OREGON DEPARTMENT OF AGRICULTURE

Directors Office
635 Capitol St, NE, Salem, OR 97301-2532
503.986.4700 | Oregon.gov/ODA

Rules Governing
Agricultural Activities in the Lower Umatilla
Groundwater Management Area

Input Received Following Meeting #2

Commenter	Pages
Eric O.	pp. 2-3
Brad S.	pp. 4-15
Carlos B./OSU	pp. 16-25, 31-54
Dani L.	pp. 26-30

Subject: FW: Comments
Date: Monday, June 2, 2025 at 12:34:27 PM Pacific Daylight Time
From: MOULUN Renee * ODA <Renee.MOULUN@oda.oregon.gov>
To: SUMMERS Sunny * ODA <Sunny.SUMMERS@oda.oregon.gov>
CC: MOULUN Renee * ODA <Renee.MOULUN@oda.oregon.gov>, STAPLETON Isaak * ODA <Isaak.STAPLETON@oda.oregon.gov>

Hi Sunny,
Some comments we received after RAC #3.

Renee Moulun, Senior Policy Advisor
Oregon Department of Agriculture – Natural Resources
635 Capitol St NE, Salem, OR 97301-2532
CELL: (971) 375-0231
WEB: Oregon.gov/ODA

From: STAPLETON Isaak * ODA <Isaak.STAPLETON@oda.oregon.gov>
Date: Thursday, May 22, 2025 at 1:03 PM
To: MOULUN Renee * ODA <Renee.MOULUN@oda.oregon.gov>
Subject: FW: Comments

From: Eric Orem [redacted]
Date: Thursday, May 22, 2025 at 12:31 PM
To: STAPLETON Isaak * ODA <isaak.stapleton@oda.oregon.gov>
Subject: Comments

Isaak,

A few comments from todays meeting. Sorry for not speaking up this is a learning opportunity for me and I find it easier to take notes and research the question and then report it back to you to consider. I agree with some of the comments made today.
-I am working on a list of farm operations over 1000 acres. So far I am coming up with 28. But trying to figure out what the percentage of acres for those operations are in the LUB. I wonder if these rules should not apply to all irrigated acres. It seems talking to bigger operations they follow "Best Management Practices" for the most part.
-The soil testing issue is very crop specific. for example using round numbers;
Corn- pre season test shows 50# available and we expect 250bu corn, extension research will

recommend 200# of N. 1-1.25# per expectant bu. What I think was trying to be stated was do you apply all 200# at planting (which is not helping the issue) or couldn't you slit apply that same 200# over 4 or so applications based on growth stage of plant. Spoon feeding when needed and then an in season test if applying over that original 200# amount. Followed by a post season test to see where we ended up.
Onions- This was an example of what testing is done by one Onion grower;

1. Zone sample field based on satellite imagery
2. Variable rate dry spread nutrients to even out the field.
3. Planter band application
4. 4 leaf soil and tissue samples.
5. 1' Samples every week until August spoon feeding in small doses.

And finally the annual nitrogen budget date would need to be flexible but should be submitted before 1st application of the spring.

Other comments I have received and data sent to me is;

1. The rules seem equivalent to a DEQ permit.
2. Soil Lab/ Agronomist availability.
3. Cost estimate to comply with rules $160-180 an acre.
4. Having standardized forms form ODA. Making it easier to comply.

Thanks,
Eric

External **Comments from Session 2 04/23/2025**

SB

Spencer, Brad [redacted]

Wednesday, May 21, 2025 at 9:37 PM

To: RULEMAKIN[redacted]nny * ODA

April_23_LUBGWMA...
519 KB

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Please see attached comments that I have added to the 04/23 Addition to the LUBGWMA Rules.

Thank You

Brad Spencer | Digital Sales Supervisor | Digital Sales Enablement

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Rules Governing
Agricultural Activities in the Lower Umatilla
Groundwater Management Area

Rules Advisory Committee Meeting #2
April 23, 2025
10:30 a.m. – 12:00 p.m.

A. Welcome and discuss agenda

B. Rules that apply to all landowners

1. XX01 Purpose and Authority
2. XX02 Geographic and Programmatic Scope
3. XX03 Definitions
4. XX04 Prohibited Acts
5. XX05 Land Application Rates and Restrictions
6. XX06 Animal Pasturing

C. RAC comments and questions

D. Close meeting

PUBLIC DRAFT

AGRICULTURAL ACTIVITIES IN
THE LOWER UMATILLA BASIN
GROUNDWATER MANAGEMENT AREA

3/18/25
Edits by RM 4/21/25

603-XX-XX01
Purpose and Authority

(1) The Lower Umatilla Basin Groundwater Management Area (LUBGWMA) is comprised of about 550 square miles in northern Morrow and northeastern Umatilla counties as shown in **Appendix A.** The Oregon Department of Environmental Quality (DEQ) has designated the area as a groundwater management area because of high levels of nitrate in water wells used for human consumption. High levels of nitrate in drinking water can cause serious health effects and is particularly dangerous for infants and pregnant persons.
(2) Understanding that agriculture within the LUBGWMA provides valuable food and fiber products to communities worldwide, these area rules are intended to prevent the discharge of nitrates into groundwater from agricultural activities while maintaining the economic viability of agriculture within the LUBGWMA. These area rules implement the Umatilla and Willow Creek Water Quality Management Area Plans as those plans address nitrate pollution in groundwater within the LUBGWMA and contain actions necessary to minimize nitrate leaching to groundwater.
(3) The Oregon Department of Agriculture's authority for these rules is ORS 561.191, ORS 568.900 – 930 and ORS 468B.184(2). Other authorities include ORS 561.200 and ORS 561.2765 - 290 as applicable.

Commented [RM1]: Note typo to the RAC

603-XX-XX02
Geographic and Programmatic Scope

(1) Operational boundaries for the agricultural lands subject to these area rules are as provided in **Appendix A** and include all lands within the LUBGWMA in agricultural use.
(2) These area rules do not apply to public lands managed by federal agencies, lands that make up the Reservation of the Confederated Tribes of the Umatilla Indian Reservation, and land or activities subject to Oregon's Forest Practices Act.
(3) All landowners conducting agricultural activities on lands in agricultural use within the LUBGWMA shall comply with these area rules as they are applicable to the size and type of agricultural operation.
(4) These area rules do not authorize violation of any federal, state, or local law or regulation.
(5) These area rules do not constitute a National Pollutant Discharge Elimination System Permit or Water Pollution Control Facility Permit issued pursuant to the Federal Clean Water Act or ORS 468B.050. Compliance with these area rules does not exempt a landowner from the Federal Clean Water Act or state water pollution control laws.

(6) The fact that it is necessary to halt or reduce activities contributing to discharges to maintain compliance with these area rules shall not be a defense for violation of these rules.
(7) The requirements in these area rules do not authorize the commission of any act causing injury to property of another or protect the landowner from liabilities under other federal, state, county, or local laws.
(8) These area rules do not apply to conditions resulting from unusual weather events or other exceptional circumstances beyond the reasonable control of the landowner. An example of reasonable control of the landowner means that technically sound and economically feasible measures are available to address conditions described in these rules.

603-XX-XX03
Definitions

For the purposes of these rules unless the context requires otherwise.

(1) "Agricultural activities" means engaging in any generally accepted, reasonable and prudent method of growing or harvesting agricultural crops and commodities.
(2) "Agronomic application rate" or "agronomic rate" means the rate of synthetic fertilizers, compost or manure required to achieve estimated crop yield with minimal leaching of nitrate.
(3) "Agricultural land(s)" means lands that may ~~are permitted to~~ be used for agricultural activities.
(4) "Agricultural operation" means (a) all agricultural land, whether or not contiguous, that is under the effective control of a landowner engaged in any commercial activity relating to the growing or harvesting of agricultural crops or the production of agricultural commodities; (b) synonym for a "farm" as defined in ORS 30.930(1).
(5) "Area Plan" or "Agricultural Water Quality Management Area Plan" means a plan for the prevention and control of water pollution from agricultural activities and soil erosion in a management area that has been designated under ORS 568.909.
(6) "Area Rules" are administrative rules adopted by the Oregon Department of Agriculture, in consultation with the Oregon Board of Agriculture and the Oregon Department of Environmental Quality, for the implementation of the Area Plans referenced in these rules.
(7) "Certifier" means a qualified irrigation and nitrogen management plan specialist as provided in OAR 603-XX-XX14.
(8) "Compost" has that meaning given in ORS 633.311(5).
(9) "Department" means the Oregon Department of Agriculture.
(10) "Director" means the director of the Oregon Department of Agriculture.
(11) "Estimated crop yield" means the near-maximum or optimum crop yield estimated for each field according to sources such as recommendations by land grant universities, the Natural Resources Conservation Service, commodity groups, or according to site-specific knowledge based on previous experience.
(12) "Fertilizer" has the meaning given in ORS 633.311(12).
(13) "Field" means an area of land that is used for agricultural activities and enclosed or otherwise marked by a physical, topographical or other boundary.
(14) "Groundwater" or "groundwater of the state" means water within the LUBGWMA that is in a saturated zone or stratum beneath the surface of land or below a surface water body.

(15) “Irrigated agricultural lands” or “irrigated agriculture” means agricultural lands irrigated to produce crops or pasture and including lands that are planted to commercial crops that are not yet marketable such as vineyards and tree crops. Irrigated lands include nurseries.
(16) “Landowner” has the meaning given in ORS 568.210 and ORS 568.903 and includes an “operator” as defined in ORS 568.900(2).
(17) “Manure” means solids or liquids excreted from an animal.
(18) “Nitrogen Management Measures” means measures to match fertilizer and nitrogen applications to agronomic demands and includes a determination of the appropriate agronomic application rate to achieve estimated crop yield. Nitrogen management measures include the 4Rs of nutrient stewardship as provided in NRCS Conservation Practice Standard Nutrient Management Code 590 (2019).
(19) “Operator” has the meaning given in ORS 568.200(2).
(20) “Pasture” means land that sustains vegetative growth in the normal growing season that is primarily used to grow forage for grazing livestock where the livestock are not confined in pens or lots or on a prepared surface and where waste is not managed using a waste water control facility.
(21) “Pollution” or “water pollution” has the meaning given in ORS 468B.005.
(22) “Saturated soil” means soil with all available pore space filled that has reached its maximum retentive capacity.
(23) “Synthetic fertilizer” means fertilizer made from ammonia, nitrogen, phosphate minerals, and other chemicals through human-controlled chemical reactions. Synthetic fertilizers include dry fertilizer, liquid fertilizer, foliar fertilizer, and any other type of fertilizer that has a guaranteed nutrient content.
(24) “Waste” or “wastes” has that meaning given in ORS 468B.005 with the clarification that waste or wastes includes but is not limited to commercial fertilizers, soil amendments, composts, animal wastes, vegetative materials and includes nitrate that enters groundwater by any means.
(25) “Water” or the “waters of the state” has the meaning given in ORS 468B.005.

603-XX-XX04
Prohibited Acts
[This rule applies to all landowners in the LUBGWMA]

(1) The discharge of waste to the groundwater of this state from agricultural activities is prohibited.
(2) Wastes may not be placed in a location where such wastes are likely to escape or be carried into groundwater by any means.
(3) The discharge of fertilizers, fumigants, or pesticides into groundwater via back flow through a water supply well is prohibited.
(4) The discharge of fertilizers, fumigants, or pesticides down a groundwater well casing is prohibited.
(5) A landowner within the LUBGWMA may not violate the provisions of 603-XX-XX05.

603-XX-XX05
Land Application Rates and Restrictions
[These rules apply to all landowners within the LUBGWMA]

(1) A landowner shall employ nitrogen management measures when making land applications of synthetic fertilizers, compost or manure.
(2) Before synthetic fertilizers, compost or manure may be applied a landowner shall:
(a) Take soil samples consistent with [SOIL SAMPLE PROTOCOL RULE]; and
(b) Take into consideration existing plant available nitrogen levels and estimated crop yields when making an application of fertilizers, compost, or manure.
(3) A landowner shall document, and upon request by the department make available for inspection, the following for each field to which synthetic fertilizers, compost, or manure are applied:
(a) The date(s) and location(s) of all nitrogen applications;
(b) The weather conditions and soil moisture at the time of application; and
(c) The agronomic application rate used.
(4) A landowner shall prevent the downward movement of nitrate in the soil by managing irrigation water so that the amount of water applied from the combination of precipitation and irrigation does not exceed the water holding capacity of the soil beyond the crop root depth.
(5) A landowner may not apply synthetic fertilizers, compost, or manure in a manner that causes direct, indirect, or precipitation-related discharge to groundwater.
(6) A landowner may not apply synthetic fertilizers, compost, or manure:
(a) To fields with a frozen surface crust (2 inches) or deeper, or if the soil is at or below zero degrees Celsius (32 degrees Fahrenheit).
(b) To fields that are snow covered.
(c) To fields with soils that are or will become saturated with forecasted precipitation prior to infiltration or incorporation.
(d) If the water table is within 12 inches or less to the surface.
(e) If precipitation is forecasted in the next 24 hours for the field location and it is likely that application will result in a prohibited act.
(f) To fields that are bare unless the landowner is preparing the bare fields for the current year's annual crop planting and the application is within 30 days of planting.

