Mapping landscape suitability for forest thinning to reduce evapotranspiration and enhance groundwater recharge in Arizona

Ryan E Lima[a,*], Neha Gupta[b], Travis Zalesky[b], Temuulen Tsagaan Sankey[a], Abraham E Springer[a], Katherine Jacobs[b]

[a] *Northern Arizona University,*

[b] *University of Arizona,*

Abstract

Literature on the relationship between forest thinning and water yield was used to develop suitability criteria to map where forest treatment is most likely to enhance groundwater recharge across the Coconino National Forest in Arizona. Rechage in the region is ephemeral and focused in periods of snowmelt and locations of enhanced permeability when soil moisture exceeds threshold levels. Our approach combines thematic maps of criteria such as average precipitation, snow dominance, slope, aspect,landscape morphology, forest density, lithology and hydrologic soil type into a GIS-Multi-Criteria Decision Making model. Pairwise comparisons were made between criteria, and Analytic Hierachy Process was used as a weighting method.

Keywords: suitability mapping, Forest thinning, Water yield, groundwater recharge, GIS-MCDM, AHP

1. Introduction

Warming associated with anthropocentric climate change has increased the number of extreme hydroclimate events in the Colorado River Basin. Droughts, heatwaves, and floods have more than doubled in frequency since 2010 [1].Since 2000, the Colorado River Basin has been in the midst of a historic drought [2, 3]. During that time, streamflow in the Colorado River has declined by 19% relative to the 1906-1999 average [4, 5].Rapid population growth in the Southwest and Arizona, in particular, is increasing the demands on already strained water supplies in the State. Reductions in streamflow have increased

*Corresponding author
Email address: `ryan.lima@nau.edu` (Ryan E Lima)

reliance on groundwater pumping, while groundwater levels have declined for decades in many groundwater basins across Arizona [6].

Concurrently, the risk of catastrophic wildfires is increasing in Western forests– an emerging driver of runoff change that will increase the impact on the water supply [3]. Forest structure in the forests of Northern Arizona and New Mexico has changed significantly post-Euro-American settlement. Many forests are overstocked relative to pre-settlement conditions due to grazing, logging, and wildfire exclusion [7, 8]. These changes have increasing the risk of catastrophic wildfire [9]. Rising temperatures and related droughts have contributed to extensive tree mortality from wildfire, disease, and insect infestation [10]. Warming temperatures have tripled the frequency and quadrupled the size of wildfires since 2000 [[11]].

Landscape-scale forest restoration efforts have been planned or implemented across much of Arizona. For example, the Four Forest Restoration Initiative (4FRI) includes plans for restoration across over 1 million hectares of Arizona's forests [12]. The primary goal of restoration efforts is to reduce wildfire risk [9, 8]. However, numerous studies have linked forest treatments to increased water yields in semi-arid forests and have emphasized the role of forest restoration in improving hydrologic services and increasing water availability [13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24].

While the connection between forest treatment and water yield is well documented, the response of forests to treatments is complex and non-linear and differs across forest types, with treatment level, and along aspect and elevational gradients [25, 26, 17, 24, 27]. Regardless of the potential for increased water yield the enhancement of groundwater recharge rarely, if ever, ranks among the primary motivations for forest treatment even among projects with the stated goal of improving watershed health [28, 29, 9, 8, 30]. This study examines forest restoration through the lens of groundwater recharge enhancement and identifying potential recharge zones. All else held equal, we map suitability for forest thinning with the goal of enhancing recharge. Suitability maps like these may complement (or supplement) existing frameworks for prioritizing landscape-scale forest management.

Suitability mapping, and particularly GIS-based Multi-criteria decision making (GIS-MCDM), is widely used to map potential recharge zones and areas suitable for Managed Aquifer Recharge (MAR), but to our knowledge, it has not yet been implemented to map recharge enhancement potential through forest thinning [31, 32]. Pairwise comparisons were made between criteria including average precipitation, snow dominance, slope, aspect, landscape morphology, forest density, lithology, and hydrologic soil type, and the Analytic Hierarchy Process (AHP) was used as a weighting method.

