI User Conference, San Diego, CA. July 10–14, 2022. https://www.esri.com/en-us/about/events/uc/agenda/virtual-map-gallery#/submission-detail/6298ebe898d581c52a690352
2. International Quaternary Association (INQUA) Congress Bursary Award, 2019.
3. Merriam Research Award, Kansas Geological Survey, 2018.
4. Third place, Thematic Map category. Preliminary surficial geology of Miami County, Kansas. ESRI User Conference, San Diego, CA, July 9–13, 2018.

TEACHING RECORD

Graduate and Postgraduate Advising Record

Committee Chair: Doctoral
Catherine Opalka, 2019-present, co-chaired with Marina Suarez (KU Geology)

Other graduate committee service
Committee Member (Masters), Kaela Nerhus, 2021-22 (KU Geology).
Committee Member (Masters), Corben Monzon, 2023-present (Kansas State University, Biological and Agricultural Engineering).

SERVICE RECORD

A. University of Kansas Service

Department of Geology

4. Courtesy Faculty Member position, Department of Geology, University of Kansas, 2017–Present.
3. Panelist, The Kansas Geological Survey, University of Kansas, Department of Geology Colloquium Series, August 2018.
2. Guest Speaker, "Holocene alluvial stratigraphy as a research tool in Kansas," University of Kansas, Department of Geology Colloquium Series, October 2017.

1. Guest Lecturer, Paleosols (graduate GEOL 728), University of Kansas, Department of Geology, March 2016.

Department of Anthropology

4. Guest Lecturer, Geoarchaeology (ANTH 517), University of Kansas, Department of Anthropology, February, 2022.
3. Guest Lecturer, Geoarchaeology (ANTH 517), University of Kansas, Department of Anthropology, February, 2020.
2. Guest Lecturer, Geoarchaeology Graduate Seminar (ANTH 849), University of Kansas, Department of Anthropology, April, 2019.
1. Guest Lecturer, Geoarchaeology (ANTH 517), University of Kansas, Department of Anthropology, April, 2018.

Department of Civil, Environmental, and Architectural Engineering

1. Field trip leader, NSF Research Experiences for Teachers: Exploring Career Opportunities through Water-Themed Engineering Research, July 2022.

Environmental Studies Program

1. Guest Lecturer, The Anthropocene: Interdisciplinary Perspectives on Environmental Change (graduate, EVRN 700), University of Kansas, Environmental Studies Program, September 2017.

Kansas Geological Survey

17. Editor-in-chief for *Midcontinent Geoscience* an open-access, peer-reviewed publication of the Kansas Geological Survey, 2018–present.
16. Member of the Stratigraphic Nomenclature Committee, Kansas Geological Survey, 2015–present.
15. Performed environmental reviews for potential geologic concerns of proposed construction and improvement projects in Kansas as requested by federal, state, and private agencies as part of their environmental due diligence requirements, 2017-present.
14. Supervised undergraduate students, graduate students, and temporary workers utilizing KGS laboratory spaces and field equipment, 2015-present.
13. Member of search committee for the hiring of Kansas Geological Survey Director, 2021-22.
12. Organized monthly Kansas Geological Survey early career scientist meetings, 2018–2020.
11. Member of search committee for the hiring of a Research Project Manager, 2020.
10. Chair of search committee for the hiring of a Geospatial Analyst, 2018.
9. Co-leader for Kansas Geological Survey Annual Legislative Field Conference, north-central Kansas – New Developments in Agriculture, Water Management, and Local Economies, Aug. 2018.
8. Guest Speaker, "Research related to assessing the effectiveness of streambank stabilization in Kansas" to the Kansas Geological Survey Advisory Council, July 2018.
7. Member of search committee for the hiring of a Groundwater Hydrologist, 2018.
6. Member of search committee for the hiring of a Hydrogeochemist, 2018.
5. Member of search committee for the hiring of a Petroleum Geoscientist (3 positions), 2017–2018.
4. Co-leader for Kansas Geological Survey Annual Legislative Field Conference, Northeast Kansas – Shaped by Glaciation and the Missouri River, Sept. 2017.

3. Guest Speaker, "Systematic mapping of Holocene paleoliquefaction features in south-central Kansas" to the Kansas Geological Survey Mapping Advisory Committee, May 2017.
2. Guest Speaker, "A stratigraphic assessment of streambank erodibility in northeastern Kansas" to the Kansas Geological Survey Advisory Council, Nov. 2016.
1. Guest Speaker, "1000 years of Drought Variability in Kansas", to the Kansas Geological Survey Advisory Council, Nov. 2012.

University

1. Co-organized "Beyond the Long Hot Summer: The Future of Water in Kansas" University of Kansas Symposium, 2013.

B. Professional Service outside the University

Local and State

8. Graduate Student Faculty, Kansas State University, 2023-present
7. Member, Kansas River Flood and Sediment Study Workshop, Nov. 2019.
6. Member, Kansas Watershed Restoration and Protection Strategy (WRAPS) Work Group, 2019-2022.
5. Judge, student presentations, Annual Meeting of the Kansas Academy of Science, Washburn University, Topeka, KS, 2018.
4. Session Chair; *Soils and Geology,* Annual Meeting of the Kansas Academy of Science, McPherson, KS, 2016.
3. Guest Speaker, "The Problem (The Long View) – Drought Cycles Over the Last 1,000 Years," Kansas Water Symposium, Dyck Arboretum of the Plains, Heston, KS, March 2015.
2. Guest Speaker, "1000 years of drought in Kansas," Wichita Water Center, Wichita, KS, March 2013.
1. Keynote Speaker, "A thousand years of drought and climate variability in Kansas: Implications for Water Resources Management," Kansas Association of Conservation Districts annual meeting, Wichita, KS, Nov. 2015.

Regional

3. Provided peer reviews for regional scientific journals, including Midcontinent Geoscience (2021, 2020).
2. Student mentor; Roy J. Shlemon Mentors Program in Applied Geology. Geological Society of America Joint Section Meeting (South-Central, North-Central, Rocky Mountain sections), Manhattan, KS, 2019.
1. Fieldtrip Co-organizer: *Looking Beneath the Plains: Geology of the Ogallala Formation and the Central High Plains of Kansas*. Geological Society of America Joint Section Meeting (South-Central, North-Central, Rocky Mountain sections), Manhattan, KS, 2019.

National

7. Geological Society of America, Quaternary Geology and Geomorphology Division, Section Meeting Liaison (North-Central and South-Central Sections), 2023.
6. Member of the USGS National Geologic Map Database (NGMDB) Technical Advisory Working Group, 2018–present.

5. Reviewer for Geological Society of America, Quaternary Geology and Geomorphology Division, Graduate Student Research Proposal Awards (up to 9 awards given), 2022, 2020, 2018, 2016.
4. Nominated for service on Geological Society of America Quaternary Geology and Geomorphology Division Panel (2021, 2019).
3. Session Chair, *Landscape Response to Neogene Climate Change*, Annual Meeting of the Geological Society of America, Phoenix, Arizona, 2019.
2. Fieldtrip co-organizer: *Getting to the Bottom of the High Plains Aquifer: New insights into the Depositional History and Stratigraphy of the Cenozoic High Plains.* Geological Society of America Annual Meeting, 2016.
1. Member of Selection Committee for SEPM (Society for Sedimentary Geology) Francis J. Pettijohn Medal for Sedimentology, 2014.

International

3. Provided solicited peer reviews for various international, peer- reviewed scientific journals, including River (2023), Journal of Hydrology (2021), Transactions of the American Society of Agricultural and Biological Engineers (2020), Journal of Sedimentary Research (2020, 2018), Catena (2018), Geomorphology (2017), Earth Surface Processes and Landforms (2017), Palaeogeography, Palaeoclimatology, Palaeoecology (2016), Geoarchaeology: An International Journal (2016, 2015).
2. Panelist for Student Mentoring and Career event at Joint Meeting of the Canadian and American Quaternary Associations, Ottawa, Canada, Aug. 7–11, 2018.
1. Invited Speaker "The application of Holocene alluvial stratigraphy to address streambank erosion and reservoir sedimentation in the Midwestern USA." Joint Meeting of the Canadian and American Quaternary Associations, Ottawa, Canada, Aug. 7–11, 2018.

A thousand years of drought and climatic variability in Kansas: Implications for water resources management

EXHIBIT
ALL-02

Anthony L. Layzell

Kansas Geological Survey

2012

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1. Introduction

Periods of severe drought are one of the greatest recurring natural disasters in North America. In any given year, droughts occur all across North America resulting in significant impacts on local economies, societies, and the natural environment. Drought conditions in the United States cost on average $6-8 billion every year, but have ranged as high as $39 billion during the three-year drought of 1987-89 (Riebsame et al., 1991). In Kansas alone, the recent 2011 drought resulted in losses in excess of $1.7 billion (Kansas Department of Agriculture, 2011).

Droughts impact both surface- and ground-water resources and often result in reductions in water supply and crop failure particularly in agriculturally sensitive areas such as the High Plains of western Kansas. This region is becoming increasingly vulnerable to drought due to a variety of factors including the increased cultivation of marginal lands and the increased use of ground-water resources from the High Plains aquifer (Woodhouse and Overpeck, 1998), where water withdrawal has exceeded recharge for many years (e.g. McGuire, 2009).

The droughts of the 1930s and the 1950s remain the benchmarks in terms of duration, severity, and spatial extent for Kansas in the 20th century. Therefore, determining how representative these historic droughts have been in terms of drought occurrence is vitally important. The key question is how unusual are severe droughts, such as the Dust Bowl? Was this drought a rare event or should we expect droughts of similar or even greater magnitude in the future?

Direct observations of temperature and precipitation from instrumental records are largely restricted to the past 100 years and are therefore too short to adequately answer these questions. Therefore, in order to assess the full range of drought variability, it is important to place historic droughts in a longer-term context by utilizing paleoclimate proxy records.

This report investigates past drought occurrences from paleoclimate records over the last 1000 years. In particular, we focus on Palmer Drought Severity Index (PDSI) reconstructions calculated from annual tree-ring chronologies. Additional paleoclimate proxies and historical records are also examined to lend further support to reported past drought variability.

2. Types and Measures of Data

2.1 Drought Indices

The Palmer Drought Severity Index (PDSI) is one of the most widely used indices to measure drought in North America. The PDSI was developed by Palmer (1965) to measure the intensity and duration of long-term drought. It uses precipitation and temperature data to determine how much soil moisture is available compared to average conditions. PDSI values therefore provide data on both relative wetness and dryness over a given period. The index typically ranges between -4 (extremely dry) and 4 (extremely wet) but the range limit is not explicitly bound. As the index is standardized to local climate, it may be applied to any part of the country to demonstrate relative wetness and dryness.

2.2 Paleoclimate Data

PDSI values calculated from instrumental data provide a valuable means to assess drought variability over the instrumental record (i.e. the past 100 years). Recently, the Kansas Geological Survey has published historic climate and PDSI data (1895 to 2011) online in the form of the Kansas High Plains Aquifer Atlas (http://www.kgs.ku.edu/HighPlains/HPA_Atlas/Climate%20and%20Climate%20Trends/index.html#). Based on these data alone, the droughts of the 1930s and 1950s appear to be anomalous in terms of their severity and duration (Fig. 1).

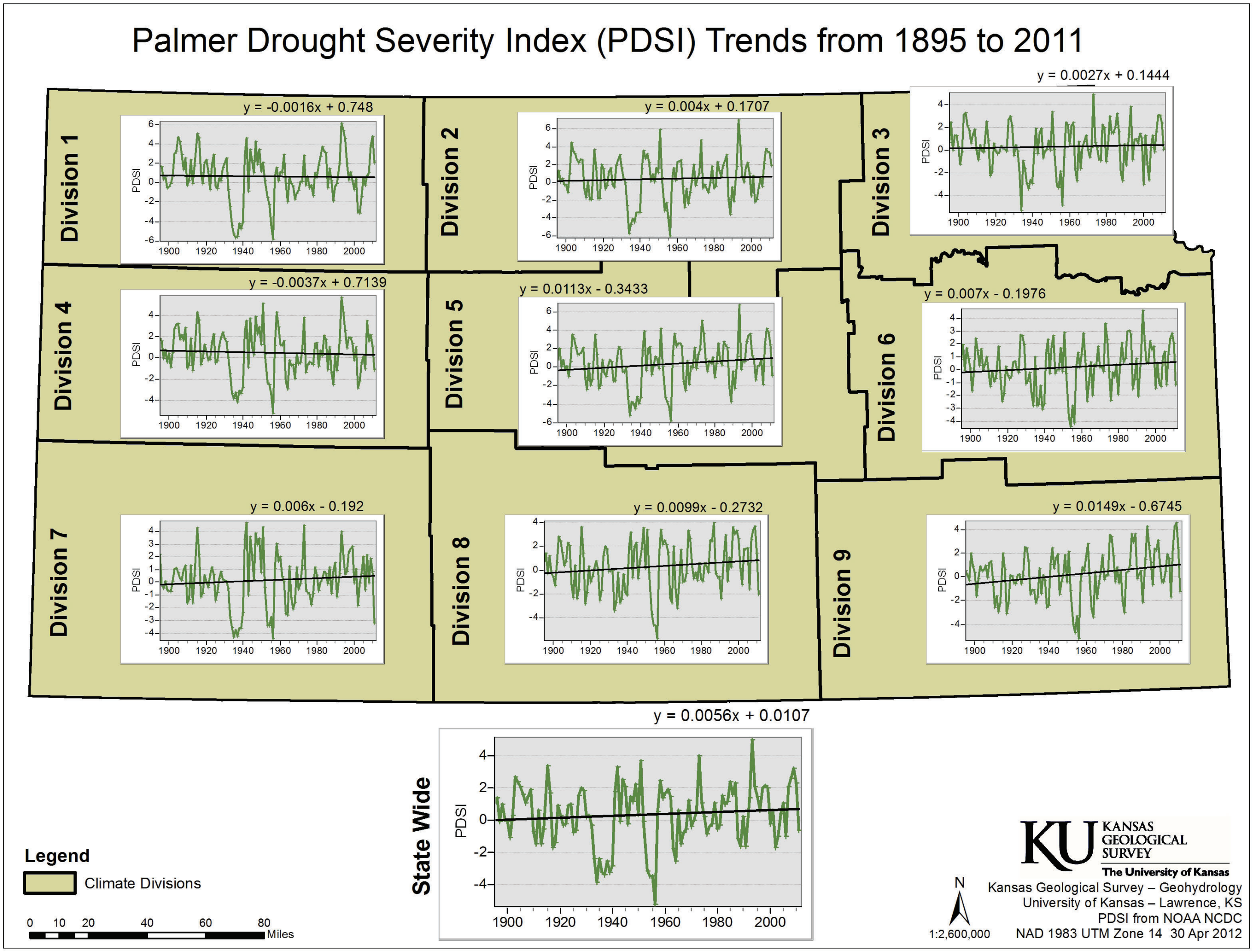

Figure 1. Instrumental PDSI trends for Kansas from 1895 to 2011. Image from the High Plains Aquifer Atlas (www.kgs.ku.edu/HighPlalins/HPA_Atlas/index.html).

However, paleoclimatic records allow one to assess the full range of drought variability by utilizing data that span longer periods of time. Long-term records have been developed from a variety of different proxies that span a range of time periods from hundreds to thousands of years. Proxies include tree-rings, sediments from lakes, sand dunes, and rivers, as well as historical and archeological records. These proxies record natural variability in drought occurrence and allow us to compare historic droughts of the 20th century with those of the past.

This report will focus on the paleoclimatic record developed from tree-ring studies. However, it is important to note that when used together, multiple proxy records provide a more complete picture of past change than that offered by any one proxy or instrumental data alone. Therefore, this report will supplement tree-ring reconstructions with data from historical, archeological, and geomorphic records in order to more fully investigate past drought variability.

2.2.1 Long-term PDSI Reconstructions

Tree-rings chronologies are based on the actual growth rate of highly drought-sensitive trees and therefore function as an important indicator of past droughts. Adequate moisture and a long growing season result in wide tree rings while drought years create very narrow rings. Importantly, individual tree-rings can be dated to the exact calendar year using cross-matching techniques.

Recently, an extensive network of annual tree-ring chronologies has been developed and made publically available through the International Tree-Ring Data Bank (http://www.ncdc.noaa.gov/paleo/treering.html). Utilizing these data, annual PDSI reconstructions have been developed for 286 grid points across most of North America (Cook and Krusic, 2004). Reconstructions utilized the nearest available tree-ring chronologies to each grid point and were produced with a well-tested point-by-point principal-components regression procedure. See Cook et al. (1999) for detailed methodology used to develop PDSI reconstructions. PDSI reconstructions are evaluated using four statistics, which indicate high overall calibration and verification (see appendix for more details).

Regression based tree-ring PDSI reconstructions tend to underestimate extreme values, although dry extremes are better represented than wet extremes, but are reasonably accurate in terms of extent and duration (Woodhouse and Overpeck, 1998). Therefore, such reconstructions facilitate accurate assessment of the relative severity of 20th-century droughts compared to droughts in the more distant past.

A previous paleoclimate report for the Ogallala region by Young and Buddemeier (2002) utilized PDSI reconstructions by Cook et al. (1999), which were developed from 425 tree-ring chronologies and extended from ~1170 to 1978 AD for western Kansas. Since the publication of this report, new PDSI reconstructions have been produced that represent a substantial spatial and temporal improvement and enable us to better assess the nature of past drought variability. New reconstructions are now based on almost twice as many tree-ring chronologies (835 in total) and extend over longer time periods (from 837 to 2003 AD for western Kansas). PDSI estimates are based on instrumental data after 1978. PDSI data are available publically in the form of the North American Drought Atlas (http://iridl.ldeo.columbia.edu/SOURCES/.LDEO/.TRL/.NADA2004/.pdsi-atlas.html). Data were obtained for six grid points in Kansas, thereby dividing the state into six regions (Northwest, Southwest, North-central, South-central, Northeast, Southeast) for analysis in this report.