603-XX-XX06
Animal Pasturing
[This rule applies to all landowners within the LUBGWMA]

(1) A landowner grazing livestock on pasture within the LUBGWMA shall rotate livestock and limit livestock numbers to prevent bare ground and promote and maintain adequate vegetative cover.
(a) In determining an appropriate stocking rate for livestock grazing on pasture, a landowner shall match livestock requirements with the available forage and frequently monitor forage growth and adjust the stocking rate and grazing period to prevent runoff or overgrazing.
(2) Where animals are concentrated to a distinct heavy use area during the rainy season, when the soil is prone to compaction or when inadequate forage growth would result in over-grazing, a landowner shall remove manure and waste feed from these areas and maintain grassy buffer strips around the area.
(3) A landowner applying synthetic fertilizer, compost, or manure to irrigated pasture shall conduct nutrient management in a manner that prevents the over-application of nitrogen and reduces the likelihood of nitrate leaching to groundwater.

(a) A landowner applying synthetic fertilizers, compost, or manure to pasture shall first conduct a soil test consistent with [CITE SOIL SAMPLE RULE] to establish plant available nitrogen in the soil.
(4) A landowner shall prevent the downward movement of nitrate in the soil by managing irrigation water so that the amount of water applied from the combination of precipitation and irrigation does not exceed the soil's water holding capacity within the forage root depth.

603-XX-XX07
Control Measures for Irrigated Agriculture on Large Acreages
[This rule applies only to landowners irrigating large acreages]

(1) [OAR 603-XX01 – XX19] govern agricultural activities on irrigated agricultural lands where the total land acreage under the ownership or control of a landowner is equal to or greater than 1,000 acres and where irrigation is used to grow crops or pasture on those acreages.
(2) These area rules describe those irrigation and nitrogen management measures necessary to minimize percolation of waste to groundwater and prevent excess nitrogen application relative to crop need.
(a) Measures include irrigation water management, an annual nitrogen budget, and annual post-harvest summary records. Records that implement these measures shall be retained by the landowner at the landowner's principal place of business for the agricultural operation and made available for inspection at the request of the department.
(3) Each landowner shall employ best practicable management practices to implement the irrigation and nitrogen management measures in these area rules according to the site-specific attributes and needs of each agricultural operation.

603-XX-XX08
Irrigation Water Management
[This rule applies only to landowners irrigating large acreages]

(1) A landowner subject to these rules shall prevent the downward movement of nitrate in the soil by managing irrigation water so that the amount of water applied from the combination of precipitation and irrigation does not exceed the soil's water holding capacity within the crop's rooting depth.
(2) A landowner subject to these rules shall base the volume of water needed for each irrigation event on at least the following information as relevant to a crop or field:
(a) Available water-holding capacity of the soil for the crop rooting depth;
(b) Management allowed soil water depletion;
(c) Current soil moisture status;
(d) Distribution uniformity of the irrigation event;
(e) Water table contribution;
(f) Computerized irrigation scheduling recommendation.
(3) A landowner subject to these rules shall plan the rate and volume of irrigation water to minimize the transport of nutrients to groundwater by:
(a) Controlling the rate of water application to limit the transport of nitrogen through the soil profile to groundwater; and

(b) Matching irrigation application quantities and rates to the crop, soil type, soil moisture content, and agronomic demands of each crop type such that irrigation does not exceed the soil's infiltration rate or water holding capacity within the crop root zone.

603-XX-XX09
Annual Nitrogen Budget
[This rule applies only to landowners irrigating large acreages]

(1) Each year, prior to the first application of synthetic fertilizers, compost, or manure, a landowner subject to these rules shall prepare an annual nitrogen budget that demonstrates that synthetic fertilizers, compost, or manure will be applied only at the agronomic application rate necessary to support estimated crop yield.
(a) An annual nitrogen budget shall cover the entire growing season and include double-crops, and winter cover crops.
(2) An annual nitrogen budget shall include all anticipated nitrogen management measures including the anticipated agronomic application rate for each crop. To determine agronomic rates:
(a) A landowner shall test soil to determine plant available nitrogen prior to planting;
(b) A landowner shall conduct soil sampling to determine plant available nitrogen and/or conduct plant tissue sampling and analysis to determine nitrogen need prior to mid-growing season application, and prior to late-season application;
(3) Because annual nitrogen budgets are prepared in advance of the crop season and based on circumstances that are forecasted, actual conditions may differ from those forecasted in a certified annual nitrogen budget.
(a) Where crop season conditions differ from those forecasted, an annual nitrogen budget may be adjusted to reflect changes in weather, water availability, or other unanticipated circumstances.
(b) Should an adjustment to an annual nitrogen budget be necessary, a landowner should document the reasons for the adjustments in the annual nitrogen budget retained at the landowner's principal place of business for the agricultural operation.
(4) A landowner's inability to follow an annual nitrogen budget may not result in enforcement action by the department. However, failure to submit proof of certification of an annual nitrogen budget by January 1 of each year, may result in an enforcement action by the department, and conditions that indicate a violation of ORS 468B.025 may result in an enforcement action by the department.
(5) Proof of certification of an annual nitrogen budget shall be submitted to the department by January 1 of each year.

603-XX-XX10
Annual Nitrogen Budget Contents
[This rule applies only to landowners irrigating large acreages]

Annual nitrogen budgets shall include each of the following elements.
(1) Landowner name: Record the name of the landowner and the name of the operator if operator is not the owner of the land. If a certifier prepares the form, then the name of the certifier shall also be included.
(2) Crop year: Record the crop year for the calendar year that the crop is harvested.

(3) Field identification and acreage: Identification and the acreage of each field.
(4) For each field, record the soil type of the field and record pre-planting levels of plant available nitrogen as determined by pre-planting soil sample results.
(a) For the first annual nitrogen budget prepared after the effective date of these rules, record the residual soil nitrate levels for each field.
(5) Nitrogen management measures: For each field, record anticipated nitrogen management measures and specify the anticipated agronomic application rate. An agronomic application rate shall include total nitrogen applied in irrigation water.
(6) Irrigation Water Management Measures: Record methodology that will be used to determine appropriate water application rates so that the amount of water applied from the combination of precipitation and irrigation does not exceed the soil's water holding capacity within the crop's rooting depth.
(7) Crop type: For each field identify the crop type for the upcoming season.
(8) Estimated crop yield: For each field, estimate yield per acre for each crop type.
(9) Anticipated Total Nitrogen: For each field, record estimated total nitrogen to be applied in irrigation water, synthetic fertilizers, compost, or manure and estimated mineralization and atmospheric deposition.
(10) Recommended or planned total nitrogen: For each field, record the nitrogen recommended or planned to meet the estimated yield.
(11) Adaptive management measures provided in 603-XX-XX12 as applicable.
(12) Certification. A landowner shall provide proof of certification of an annual nitrogen budget to the department by [SPECIFY DATE].

603-XX-XX11
Post Harvest Summary Records
[This rule applies only to landowners irrigating large acreages]

Each year, a landowner subject to these rules shall prepare a post-harvest summary record to evaluate the effectiveness of their annual nitrogen budget. A post-harvest summary record shall include each of the following elements.
(1) Landowner name: Record the name of the landowner and the name of the operator if operator is not the owner of the land. If a certifier prepares the form, then the name of the certifier shall also be included.
(2) Crop year (harvested): Record the crop year for the calendar year that the crop is harvested.
(3) Crop type: For each field, record the type of crop harvested.
(4) Crop harvest yield: Record the crop harvest yield in crop production units per acre and include all harvested materials from primary harvest, secondary crop harvests, and crop residue (lb/acre).
(5) Nitrogen management measures: Record nitrogen management measures implemented including the agronomic application rate used for each crop.
(6) Total nitrogen applied (lbs/acre): For each field, record the total nitrogen applied as follows:
(a) Total nitrogen applied through irrigation water;
(b) Total nitrogen applied through synthetic fertilizers;
(c) Total nitrogen applied through compost; and
(d) Total nitrogen applied through manure.

(7) For each field, a determination according to 603-XX-XX12 of whether the annual nitrogen budget was followed and a description of the methodology used to make this conclusion.
(8) For each field, describe any applicable adaptive management measures to be employed in the following year's annual nitrogen budget.

OAR 603-XX-XX12
Annual Nitrogen Budget Evaluation

(1) A landowner is following an annual nitrogen budget if, for each field, plant-available nitrogen from all sources does not exceed the total nitrogen required to reach each a crop's estimated yield, and environmental loss or post-harvest soil nitrate levels are low or showing a trend of decreasing.
(a) A landowner may determine whether they followed their annual nitrogen budget by using either one or both of the methods described in subsections (2) and (3) of this section.
(2) A landowner may compare the sum of all nitrogen inputs with the sum of all nitrogen outputs as follows:
(a) Total nitrogen input is calculated as the sum of all nitrogen inputs from applied synthetic fertilizers, compost, manure, irrigation water, and estimated mineralization and atmospheric deposition.
(b) Total nitrogen output is calculated as the sum total nitrogen removed from crop yield removal (lb/acre x N content of crop) and from crop biomass harvested (lb/acre) multiplied by tissue nitrogen concentration (%).
(c) Environmental nitrogen loss may occur through leaching, denitrification, volatilization or leaching. Environmental nitrogen (N) loss may be estimated as follows:

$$\text{Environmental N loss} = \Sigma\text{N Inputs} - \Sigma\text{N Removal}$$

(3) A landowner may determine soil nitrate levels in post-harvest soil samples consistent with [CITE SOIL SAMPLE PROTOCOL RULE].
(a) Low postharvest soil nitrate concentrations limit the loss of soil nitrate below the root zone during the winter and indicate that a landowner has applied fertilizers and/or organic nutrients at an agronomic rate.
(b) Increasing or high postharvest soil nitrate concentrations may indicate that a landowner has not applied fertilizers and/or organic nutrients at an agronomic rate.
(4) For each field, a landowner shall determine and record in their post-harvest summary report whether their annual nitrogen budget was followed or not.
(5) Adaptive Management Measures: For each field where an annual nitrogen budget was not followed, a landowner shall record in the following year's annual nitrogen budget, the adaptive management measures they will employ according to Table 1.
(a) Table 1: Adaptive Management Measures

Annual Nitrogen Budget Followed?	**Required Actions**	**Required Actions Based Upon Trends (after 2 Consecutive Years)**
Yes	- No changes to current practices required	- N/A
No	Document reason(s) for not following ANB .	- N/A

Year 1	Reevaluate nitrogen budget assumptions for estimated crop yield, nitrogen volatilization, mineralization and other sources of nitrogen. - Verify actual land application rates and recalibrate land application equipment as necessary.	
No Year 3	**Continue the actions for Year 1 and**: - Document reason(s) for not following the ANB in post-harvest summary record. - Adjust land application timing so nutrient availability aligns with peak crop uptake. - Stop land application after peak crop uptake. - Collect and analyze an additional fall soil sample at the second foot depth (24-36 inches).	**Continue the actions in the Required Actions column and:** - Reduce nitrogen application to fields. - Hire a professional/consultant to develop annual nitrogen budget and application rates.
No Year 5	**Continue the actions for Year 3 and:** - Assume no nitrogen losses from denitrification and volatilization on the annual nitrogen budget for all applicable fields. - Enhance nitrogen removal via cropping. - Reduce nitrogen application amount to field.	**Continue the actions in the Required Action column and:** - Stop land application of nitrogen to the field. - Hire a professional/consultant to develop annual nitrogen budgets and application rates and implement nitrogen management measures advised. - Collect additional post-harvest soil samples at the second, third, and fourth foot depth or until refusal or groundwater is reached and analyze for nitrate.

(7) A landowner shall certify the post-harvest summary record as described in [CITE CERTIFICATION RULE] and provide proof of certification to the department by [x date].

603-XX-XX13
Residual Soil Nitrate Levels
[This rule applies only to landowners irrigating large acreages]

(1) A landowner subject to these rules shall determine residual soil nitrate levels for each field under their ownership or control using the soil sampling protocol in [CITE SOIL SAMPLE PROTOCOL RULE]:
(a) Initial residual nitrate soil samples shall be taken in the spring prior to planting; and
(b) Thereafter, residual soil nitrate samples shall be taken in the fall, post-harvest, once every five years.
(c) Soil sample results shall be certified by the processing laboratory.
(2) A landowner shall record residual soil nitrate levels for each field under their ownership or control on a worksheet supplied by the department and shall submit completed worksheets to the department within 30 days of obtaining sample results from the processing laboratory.
(a) Notwithstanding who the operator is, a landowner shall assure that residual soil nitrate samples are taken, recorded, and sample results submitted consistent with this rule.
(3) Where a residual soil nitrate sample indicates a violation of ORS 468B.025, the department may proceed to determine a landowner's compliance with the rules governing a landowner irrigating large acreages and if necessary, may proceed with appropriate enforcement.