Forest treatments such as thinning and burning can significantly impact the hydrologic cycle of forests [25]. For example, forest thinning in Arizona has been associated with increased snow cover days [33, 34, 35], greater soil moisture [36, 37], and greater forest canopy moisture [38]. However, the response of forests to treatments is complex and non-linear and differs across forest types, with treatment level, and along aspect and elevational gradients [25, 26, 17, 24, 27].

Water yield can decrease with reductions in forest cover in drier forests with little topographic shading or SW aspects due to increased water use by remaining vegetation and increased snow sublimation or direct evaporation of soil moisture [39, 40]. Biederman and others [26] found that low-elevation forests in Arizona may produce less streamflow following reductions in canopy cover due to wildfire, highlighting the importance of elevation and particularly water-energy asynchrony to water yield [41]. The effects of forest treatment appear to have little or no effect on water yield in areas receiving less than 500mm of annual precipitation [26, 42, 43, 17, 24].

1.1. Literature Reviewed

1.2. Study Area

Coconino National forest is 812605 Ha

Ponderosa Pine covers 336,046 Ha of the Coconino = 41.35%

1.3. Acknowledgments

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1.4. Open research

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References

[1] K. E. Bennett, C. Talsma, R. Boero, Concurrent Changes in Extreme Hydroclimate Events in the Colorado River Basin, Water 13 (7) (2021) 978. doi:10.3390/w13070978.
URL https://www.mdpi.com/2073-4441/13/7/978

[2] D. M. Meko, C. A. Woodhouse, A. G. Winitsky, Tree-Ring Perspectives on the Colorado River: Looking Back and Moving Forward, JAWRA Journal of the American Water Resources Association 58 (5) (2022) 604–621. doi:10.1111/1752-1688.12989.
URL https://onlinelibrary.wiley.com/doi/10.1111/1752-1688.12989

[3] A. P. Williams, B. I. Cook, J. E. Smerdon, Rapid intensification of the emerging southwestern North American megadrought in 2020–2021, Nature Climate Change 12 (3) (2022) 232–234. doi:10.1038/s41558-022-01290-z.
URL https://www.nature.com/articles/s41558-022-01290-z

[4] D. Hogan, J. D. Lundquist, Recent Upper Colorado River Streamflow Declines Driven by Loss of Spring Precipitation, Geophysical Research Letters 51 (16) (2024) e2024GL109826. doi:10.1029/2024GL109826.
URL https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2024GL109826

[5] B. Udall, J. Overpeck, The twenty-first century Colorado River hot drought and implications for the future, Water Resources Research 53 (3) (2017) 2404–2418. doi:10.1002/2016WR019638.
URL https://agupubs.onlinelibrary.wiley.com/doi/10.1002/2016WR019638

[6] D. E. Tadych, M. Ford, B. G. Colby, L. E. Condon, Historical patterns of well drilling and groundwater depth in Arizona considering groundwater regulation and surface water access, JAWRA Journal of the American Water Resources Association (2024) 1752–1688.13234doi:10.1111/1752-1688.13234.
URL https://onlinelibrary.wiley.com/doi/10.1111/1752-1688.13234

[7] W. Covington, M. M. Moore, Southwestern ponderosa pine forest structure: changes since Euro-American settlement, Journal of forestry. 92 (1994) 39–47, place: Bethesda, MD : Publisher: Society of American Foresters,.

[8] P. Friederici, Ecological Restoration of Southwestern Ponderosa Pine Forests, no. v.2 in Science Practice Ecological Restoration, Island Press, Chicago, 2013.