3. Analyses

3.1 Drought Severity

Figure 2 contains plots of annually resolved PDSI tree-ring reconstructions for six regions in Kansas. *These plots highlight numerous years in the past where drought conditions exceeded the severity of the 1930s and 1950s droughts in each region*. The peak individual drought years during the 1930s and 1950s droughts were determined to be 1934 and 1956 respectively. PDSI values for these years are highlighted with dashed lines on figure 2 and provide a benchmark by which to assess drought occurrence within each region. This type of analysis, however, does not favor regional comparisons as different PDSI thresholds are used in each region.

In order to facilitate regional comparison, we averaged the six regional PDSI values for 1934 and 1956 respectively, generating two thresholds by which to compare the different regions. These thresholds enable us to determine the number of years where droughts of a similar or greater magnitude occurred (i.e. years where PDSI is less than the threshold values). The averaged PDSI values for 1934 and 1956 are -4.9 and -5.9 respectively. Figure 3 highlights the total number of drought years in each region where PDSI values were less than or equal to the threshold values. Note that data were unavailable for some regions between 837-1000 AD and therefore, in order to facilitate fair comparison between regions, this analysis was restricted to data post 1000 AD.

The PDSI data indicate that western Kansas has experienced more severe droughts than eastern Kansas over the past 1000 years. Furthermore, the data also indicate that northern Kansas has typically experienced more severe droughts than southern Kansas. The west to east trend is not surprising given the strong latitudinal

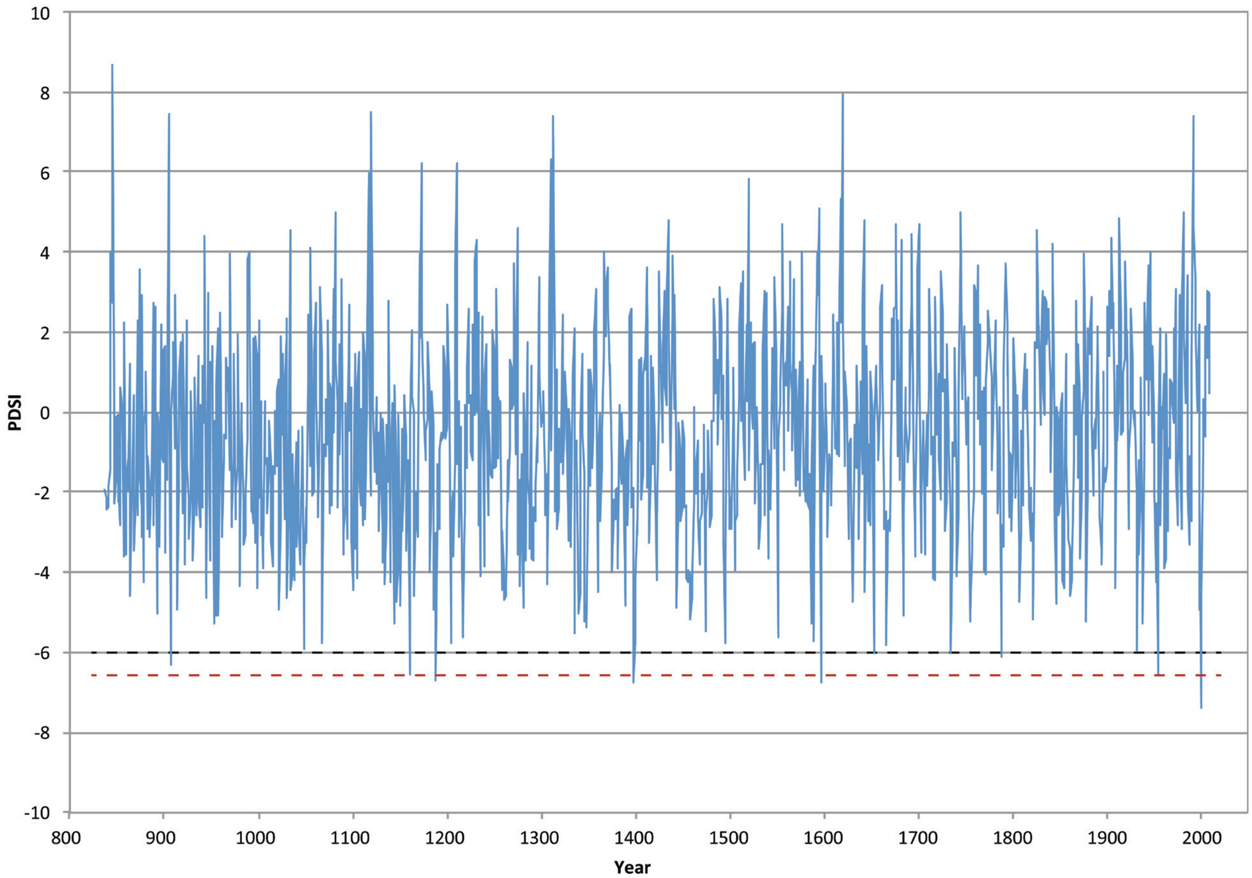

Figure 2a. Annual PDSI reconstructions from tree rings for northwestern Kansas. Dashed lines indicate the 1934 (black) and 1956 (red) PDSI values.

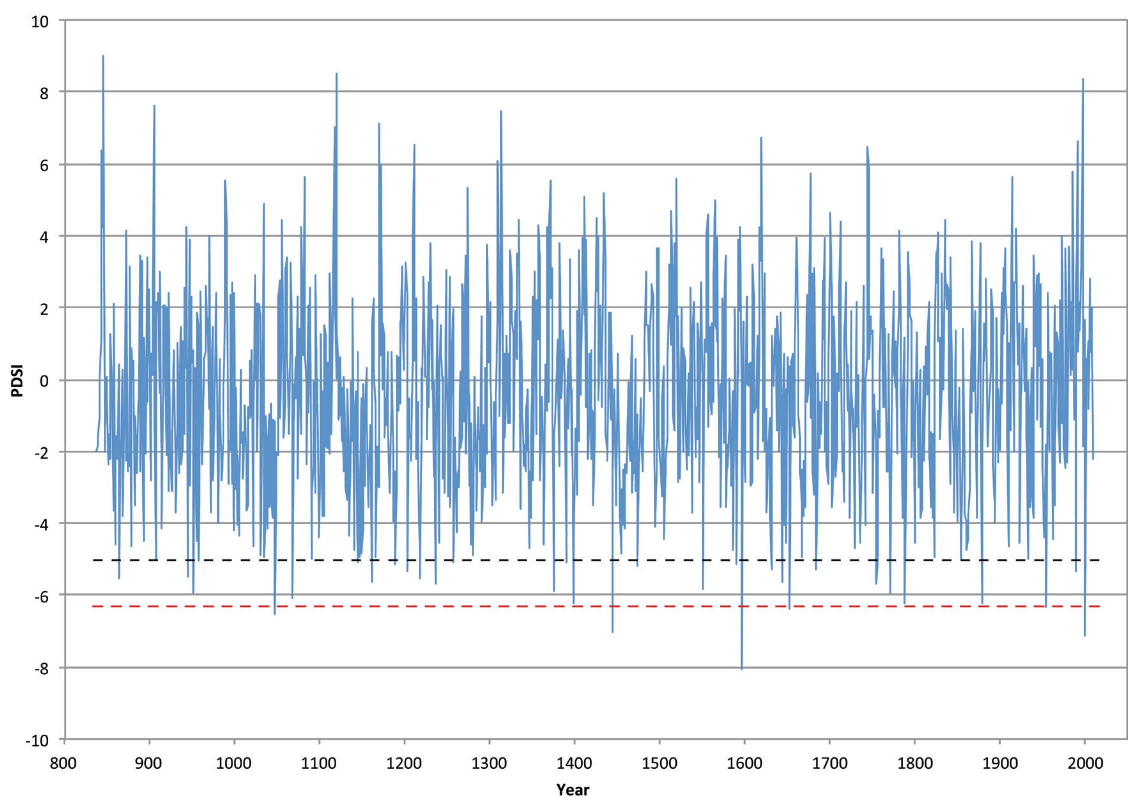

Figure 2b. Annual PDSI reconstructions from tree rings for southwestern Kansas. Dashed lines indicate the 1934 (black) and 1956 (red) PDSI values.

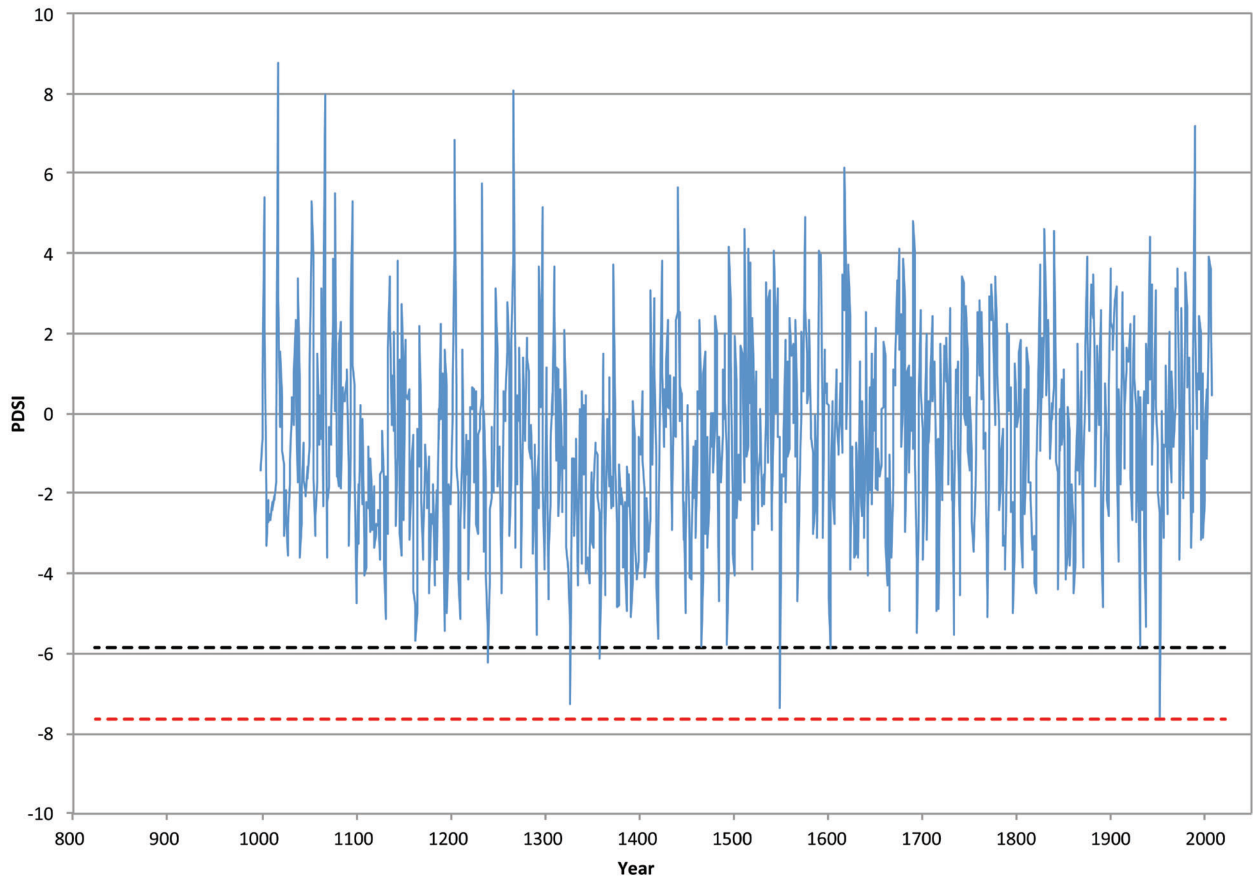

Figure 2c. Annual PDSI reconstructions from tree rings for north-central Kansas. Dashed lines indicate the 1934 (black) and 1956 (red) PDSI values.

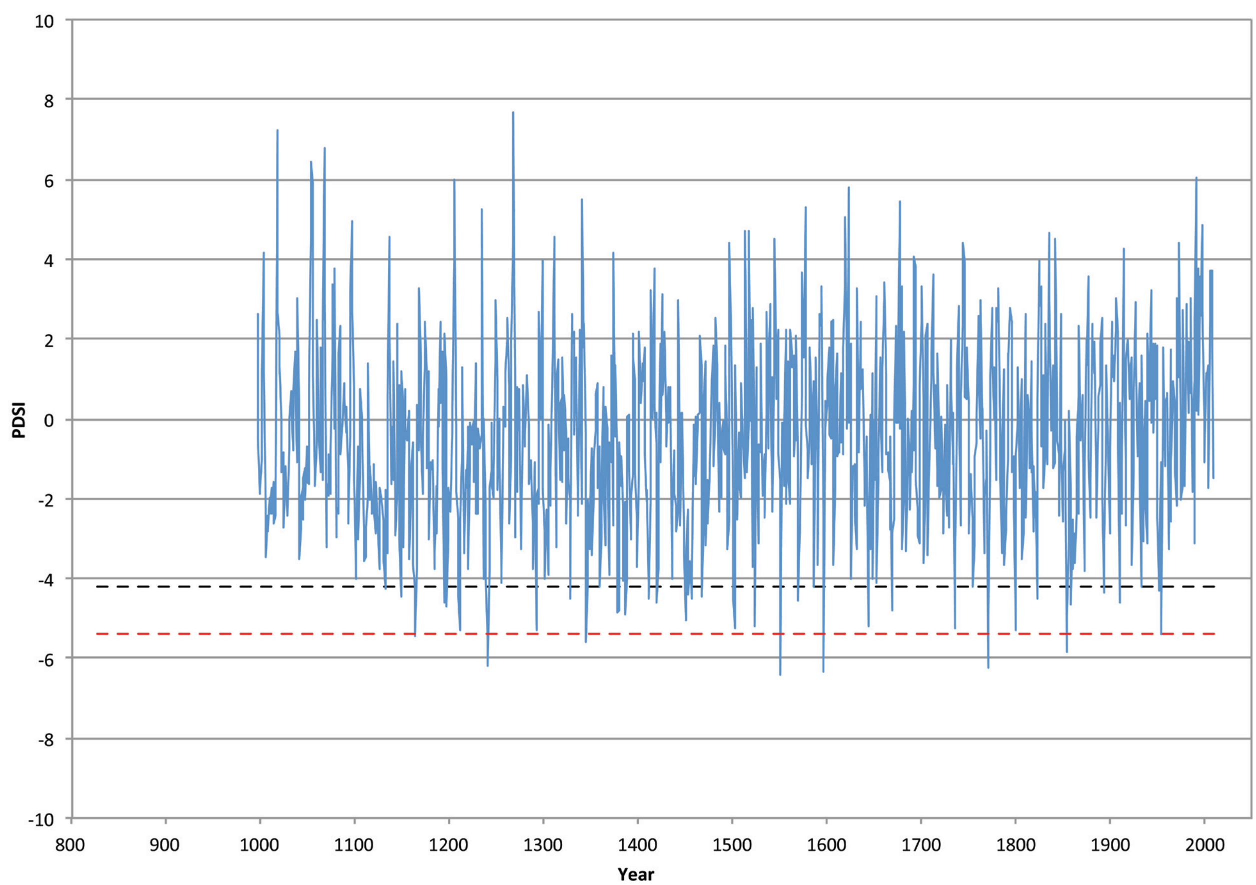

Figure 2d. Annual PDSI reconstructions from tree rings for south-central Kansas. Dashed lines indicate the 1934 (black) and 1956 (red) PDSI values.

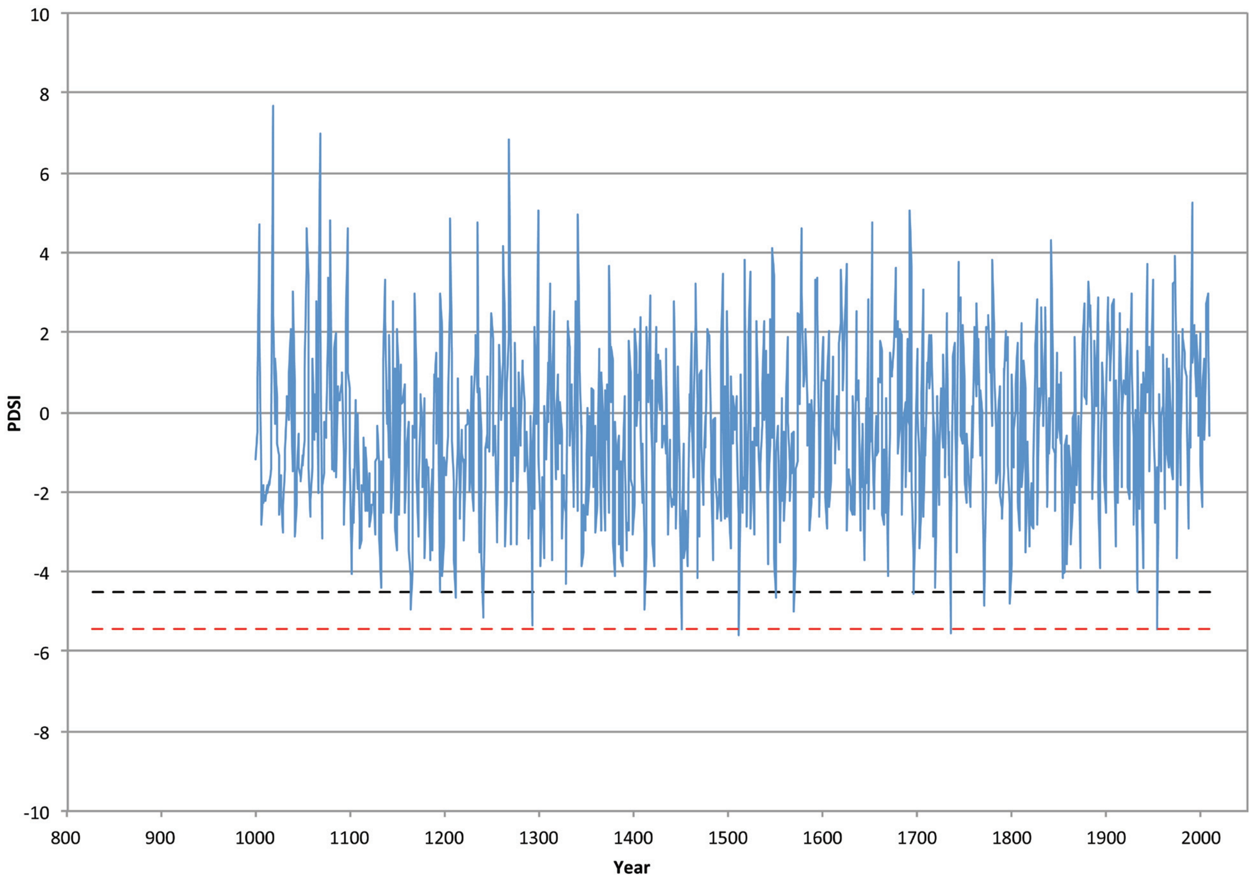

Figure 2e. Annual PDSI reconstructions from tree rings for northeastern Kansas. Dashed lines indicate the 1934 (black) and 1956 (red) PDSI values.