603-XX-XX14
Certification of Annual Nitrogen Budgets, Post Harvest Summary Records and Residual Soil Nitrate Levels
[This rule applies only to landowners irrigating large acreages]

(1) Annual nitrogen budgets, post-harvest summary records, and residual soil nitrate sample results shall be certified in one of the following ways:
(a) Certified by an irrigation and nitrogen management plan specialist. In certifying a plan, a specialist shall attest that the record accurately reflects the conditions and management of the agricultural operation, that they can answer questions relevant to the document certified and are competent and proficient by education and experience relevant to the development of the document. These specialists may include Professional Soil Scientists, Professional Agronomists, or Crop Advisors certified by the American Society of Agronomy, Technical Service Providers certified in nutrient management in Oregon by the National Resource Conservation Service (NRCS);
(b) Self-certified by the landowner who attests that the document adheres to a site-specific recommendation from the NRCS or the Oregon State University Cooperative Extension [NEED SPECIFICS]; or
(c) Self-certified by the landowner if the landowner states that they apply no fertilizer to any field on the agricultural operation.
(2) Each record for which proof of certification is required shall include the name of the farm operator if different than the landowner, certifier, the date of plan certification, and certification method used.
(a) Each submission of proof of certification shall be contained on a form provided by the department and contain a statement stating that under penalty of law, the certified record is true, accurate and complete.

603-XX-XX15
Soil Sampling Protocol

(1) A landowner taking pre-planting soil samples or soil samples taken prior to application of synthetic fertilizers, compost, or manure shall collect separate composite soil samples at the depth of the root zone according to guidance contained in EC628.
(2) A landowner using post-harvest soil samples to determine whether they have followed an annual nitrogen budget shall collect separate composite post-harvest soil samples after harvest of annual crops and before 3 inches of rainfall accumulates. September 1 shall be the start date for tallying the accumulation of rainfall.
(a) Separate composite soil samples shall be collected at the 0-12 inch depth, the 12-24 inch depth and the 24 – 36 inch depth according to guidance contained in PNW 570-E, EM 8832-E for post-harvest nitrate-nitrogen.
(b) If the soil sample is taken after 3 inches of rainfall accumulates, a landowner shall collect an additional composite soil sample for the 72 - 84 inch depth to account for nitrate leaching.

Subject: FW: Water-holding capacity in soils - LUBGWMA Rulemaking
Date: Monday, June 2, 2025 at 12:36:14 PM Pacific Daylight Time
From: MOULUN Renee * ODA <Renee.MOULUN@oda.oregon.gov>
To: SUMMERS Sunny * ODA <Sunny.SUMMERS@oda.oregon.gov>
CC: STAPLETON Isaak * ODA <Isaak.STAPLETON@oda.oregon.gov>, MOULUN Renee * ODA <Renee.MOULUN@oda.oregon.gov>

Hi Sunny,

Comments received after RAC #2.

Renee Moulun, Senior Policy Advisor
Oregon Department of Agriculture – Natural Resources
635 Capitol St NE, Salem, OR 97301-2532
CELL: (971) 375-0231
WEB: Oregon.gov/ODA

From: Bonilla, Carlos A <carlos.bonilla@oregonstate.edu>
Date: Tuesday, May 20, 2025 at 4:16 PM
To: MOULUN Renee * ODA <Renee.MOULUN@oda.oregon.gov>, STAPLETON Isaak * ODA <Isaak.STAPLETON@oda.oregon.gov>
Subject: Water-holding capacity in soils - LUBGWMA Rulemaking

Hi Isaak and Renee,
During the previous RAC meeting, some members requested clarification of the concept of water-holding capacity in soils. This term is used in the draft as a threshold to prevent the downward movement of nitrate due to the combination of precipitation and irrigation. Water holding capacity is an intuitive term that can have more than one interpretation. So, a better option to express what the RAC draft pretends would be the Field Capacity (FC), which is the water content, on a mass or volume basis, remaining in soil 2 or 3 days after having been wetted with water and after free drainage is negligible. In other words, FC indicates the maximum amount of water (rain or irrigation) the soil can contain without draining the excess to the deeper depths. Even though it was initially measured in the field, FC is a simple procedure in most soil labs today and a standard in irrigation design.

If you want to use it and build a glossary for the RAC, see the definition and source I included at the bottom.
I hope this helps. Feel free to let me know if you have any questions.

Regards
Carlos

Definition:
Field capacity: The content of water, on a mass or volume basis, remaining in a soil 2 or 3 days after having been wetted with water and after free drainage is negligible. See also available water.

Source: Soil Science Glossary Terms Committee, 2008. Glossary of Soil Science Terms 2008. Madison: SSSA, p. 92.

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From: Bonilla, Carlos A <carlos.bonilla@oregonstate.edu>
Sent: Monday, May 19, 2025 12:44 PM
To: STAPLETON Isaak * ODA <Isaak.STAPLETON@oda.oregon.gov>
Cc: Sasidharan, Salini <salini.sasidharan@oregonstate.edu>; Qin, Ruijun <ruijun.qin@oregonstate.edu>; Moore, Amber D <amber.moore@oregonstate.edu>
Subject: LUBGWMA Rulemaking References list

Hi Isaak,
I shared the LUBGWMA Rulemaking References list with my colleagues Salini Sasidharan, Amber Moore, and Ruijun Qin. They kindly added some additional publications based on their expertise. See it attached. Feel free to use them if convenient, or contact us with any questions. I hope it helps.
Regards
Carlos

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Rules Governing Agricultural Activities in
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3/18/25

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NRCS Comprehensive Nutrient Management Planning (CNMP) Technical Guide
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Date: Friday, May 9, 2025 at 1:07 PM
To: MOULUN Renee * ODA <Renee.MOULUN@oda.oregon.gov>, STAPLETON Isaak * ODA <isaak.stapleton@oda.oregon.gov>
Subject: LUBGWMA RAC - language suggestions

mailto:isaak.stapleton@oda.oregon.gov

Hi Renee and Isaak –

After the April RAC call, I had a list of areas marked that you had asked for input. I converted the draft rules pdf file into a word document and added some suggestions in track changes; they should be on pages 2-4. Thanks for the opportunity to send these in.
Have a great weekend,
Dani

PUBLIC DRAFT

AGRICULTURAL ACTIVITIES IN
THE LOWER UMATILLA BASIN
GROUNDWATER MANAGEMENT AREA

3/18/25
Edits by RM 4/21/25

603-XX-XX01
Purpose and Authority

(1) The Lower Umatilla Basin Groundwater Management Area (LUBGWMA) is comprised of about 550 square miles in northern Morrow and northeastern Umatilla counties as shown in **Appendix A.** The Oregon Department of Environmental Quality (DEQ) has designated the area as a groundwater management area because of high levels of nitrate in water wells used for human consumption. High levels of nitrate in drinking water can cause serious health effects and is particularly dangerous for infants and pregnant persons.
(2) Understanding that agriculture within the LUBGWMA provides valuable food and fiber products to communities worldwide, these area rules are intended to prevent the discharge of nitrates into groundwater from agricultural activities while maintaining the economic viability of agriculture within the LUBGWMA. These area rules implement the Umatilla and Willow Creek Water Quality Management Area Plans as those plans address nitrate pollution in groundwater within the LUBGWMA and contain actions necessary to minimize nitrate leaching to groundwater.
(3) The Oregon Department of Agriculture's authority for these rules is ORS 561.191, ORS 568.900 – 930 and ORS 468B.184(2). Other authorities include ORS 561.200 and ORS 561.2~~6~~75 - 290 as applicable.

Commented [RM1]: Note typo to the RAC

603-XX-XX02
Geographic and Programmatic Scope

(1) Operational boundaries for the agricultural lands subject to these area rules are as provided in **Appendix A** and include all lands within the LUBGWMA in agricultural use.
(2) These area rules do not apply to public lands managed by federal agencies, lands that make up the Reservation of the Confederated Tribes of the Umatilla Indian Reservation, and land or activities subject to Oregon's Forest Practices Act.
(3) All landowners conducting agricultural activities on lands in agricultural use within the LUBGWMA shall comply with these area rules as they are applicable to the size and type of agricultural operation.
(4) These area rules do not authorize violation of any federal, state, or local law or regulation.
(5) These area rules do not constitute a National Pollutant Discharge Elimination System Permit or Water Pollution Control Facility Permit issued pursuant to the Federal Clean Water Act or ORS 468B.050. Compliance with these area rules does not exempt a landowner from the Federal Clean Water Act or state water pollution control laws.

(6) The fact that it is necessary to halt or reduce activities contributing to discharges to maintain compliance with these area rules shall not be a defense for violation of these rules.
(7) The requirements in these area rules do not authorize the commission of any act causing injury to property of another or protect the landowner from liabilities under other federal, state, county, or local laws.
(8) These area rules do not apply to conditions resulting from unusual weather events or other exceptional circumstances beyond the reasonable control of the landowner. An example of reasonable control of the landowner means that technically sound and economically feasible measures are available to address conditions described in these rules.

603-XX-XX03
Definitions

For the purposes of these rules unless the context requires otherwise.

(1) "Agricultural activities" means engaging in any generally accepted, reasonable and prudent method of growing or harvesting agricultural crops and commodities.
(2) "Agronomic application rate" or "agronomic rate" means the rate of synthetic fertilizers, compost or manure required to achieve estimated crop yield with minimal leaching of nitrate.
(3) "Agricultural land(s)" means lands that may ~~are permitted to~~ be used for agricultural activities.
(4) "Agricultural operation" means (a) all agricultural land, whether or not contiguous, that is under the effective control of a landowner engaged in any commercial activity relating to the growing or harvesting of agricultural crops or the production of agricultural commodities; (b) synonym for a "farm" as defined in ORS 30.930(1).
(5) "Area Plan" or "Agricultural Water Quality Management Area Plan" means a plan for the prevention and control of water pollution from agricultural activities and soil erosion in a management area that has been designated under ORS 568.909.
(6) "Area Rules" are administrative rules adopted by the Oregon Department of Agriculture, in consultation with the Oregon Board of Agriculture and the Oregon Department of Environmental Quality, for the implementation of the Area Plans referenced in these rules.
(7) "Certifier" means a qualified irrigation and nitrogen management plan specialist as provided in OAR 603-XX-XX14.
(8) "Compost" has that meaning given in ORS 633.311(5).
(9) "Department" means the Oregon Department of Agriculture.
(10) "Director" means the director of the Oregon Department of Agriculture.
(11) "Estimated crop yield" means the near-maximum or optimum crop yield estimated for each field according to sources such as recommendations by land grant universities, the Natural Resources Conservation Service, commodity groups, or according to site-specific knowledge based on previous experience.
(12) "Fertilizer" has the meaning given in ORS 633.311(12).
(13) "Field" means an area of land that is used for agricultural activities and enclosed or otherwise marked by a physical, topographical or other boundary.
~~(13)~~ "Management unit" means a defined portion of a farm or agricultural operation that is managed consistently with respect to crop selection, irrigation practices, and nutrient application decisions.
(14) "Groundwater" or "groundwater of the state" means water within the LUBGWMA that is in a saturated zone or stratum beneath the surface of land or below a surface water body.

(15) “Irrigated agricultural lands” or “irrigated agriculture” means agricultural lands irrigated to produce crops or pasture and including lands that are planted to commercial crops that are not yet marketable such as vineyards and tree crops. Irrigated lands include nurseries.
(16) “Landowner” has the meaning given in ORS 568.210 and ORS 568.903 and includes an “operator” as defined in ORS 568.900(2).
(17) “Manure” means solids or liquids excreted from an animal.
(18) “Nitrogen Management Measures” means measures to match fertilizer and nitrogen applications to agronomic demands and includes a determination of the appropriate agronomic application rate to achieve estimated crop yield. Nitrogen management measures include the 4Rs of nutrient stewardship as provided in NRCS Conservation Practice Standard Nutrient Management Code 590 (2019).
(19) “Operator” has the meaning given in ORS 568.200(2).
(20) “Pasture” means land that sustains vegetative growth in the normal growing season that is primarily used to grow forage for grazing livestock where the livestock are not confined in pens or lots or on a prepared surface and where waste is not managed using a waste water control facility.
(21) “Pollution” or “water pollution” has the meaning given in ORS 468B.005.
(22) “Saturated soil” means soil with all available pore space filled that has reached its maximum retentive capacity.
~~(22)~~ “Water holding capacity” means the amount of water retained by the soil without additional downward movement of water through the soil profile.
(23) “Synthetic fertilizer” means fertilizer made from ammonia, nitrogen, phosphate minerals, and other chemicals through human-controlled chemical reactions. Synthetic fertilizers include dry fertilizer, liquid fertilizer, foliar fertilizer, and any other type of fertilizer that has a guaranteed nutrient content.
(24) “Waste” or “wastes” has that meaning given in ORS 468B.005 with the clarification that waste or wastes includes but is not limited to commercial fertilizers, soil amendments, composts, animal wastes, vegetative materials and includes nitrate that enters groundwater by any means.
(25) “Water” or the “waters of the state” has the meaning given in ORS 468B.005.

603-XX-XX04
Prohibited Acts
[This rule applies to all landowners in the LUBGWMA]

(1) The discharge of waste to the groundwater of this state from agricultural activities is prohibited.
(2) Wastes may not be placed in a location where such wastes are likely to escape or be carried into groundwater by any means.
(3) The discharge of fertilizers, fumigants, or pesticides into groundwater via back flow through a water supply well is prohibited.
(4) The discharge of fertilizers, fumigants, or pesticides down a groundwater well casing is prohibited.
(5) A landowner within the LUBGWMA may not violate the provisions of 603-XX-XX05.