[9] C. D. Allen, M. Savage, D. A. Falk, K. F. Suckling, T. W. Swetnam, T. Schulke, P. B. Stacey, P. Morgan, M. Hoffman, J. T. Klingel, Ecological restoration of southwestern ponderosa pine ecosystems: a broad perspective, Ecological Applications 12 (5) (2002) 1418–1433. doi:10.1890/1051-0761(2002)012[1418:EROSPP]2.0.CO;2.
URL http://doi.wiley.com/10.1890/1051-0761(2002)012[1418:EROSPP]2.0.CO;2

[10] L. T. Berner, B. E. Law, A. J. H. Meddens, J. A. Hicke, Tree mortality from fires, bark beetles, and timber harvest during a hot and dry decade in the western United States (2003–2012), Environmental Research Letters 12 (6) (2017) 065005. doi:10.1088/1748-9326/aa6f94.
URL https://iopscience.iop.org/article/10.1088/1748-9326/aa6f94

[11] V. Iglesias, J. K. Balch, W. R. Travis, U.s. fires became larger, more frequent, and more widespread in the 2000s, Science Advances 8 (11) (03

2022). doi:10.1126/sciadv.abc0020.
URL http://dx.doi.org/10.1126/sciadv.abc0020

[12] C. A. Schultz, T. Jedd, R. D. Beam, The Collaborative Forest Landscape Restoration Program: A History and Overview of the First Projects, Journal of Forestry 110 (7) (2012) 381–391. doi:10.5849/jof.11-082.
URL https://academic.oup.com/jof/article/110/7/381-391/4599006

[13] J. Bosch, J. Hewlett, A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration, Journal of Hydrology 55 (1-4) (1982) 3–23. doi:10.1016/0022-1694(82)90117-2.
URL https://linkinghub.elsevier.com/retrieve/pii/0022169482901172

[14] M. B. Baker, Effects of Ponderosa Pine Treatments on Water Yield in Arizona, Water Resources Research 22 (1) (1986) 67–73. doi:10.1029/WR022i001p00067.
URL https://agupubs.onlinelibrary.wiley.com/doi/10.1029/WR022i001p00067

[15] G. J. Gottfried, Moderate timber harvesting increases water yields from an Arizona Mixed Conifer Watershed, JAWRA Journal of the American Water Resources Association 27 (3) (1991) 537–546, publisher: John Wiley & Sons, Ltd.
URL https://onlinelibrary.wiley.com/doi/abs/10.1111/j.1752-1688.1991.tb01454.x

[16] B. D. Smerdon, T. Redding, J. Beckers, An overview of the effects of forest management on groundwater hydrology, Journal of Ecosystems and Management (Mar. 2009). doi:10.22230/jem.2009v10n1a409.
URL https://jem-online.org/index.php/jem/article/view/409

[17] C. B. Zou, P. F. Ffolliott, M. Wine, Streamflow responses to vegetation manipulations along a gradient of precipitation in the Colorado River Basin, Forest Ecology and Management 259 (7) (2010) 1268–1276. doi:10.1016/j.foreco.2009.08.005.
URL https://linkinghub.elsevier.com/retrieve/pii/S0378112709005350

[18] C. J. W. Wyatt, Estimating groundwater yield following forest restoration along the Mogollon Rim, Master's thesis, Northern Arizona University, Flagstaff, AZ (2013).
URL https://cdm17192.contentdm.oclc.org/digital/collection/p17192coll1/id/476/rec/3

[19] H. A. Moreno, H. V. Gupta, D. D. White, D. A. Sampson, Modeling the distributed effects of forest thinning on the long-term water balance and stream flow extremes for a semi-arid basin in the southwestern US (Oct. 2015). doi:10.5194/hessd-12-10827-2015.
URL https://hess.copernicus.org/preprints/12/10827/2015/hessd-12-10827-2015.pdf

[20] S. Simonit, J. P. Connors, J. Yoo, A. Kinzig, C. Perrings, The Impact of Forest Thinning on the Reliability of Water Supply in Central Arizona, PLOS ONE 10 (4) (2015) e0121596. doi:10.1371/journal.pone.0121596.
URL https://dx.plos.org/10.1371/journal.pone.0121596

[21] C. Wyatt, F. C. O'Donnell, Abraham E. Springer, Semi-Arid Aquifer Responses to Forest Restoration Treatments and Climate Change, Ground Water (2015). doi:10.1111/gwat.12184.