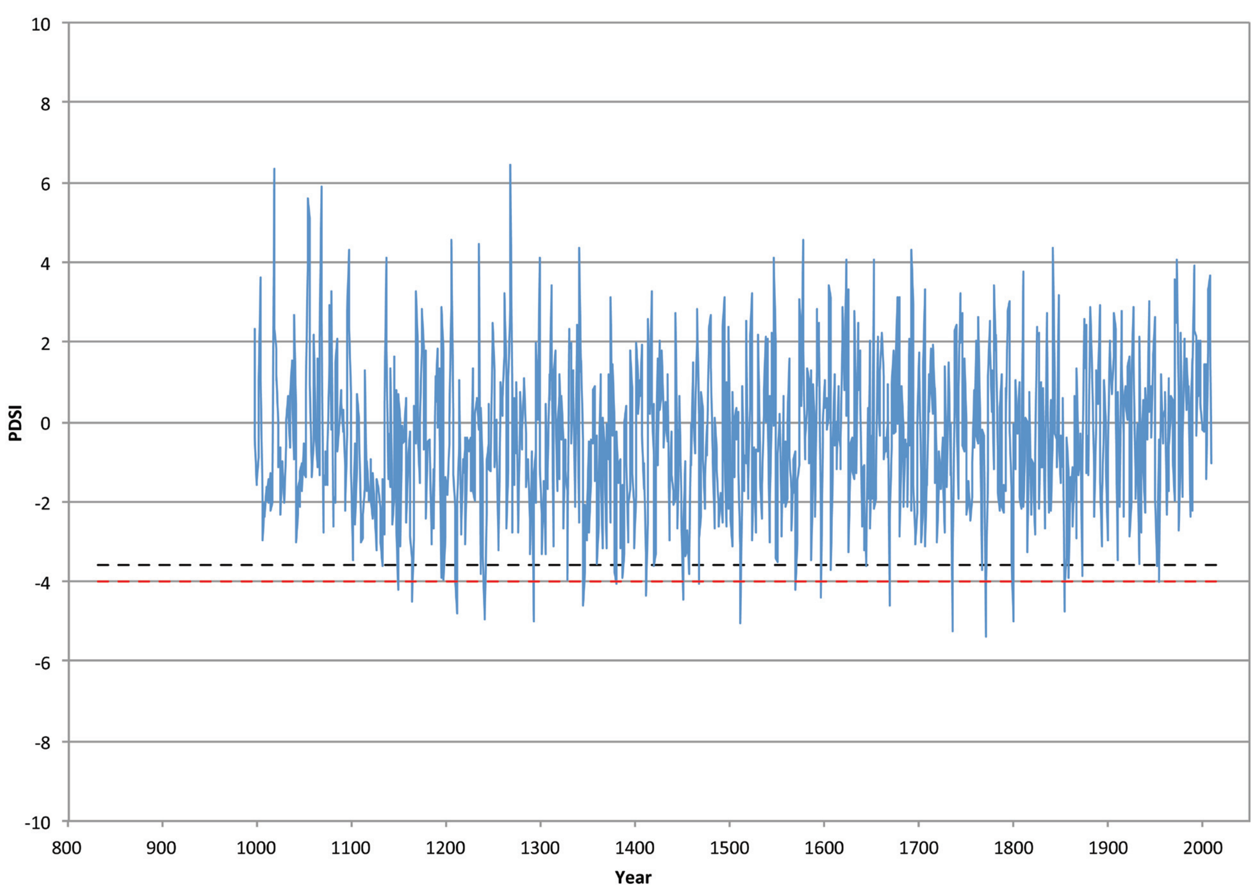

Figure 2f. Annual PDSI reconstructions from tree rings for southeastern Kansas. Dashed lines indicate the 1934 (black) and 1956 (red) PDSI values.

climate gradient in Kansas. The north to south trend can be explained by investigating the spatial patterns of historic 20th-century droughts. For example, the Dust Bowl drought was spatially centered over the Pacific Northwest and later over the northern Plains while the 1950s drought, in contrast, was centered over the southern Great Plains and later shifted into the southwest US (e.g. Stahle et al., 2007; Fig. 4). Hoerling et al. (2009) suggest that the 1950s drought was driven by changes in sea-surface temperatures, more specifically the El Niño-Southern Oscillation. They found that during La Niña years, characterized by cold sea-surface temperatures in the equatorial Pacific, droughts are common in the southern Plains. In contrast, they suggest that the Dust Bowl drought was caused by random atmospheric variation rather than changes in ocean temperatures. Therefore, the PDSI data appear to suggest that the random forcing mechanisms of the Dust Bowl drought have been more common over the past 1000 years than those that resulted in the 1950s drought.

Another way to analyze the PDSI data is to determine how many years exceed the threshold in a given century. By this method *we should expect individual drought years at least as severe as 1934 on average 3-4 times a century in western Kansas, 2-3 times in central Kansas, and about once a century in eastern Kansas*.

However, this analytical method (i.e. using averaged PDSI thresholds) can be misleading. For example, figure 3 indicates that there are no droughts in the paleorecord that exceed the 1956 threshold in eastern Kansas. This is misleading because of the strong regional expression of drought in the state. For example, in southeastern Kansas the 1956 PDSI was -4.0, which indicates extreme drought. However, because drought conditions were more severe elsewhere in the state, the regionally averaged threshold for 1956 is skewed to -5.9. While there are no past drought years with PDSI values less than -5.9 in southeastern Kansas, there are at least 22 past drought years with PDSI values less than -4.0 (see Fig. 2f). We therefore suggest that both methods of analysis (i.e. assessing drought severity *within* and *between* regions) should be used in conjunction when assessing the variability of drought severity across Kansas.

3.2 Drought Duration

One of the key characteristics of the 1930s and 1950s droughts was not only their severity in a given year but their *duration*. Individual drought years are therefore not necessarily good indicators of cumulative socioeconomic or environmental impacts as one dry year may be accommodated if it is sufficiently offset by wetter conditions the following year (Cook et al., 2007). For example, the 2002 drought year in southwestern Kansas was more severe than the peak year of the Dust Bowl (PDSI values of -7.1 and -5.0 respectively). However, 2002 was bounded by years of positive PDSI values whereas the Dust Bowl drought consisted of several consecutive years of drought conditions. It is therefore important to assess the duration of past periods of drought.

The duration of droughts is more difficult to estimate because climatic variability tends to punctuate dry multi-year intervals with occasional wet years (Cook et al., 2009). Furthermore, there is no unique solution for calculating drought duration. For example, the 1930s and 1950s droughts have been estimated to have lasted 12 and 14 years (Stahle et al., 2007) or 7 and 8 years (Andreadis et al., 2005) respectively. One method to determine drought duration is to utilize a low-pass filter, such as a moving-average, which allows for analysis of decadal to multi-decadal changes in aridity.

Figure 5 contains plots of PDSI values smoothed over 10- and 50-year periods. For this analysis we determine the beginning and end of a drought period from the smoothed data by identifying when it is preceded or followed by more than two consecutive years of positive PDSI values. Using this technique we identify the duration of the 1930s and 1950s droughts in Kansas as lasting 13 and 18 years respectively.

Using these durations we are able to identify several periods of past drought with durations similar (i.e. 10-20 years) to the severe historic droughts of the 20th century. These droughts are highlighted in figure 5 by light gray bars. Figure 6 shows the number of droughts of similar duration to the historic 20th century droughts over the past 500 years. We limit this analysis to the past 500 years because the majority of droughts prior to this appear to be of much greater duration. Drought duration over the past 500 years illustrates a similar pattern to

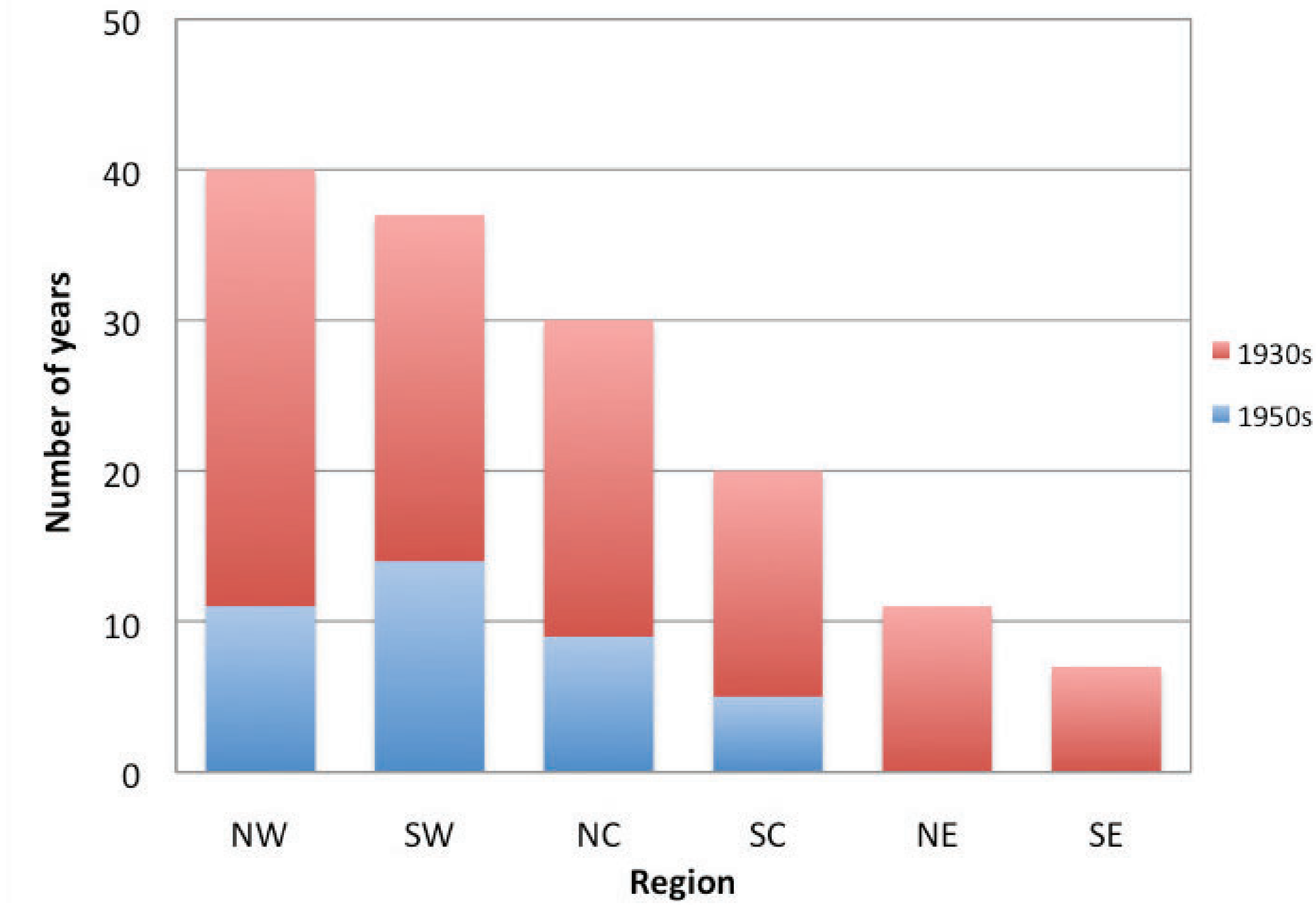

Figure 3. Number of drought years more severe than the peak years of the 1930s and 1950s droughts. Note that this analysis uses threshold PDSI values averaged across all six regions.

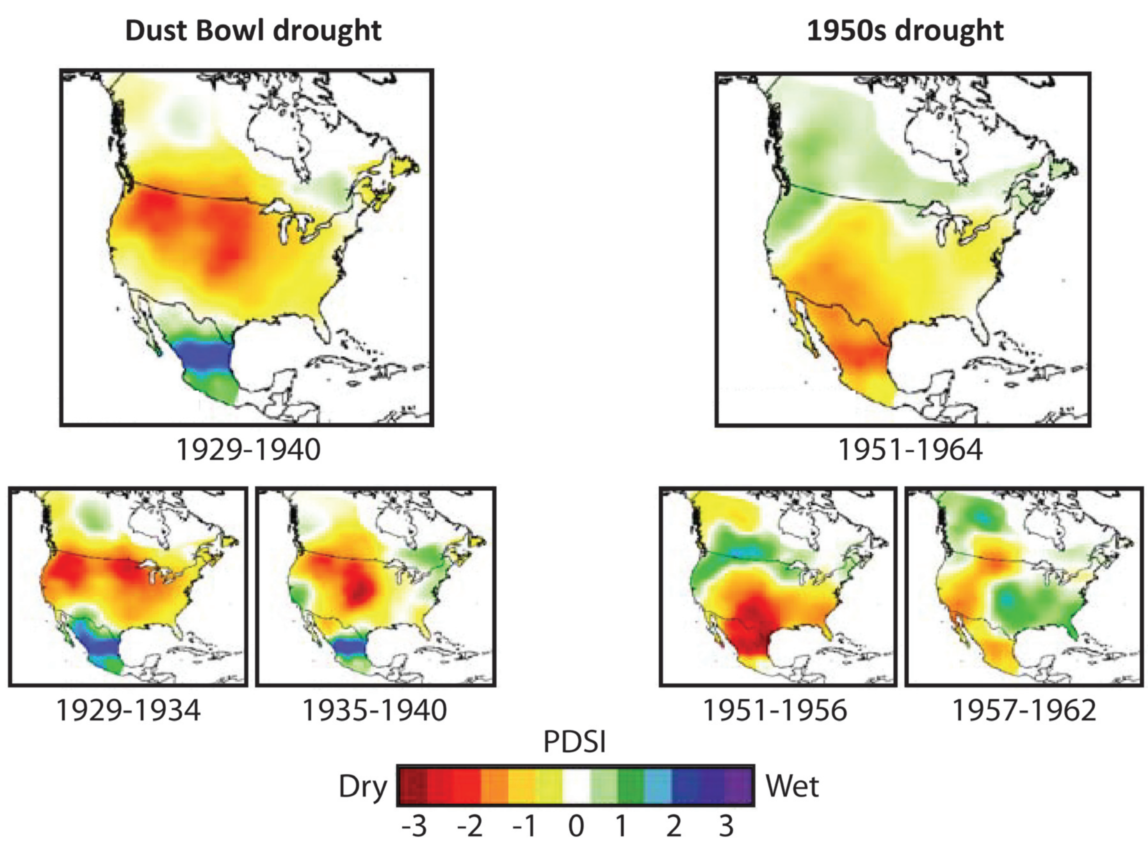

Figure 4. Mapped spatial patterns of the 1930s and 1950s droughts using instrumental PDSI data. Figure modified from Stahle et al. (2007).