603-XX-XX05
Land Application Rates and Restrictions
[These rules apply to all landowners within the LUBGWMA]

(1) A landowner shall employ nitrogen management measures when making land applications of synthetic fertilizers, compost or manure.
(2) Before Prior to the first calendar year application of synthetic fertilizers, compost or manure may be applied a landowner shall:
(a) Take soil samples consistent with [SOIL SAMPLE PROTOCOL RULE]; and
(b) Take into consideration existing plant available nitrogen levels and estimated crop yields when making an application of fertilizers, compost, or manure.
(3) A landowner shall document, and upon request by the department make available for inspection, the following for each field to which synthetic fertilizers, compost, or manure are applied:
(a) The date(s) and location(s) of all nitrogen applications;
(b) The weather conditions and soil moisture at the time of application; and
(c) The agronomic application rate used.
(4) A landowner shall prevent the downward movement of nitrate in the soil by managing irrigation water so that the amount of water applied from the combination of precipitation and irrigation does not exceed the water holding capacity of the soil beyond the crop root depth.
(5) A landowner may not apply synthetic fertilizers, compost, or manure in a manner that causes direct, indirect, or precipitation-related discharge to groundwater.
(6) A landowner may not apply synthetic fertilizers, compost, or manure:
(a) To fields with a frozen surface crust (2 inches) or deeper, or if the soil is at or below zero degrees Celsius (32 degrees Fahrenheit).
(b) To fields that are snow covered.
(c) To fields with soils that are or will become saturated with forecasted precipitation within 24 hours, where the application is likely to result in a prohibited act. prior to infiltration or incorporation.
(d) If the water table is within 12 inches or less to the surface.
(e) If precipitation is forecasted in the next 24 hours for the field location and it is likely that application will result in a prohibited act.
(f) To fields that are bare unless the landowner is preparing the bare fields for the current year's annual crop planting and the application is within 30 days of planting.

603-XX-XX06
Animal Pasturing
[This rule applies to all landowners within the LUBGWMA]

(1) A landowner grazing livestock on pasture within the LUBGWMA shall rotate livestock and limit livestock numbers to prevent bare ground and promote and maintain adequate vegetative cover.
(a) In determining an appropriate stocking rate for livestock grazing on pasture, a landowner shall match livestock requirements with the available forage and frequently monitor forage growth and adjust the stocking rate and grazing period to prevent runoff or overgrazing.
(2) Where animals are concentrated to a distinct heavy use area during the rainy season, when the soil is prone to compaction or when inadequate forage growth would result in over-grazing, a landowner shall remove manure and waste feed from these areas and maintain a 35ft vegetated buffer strip down-gradient from grassy buffer strips around the area.
(3) A landowner applying synthetic fertilizer, compost, or manure to irrigated pasture shall conduct nutrient management in a manner that prevents the over-application of nitrogen and reduces the likelihood of nitrate leaching to groundwater.

OSU provided this reference in response to the draft rules.

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To: MOULUN Renee * ODA <Renee.MOULUN@oda.oregon.gov>
Subject: Fwd: OSU LUBGWMA Working Group - Report 1

Hi Renee,
Amber Moore provided me with the link and the PDF of the publication you were missing.
Regards
Carlos

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REPORT

Application of forensic hydrology to develop a conceptual model for a stratigraphically and structurally compartmentalized alluvial aquifer in the Lower Umatilla Basin, USA

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Abstract
Alluvial deposits provide vital freshwater aquifers, necessitating a detailed understanding of sustainable groundwater management. Frequent reassessment of aquifer permeability is crucial to address spatial heterogeneity to refine or revise historical hydrogeologic models. From a geologic perspective, the recognition of aquifers as being inherently heterogeneous is essential for the integration of historical geologic context into studies, can overcome the limitations of traditional homogeneous models, and update existing conceptual models with new data to test alternative hypotheses. Fine-scale spatial and temporal variability can reveal behaviors that homogeneous models cannot predict, leading to more accurate models for contaminant transport and site characterization. This study applied a forensic hydrology framework with multiple working hypotheses to investigate spatial variability and heterogeneity of the alluvial aquifer in the Lower Umatilla Basin Groundwater Management Area (Lower Umatilla Basin GWMA), Oregon, USA. Previously unrecognized channeled filled belts (CFBs) containing low-permeability, fine-grained deposits that act as potentially serviceably impermeable barriers to groundwater flow. Seven geological cross sections were created using well logs from the State of Oregon well database. Findings suggest that CFBs, folds, and faults may have compartmentalized the aquifer, influencing groundwater flow patterns. Steep hydraulic gradients support the presence of potentially serviceably impermeable barriers. The clustering of mean groundwater levels within aquifer compartments led to the development of a new hydrogeologic conceptual model (here termed conceptual model 2), potentially revealing new groundwater flow directions in the GWMA. These findings will aid in further investigation into groundwater management challenges within the GWMA through data collection and numerical modeling.

Keywords Forensic hydrology · Alluvial aquifers · Channelled filled belt · Groundwater flow · USA

Introduction

The ever-increasing abstraction of groundwater from heavily stressed aquifers, driven by erratic precipitation and more frequent and severe droughts, has exacerbated the degradation of this globally important resource (Gautam et al. 2023; Schiavo 2022; Sehgal et al. 2021; Fishman et al. 2011). Because of their widespread occurrence and low development costs, shallow alluvial aquifers are globally important groundwater abstraction sources for agricultural, industrial, and domestic applications (Gholami et al. 2015; Liu et al. 2014; Mohammed et al. 2014). In addition, the baseflow, derived from alluvial aquifers, regulates the river ecosystem and overall catchment outflow (Käser and Hunkeler 2016). Groundwater quality and quantity of shallow alluvial aquifers can be influenced by natural and anthropogenic factors such as hydrodynamic characteristics, permeability architecture and structural geology of the aquifer, geogenic and legacy contaminant leaching from the vadose zone, quality of natural and artificial recharge water, domestic and industrial wastewater management, agricultural practices of a region, and implementation of best management practices (Mohammed et al. 2014). These factors can perturb fragile alluvial aquifer systems, potentially limiting groundwater availability (Jang and Chen 2015; Arauzo et al.

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2011), and may increase the risk of contaminants migrating to deeper aquifers and surface-water bodies, causing socio-economic and ecological problems.

Hydrogeological conceptual models, which consist of hypotheses explaining groundwater systems, are significant sources of uncertainty in groundwater flow and transport modelling. To address this uncertainty, two major approaches are commonly used—the consensus model approach and the multimodel approach. The consensus model approach integrates all available data and expert knowledge into a single model, progressively refining it to represent the current understanding of the system. This method aims to reduce conceptual uncertainty by increasing model complexity, though it can become computationally demanding and intractable. This approach is useful for starting new models based on new hypotheses and refining them as more data becomes available. Conversely, the multimodel approach involves developing an ensemble of different conceptual models, each representing an alternative or overlapping hypothesis. This method is particularly beneficial in data-scarce environments as it reduces the likelihood of conceptual surprises and provides a more comprehensive understanding of the hydrogeological system by considering multiple plausible scenarios. Instead of viewing these models as competing or dueling, this approach highlights that no single model is "true." Each model embodies assumptions and uncertainties that must be resolved through further study and data collection. In practice, the comparison of multiple conceptual models can evaluate different observations, enhancing the understanding of groundwater systems by systematically testing alternative models. Ground truthing is essential to accept, reject, or modify any hypothesis and its corresponding conceptual model. This iterative process increases confidence in model predictions and provides a more reliable basis for informing sustainable management decisions, ensuring that models remain robust and adaptable as new data and insights emerge (Enemark et al. 2019; Brassington and Younger 2010; Neuman et al. 2003).

An accurate and reliable hydrogeologic conceptual model of alluvial deposits in the floodplains of large river systems has immense potential to address the aforementioned challenges by identifying the boundary conditions, hydrologic sources, and sinks for the flow and transport in an aquifer system (Dalla Libera et al. 2020). However, spatial heterogeneity and anisotropy in the vertical and horizontal structure and distribution of aquifer materials make it challenging to develop hydrogeologic conceptual models for massive alluvial aquifer systems. This gives rise to extensive simplifications through assumptions on sedimentary architecture and hydraulic properties of alluvial deposits by conceptualizing them as homogeneous and isotropic, which leads to high prediction uncertainties and reduced reliability of the conceptual model (Christiansen et al. 2011). Additionally, the scale of the study largely regulates the discretization and boundary conditions of the conceptual model (Morway et al. 2013). This oversimplification surprisingly overlooks the finer-scale flow processes in aquifer systems, leading to impractical long-term planning and decision-making for addressing groundwater issues. Therefore, the new hydrogeologic conceptualization with stratigraphic and hydrologic compartmentalization, which divides aquifers into discrete and relatively isolated hydrologic units, addresses the problem of oversimplification, making the flow and transport model reliable in long-term sustainability-related decision-making (Rhodes et al. 2017). The study area for this investigation is characterized by scablands associated with megafloods of the Columbia River in northeast Oregon, USA (Bretz 1925; O'Connor et al. 2020). Compartmentalization might address key research questions, such as whether the tacit assumption that the alluvium underlying the scablands is homogeneous and isotropic is accurate, and whether the degree of compartmentalization in the alluvium justifies the observed degradation in groundwater quantity and quality.

Understanding the paleogeography of sedimentary basins necessitates an integrated approach that combines sedimentology, stratigraphy, tectonics, and diagenetic relationships of the sedimentary successions filling the basin (Hiatt 2000). Stratigraphic compartmentalization arises from stratigraphic heterogeneities and can be categorized into microscopic (pore/grain-scale), mesoscopic (well-scale), and macroscopic (inter-well-scale) levels, where interwell-scale heterogeneities encompass lateral bed discontinuities caused by stratigraphic pinch-outs and erosional cut-outs (Ejeke et al. 2017). The recognition and modeling of aquifer/reservoir compartmentalization by integrating well logs and geophysical data for a robust interpretation, is quite common in petroleum and gas industries, for optimum reservoir prediction, and development for reliably modeling reservoir compartmentalization (Ejeke et al. 2017). An example is the Bell Creek oilfield in southeastern Montana, USA, where a revised model of a compartmentalized reservoir (channel belt), initially leading to significant oil discoveries in the 1960s, is now used for carbon sequestration, utilizing low permeability seals provided by abandoned channel fills (mud plugs) in the sedimentary reservoir rocks (Sharaf and Sheikha 2021).

Similarly, there have been several attempts to characterize alluvial successions to understand the various processes regulating groundwater variability and heterogeneity in alluvial aquifer systems using a wide array of methods. This includes probabilistic (Schiavo 2022), machine learning, geochemical modeling, and combined tracer-numerical modeling (Dalla Libera et al. 2020; Liu et al. 2014; Mohammed et al. 2014; Sharif et al. 2008), dendrochronology (Gholami et al. 2015), coupling hydrogeophysics with hydrodynamic modeling (Martin et al. 2021), hydrogeophysical imaging

(Mele et al. 2012), hydrogeochemical variability, seismic structural study, hierarchical cluster analysis and geostatistical methods (Chihi et al. 2015), and modern data-driven approaches like dynamic factor analysis and wavelet analysis (Oh et al. 2017). Some researchers have attempted to compartmentalize alluvial successions using structural geology approaches by accounting for folds and faults (Mohamed and Worden 2006), the relationship between tectonic structures and hydrogeochemical compartmentalization in aquifers (Mele et al. 2012), and intermittent clay layers regulating the spatial extent and connectivity of vertical compartments in regards to collecting and transmitting the precipitation water to streams (Martin et al. 2020). Therefore, developing conceptual models for alluvial aquifers is essential for integrating multiple structural geologic features, as this approach helps to better understand groundwater variability, heterogeneity, and compartmentalization, ultimately enhancing water resource management and predictive modeling.

The river channel belt is the corridor formed during one river avulsion cycle and includes the active river channel and associated bars, the immediate overbank with levees and lateral splays, and abandoned channel reaches from events like meander cut-offs. The channel belt may feature various channel morphologies (straight, sinuous, meandering, braided, or anabranching) and includes point bars, mid-channel bars, and lateral bars (Nyberg et al. 2023). In a recent study, Nyberg et al. (2023), revealed that river channel belts, encompassing levees, bars, splays, and overbank landforms, cover a global surface area of 30.5×10^5 km^2, seven times larger than river channels. Their study emphasizes that understanding and incorporating channel belts into flood mitigation, freshwater management, and ecosystem accounting is crucial for predicting river behavior and managing freshwater resources. Furthermore, Rhodes et al. 2017 identified that abandoned river channels filled with silt (mud plug) can potentially act as hydraulic barriers. These barriers can disconnect river bank storage from the main alluvial aquifer system in floodplains and restrict flow between the aquifer and the river when the water table is higher than the river stage. Although the analyses presented in these studies were data-rich, a comprehensive basin-scale investigation of how stratigraphic heterogeneities and compartmentalization within alluvial successions influence groundwater variability and connectivity is limited. Such a study holds immense potential for improving qualitative and quantitative groundwater development-related decision-making beyond mere scientific discovery.