[22] F. C. O'Donnell, W. T. Flatley, A. E. Springer, P. Z. Fulé, Forest restoration as a strategy to mitigate climate impacts on wildfire, vegetation, and water in semiarid forests, Ecological Applications 28 (6) (2018) 1459–1472. doi:10.1002/eap.1746.
URL https://esajournals.onlinelibrary.wiley.com/doi/10.1002/eap.1746

[23] E. R. Schenk, F. O'Donnell, A. E. Springer, L. E. Stevens, The impacts of tree stand thinning on groundwater recharge in aridland forests, Ecological Engineering 145 (2020) 105701. doi:10.1016/j.ecoleng.2019.105701.
URL https://linkinghub.elsevier.com/retrieve/pii/S0925857419304252

[24] A. R. Hibbert, Managing vegetation to increase flow in the colorado river basin, Tech. rep. (1979).

[25] A. D. Del Campo, K. Otsuki, Y. Serengil, J. A. Blanco, R. Yousefpour, X. Wei, A global synthesis on the effects of thinning on hydrological processes: Implications for forest management, Forest Ecology and Management 519 (2022) 120324. doi:10.1016/j.foreco.2022.120324.
URL https://linkinghub.elsevier.com/retrieve/pii/S0378112722003188

[26] J. A. Biederman, M. D. Robles, R. L. Scott, J. F. Knowles, Streamflow Response to Wildfire Differs With Season and Elevation in Adjacent Headwaters of the Lower Colorado River Basin, Water Resources Research 58 (3) (2022) e2021WR030687. doi:10.1029/2021WR030687.
URL https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2021WR030687

[27] R. Moore, S. Wondzell, Physical hydrology and the effects of forest harvesting in the pacific northwest: A review, Journal of the American Water Resources Association 41 (4) (2005) 763–784. doi:10.1111/j.1752-1688.2005.tb04463.x.
URL http://doi.wiley.com/10.1111/j.1752-1688.2005.tb04463.x

[28] J. A. Stanturf, B. J. Palik, R. K. Dumroese, Contemporary forest restoration: A review emphasizing function, Forest Ecology and Management 331 (2014) 292–323. doi:10.1016/j.foreco.2014.07.029.
URL https://linkinghub.elsevier.com/retrieve/pii/S0378112714004654

[29] S. Filoso, M. Bezerra, K. C. B. Weiss, M. A. Palmer, Impacts of forest restoration on water yield: A systematic review, PLOS ONE 12 (8) (2017) e0183210. doi:10.1371/journal.pone.0183210.
URL https://dx.plos.org/10.1371/journal.pone.0183210

[30] F. C. O'Donnell, The influence of restoration treatments on hydrologic output in fire-adapted forests of the southwest, Tech. rep., Flagstaff, AZ (11 2016).
URL https://cdm17192.contentdm.oclc.org/digital/collection/p17192coll1/id/662/rec/1

[31] S. Fathi, J. Hagen, A. Matanó, G. E. H. Nogueira, Review of GIS Multi-Criteria Decision Analysis for Managed Aquifer Recharge in Semi-Arid Regions, Springer International Publishing, Cham, 2021, pp. 19–52, dOI: 10.1007/978-3-030-68124-1_2. doi:10.1007/978-3-030-68124-1_2.
URL https://link.springer.com/10.1007/978-3-030-68124-1_2

[32] P. Raja Shekar, A. Mathew, Assessing groundwater potential zones and artificial recharge sites in the monsoon-fed murredu river basin, india: An integrated approach using gis, ahp, and fuzzy-ahp, Groundwater for Sustainable Development 23 (2023) 100994. doi:10.1016/j.gsd.2023.100994.
URL https://linkinghub.elsevier.com/retrieve/pii/S2352801X23000942

[33] T. Sankey, J. Donald, J. McVay, M. Ashley, F. O'Donnell, S. M. Lopez, A. Springer, Multi-scale analysis of snow dynamics at the southern margin of the North American continental snow distribution, Remote Sensing of Environment 169 (2015) 307–319. doi:10.1016/j.rse.2015.08.028.
URL https://linkinghub.elsevier.com/retrieve/pii/S0034425715301140