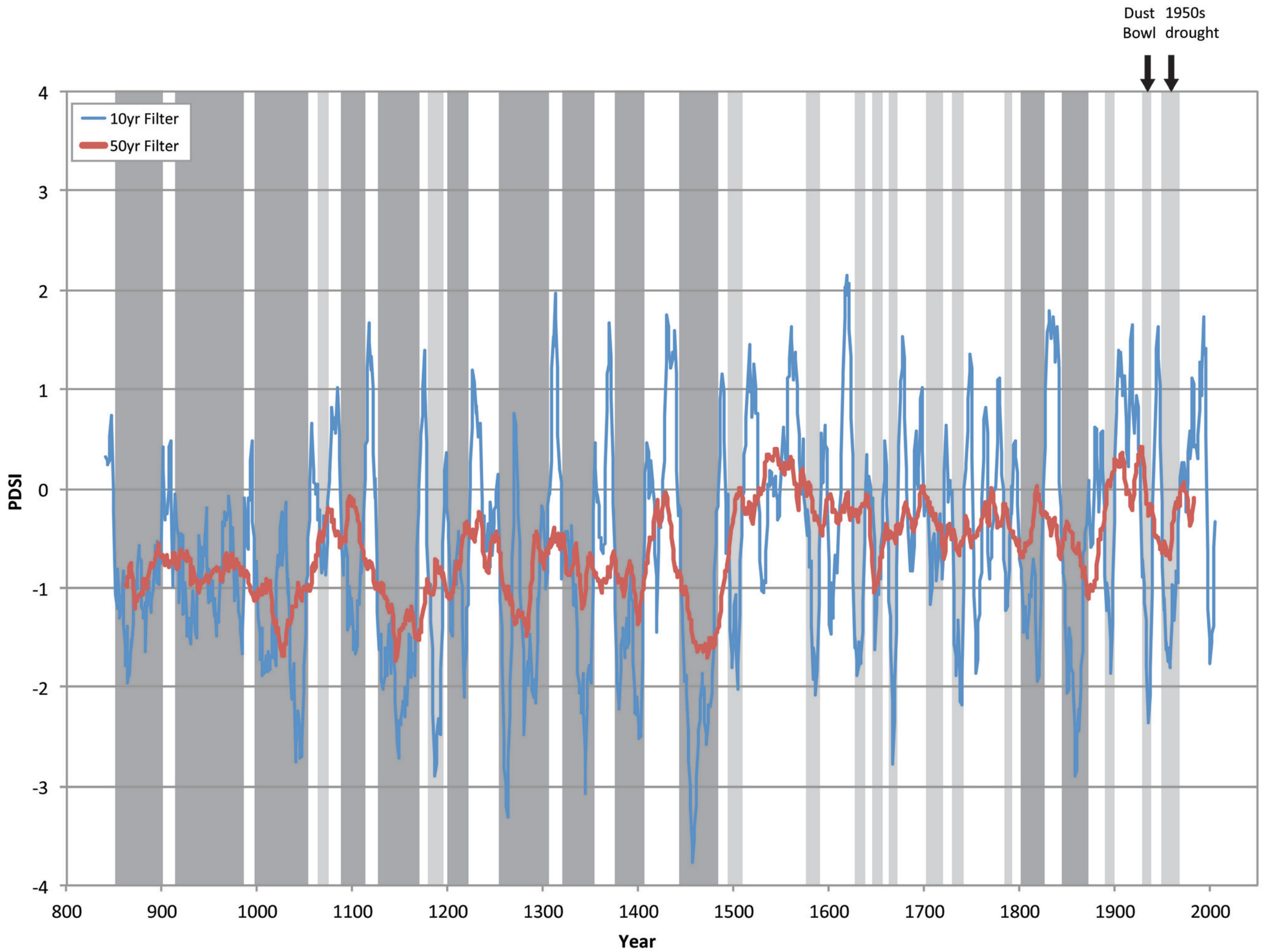

Figure 5a. Smoothed PDSI reconstructions for northwestern Kansas. Light-gray bars indicate droughts of similar duration to the 1930s and 1950s droughts while dark-gray bars indicate droughts of greater duration.

drought severity with western and northern Kansas experiencing more decadal drought periods than eastern Kansas. From these data *we should expect decadal droughts on average two times a century in western Kansas and about once a century in eastern Kansas*.

3.2.1 Megadroughts

Droughts of unusually long duration compared to those observed in the instrumental record are often called 'megadroughts.' In order to constitute a megadrought, a past multi-year drought must exceed the duration of the most extreme droughts in the 20th century. Therefore, for this study, a megadrought is defined as a drought lasting more than 20 years in duration.

PDSI reconstructions highlight several periods of extreme drought in the past with much longer durations compared to those of the 20th century, particular prior to 1500 AD. These multi-decadal droughts are highlighted in figure 5 by dark gray bars. Additionally, documented megadroughts are typically at least as severe as the 1930s and 1950s droughts.

It is important to validate the occurrence of past megadroughts by utilizing other proxy records. Figure 7 synthesizes the records of drought variability shown in figure 5 and in addition highlights different lines of environmental and societal evidence that support drought conditions during documented megadroughts.

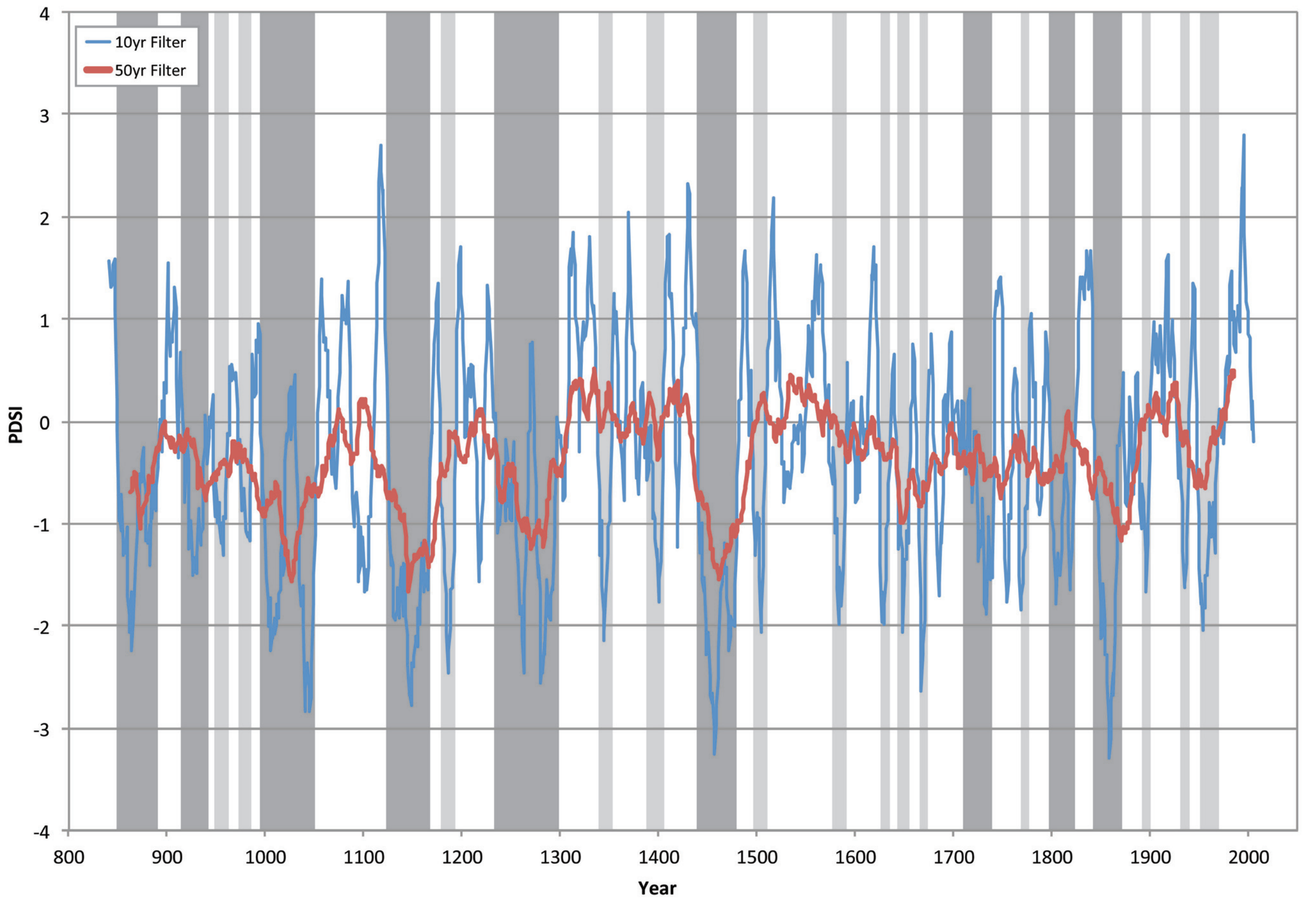

Figure 5b. Smoothed PDSI reconstructions for southwestern Kansas. Light-gray bars indicate droughts of similar duration to the 1930s and 1950s droughts while dark-gray bars indicate droughts of greater duration.

3.2.2. Megadroughts from 1500 to 2011 AD

PDSI reconstructions indicate the likely occurrence of megadroughts in the beginning and middle part of the 19th century, which persisted on average for 30 years (Figs. 5 and 7). Drought conditions around 1850 are noted in a variety of historical data, including early meteorological records (Ludlum, 1971). Stahle et al. (2007) cite evidence from the Kiowa of the southern Great Plains that cites 1855, known among the Kiowa as the "sitting summer," as a year of severe drought. Woodhouse and Overpeck (1998) note that drought conditions were also documented in Kansas newspapers in 1860. Woodhouse et al. (2002) used streamflow reconstructions from eastern Colorado to document a period of remarkable sustained drought from approximately 1845 to 1856. This period of drought, together with human impacts, may have also resulted in a severe decline in the populations of the Great Plains bison (Woodhouse et al., 2002). Historical accounts from early explorers in the region during the 19th century report periods of blowing sand indicative of eolian activity and sand-dune activation for an area extending from northern Nebraska to southern Texas (Muhs and Holiday, 1995). Eolian activity is primarily driven by droughts severe enough to remove the stabilizing effects of vegetation. Forman et al. (2008) observed discrete episodes of sand deposition in the Arkansas River valley of southwestern Kansas between 1620-1680 and 1800-1820 AD (Fig. 6).

3.2.3 Megadroughts from 850 to 1500 AD

PDSI data highlight several likely past megadroughts from 850 to 1500 AD (Figs 5 and 7). Although these mega-droughts were punctuated with wet intervals, overall they suggest protracted aridity lasting on average 40-50 years in duration. The longest megadrought on record occurred in north-central Kansas and lasted 110 years

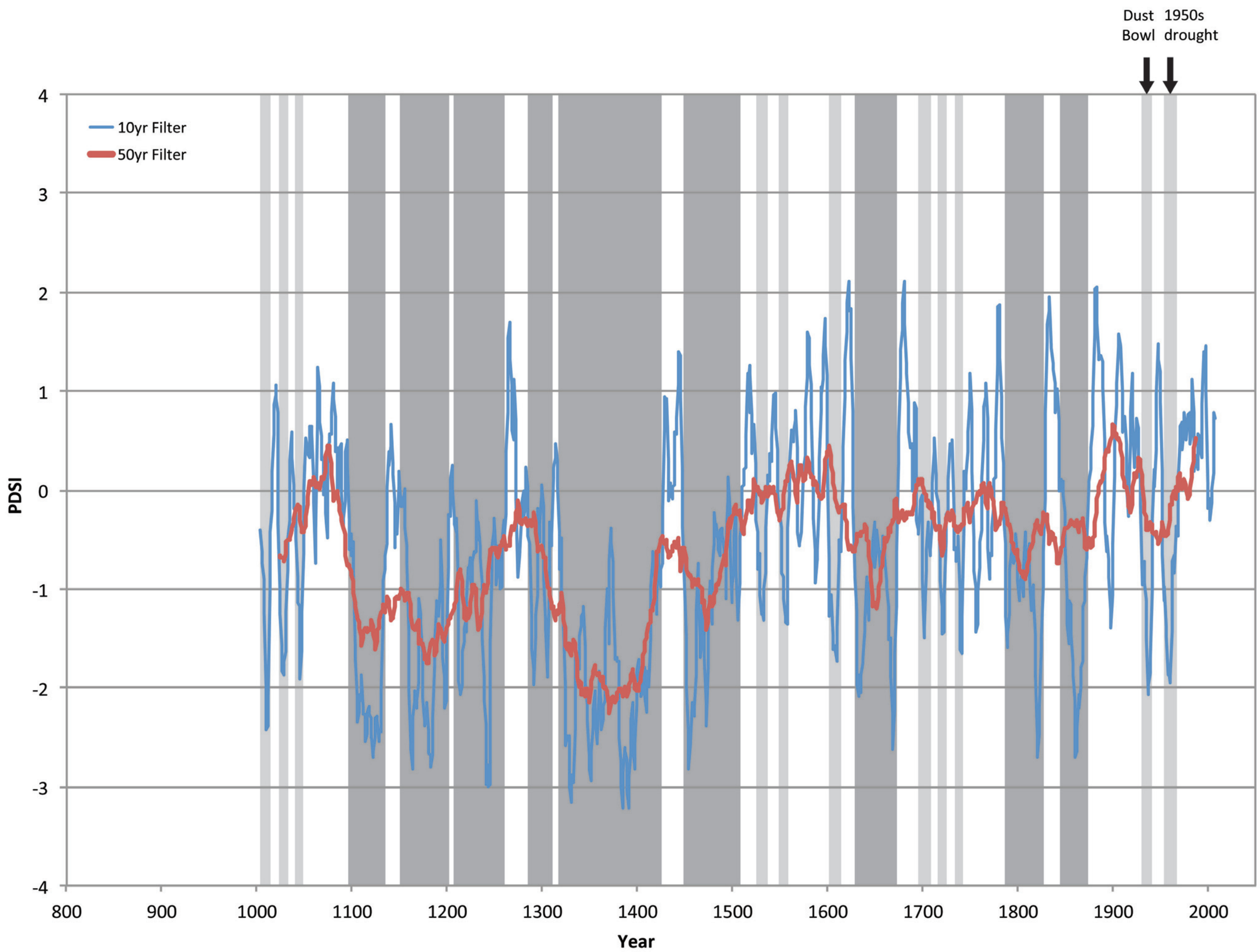

Figure 5c. Smoothed PDSI reconstructions for north-central Kansas. Light-gray bars indicate droughts of similar duration to the 1930s and 1950s droughts while dark-gray bars indicate droughts of greater duration.

from 1317 to 1427 AD. This megadrought was also much more severe than historic 20th-century droughts. Figure 7 highlights the spatial variability of megadroughts across the state. For example, the protracted 110-year megadrought in north-central Kansas was separated into two separate decadal droughts in western Kansas.

Most dune records from the central Great Plains show significant sand-dune activation due to increasing aridity and reductions in vegetation cover between 950-1350 AD. Evidence of sand-dune mobilization from the Great Bend Sand Prairie in south-central Kansas – the largest dune field in Kansas – has been documented between 1050-1250 and 1450-1650 AD (Arbogast, 1996). Halfen et al. (2011) also identified active dune migration in south-central Kansas between 1000-1100 AD. Dunes in the Cimarron River valley of southwestern Kansas were active between 1050 and 1250 AD (Lepper and Scott, 2005) while dunes in the Abilene dune field of north-central Kansas were active more broadly between 890-1490 AD (Hanson et al., 2010). The time intervals for dune activation overlap periods of megadroughts identified from PDSI reconstructions.

Support for the occurrence of megadroughts between 850 and 1500 AD can also be gleaned from the archeological record, which highlights the destabilizing effects of past severe droughts. Benson et al. (2007) suggest that multi-decadal droughts between 990-1060, 1135-1170, and 1276-1297 AD had significant impacts on a variety of prehistoric populations in the Southwest, including Anasazi and Fremont cultures, and the Midwest, such as the Mississippian society.

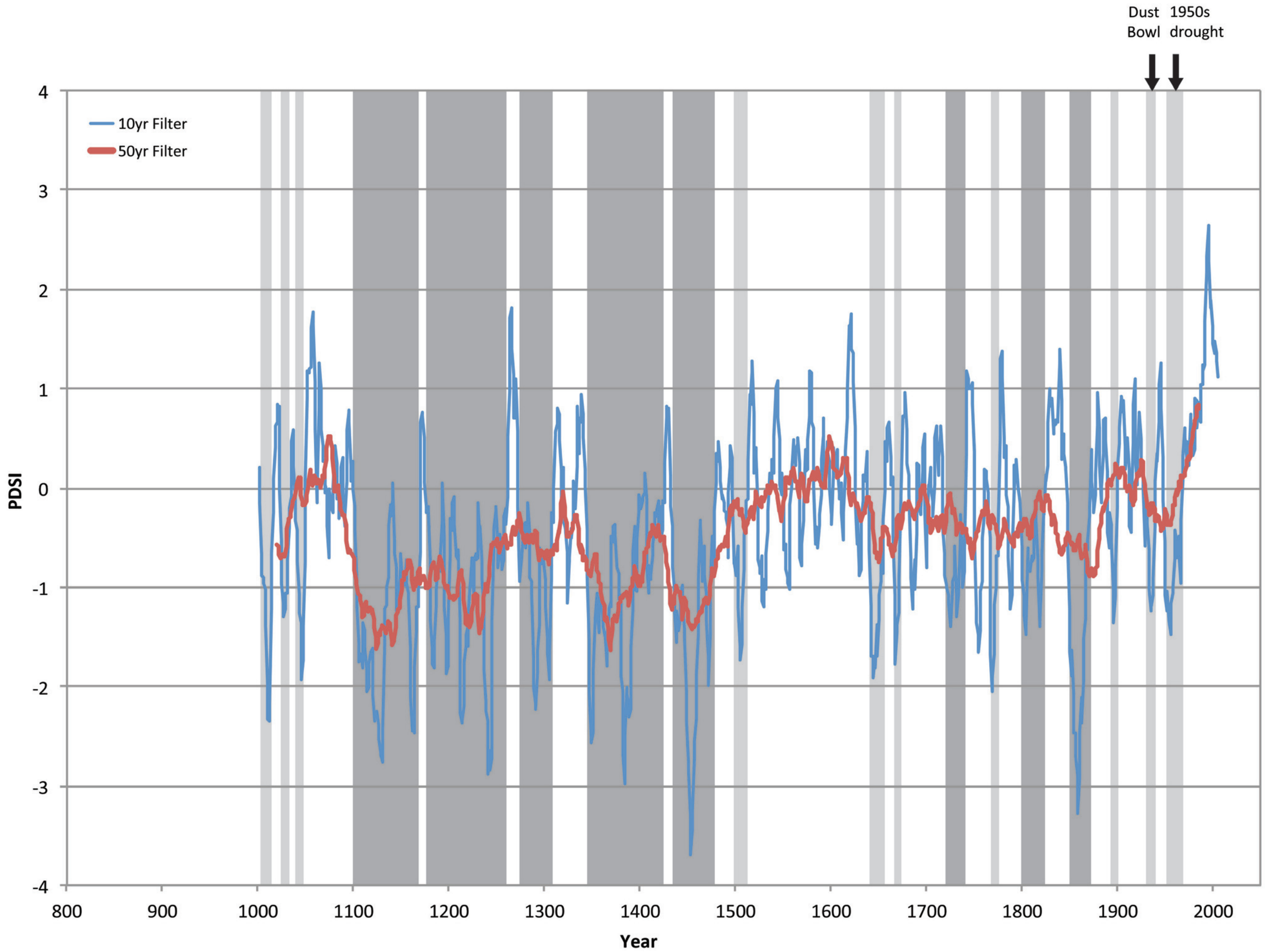

Figure 5d. Smoothed PDSI reconstructions for south-central Kansas. Light-gray bars indicate droughts of similar duration to the 1930s and 1950s droughts while dark-gray bars indicate droughts of greater duration.