A careful review of past studies reveals limited efforts to assess the compartmentalization of alluvial aquifers formed by successive megafloods characterized by cut-fill phenomena and abandoned channel fills. In this study, the abandoned channel-fills with low-permeability fine-grained deposits (mud-dominated channel abandonment facies), because of successive cut-fill associated with megafloods and slack water deposits, are referred to as channeled filled belts (CFBs). A few studies have been conducted to investigate vertical and horizontal compartments separately. The Pleistocene megafloods significantly shaped the Channeled Scablands of the Columbia River Basin and Umatilla Basin, Oregon, USA. These cataclysmic events eroded the basalt bedrock and overlying sediments, creating a complex landscape of anastomozing channels, cataracts, streamlined hills, rock basins, and immense gravel bars at basin-to -regional scales. This flooding transformed preexisting valleys into a network of channels, profoundly altering the landscape and influencing the distribution of groundwater resources in the region (Baker et al. 2016). However, the effectiveness of CFBs in compartmentalizing entire floodplains because of low-permeable deposits remains understudied, despite Bretz (1925) previously delineating potential regions for CFBs in the Columbia River basin (Figure S1 of the electronic supplementary material (ESM). CFBs are extensive zones where multiple abandoned or low-flow river channels have been filled with heterogeneous sediments over time, reflecting complex depositional processes and past river dynamics. These belts significantly influence groundwater flow and storage because of their varied sediment types and structures, making them crucial for understanding spatial heterogeneity in aquifers and achieving effective groundwater management such as sustainable extraction and managed aquifer recharge practices (Bridge 2003). In addition, in the scablands, the massive erosion and deposition from the megafloods would have significantly altered the landscape, potentially impacting the distribution and integrity of serviceably impervious barriers (Baker et al. 2016). Serviceably impervious barriers are geological strata that, while not entirely impermeable, effectively restrain most water movement under normal conditions. These barriers contain small pores, microscopic seams, and larger cracks in soil pedon scales, allowing some water to pass through, yet they still function as reliable confining layers in hydrogeological contexts. Despite some leakage, they successfully maintain hydraulic gradients and support the formation of artesian wells (Bredehoeft et al. 1983). Therefore, it is recognized that evaluating sedimentary architecture, and structural geology that can produce serviceably impervious barriers, topography, and groundwater levels (GWL) will help further refine the spatial heterogeneities and conceptualize a compartmentalized alluvial aquifer (Enemark et al. 2019). Understanding compartmentalization in these alluvial aquifers is crucial for sustainable groundwater management, as it helps in identifying distinct hydrogeological units that can impact groundwater flow, storage, and recharge efficiency.

Forensic hydrology, which systematically analyzes cause–effect relationships in complex hydrological settings, provides a novel approach to understanding groundwater systems (Hurst 2007; Lischeid et al. 2017). Applying this methodology to the development of a conceptual model for megaflood-induced scabland basins is crucial, given the challenges posed by the lack of relevant data. This approach will enhance the identification of potential aquifer compartments within the alluvium, segmented into discrete and relatively isolated subbasins based on sedimentary architecture and structural geology. The objective of this consensus conceptual model development includes the delineation of potential compartments using the spatial variability in the permeability architecture of alluvial successions, structural geology, and groundwater levels. This study aims to improve the understanding of groundwater flow directions in alluvial deposits, thereby supporting more effective water resource management at the study location, the Lower Umatilla Basin groundwater management area, in Oregon USA. In 1995, for the first time, a conceptual model, hereafter referred to as conceptual model 1, was developed for the Lower Umatilla GWMA by various agencies in Oregon (Grondin et al. 1995). This study aimed to develop a new conceptual model, hereafter referred to as conceptual model 2, using the additional geological information collected over the last 25 years (1995–2023) and the pre-1990 information available at the basin, by employing multiple working hypotheses and a forensic hydrology approach.

Materials and methods

Study area

The Oregon Department of Environmental Quality (DEQ) has designated three groundwater management areas (GWMAs) within the alluvium of the Columbia, Willamette, Owyhee and Malheur, and Umatilla River systems in response to elevated nitrates in groundwater (Fig. 1). The present study focuses on the Lower Umatilla Basin GWMA, which falls within the Morrow and Umatilla counties of northeastern Oregon, USA. The Lower Umatilla Basin GWMA extends from 45˚41′30″ N to 45˚56′4″ N latitudes and from 119˚59′59″ W to 119˚7′12″ W longitudes with a total geographic area of 1454.58 km^2 (562 mi^2). The climate of the Lower Umatilla Basin GWMA is characterized by cool, dry winters and hot, dry summers, with average daily temperatures ranging from 0.11 °C in January to 23.16 °C in July (Gautam et al. 2023; Herrera et al. 2017; Yazzie and Chang 2017; DEQ 1995, 2007). Annual precipitation varies from about 203 mm (8 inches) near the river to about 254 mm (10 inches) near the southern boundary of the Lower Umatilla Basin GWMA (DEQ 1995), showing an elevation range of approximately 84–305 m or 259–1126 US feet (ft) (Fig. 1). About 70% of the annual total falls from October through March (DEQ 1995). The Lower Umatilla Basin GWMA encompasses significant hydrogeological features, including the expansive Columbia River and its floodplain, shaped by some of the world's largest flood events. The alluvial deposition found in this region can be traced back to "Bretz's floods," which were composed of several megaflood events (Figure S1 of Bretz 1925). It also includes run-of-the-river hydroelectric generation from Umatilla Lake and Wallula Lake, associated with the John Day and McNary dams. Cities of Boardman, Irrigon, Umatilla, Hermiston, Stanfield, and Echo are within the Lower Umatilla Basin GWMA that support agricultural land use via wastewater treatment and land applications, confined and unconfined animal feeding operations, open pasture livestock rearing, food production industries, as well as defense-related installations such as an ordnance depot, and bombing range.

Hydrogeological data collection and preprocessing

To achieve a better understanding of the aquifer system of the study area, the methodology as depicted in Fig. 2 was followed. The first phase comprised identifying important hydrologic sources, sinks, and boundaries at the study area, including the Umatilla River, Cold Spring Canyon River, Butter Creek, Juniper, and Six Mile Canyons, along with Carty and Cold Spring reservoirs, wetlands, folds, and faults (Fig. 3). Unlike other areal water bodies, the Juniper Canyon exhibits stagnant water patches rather than a continuous flow, likely comparable to the wetlands found near the city of Boardman. Lake Umatilla covers a significant portion of the northern boundary, while Lake Wallula marks the northeastern boundary of the Lower Umatilla Basin GWMA downstream to the Wallula Gap—Waltham (2010), Figure S2 of the ESM. Folds and faults presumed to have disrupted the deposition of the alluvium are depicted in Fig. 3. The second phase was to collect all publicly available geological data in the study area, including existing maps, borehole logs, and cross-sections to define the boundaries of the aquifer. The green circles in Fig. 3 represent the wells reported to the Oregon Department of Water Resources (OWRD) as of February 2023, available through their public online database platform, the Groundwater Information System (GWIS). The well logs used in this study to understand the hydrogeological settings of the Lower Umatilla Basin GWMA were also collected from the GWIS well report query. In addition, a large number of publicly available technical reports from various state agencies and local and federal institutions were used to collect additional geological information.

Figure 4 illustrates the history of well-drilling activities in Lower Umatilla Basin GWMA, revealing a doubling of wells since 1995, provides additional geological information collected over the last 25 years (1995–2023) for improving the conceptualization of the region. Figure 5 shows the six cross-section lines used in conceptual model 1—details

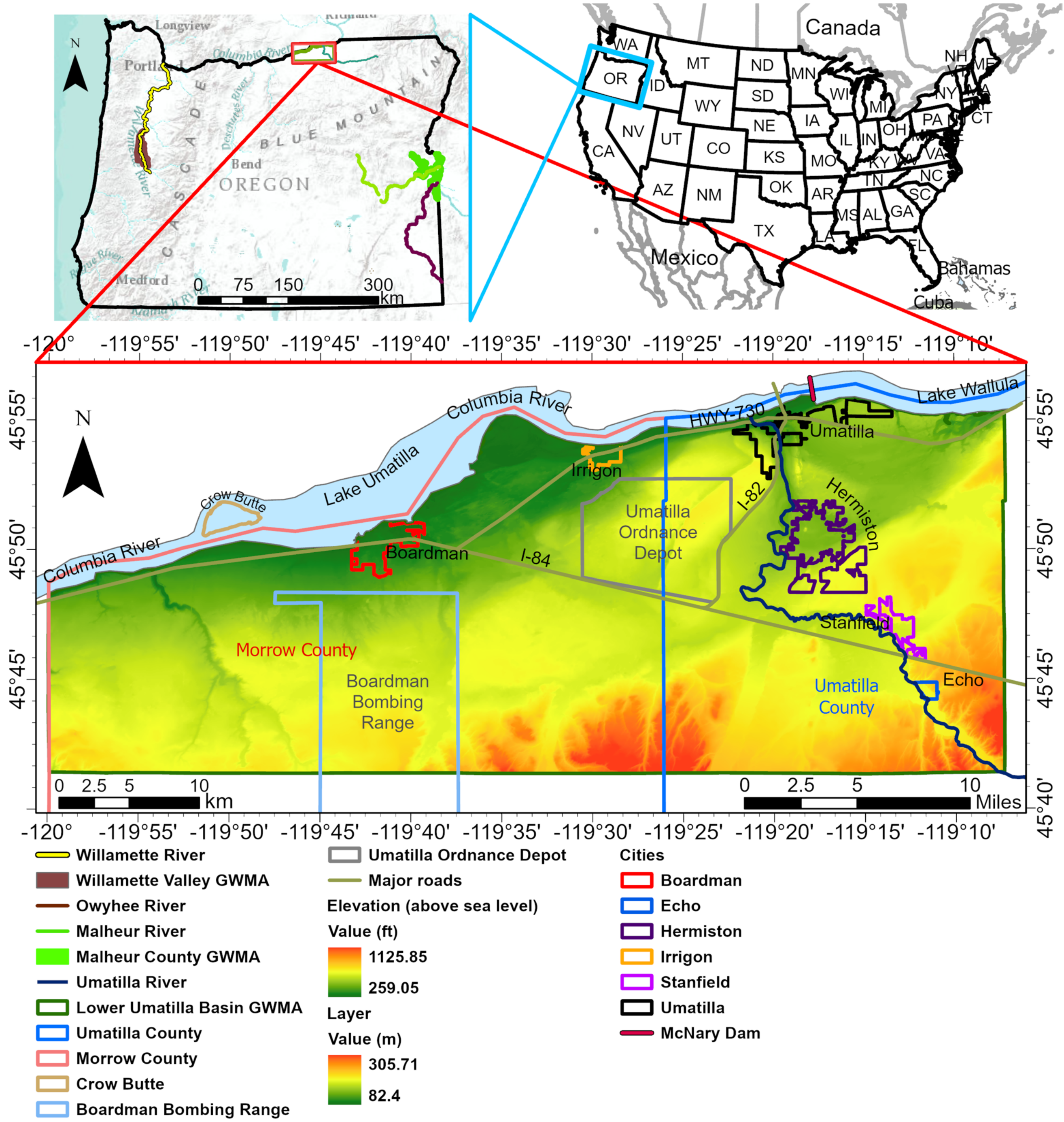

Fig. 1 Oregon's three major river systems associated with groundwater management areas (GWMAs). The study GWMA, Lower Umatilla Basin GWMA, in northeast Oregon is highlighted, showing its topography (elevation above mean sea level, AMSL) and key geographical features

can be found in the ESM and Grondin et al. (1995)—along with an additional CS line, GG′, used in this study (conceptual model 2) to obtain the longitudinal cross-section of the Lower Umatilla Basin GWMA. The circles with color codes represent the wells used for the corresponding cross-section lines. Publicly available drilling logs for 174 wells representing the seven CS, were extracted from the well reports archived in the OWRD well-log database to construct geologic cross-sections along the indicated lines. Most well logs were only available as handwritten scanned documents, and these data were transcribed into an Excel spreadsheet for hydrogeologic analysis. As depicted in Fig. 5, all the cross-section (CS) lines, except AA′, incorporate a large number of projected wells to enhance, rather than replicate, the

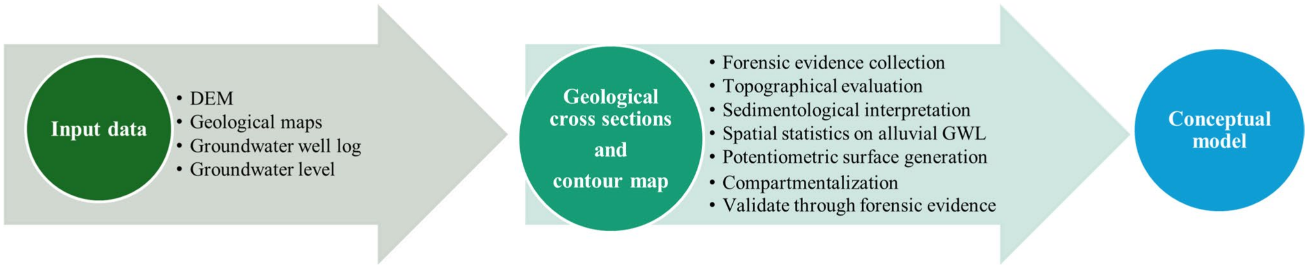

Fig. 2 Methodological chart showing the required data and procedural steps for developing a conceptual model to delineate the potential hydrogeological compartments and channeled filled belts in the Lower Umatilla GWMA