[34] A. Belmonte, T. Sankey, J. Biederman, J. Bradford, S. Goetz, T. Kolb, UAV-Based Estimate of Snow Cover Dynamics: Optimizing Semi-Arid Forest Structure for Snow Persistence, Remote Sensing 13 (5) (2021) 1036. doi:10.3390/rs13051036.
URL https://www.mdpi.com/2072-4292/13/5/1036

[35] J. Donager, T. T. Sankey, A. J. Sánchez Meador, J. B. Sankey, A. Springer, Integrating airborne and mobile lidar data with UAV photogrammetry for rapid assessment of changing forest snow depth and cover, Science of Remote Sensing 4 (2021) 100029. doi:10.1016/j.srs.2021.100029.
URL https://linkinghub.elsevier.com/retrieve/pii/S266601722100016X

[36] A. Belmonte, T. Ts. Sankey, J. Biederman, J. B. Bradford, T. Kolb, Soil moisture response to seasonal drought conditions and post-thinning forest structure, Ecohydrology 15 (5) (2022) e2406. doi:10.1002/eco.2406.
URL https://onlinelibrary.wiley.com/doi/10.1002/eco.2406

[37] T. Sankey, J. Tatum, Thinning increases forest resiliency during unprecedented drought, Scientific Reports 12 (1) (2022) 9041. doi:10.1038/s415

98-022-12982-z.
URL https://www.nature.com/articles/s41598-022-12982-z

[38] T. Sankey, A. Belmonte, R. Massey, J. Leonard, Regional-scale forest restoration effects on ecosystem resiliency to drought: a synthesis of vegetation and moisture trends on Google Earth Engine, Remote Sensing in Ecology and Conservation 7 (2) (2021) 259–274. doi:10.1002/rse2.186.
URL https://zslpublications.onlinelibrary.wiley.com/doi/10.1002/rse2.186

[39] J. A. Biederman, A. J. Somor, A. A. Harpold, E. D. Gutmann, D. D. Breshears, P. A. Troch, D. J. Gochis, R. L. Scott, A. J. H. Meddens, P. D. Brooks, Recent tree die-off has little effect on streamflow in contrast to expected increases from historical studies, Water Resources Research 51 (12) (2015) 9775–9789. doi:10.1002/2015WR017401.
URL https://agupubs.onlinelibrary.wiley.com/doi/10.1002/2015WR017401

[40] S. A. Goeking, D. G. Tarboton, Forests and Water Yield: A Synthesis of Disturbance Effects on Streamflow and Snowpack in Western Coniferous Forests, Journal of Forestry 118 (2) (2020) 172–192. doi:10.1093/jofore/fvz069.
URL https://academic.oup.com/jof/article/118/2/172/5734757

[41] R. Webb, J. Knowles, A. Fox, A. Fabricus, T. Corrie, K. Mooney, J. Gallais, N. Frimpong, C. Akurugu, G. Barron-Gafford, P. Blanken, S. Burns, J. Frank, M. Litvak, Energy-water asynchrony principally determines water available for runoff from snowmelt in continental montane forests, Hydrological Processes 38 (10) (10 2024). doi:10.1002/hyp.15297.
URL http://dx.doi.org/10.1002/hyp.15297

[42] R. W. Carroll, J. L. Huntington, K. A. Snyder, R. G. Niswonger, C. Morton, T. K. Stringham, Evaluating mountain meadow groundwater response to Pinyon-Juniper and temperature in a great basin watershed, Ecohydrology 10 (1) (2016) e1792. doi:10.1002/eco.1792.
URL https://onlinelibrary.wiley.com/doi/10.1002/eco.1792

[43] H. D. Adams, C. H. Luce, D. D. Breshears, C. D. Allen, M. Weiler, V. C. Hale, A. M. S. Smith, T. E. Huxman, Ecohydrological consequences of drought- and infestation- triggered tree die-off: insights and hypotheses, Ecohydrology 5 (2) (2012) 145–159. doi:10.1002/eco.233.
URL https://onlinelibrary.wiley.com/doi/10.1002/eco.233