The 13th century drought is commonly referred to as the "Great Drought" in the southwest and contributed to significant social change in the Four Corners region through severe population loss and the abandonment of Anasazi settlements. This megadrought would have strongly impacted maize agriculture, which had become the dietary staple of the Anasazi (Benson et al., 2007). Rapid population declines have been documented from archeological sites starting at 1130 and 1280 AD. Studies have also reported population declines in the Fremont cultures located in the Four Corners region around 1000 AD, which may be attributable to the 990-1060 drought.

Severe multi-decadal droughts during the 14th and 15th centuries likely contributed to the decline of Mississippian agricultural societies (e.g. Cobb and Butler, 2002; Cook et al., 2007). Cook et al. (2007) suggest that widespread droughts at this time would likely have caused a sequence of poor harvests that would have proved disastrous. Several Mississippian settlements were abandoned by 1450 including Cahokia, located near the confluence of the Mississippi and Missouri rivers, and Spiro, situated in eastern Oklahoma. Evidence also suggests that the late 13th century megadrought also impacted the Cahokia region (e.g. Benson et al., 2007).

Overall the paleoclimate record suggests that Kansas has experienced droughts of far greater duration in the past than any experienced in the 20th century. This conclusion is supported by several historic, geomorphic, and archeological studies.

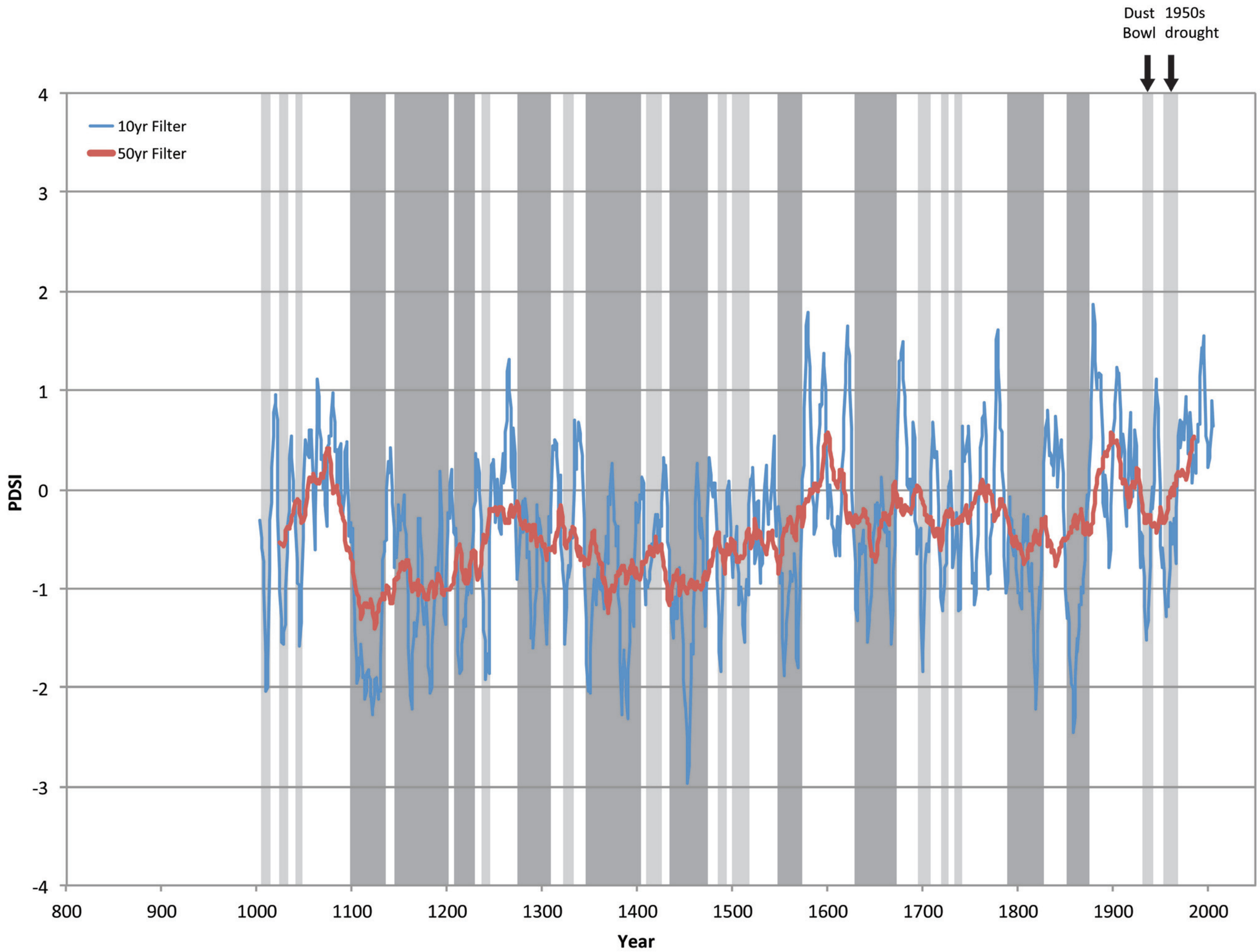

Figure 5e. Smoothed PDSI reconstructions for northeastern Kansas. Light-gray bars indicate droughts of similar duration to the 1930s and 1950s droughts while dark-gray bars indicate droughts of greater duration.

3.3 The Medieval Warm Period

Many of the past megadroughts documented in the paleoclimate record occurred during an era known as the Medieval Warm Period (MWP). The occurrence of several megadroughts during the MWP is troubling as it suggests that the climate system has the capacity to get 'stuck' in drought-inducing modes over the Great Plains that can last several decades to a century or more (Cook et al., 2009).

The MWP has been suggested as an approximate analog for likely future warming and drought conditions (e.g. Woodhouse et al., 2010) and thus serves as an important period to investigate. The MWP lasted from approximately 900 to 1300 AD and was characterized by significant climatic variability compared to the modern period. This period was identified by Lamb (1965) as a period of unusual warm temperatures in northern Europe but has since been documented in proxy records from across the globe (e.g. Graham et al., 2011). Other paleoclimate studies record a series of severe droughts across western North America (Cook et al., 2004) during this period, extending eastward into the central Great Plains (e.g. Daniels and Knox, 2005). In addition, the paleoclimatic data suggest a drought-regime change about 500 years ago (Fig. 7). The shift around 1500 AD to droughts of shorter duration may coincide with the onset of cooler climatic conditions during the Little Ice Age.

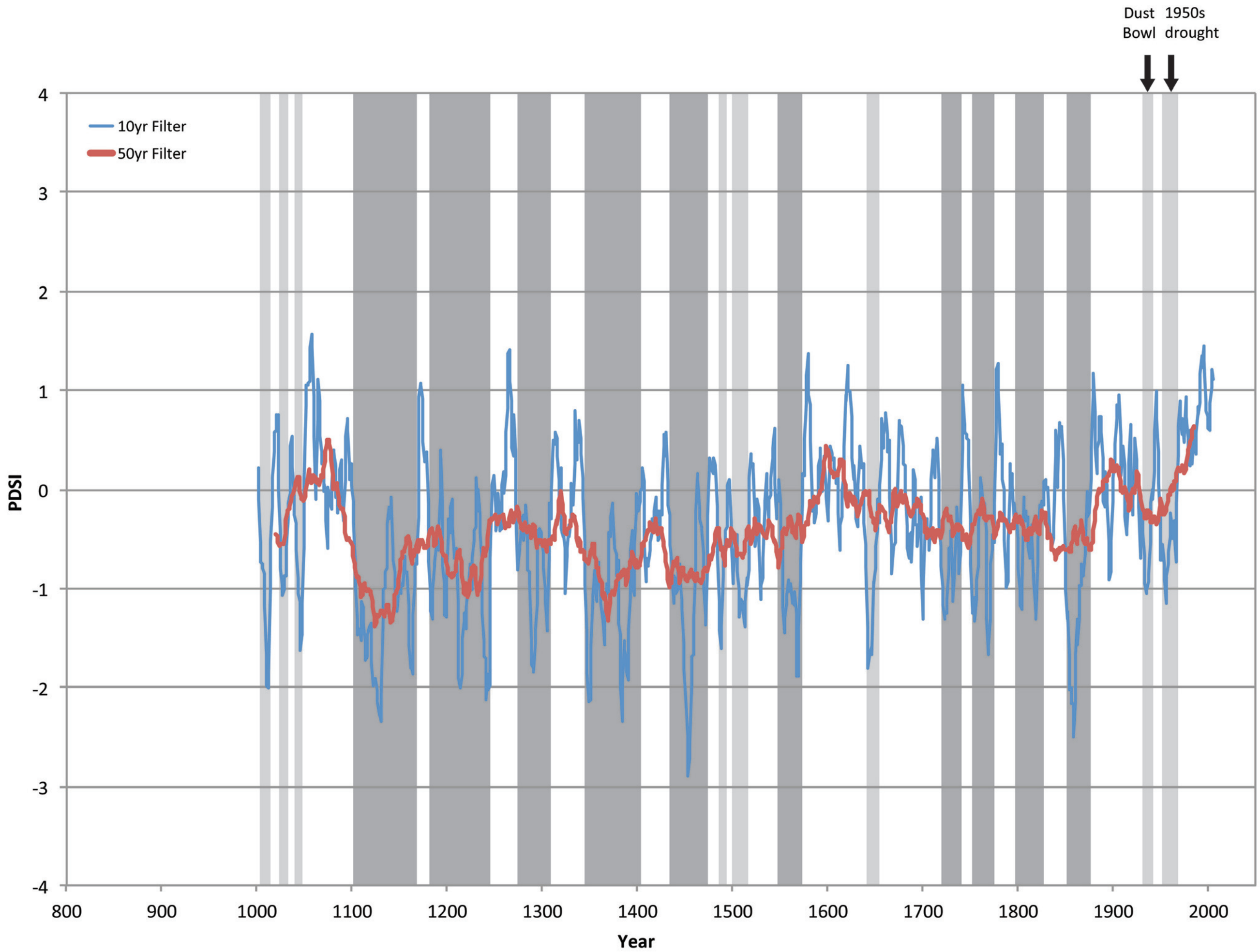

Figure 5f. Smoothed PDSI reconstructions for southeastern Kansas. Light-gray bars indicate droughts of similar duration to the 1930s and 1950s droughts while dark-gray bars indicate droughts of greater duration.

3.4 Risk analysis

Utilizing a similar approach to a previous paleoclimate report published by the Kansas Geological Survey (Young and Buddemeier, 2002), we can provide a quantitative analysis for assessing the risk of drought in Kansas. The paleoclimate data indicate that for western Kansas a drought as severe as the Dust Bowl has occurred on average 3 to 4 times a century. If "3 to 4 times a century" means that there has been on average 3.5 droughts more severe than the Dust Bowl per 100 years, then there is a 3.5% chance that any given year within a 100-year period will have such a severe drought. We can further estimate probabilities for shorter periods using simple arithmetic. For example, there is a 35% chance of a severe drought year in any decade, a 70% chance over a 20-year planning horizon and, in terms of probability, a 100% chance over the estimated 40-year working lifetime of an individual farmer in western Kansas. In eastern Kansas the probabilities are lower as droughts as severe as the Dust Bowl have only occurred about once every century.

We can do a similar analysis for drought duration. For western Kansas, decadal-length droughts have occurred on average twice a century. Therefore, there is a 20% chance of a Dust Bowl length drought in a given decade, a 40% chance over a 20-year period, and an 80% chance over a 40-year period in western Kansas.

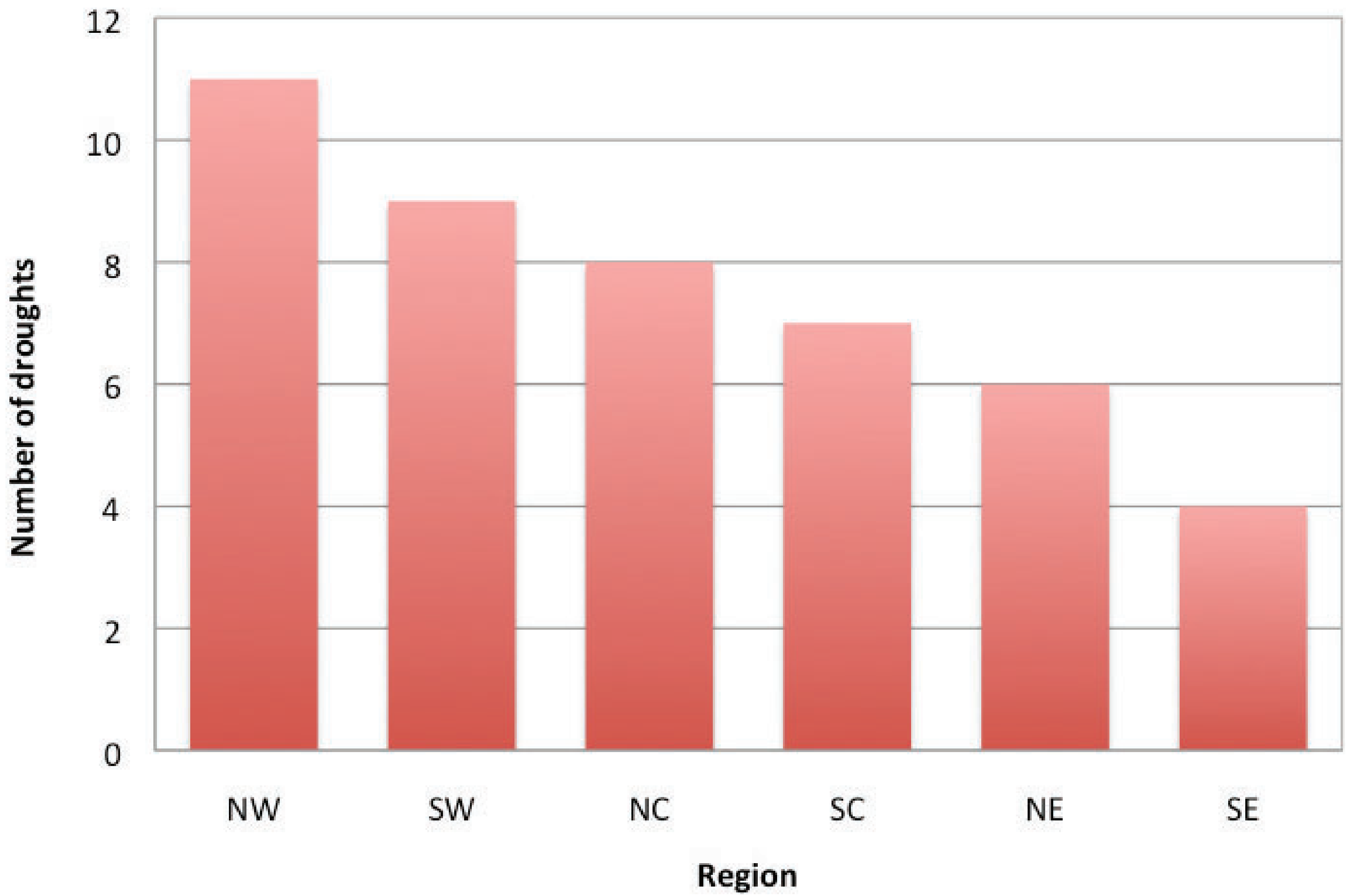

Figure 6. Number of drought periods from 1500 to 2011 AD of similar duration to the 1930s and 1950s droughts (i.e. lasting 10-20 years) by region.

4. Policy and Management Implications

Drought conditions have a significant impact on surface- and ground-water resources through heightened demand and reductions in water supply. Water systems are commonly designed to handle the "drought of record," identified as the most severe hydrological event from the instrumental record. For the state of Kansas, the 1950s drought (1952-57) remains the planning benchmark and is used to calculate reservoir yield through droughts with a 2% chance of occurrence in any one year (K.A.R. 98-5-8). However, this report provides multiple lines of evidence to support the conclusion that drought variability in the 20th century is just a subset of the full range of variability that one should expect under naturally occurring climatic conditions. In other words, in terms of the long-term record of drought variability, the 1930s and 1950s droughts are not unusual. In fact, the paleoclimatic record indicates that droughts of greater severity and longer duration have occurred in the past. Furthermore, it is possible that the conditions that led to past megadroughts, such as those that occurred during the MWP, could occur in the future. Such severe drought conditions are of great concern because modern-day agricultural and water systems may not have the resilience to survive droughts beyond the "worst case scenario" droughts of the past 100 years (Cook et al., 2007).