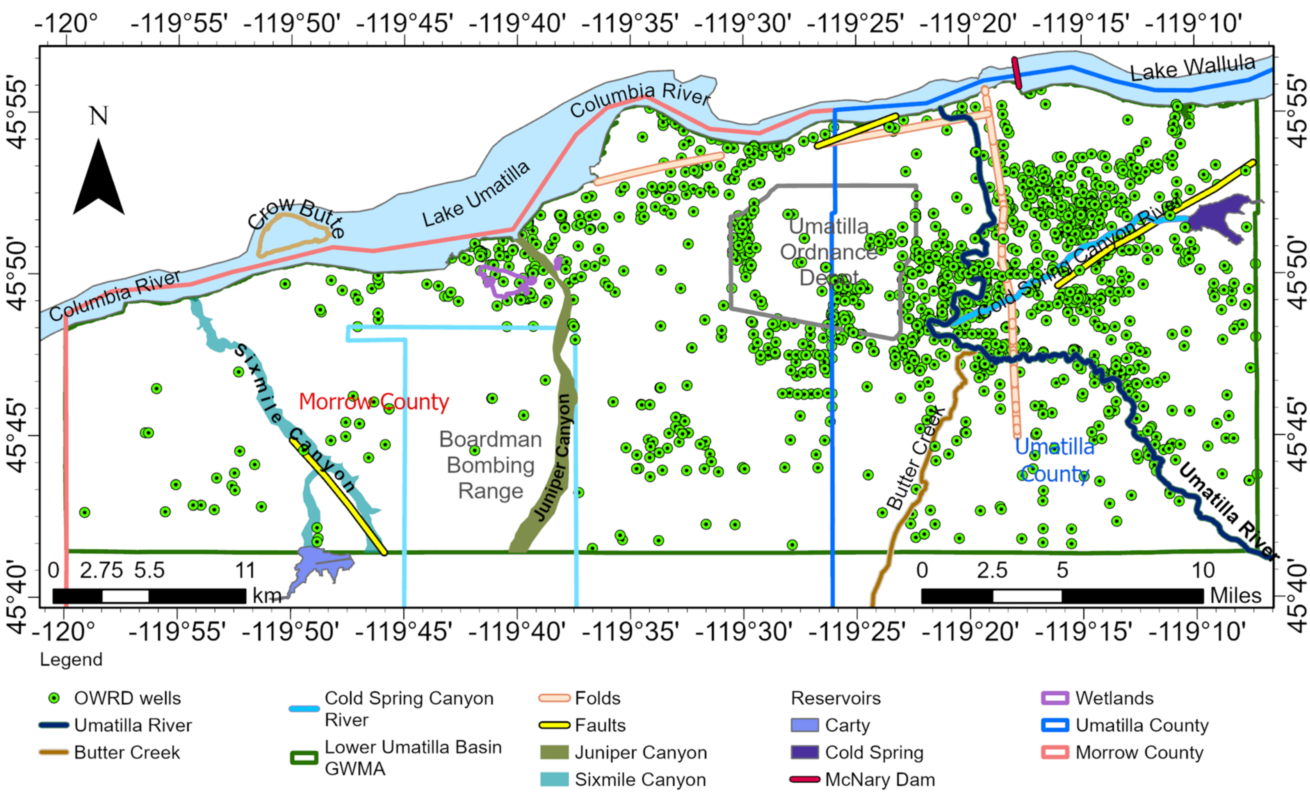

Fig. 3 The hydrogeologic features and county boundaries of the Lower Umatilla Basin GWMA. The green circles indicate the locations of the wells collected from the Oregon Department of Water Resources as of February 2023, available through their public database platform, the Groundwater Information System

geologic cross-sections drawn in 1995. Cross-section AA′ has fewer wells because the alluvial aquifer pinches out in the western part of the study area. The well logs, which detail depth ranges from the Earth's surface alongside the corresponding lithology, had varying nomenclatures for the stratigraphies as observed by multiple drillers. This study standardized the well logs for all cross-sections (CSs) by analyzing these varied stratigraphies. It should be noted that additional wells may exist within the study area that are not documented on the public website; collecting such information was beyond the scope of this study. Consequently, data from unreported wells or data that are not available on public online platforms were not included in the current research phase. However, the authors plan to continue data collection efforts and further evaluate the proposed conceptual model in future studies to enhance its accuracy and effectiveness.

Focusing solely on the alluvial formation and the wells tapping into it, GWL data for 660 alluvial wells were extracted on February 7, 2023, from the OWRD's GWIS online database, comprising 339,879 wells for the entire State of Oregon. A total of 660 wells were identified for the study site with water level data, and the downloaded data

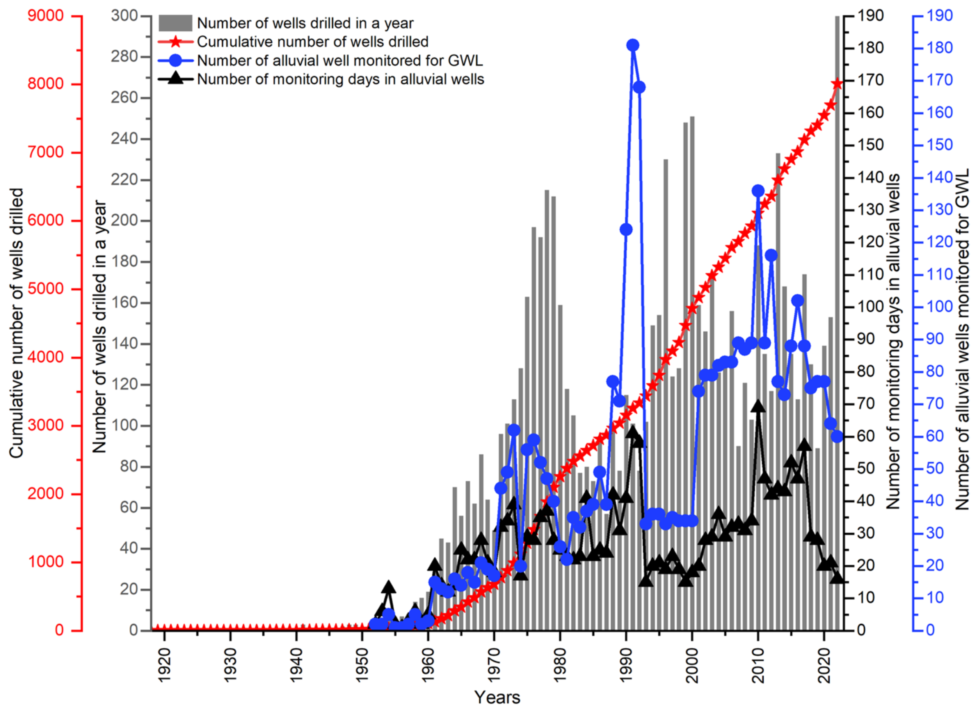

Fig. 4 Historical summary of well-drilling activity in the Lower Umatilla Basin GWMA between 1918 and 2023

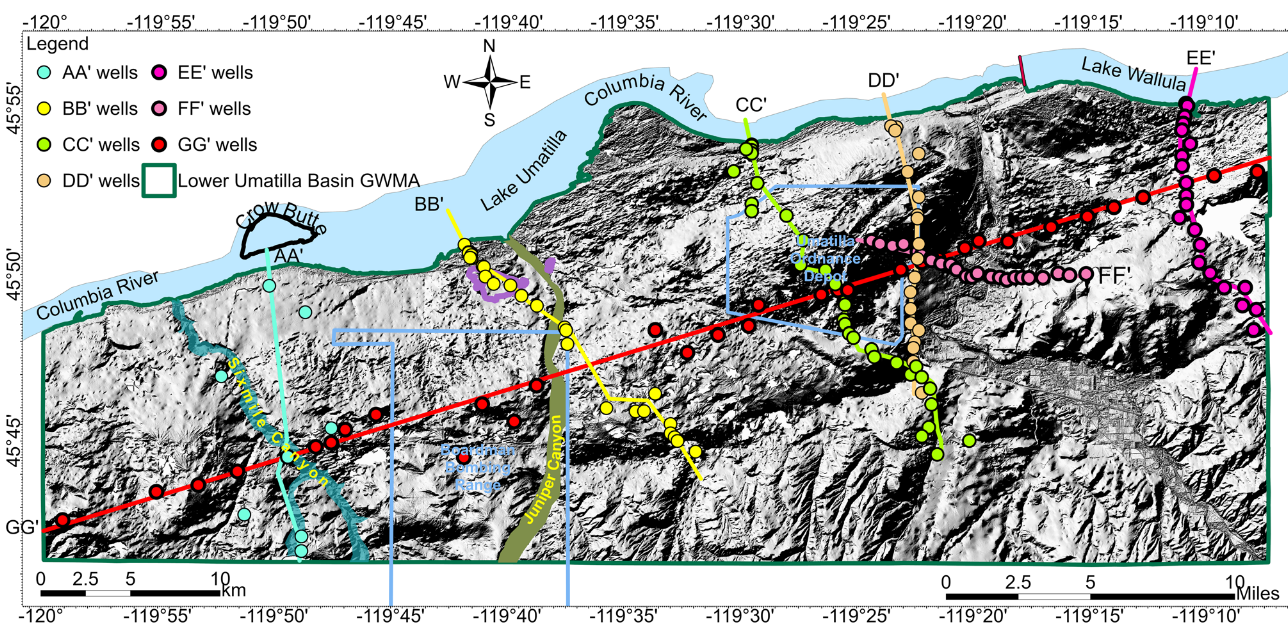

Fig. 5 The six cross-section lines utilized in conceptual model 1 (further details can be found in the ESM and Grondin et al. (1995), along with the GG', which is an additional CS line used in this study (conceptual model 2) to obtain the longitudinal cross-section of the Lower Umatilla Basin GWMA. The circles are color-coded to represent the wells that were used to construct the corresponding cross sections

were formatted to organize the measurements for individual dates corresponding to 660 well IDs. Statistical analysis was conducted on the monitoring activities from the beginning of GWL monitoring in the Lower Umatilla Basin GWMA in 1952 until 2023 (Fig. 4). Notably, the highest total number of wells monitored in a single year peaked at 181 in 1991, followed by 168 in 1992. Despite numerous monitoring campaigns (black triangles in Fig. 4) performed in individual years, the total number of monitored wells fell below 100 in most years. However, around 19 recorder wells (wells with pressure transducers) are present that have been collecting daily water levels over the last 12 years, as shown in

Figure S12 of the ESM. This highlights the limited daily and monthly coverage of data from the monitoring wells in the Lower Umatilla Basin GWMA. Therefore, this study focused on GWL data collected in the form of the GWIS Sheet from the OWRD's GWIS online database, comprising 339,879 wells for the spatial analysis presented.

The digital elevation model (DEM) for the Lower Umatilla Basin GWMA was extracted from the United States Geological Survey (USGS) 10-m LiDAR data (United States Geological Survey 2021). These data were used to develop the surface profile for the CS lines and investigate the surface impressions of CFBs using ArcGIS software (ArcGIS Pro, ESRI). There were multiple anticlines and normal faults present in the Columbia River Basalt (CRB) in the vicinity of the Lower Umatilla Basin GWMA based on the Oregon Geological Data Compilation (OGDC)-Release 6 (Smith and Roe 2015). The development of conceptual model 2 only considered the features having surface expression disrupting the shallow aquifer system (Fig. 3) with the potential to impact the groundwater circulation in the alluvial aquifer system.

Forensic hydrology, multiple working hypotheses, and compartmentalization

The analysis of nitrate trends in the Lower Umatilla Basin GWMA reveals that concentrations have remained relatively static or increased at specific locations over the past 30 years, despite the implementation of best management practices. The analysis is limited by data gaps, irregular monitoring frequencies, and the lack of incorporation of detailed aquifer hydrogeology (Richerson 2012), which hinders the ability to perform large-scale numerical models for accurate nitrate mass balance. To improve future evaluations and recommendations, there is a critical need to develop a comprehensive understanding of the basin's hydrogeological framework using new and readily available information to identify data gaps, implement a new monitoring network, identify the best management plan informed by local-to-plot-scale hydrogeological makeup, integrate nitrate data, and develop a basin-scale numerical model. Therefore, this study employs a forensic hydrology approach to investigate and understand the perplexing spatiotemporal observations of nitrate concentrations in the Lower Umatilla Basin GWMA groundwater.

Forensic science has recently expanded as the scientific community is increasingly called upon to analyze the chronology of anthropogenic or natural activities. This involves detecting, recognizing, recovering, examining, and interpreting evidence to understand suspicious events causing social and environmental crises in the field of environmental forensic science (Gutierrez-Lopez 2022). The insurance industry requires experts in hydrological processes to evaluate triggers of crises such as floods, flash floods, mudflows, landslides, catastrophic failures of hydraulic works, overflows of drains, canals, and lagoons, fluvial alterations, and soil and aquifer contamination, a field commonly referred to as forensic hydrology (Zarei et al. 2023; Delpasand et al. 2021; Ruffell et al. 2017; Gallego et al. 2016; Graham et al. 2010).

The Lake Missoula flood, initially dismissed because of its perceived "Biblical" scale, was later confirmed following geological investigations of the Channeled Scablands in eastern Washington, an event significantly impacting the landscape of eastern Washington, the Columbia Gorge, and the Willamette Valley in Oregon. Early studies by Bretz identified multiple flood events, with subsequent research by Waitt suggesting 40 floods based on rhythmites in the Walla Walla Valley and Atwater documenting over 89 floods from the Sanpoil River Valley. These findings pointed to recurring floods over approximately 3000 years. In contrast, Shaw and colleagues, in the 1990s, presented evidence supporting a single major flood event, consistent with Bretz's original hypothesis (Waitt Jr 1980; Atwater 1987; Shaw et al. 1999). These varying interpretations underscore the challenges inherent in validating hydrological conceptual models that encompass both paleogeographical and modern hydrogeological data. Forensic hydrogeological investigations are essential in such contexts, particularly when assessing complex megafloods, as they enable the refinement of groundwater flow and storage models in alluvial aquifers through comprehensive ground truthing and data collection (Markwick 2019; Bretz 1925; Martin 2021).

Revisiting the hydrogeology of the Lower Umatilla Basin GWMA aimed to accumulate evidence and new information through systematic hydrologic research activities. This study employed advanced GIS tools, Excel and Python script-based large-data processing and remote-sensing data products to enhance the efficiency of the existing investigation, interpretation, visualization, and mapping, with scientists and engineers acting as "geodetectives" to uncover new insights (Gutierrez-Lopez 2022; Lischeid et al. 2017; Ribaux and Talbot Wright 2014). Conceptual Model 1—Grondin et al. (1995); Figure S3 of the ESM—and subsequent studies in the area were reevaluated using new interpretations from recent literature on the compartmentalization of alluvial groundwater systems recognized globally (Martin et al. 2020; Rhodes et al. 2017; Mohamed and Worden 2006). This integrated approach aims to address the limitations of previous studies by incorporating detailed hydrogeological data and modern analytical techniques to develop a more accurate and effective model for managing groundwater resources in the Lower Umatilla Basin GWMA.

The CFB conceptual model presented in this study (conceptual model 2) was designed to build upon, rather than duplicate, conceptual model 1, following the tradition of multiple working hypotheses suggested by T.C. Chamberlin in the late 1880s. The idea of potential groundwater compartments in the alluvial deposits of the Lower Umatilla Basin GWMA is not new; Bretz (1925) identified the channels in the study area. The presence of CFBs was mapped in conceptual model 1 via geologic cross-sections, steep hydraulic gradients indicated by closely spaced groundwater level contours (as described by Rhodes et al. 2017), age difference between the well waters sampled by Frans et al. (2009) in the central region of the Lower Umatilla Basin GWMA, and surface impressions of the channels through DEMs of the GWMA.

From a forensic hydrologic perspective, the working hypotheses formulated to trace the potential low permeable regions or barriers observed through hydraulic gradients included:

1. *Folds and Faults*. These can act as potential zones of low permeability that impede both surface-water flow during flooding events and subsurface groundwater flow. In such cases, the permeability architecture of the alluvium may be hydraulically disrupted, or the sedimentation process modified by folding.
2. *Buried, channeled filled belts*. These structures, with deposits of low permeable materials, can function as hydraulically connected or disconnected entities and may serve more as zones of low permeability rather than conduits to groundwater flow. Fine-scale heterogeneity may create localized hydraulic connections, but these need to be confirmed through ground truthing.
3. *Flood kinetic energy*. The kinetic energy of floodwaters in the scabland region regulates the deposition of coarse- and fine-grained materials.

In this study, all of the aforementioned low permeable geological features are referred to as potentially serviceably impermeable barriers, which significantly limit groundwater flow under very low, negligible, or no flow conditions, potentially creating, in geological years, hydraulically disconnected areas. These low permeability zones can lead to heterogeneity in permeability architecture that may effectively segment the aquifer into distinct zones or subunits (referred to as potential compartments) with varying hydraulic properties such as transmissivity and permeability. While these features may be hydraulically connected over geological time scales, the connection is insufficient to facilitate meaningful groundwater exchange, potentially leading to areas that behave as hydraulically isolated zones over extended periods, spanning years, decades, or centuries. This has implications for understanding subsurface flow dynamics and groundwater resource management.

These hypotheses were formulated through the forensic evaluation of the conceptual model 1 GWL-contour map and a new contour map prepared with the additional GWL data by replicating the same scale and same contour interval of 50 ft. (Figures S3 and S4 of the ESM). This process integrated the probable locations of the serviceably impermeable barriers into the groundwater flow. The hypothesis on the role of faults and folds was reinforced by the observation that faults in conceptual model 1 disrupt the alluvial deposition. Additionally, USGS data obtained from Smith and Roe (2015) also delineates the folds in the study region which act as the front-facing step (Jackson et al. 2013). Following the characteristics of a front-facing step, it was hypothesized that the regions with highly turbulent flood water deposited coarse-grained materials, while areas where the flow was obstructed and lost kinetic energy as it passed over a fold deposited fine-grained sediments. These fine-grained sediments may act as a potential barrier to groundwater flow (Fig. 6).

The original cross-sections used in conceptual model 1 were redrawn to investigate the potential presence of flow barriers, specifically low-permeability fine-grained deposits (mud-dominated-channel-abandonment facies). These barriers are believed to result from successive cut-fill processes associated with megafloods and slack-water deposits, referred to as CFBs, alluvium disrupted by folds and faults, and low-permeability deposits caused by front-facing steps. Collected well logs were preprocessed as described in section 'Hydrogeological data collection and preprocessing. The logs were standardized based on the uniformity and gradation of materials regulating the total porosity and permeability of the succession. Given the considerable uncertainty in using well-log databases maintained by state agencies (OWRD 2024), particularly regarding depth and lithologies over large areas, these challenges were mitigated by grouping the logs into standardized categories. Rapid changing and thin lithological layers were added to adjacent shallower or deeper major layers based on interpretations from the driller's log descriptions and tracking the dominant lithological classes present. These adjustments helped mitigate uncertainties inherent in these logs that are due to the absence of borehole geophysics under practical limiting conditions. This adaptable classification framework addresses geological specificity and data limitations, offering a standard methodology for advancing subsurface characterization amidst uncertainty and variability in diverse geological settings. The well-log classification for this study is presented in Table 1.

The 10-m DEM was used to create the surface topography for the cross-sectional lines, and the cross-sections were hand drawn to focus on the alluvial successions, capturing the vertical and horizontal distribution of materials and tracking the presence or absence of low permeable deposits. The groundwater compartments were delineated by sketching the well logs, CFBs, and the stratigraphy of the alluvial deposits. The successions, with tan siltstone,

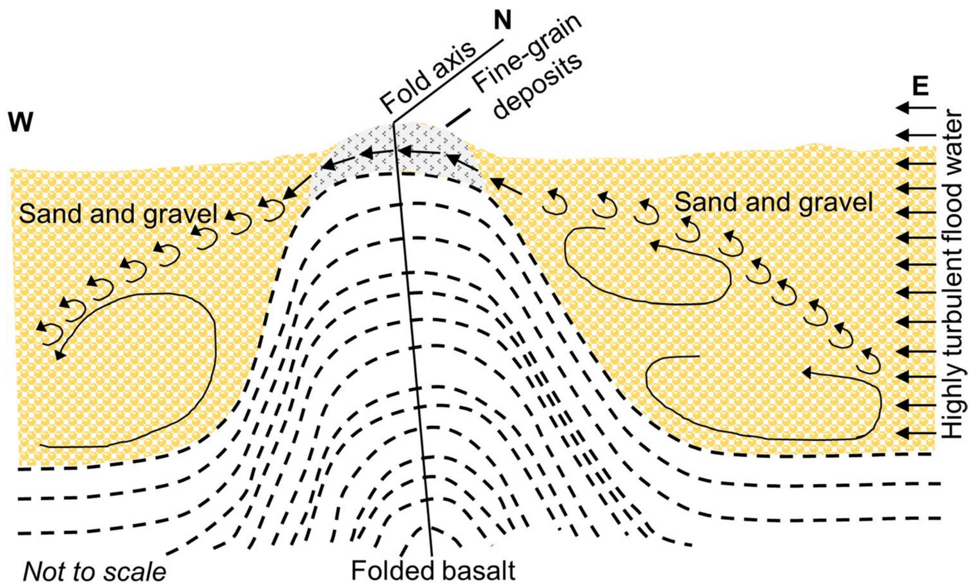

Fig. 6 Conceptual diagram portraying the role of folding in the sediment deposition as a front-facing step, creating a barrier for groundwater flow. This diagram is not to scale because the dimensional details on the folding and the lateral extent of its impact on sediment deposition are not available

Table 1 The lithologies available in the driller log reported to OWRD and the standardized classes, along with the permeability characteristics considered in conceptual model 2 corresponding to each category

Lithology from driller logs	Standardized class	Permeability range (m/s)
Sand and gravel, gravel, cobbles, boulders	Gravel	Highly permeable (10^{-3}–1)
Fine, medium, or coarse sand, silty sand, sandy soil, silt with sand layers	Sand	Permeable (10^{-5}–10^{-2})
Silt	Silt	Moderately permeable (10^{-8}–10^{-5})
Sandstone	Sandstone	Permeable (10^{-10}–10^{-5})
Tan siltstone	Tan siltstone	Low permeability (10^{-11}–10^{-8})
Boulder/gravel/sand and clay, sandy clay	Partially or fully cemented sand/gravel	Low permeability (10^{-12}–10^{-7})
Brown/ red/ black clay	Clay	Low permeability (10^{-13}–10^{-9})
Claystone	Claystone	Low permeability (10^{-13}–10^{-9})
Breccia	Breccia	Low permeability (10^{-13}–10^{-9})

partially or fully cemented sand/gravel, clay, claystone, and breccia, were inferred as CFBs, and the lateral extents of CFBs were extrapolated based on the location of the wells reported with the aforesaid deposits. Although differentiating the vertical compartments using the driller's logs was challenging, the stratigraphy was matched with the unique deep geotechnical trenches known as "the Big Cut" near Pebble Springs, south of Arlington and west of the Lower Umatilla Basin GWMA (Martin 2021). This helped to classify the identified facies. The well logs were then correlated and interpolated to derive the inter-well stratigraphy (Moreton et al. 2002). The study aimed to produce the stratigraphy as fine as possible, despite the high uncertainty in the data, marking areas of low confidence and high uncertainty with dashed lines and question marks. This process helped identify low-permeable materials and better determine the spatial extent of alluvial deposits affected by folds and faults. Probable barrier locations were identified from steep hydraulic gradients in the GWL contour map. The spatial variability of GWL in different compartments was conceptualized using the contour map. The contour interval was taken from Grondin et al. (1995); however, the feasibility of the opted contour interval in conceptual model 2 was critically assessed by analyzing the GWL statistics of individual alluvial wells spanning from 1952 to 2023. Because of the irregular placement of GWL observation locations and limitations of the contouring package in ArcGIS Pro, manual digitization, as described by Mohamed and Worden (2006), was employed to finalize the contours. This method effectively illustrated the role of potential compartmentalization in conceptualizing the groundwater system of the Lower Umatilla Basin GWMA. This study also gave special attention to data visualization to illustrate the hydrogeologic stratigraphy observed through different analyses by producing three-dimensional (3D) dioramas of the study area.

Results and discussion

Using the available data, all the original cross-sections from conceptual model 1 were redrawn and supplemented by a new cross-section to tie all the cross-sections together to build conceptual model 2, as shown in Fig. 4. As discussed in the previous section, the well logs were correlated and interpolated to obtain the inter-well stratigraphy (Moreton et al. 2002). According to the literature, the width of channel fills may commonly vary from a few feet to a few miles (2–3 miles: Moreton et al. 2002; Beerbower 1969), depending on the size of the catastrophic event responsible for its generation. Preliminary observations of the cross-sections indicate that the dimensions of the CFBs in this study are on the mile scale, which is coarser than the well spacing. Therefore, the well logs could capture the spatial extent of the CFBs with minor uncertainty, despite the inherent uncertainties in the well logs. Cross-section CC′, which is representative of conceptual model 2, illustrates the distribution of the gravel, sand, and low permeability clay in the north-to-south direction starting from the Columbia River to Butter Creek, as shown in Fig. 6. As discussed in section 'Materials and methodology', this study traced the abrupt changes in GWL, locations of the low permeability deposits like clay, poorly graded sand/gravel with clay as cemented formations, and claystone (Fig. 7). It also identified locations with folds and faults as probable serviceably impermeable barriers to groundwater flow.

Channeled filled belts serve as the principal hydrologic boundaries in the central portion of the Lower Umatilla Basin GWMA. In the north, one CFB near well MORR51830, close to the Columbia River, contains cemented sediments. Another CFB, located between wells UMAT1563 and UMAT57963, comprises cemented sediments, clay, and claystone (Fig. 8). These two CFBs can potentially act as serviceably impermeable barriers to groundwater interaction between (1) the gravel deposits along the Columbia Riverbank and the sand and gravel deposits in the central regions around the Umatilla Ordnance Depot, and (2) the sand and gravel deposits in the central regions around the Umatilla Ordnance Depot and the Alkali Canyon Formation near the southern boundary of the Lower Umatilla Basin GWMA. This permeability architecture aligns with the OWRD's designation of the Ordnance Gravel Critical Groundwater Area in 2021 and the findings of the Final Record of Decision by the Defence Environmental Restoration Program (DERP) in 1994 regarding the role of low-permeable facies and northwestward groundwater flow directions. The compartmentalization of the sand and gravel by CFBs can limit recharge to underlying aquifer materials, contributing to groundwater depletion.