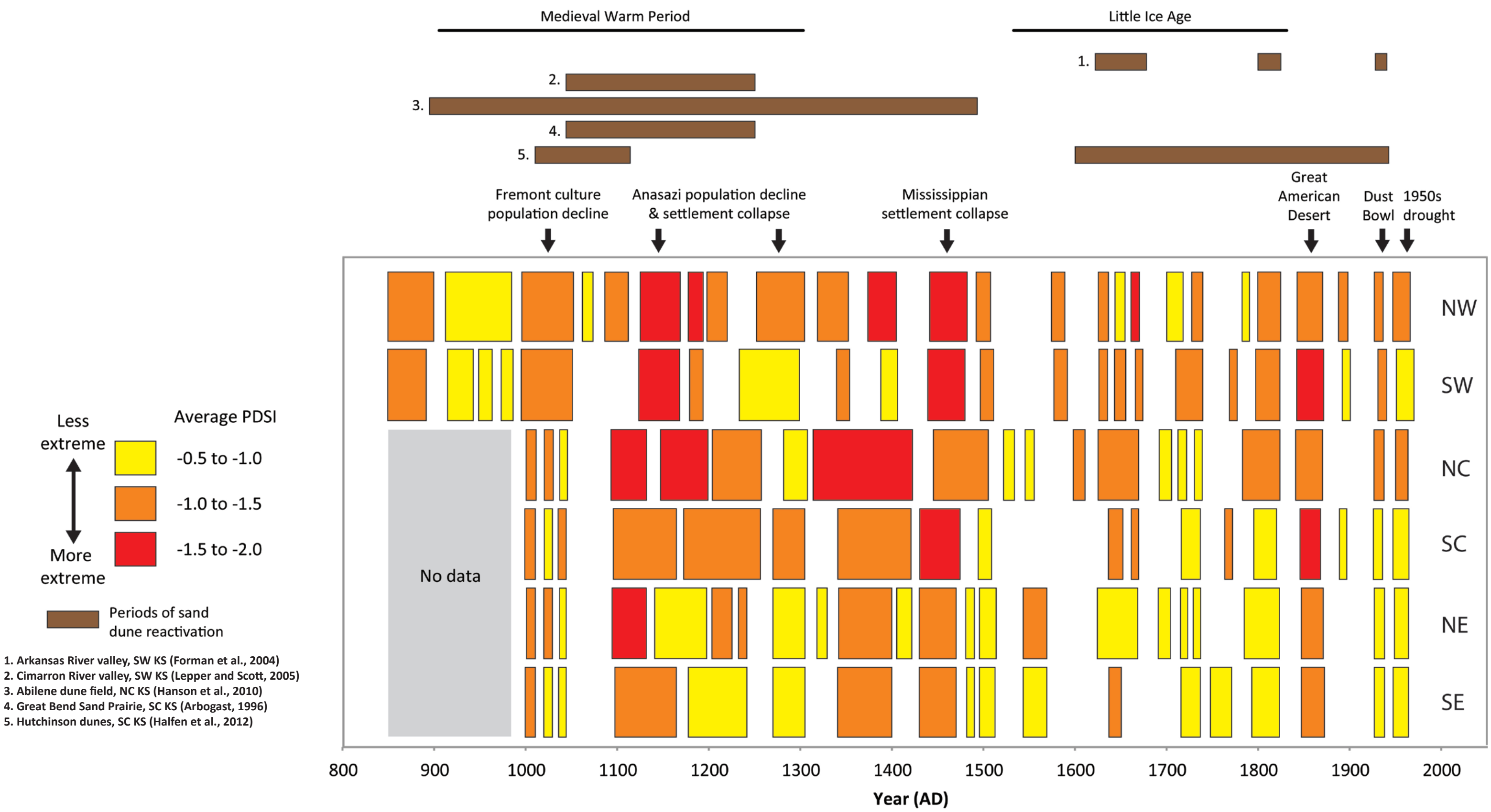

Figure 7. Synthesis of regional reconstructed PDSI data with additional paleoenvironmental proxy data from geomorphic and archeological sources.

In terms of water-resource management, paleoclimatic data have important implications. For example, reservoirs are typically designed with conservation pools to specific meet water demand during drought conditions. However, would these designs be adequate under megadrought conditions? Additionally, management of aquifer resources must be designed to accommodate high demand during protracted droughts while sustaining or extending the usable lifetime of the resource.

Woodhouse and Overpeck (1998) highlight two factors that may compound the susceptibility of the Great Plains to future drought: 1) increased vulnerability due to land-use practices, specifically the use of irrigation to bring marginal lands into agricultural production, and 2) the enhanced likelihood of drought due to global warming. Furthermore, certain factors present challenges to effective water-resource management including 1) current levels of uncertainty in predicting future drought occurrence, 2) the assumption of climatic stationarity by water-resource planners, and 3) competing management interests (e.g. Lins and Stakhiv, 1998; Hartmann, 2005).

Given these challenges, it would be wise to adopt a probabilistic approach to drought forecasting and planning that incorporates the full range of drought variability indicated in the paleoclimatic record.

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Appendix: Calibration and Verification Statistics

The data used in this report were obtained from the North American Drought Atlas (Cook and Krusic, 2004). Cook and Krusic used four statistics as measures of association between the actual and estimated PDSI in order to test the fidelity of PDSI reconstructions.

1) Calibration R-SQuare (CRSQ). This statistic measures the percent PDSI variance explained by the tree-ring chronologies at each grid point over the 1928-1978 calibration period, based on a regression modeling procedure described in Cook et al. (1999). As defined here, CRSQ is equivalent to the "coefficient of multiple determination" found in standard statistic texts. It ranges from 0 (no calibrated variance) to 1.0 (perfect agreement between instrumental PDSI and the tree-ring estimates). The former represents complete failure to estimate PDSI from tree rings and the latter is not plausible if the model is not seriously over-fit.

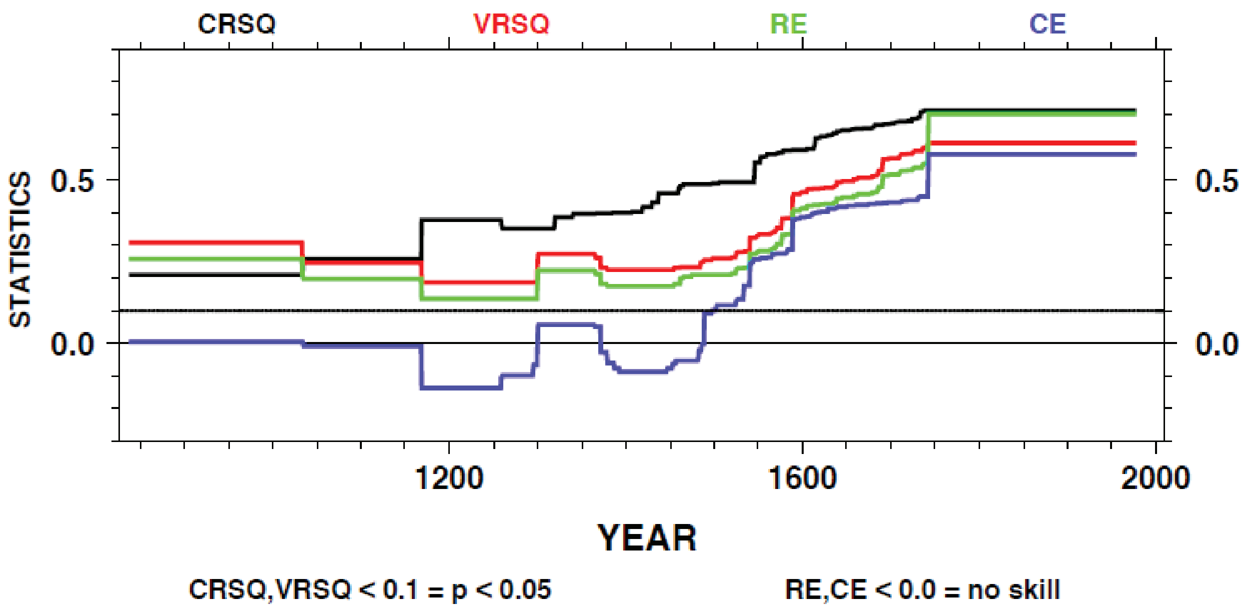
2) Verification R-SQuare (VRSQ). This statistic measures the percent PDSI variance in common between actual and estimated PDSI in the 1900-1927 verification period. It is calculated as the square of the Pearson correlation coefficient, which is a well known measure of association between two variables. VRSQ also ranges from 0 to 1.0 (VRSQ is assigned a 0 value if the correlation is negative). Roughly speaking, VRSQ>0.11 is statistically significant at the 1-tailed 95% level using our 28-year verification period data.

3) Verification reduction of error (RE). This statistic was originally derived by Edward Lorenz as a test of meteorological forecast skill. Unlike CRSQ and VRSQ, RE has a theoretical range of -infinity to 1.0. Over the range 0-1.0, RE expresses the degree to which the estimates over the verification period are better than "climatology," i.e. the calibration period mean of the actual data. So, a positive RE means that the PDSI estimates are better than just using the calibration period mean as a reconstruction of past PDSI behavior. A negative RE is generally interpreted as meaning that the estimates are worse than the calibration period mean and, therefore, have no skill. The use of the calibration period mean as the "yardstick" for assessing reconstruction skill makes this statistic more difficult to pass than VRSQ. However, it is also less robust, meaning that it is very sensitive to even a few bad estimates in the verification period. Therefore, RE>0 is interpreted as evidence for a reconstruction that contains some skill over that of climatology.

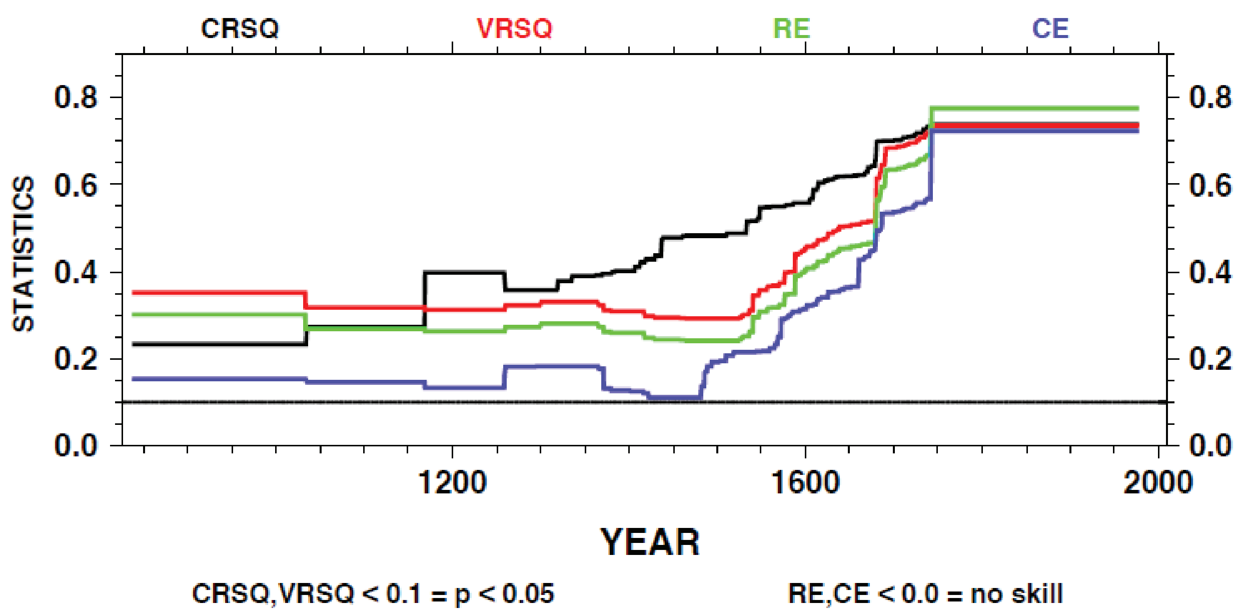
4) Verification coefficient of efficiency (CE). This statistic comes from the hydrology literature and is very similar to the RE. It too has a theoretical range of -infinity to 1.0. The crucial difference is that the CE uses the verification period mean of the withheld actual data as the "yardstick" for assessing the skill of the estimates. This seemingly minor difference is important because it results in the CE being even more difficult than the RE to pass (i.e., a CE>0).

Here we include the calibration and verification statistics for the six gridpoints utilized in this report. Note that all data are statistically significant for the period of record with the exception of northwestern Kansas, which fails the notoriously hard-to-pass CE test before 1500 AD. Overall the PDSI data are well calibrated and verified.

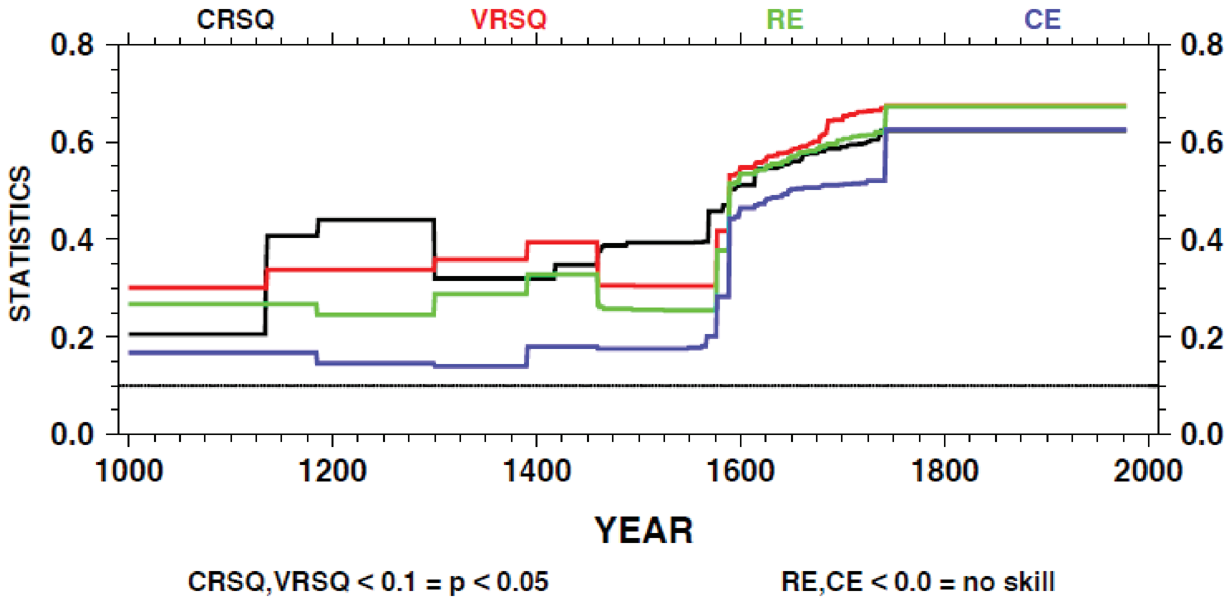
Northwestern Kansas



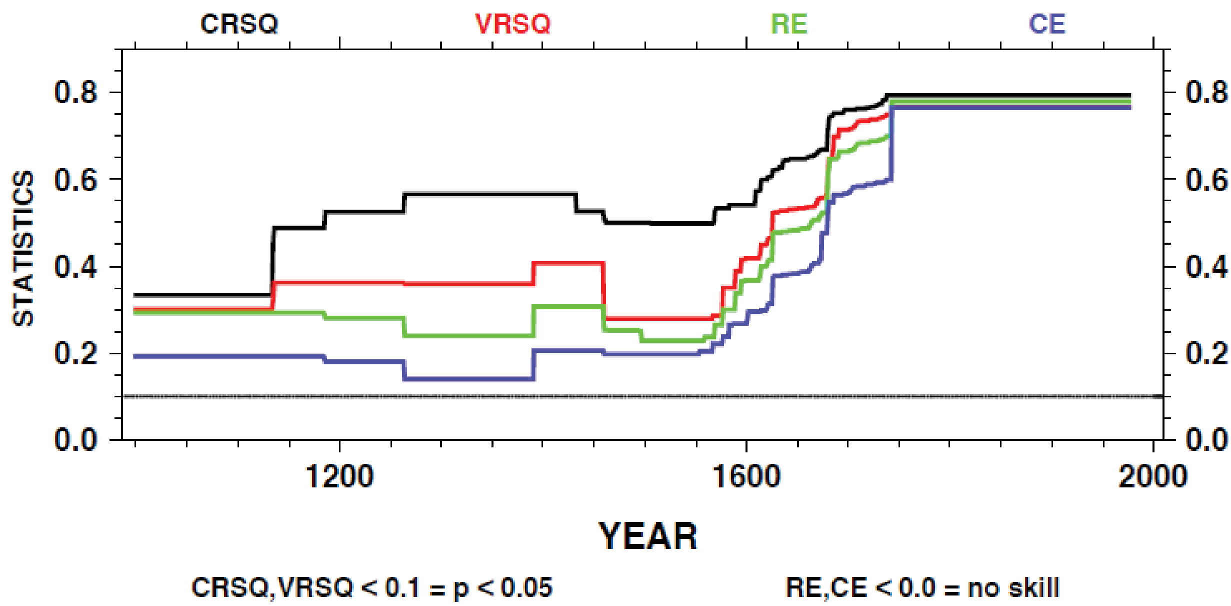
Southwestern Kansas



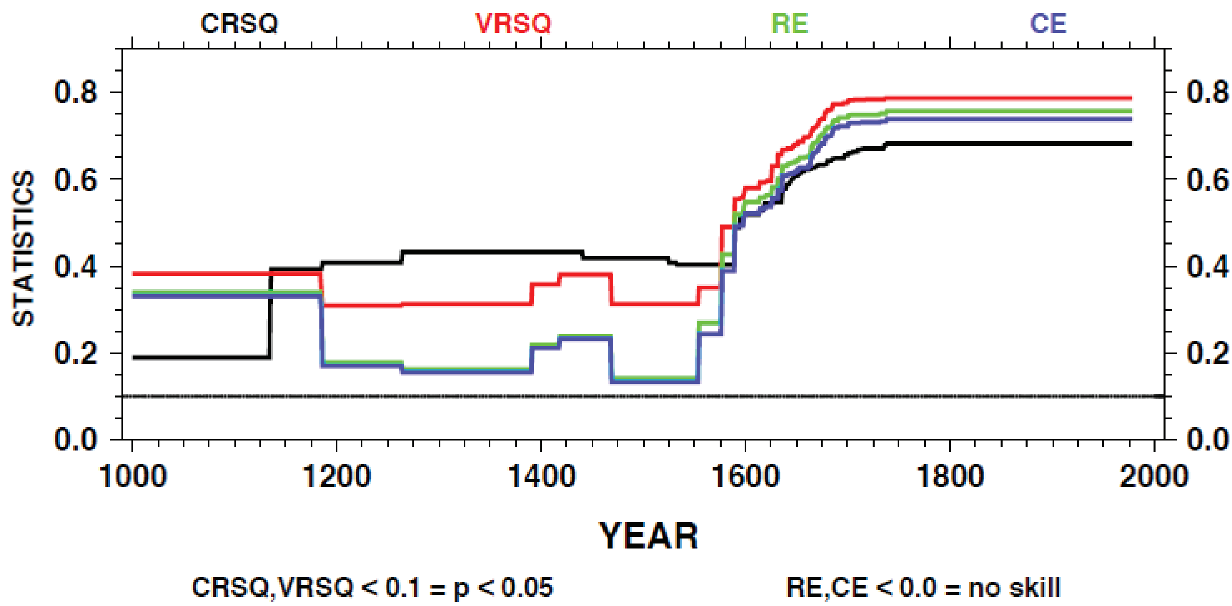
North-central Kansas



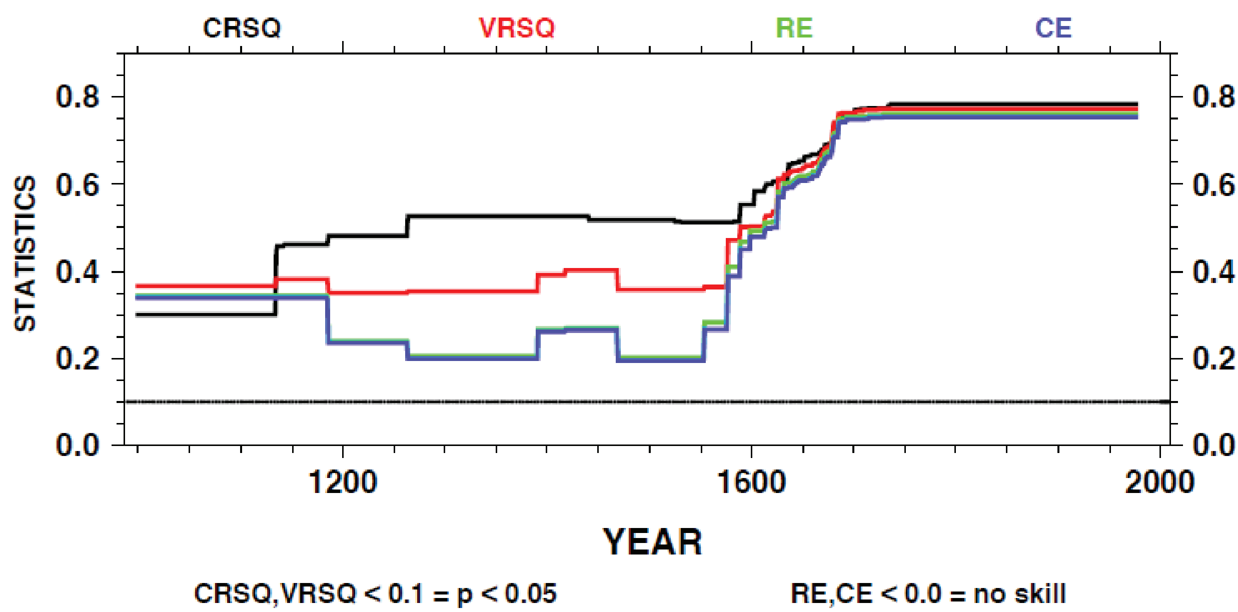
South-central Kansas



Northeastern Kansas



Southeastern Kansas



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Public Information Circular 35 • August 2013

EXHIBIT
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Kansas Droughts: Climatic Trends Over 1,000 Years

Anthony L. Layzell and **Catherine S. Evans**, Kansas Geological Survey

Environmentally and economically, drought is one of the most costly natural disasters in North America. Yet it rarely gets the same public attention that other, more spectacular, natural disasters receive. While tornadoes, floods, wildfires, and hurricanes leave behind well-defined swaths of devastation in relatively short order, droughts whittle away at water quality and quantity, topsoil, crop yields, and other natural and socioeconomic resources over months and years, even decades.

In any given year, drought conditions of some degree are occurring somewhere in North America. For 1988—midway through a three-year drought in the central and eastern United States—the estimate of national drought damage was a record $40 billion (National Climatic Data Center, 2012), or $78.5 billion in 2013 dollars. In 2011, losses in Kansas alone exceeded $1.7 billion (Kansas Department of Agriculture, 2011). The 1930s and 1950s droughts, however, remain the benchmarks for the 20th century in terms of duration, severity, and spatial extent. The historically unprecedented dust storms in the 1930s, exacerbated by the rapid spread of farming practices unsuitable for the semi-arid High Plains, helped make the Dust Bowl the most memorable drought in modern times (fig. 1). Two decades later, 1956 surpassed 1934 as the single most severe drought year ever documented statewide based on instrumental precipitation and temperature readings.

Yet the major 20th-century droughts, as impressive as they were, do not rank as the two most intense or enduring droughts to hit Kansas. For decades, scientists have been collecting and analyzing data to reconstruct **paleoclimates**—past climates dating back thousands of years—from clues in tree rings, sediments, and other **proxies**. Several past drought episodes, it turns out, have exceeded those of the 1930s and 1950s in severity, extent, and duration (Layzell, 2012). If such a drought occurred today, reductions in surface-water and groundwater resources would threaten municipal, industrial, and agricultural water supplies and cause widespread crop failure.

Figure 1—Drifts of wind-blown soil on a farm near Liberal, Kansas, March 1936 (photo by Arthur Rothstein: Library of Congress).

Being able to better forecast and plan for severe drought conditions is vital. Temperature and precipitation records are indispensable for understanding climate change but are largely restricted to the past 100 years. To assess the full range of drought variability that has occurred over 1,000 or more years, climatologists and other scientists measure the severity of pre-20th-century droughts using reconstructed paleoclimatic data from proxies and analyze the results in combination with more than a century of instrumental data.

Drought Measurement and The Palmer Drought Severity Index (PDSI)

Several indices have been developed to measure drought. The Palmer Drought Severity Index (PDSI), one of the most widely used indices in North America, was introduced in 1965 and is used to measure the severity of a drought occurrence for a specified period. PDSI values can be calculated from weather data collected using thermometers, rain gauges, and other instruments—available for most of North America since about 1895—or from paleoclimatic data reconstructed from tree rings and other proxy evidence.

PDSI values, representing relative wetness and dryness, are assigned after recorded precipitation and temperature

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data or proxy data are analyzed to determine how much soil moisture was available at a specific time compared to how much would be available under average conditions. The values typically range from -4 (extremely dry) to 4 (extremely wet), although the range is unlimited. Although a PDSI value of -4 or less (even more extreme) is daunting, a persistent drought averaging moderate (-2) to severe (-3) PDSI values over many years may actually cause more damage than a more severe but shorter episode. Plotted PDSI values provide a picture of climate variability over time and can be used to calculate the duration of drought conditions. The extent of the 1930s and the 1950s droughts—and the relatively wet years in between—are evident in the PDSI trends for Kansas from 1895 to 2011 (fig. 2).

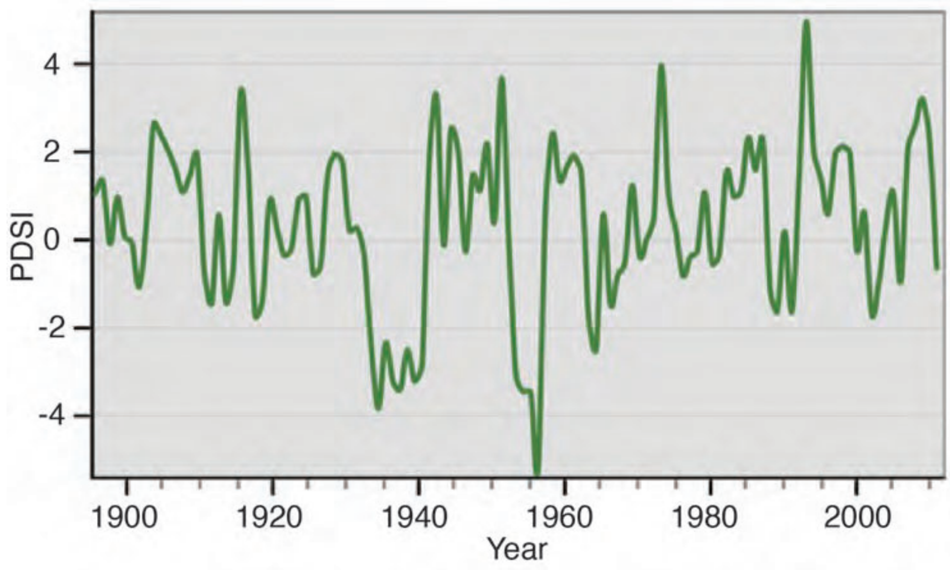

Figure 2—Palmer Drought Severity Index (PDSI) trends in Kansas, 1895–2011 (High Plains Aquifer Atlas, 2012).

Tree-Ring Chronologies and Other Proxies

Data gleaned from various proxies provide insight into paleoclimates in North America dating back hundreds to thousands of years, depending on location. Annual growth rings in living trees and preserved wood are measured to reconstruct climatic patterns over extensive areas. Wide tree rings in highly drought-sensitive trees typically indicate a long growing season with adequate moisture, and very narrow rings usually signify drought conditions (fig. 3). The exact calendar year a tree ring was formed can be determined by crossdating, a technique that statistically matches the patterns in tree-ring characteristics among several living or dead trees in a region.

Data collected on crossdated trees in a given area form a tree-ring chronology, which can then be used to identify wide-ranging climatic trends. Synthesized data from hundreds of interlinking chronologies have been used to re-create annual climate patterns dating back at least a thousand years throughout most of North America. An extensive and ever-expanding network of annual tree-ring chronologies is accessible through the International Tree-Ring Data Bank (http://www.ncdc.noaa.gov/paleo/treering.html).

Reconstructed PDSI values based on tree-ring chronologies are available for as far back as 837 AD in western Kansas and the whole state by 1000 AD. In several studies of North American drought, up to 835 tree-ring chronologies were used to reconstruct annual growing-season PDSI values across the continent (Cook and Krusic, 2004; Cook et al., 2004; Stahle et al., 2007). Although trees, and thus tree-ring chronologies, are sparse in the Great Plains, investigators have been able to determine paleoclimatic patterns there using predictive models that rely partially on chronologies from surrounding regions. The integrity of this methodology has been verified by matching reconstructed 20th-century PDSI values for the Great Plains to PDSI values based on 20th-century Great Plains instrumental record (Cook and Krusic, 2004; Stahle et al., 2007).

A diverse variety of other proxies, derived from sand dunes, lake sediment, coral reefs, ice sheets, rock formations, microfossils, cave deposits, archaeological discoveries, and historical records, help verify past droughts identified in tree-ring studies. For example, evidence from once-active sand dunes in Kansas testifies to the periodic droughts that occurred in the state over several centuries (Arbogast, 1996), while far-off ice cores in Greenland and coral reefs in the South Pacific hold clues to worldwide paleoclimatic patterns (NOAA, 2010) that may have contributed to periods of aridity in the Great Plains.

Drought Severity and Duration

A key characteristic distinguishing the 1930s and 1950s droughts from other modern drought periods is aridity that was not only severe but also long lasting. The negative effects of one extremely dry year can be overcome relatively quickly when it is preceded or followed by a wetter year, but several years of nearly uninterrupted

Figure 3—Cross section showing tree rings of a Douglas-fir (Pseudotsuga menziesii) *from the Zuni Mountains, New Mexico (courtesy of Laboratory of Tree-Ring Research, University of Arizona: photo by R. K. Adams).*

drought can lead to serious long-lasting socioeconomic and environmental problems. The PDSI value for 2002 in southwestern Kansas was -7.1, compared to -5.0 for the peak year of the Dust Bowl, yet the situation was not as dire in 2002 because it was bounded by years with positive PDSI values.

Year to year, climatic conditions vary across the state, with droughts hitting some regions harder than others. Since 1000 AD, southwestern Kansas has experienced a greater number of extreme droughts than southeastern Kansas (fig. 4). This west to east trend mirrors the strong longitudinal

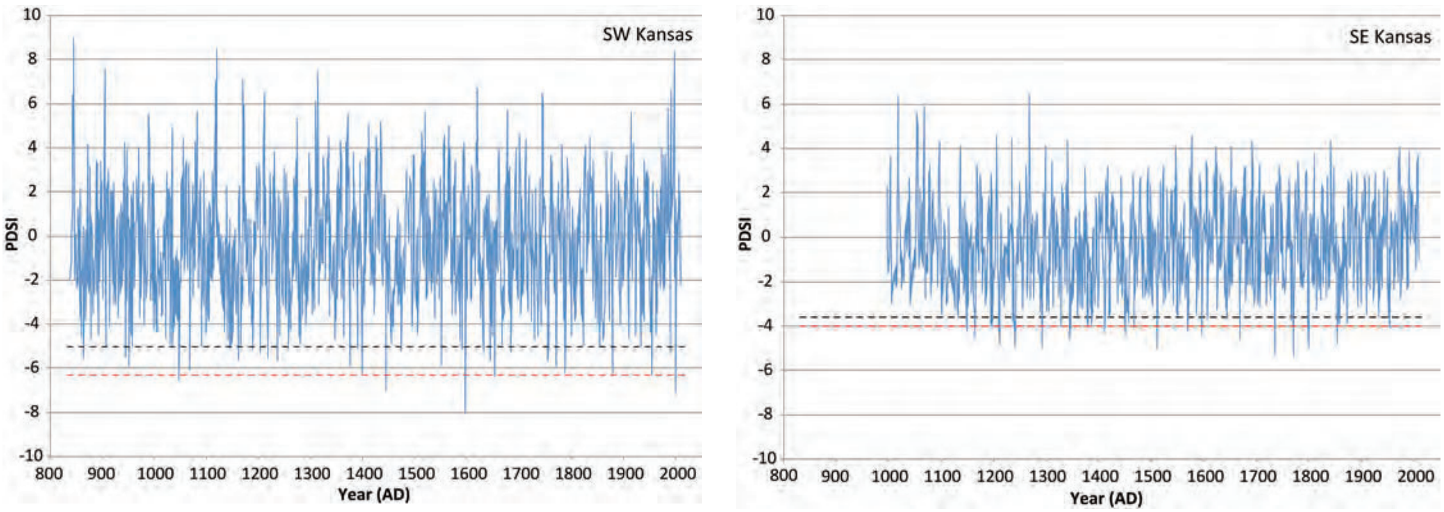

Figure 4—Annual PDSI reconstructions showing drought severity in southwestern Kansas (left) and southeastern Kansas (right). Dashed lines indicate 1934 (black) and 1956 (red) PDSI values (Layzell, 2012). PDSI values are from Cook and Krusic, 2004. Reconstructions for all six Kansas regions are online at http://www.kgs.ku.edu/Hydro/Publications/2012/OFR12_18/index.html).

climate gradient in Kansas (High Plains Aquifer Atlas, 2012). Average precipitation today gradually increases from about 15 inches along the Colorado border to 45 inches in the southeastern corner of the state (High Plains Aquifer Atlas, 2012).

Just as drought severity varies from west to east, it also varies from north to south. Overall, PDSI data indicate that northern Kansas has on average experienced more severe droughts than southern Kansas in the past millennium, possibly because conditions that created droughts on the northern Great Plains occur more often. Several studies suggest that some droughts may be driven by changes in sea surface temperature (SST), particularly in the equatorial Pacific (Stahle et al., 2007). When the equatorial Pacific SST is cold, droughts are common in the southern plains as frontal weather systems are driven more northward. The 1950s drought fit that pattern. In contrast, the Dust Bowl, centered on the Pacific Northwest and northern Plains, was likely influenced by other conditions. These include warm Atlantic SST anomalies that prevented moisture from entering the Great Plains from the Gulf of Mexico (Schubert et al., 2004), and possibly a random atmospheric variation (Hoerling et al., 2009). The maps in fig. 5 illustrate the differences in spatial patterns between the two major 20th-century droughts.

Calculating the duration of droughts can be difficult because multi-year dry intervals are often punctuated with occasional wet years. Furthermore, there is no single method for calculating duration. For this publication, the durations of the 1930s and 1950s drought episodes in Kansas were calculated by smoothing PDSI values—that is, filtering out the extreme high and low values by averaging over a 10- or 50-year period—to identify long-term patterns of drought duration. The beginning and end of each drought period are demarcated by periods of more than two consecutive years of positive PDSI values. In fig. 6, smoothed PDSI values were plotted to show the duration of droughts in southwestern and southeastern Kansas.

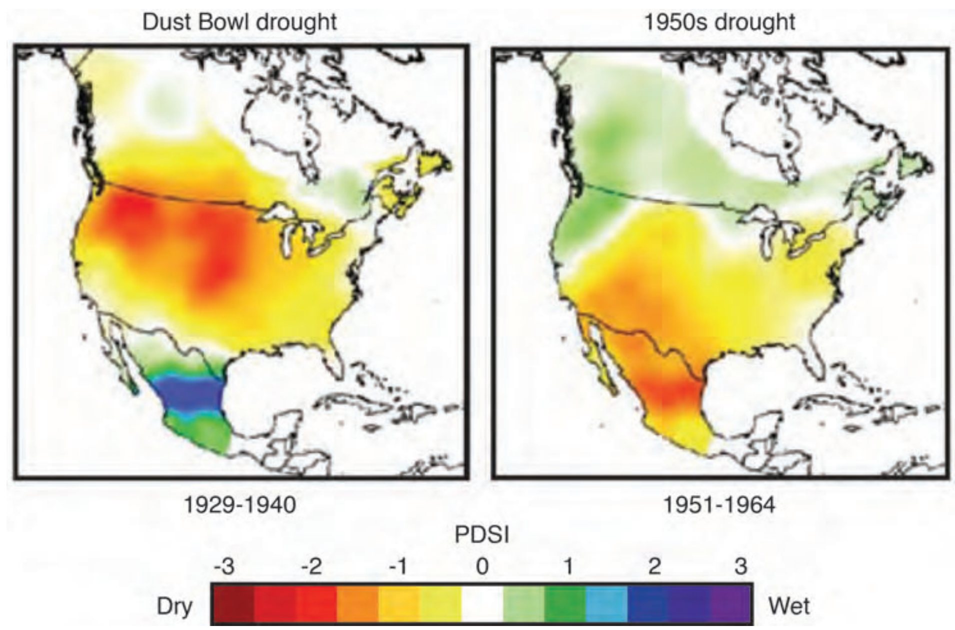

Figure 5—Spatial patterns of the 1930s and 1950s droughts mapped from instrumental PDSI data (modified from Stahle et al., 2007).

Megadroughts

Droughts of unusually long duration are commonly referred to as "megadroughts," although there is no standard definition of the term (Stahle et al., 2007). This public information circular considers a megadrought to be any multi-year drought that significantly exceeds the duration of the most extreme droughts of the 20th century. Lasting 20 or more years, these extreme episodes do contain individual years of normal or even above-average precipitation.

Megadroughts appear to be most prevalent in Kansas between 850 AD and 1500 AD (fig. 7). The longest one occurred in north-central Kansas from 1317 to 1427. As north-central Kansas was enduring near-continuous drought for 110 years, northwestern Kansas experienced two long-term droughts separated by a wetter period and southwestern Kansas conditions did not reach megadrought proportions (see fig. 6). These differences underscore how much circumstances can vary over a short distance.

Many of the known megadroughts in North America occurred during the **Medieval Warm Period** (MWP), a time of significant climatic variability that lasted from about 900 to 1300. First identified in northern Europe, the MWP was later documented in other areas of the world, including parts of the western United States (Cook et al., 2004). A shift around 1500 to droughts of shorter duration may coincide with the onset of cooler climatic conditions during a period known as the **Little Ice Age**. Many dune records from the central Great Plains show significant sand dune activation—a sign of increased aridity and reduced vegetation—during these periods. A variety of sand-dune mobilizations have been documented from the 9th to the early 20th century in Kansas (fig. 7).

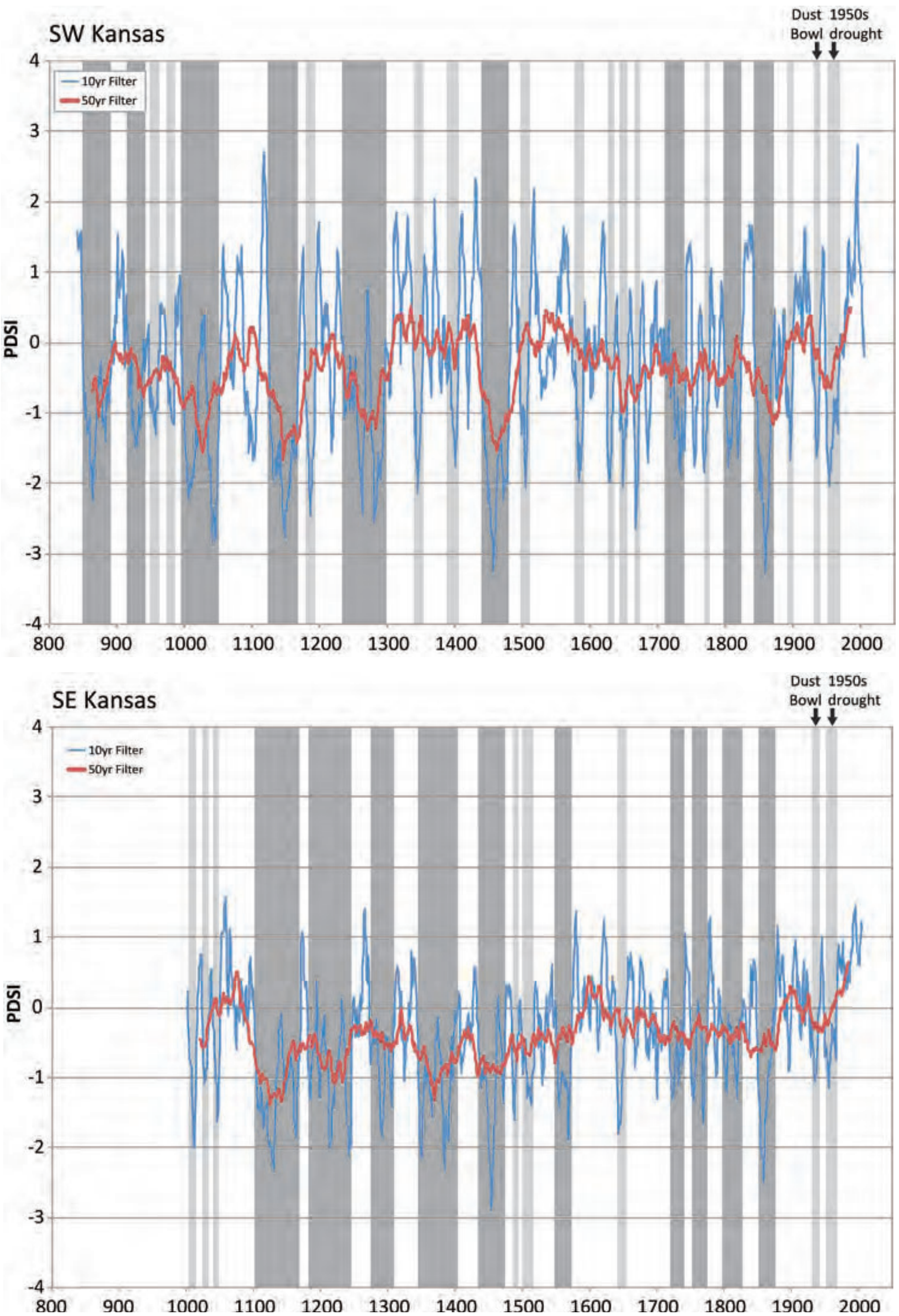

Figure 6—Smoothed PDSI reconstructions showing drought durations for southwestern Kansas (top) and southeastern Kansas (bottom). Light gray bars indicate episodes of similar duration to the 1930s and 1950s droughts and dark gray bars represent episodes of greater duration. Annual PDSI values have been smoothed to filter out anomalous high and low values over a 10-year range (blue) and a 50-year range (red) (Layzell, 2012). PDSI values are from Cook and Krusic, 2004. Reconstructions for all six Kansas regions are online at http://www.kgs.ku.edu/Hydro/Publications/2012/OFR12_18/index.html.

Archaeological and Historical Corroboration of Megadroughts

Evidence that megadroughts destabilized North American civilizations between 850 and 1500 AD is found in the archaeological record. Although drought probably affected populations in the Great Plains during that time, clues there are sparse. Archaeological evidence of agricultural societies in adjacent regions, however, provides signs of widespread drought conditions that most likely also afflicted the plains people.

Several major droughts may have undermined Native American cultures between the 11th and 15th centuries. The population of the Fremont cultures in the Four Corners region of the U.S. Southwest declined around 1000 AD in the midst of a multi-decade drought (fig. 7). The 13th-century drought commonly referred to as the "Great Drought" contributed to the abandonment of Anasazi agricultural settlements in the same region and also appears to have impaired Mississippian agricultural societies hundreds of miles to the northeast (Benson et al., 2007). Further megadroughts in the 14th and 15th centuries likely contributed to the abandonment of Cahokia near present-day St. Louis by 1450 (Cook et al., 2007).

Widespread drought during the Stephen Long expedition in 1819–1820 probably influenced the explorers' perception of the western Great Plains as the "Great American Desert." "The chief produce of these tracts of unmixed sand, is the sunflower, often the dense and almost exclusive occupant," wrote expedition member Edwin James. Jacob Fowler noted that on his way to Santa Fe in 1821, the sand hills along the Arkansas River in south-central Kansas were "distetute of vigetation as they are Bald" (Muhs and Holliday, 1995).

Set-tan (Little Bear) of the Kiowa recorded in his 60-year calendar history that during the hot "sitting summer" of 1855, the prairie grasses dried out and the Kiowa had to stop frequently to rest

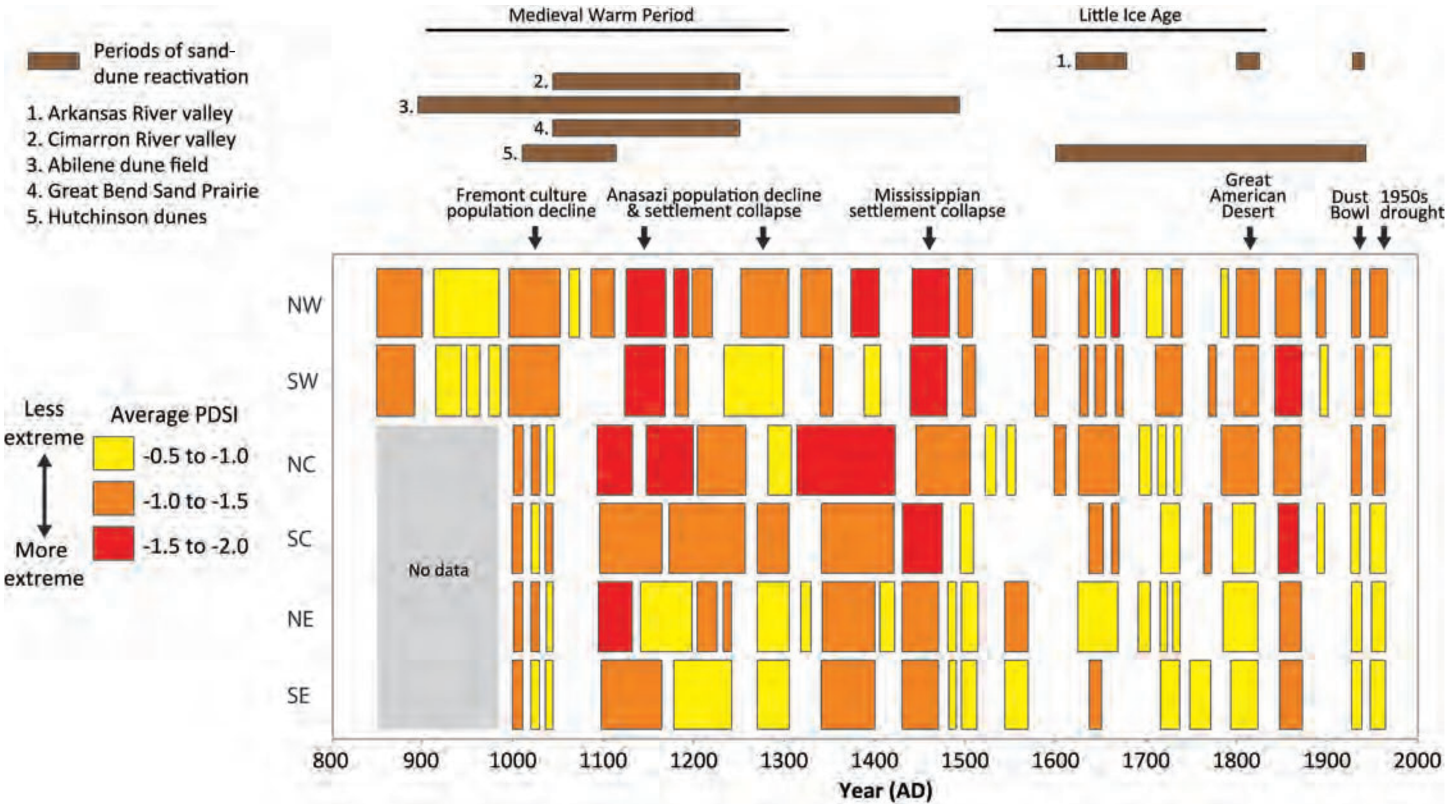

Figure 7—Synthesis of reconstructed PDSI data for the six regions of Kansas showing the severity and duration of droughts since about 850 AD. Events identified using geomorphic (sand dune), archaeological, and historical proxies are marked (Layzell, 2012). Sand-dune reactivation information from 1. Forman et al., 2008; 2. Lepper and Scott, 2005; 3. Hanson et al., 2010; 4. Arbogast, 1996; and 5. Halfen et al., 2012.

their emaciated horses (Stahle et al., 2007). Accounts from early settlers in eastern Kansas Territory also expounded on drought conditions that lasted from at least 1854 into the early 1860s, with only short reprieves. Newspapers reported suffocating dust storms, crop failures, prairie fires, “scorching, withering, blighting” winds, and the outward migrations of many newly arrived settlers (Malin, 1946). By the mid-1890s, locals around Garden City observed that area sand hills were becoming less extensive. Following brief reactivation of sand in small areas during the Dust Bowl years, dunes on the south side of the Arkansas River from just east of Pueblo, Colorado, to near Wichita are now mostly stabilized by vegetation (Muhs and Holliday, 1995).

Drought Risks, Water Resources, and Future Prospects

Paleoclimatic data collected for western Kansas indicate a drought as severe as the Dust Bowl occurs there, on average, three to four times a century. Based on that probability, there is a 35% chance for a severe drought year in any decade, a 70% chance within a 20-year span, and a 100% chance over the estimated 40-year working lifetime of a western Kansas farmer. Eastern Kansas averages about one such drought a century. In terms of duration, western Kansas averages two droughts a century spanning one decade or more.

As groundwater usage in western Kansas escalated, starting in the 1950s, the semi-arid region became even more susceptible to the effects of sustained drought. The High Plains aquifer system, which consists largely of the Ogallala aquifer, is the primary source of municipal, industrial, and irrigation water in western and central Kansas. In drought years, greater than normal amounts of groundwater are withdrawn from the aquifer to compensate for the lack of precipitation, particularly during the growing season. From 1996 to 2012, the overall average water level in the Kansas portion of the High Plains aquifer dropped 14 feet. Southwestern Kansas on its own experienced an average decline of 32.5 feet during that time. Under drought conditions in 2011 and 2012, water levels in southwestern Kansas declined 3.56 feet and 4.26 feet, respectively (Kansas Geological Survey, 2013).

The KGS continuously monitors three wells in the High Plains aquifer—in Thomas, Scott, and Haskell counties—and is correlating groundwater-level data from those wells with values from the PDSI and other drought climatic indices. Based on those correlations, researchers are able to predict how water levels would likely respond to increased pumping for irrigation and other uses under drought conditions similar to or greater than those in the 1930s and 1950s (Butler et al., 2013). (Live water-level readings from the wells can be accessed at http://www.kgs.ku.edu/HighPlains/HPA_Atlas/Index%20Well%20Program/#.)

Eastern Kansas depends mainly on surface water from federal reservoirs, the source of municipal and industrial water for more than two-thirds of the state’s population. Sedimentation has diminished storage in most of these lakes over time, and a sustained period of drought could lead to unprecedented water shortages (Kansas Water Office, 2008).

Water systems and management plans are commonly designed to handle the “drought of record,” that is, the most severe hydrological event documented in the instrumental record. For the state of Kansas, the drought years from 1952 to 1957 remain the planning benchmark. Planning for a worst-case scenario of only a five-year duration, however, does not prepare the state for multi-decade megadroughts that modern-day agricultural and water systems—dependent on the state's limited groundwater and surface-water resources—may not have the resilience to withstand. Continued investigations into centuries of past climatic and drought variability will provide a clearer understanding of how climate and global warming affect aridity and will enable scientists and policymakers to better forecast droughts and plan for the sustainability of the state's groundwater and surface-water resources.

Glossary

Little Ice Age—Not a true ice age, this cooling period is loosely defined as lasting from about the 16th to mid-19th century, although its start and end dates are not fully agreed upon and its duration varies from location to location.

Medieval Warm Period—A climatic period lasting from about 900 to 1300 AD when average temperatures in Europe and adjacent regions of the North Atlantic are thought to have been equal to or greater than today's.

Paleoclimates—Climates that occurred before instrumental weather measurements were available and whose occurrence and patterns have been identified with evidence from tree rings, ice cores, and other proxies.

Proxy—Natural and human-made resources—such as tree rings, sedimentary deposits, archaeological artifacts, and historical journals—that have properties that date them to a specific time. Proxies can be used to determine climatic events that occurred before instrumental, direct-measurement records were kept.

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KANSAS GEOLOGICAL SURVEY
The University of Kansas

The mission of the Kansas Geological Survey, operated by the University of Kansas in connection with its research and service program, is to conduct geological studies and research and to collect, correlate, preserve, and disseminate information leading to a better understanding of the geology of Kansas, with special emphasis on natural resources of economic value, water quality and quantity, and geologic hazards.

The Geology Extension program furthers the mission of the KGS by developing materials, projects, and services that communicate information about the geology of Kansas, the state's earth resources, and the products of the Kansas Geological Survey to the people of the state.

Public Information Circular 35
August 2013

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