There are distinct vertical compartments with intermediate clay and cemented sand/gravel layers, as observed in Fig. 8. However, the uncertainty associated with the layer boundaries is due to the uncertainty in driller logs. As depicted by Bretz (1925) and other subsequent studies, the alluvial succession currently observed was not generated by a single event. Instead, the stratigraphy has resulted

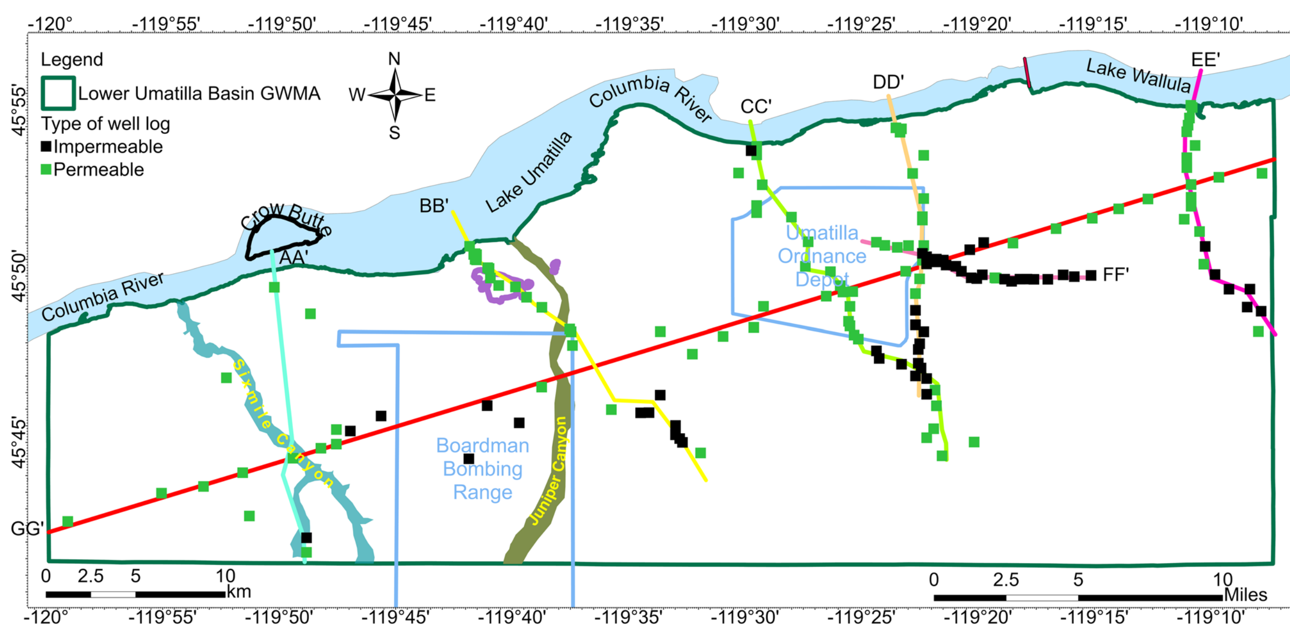

Fig. 7 Distribution of permeable and impermeable well logs used for drawing the cross-sections used in this study. The black squares represent the impermeable and green represents permeable well logs taken into consideration while drawing the cross sections

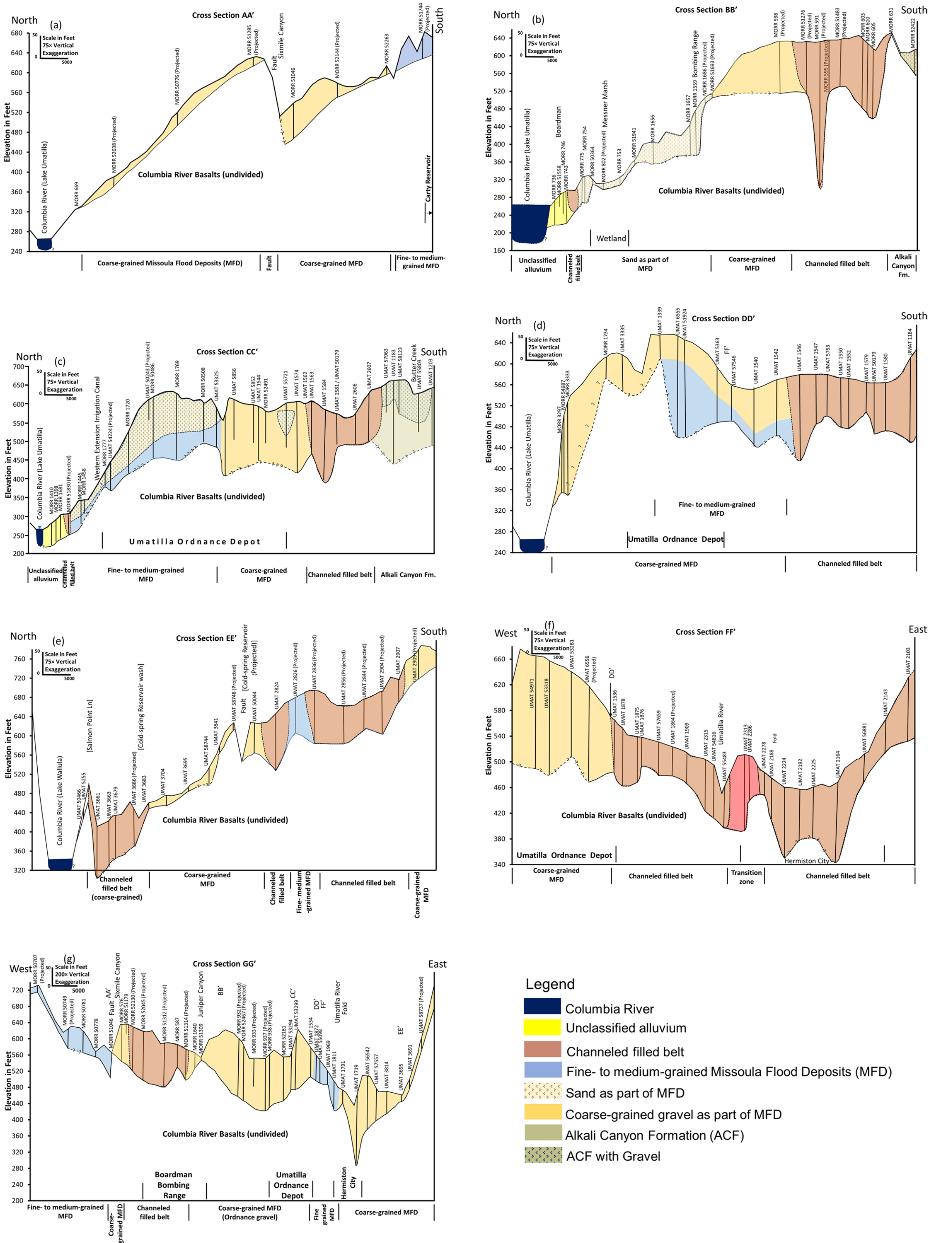

Fig. 8 Cross sections **a** AA′, **b** BB′, **c** CC′, **d** DD′, **e** EE′, **f** FF′, and **g** GG′ with CFBs delineated as low permeable materials in conceptual model 2. The high-resolution images for the individual cross sections can be found in figures S5–S11 of the ESM

from multiple megafloods sequentially cutting and filling the prior succession, starting from the scouring of basalt to form paleochannels and canyons during the Spokane Flood. During megafloods, the high-energy floodwaters erode the riverbanks and floodplains to create channels. As the floodwaters recede, the energy of the system decreases, leading to the deposition of sediments in lower energy areas, such as floodplains or the newly formed channels. These “cut and fill” interpretations are consistent with the lithologies mapped in the unique deep geotechnical trenches known as “the Big Cut,” associated with locating a nuclear power plant in the vicinity of Pebble Springs, south of Arlington and west of the Lower Umatilla Basin GWMA, as described by Martin (2021).

The cross sections AA′ (near Six Mile Canyon in Fig. 8a), EE′ (near Cold Spring Reservoir in Fig. 8e), and GG′ (near Hermiston in Fig. 8f) illustrate the role of structural geology regarding the compartmentalization of the alluvium. This study assumes that megafloods eroded the north–south fold near Hermiston, and the CFB formation in that region transitions from coarse-grained material to fine-grained clay between CFB-1 and CFB-2 (Fig. 8f). As depicted in cross-sections FF′, GG′, and EE′, there are coarse-grained deposits in the northwest corner of the Lower Umatilla Basin GWMA and the CFB-1. Unlike the other CFBs in the Lower Umatilla Basin GWMA, CFB-1 is not a barrier to groundwater movement. Additional CFBs similar to CFB-1 could have been delineated, but for simplicity, only CFB-1 is mapped because of its significant role in the formation and hydrologic function of CFB-2. The proposed concept posits that up to 200 miles^3 of floodwaters per day roared through a gap capable of discharging less than 40 miles$^{3/}$day (Figure S2 of the ESM; Waltham 2010). The peak flow was estimated to be about 10 million m^3/s, roughly 50 times the flow of the Amazon River and 10 times the combined flow of all the rivers in the world. This immense flow scoured the floodplain west of the Wallula Gap, creating several CFBs including CFB-1 and CFB-2. The kinetic energy of the floodwaters decreased as they encountered landforms, depositing coarse-grained materials in the northeast corner and fine-grained materials in the west and southwest parts. All of the cross-sections were integrated to map the hydrologic boundaries of the Lower Umatilla Basin GWMA. In this process, the locations of CFBs and other barriers were delineated, as presented in Fig. 9.

Cross-section EE′ delineated CFB-1 but showed that it carries highly permeable material like sand and gravel. CFB-1, shown herein, establishes the generation of CFB-2

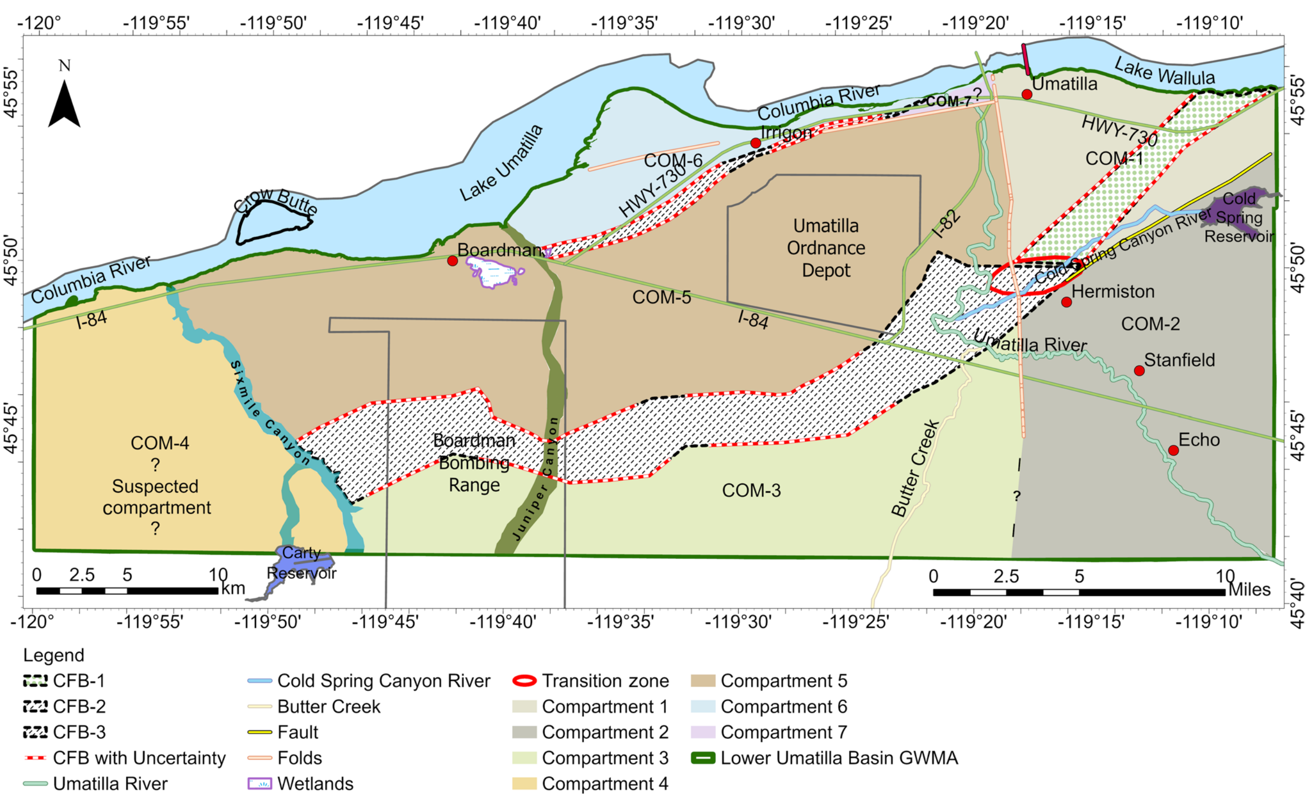

Fig. 9 CFBs and the other serviceably impermeable barriers that are responsible for the compartmentalization of the Lower Umatilla Basin GWMA based on conceptual model 2. The CFBs were demarcated by black and red dashed lines according to the level of confidence in delineating the boundary with moderate to high uncertainty, respectively. Queried where uncertain

with low permeable deposits from the multiple flood events beyond the transition zone. The transition from coarse-grained deposits, thought to have moderate to high permeability to low permeable deposits in CFB-2, was confirmed by FF′, DD′, CC′, and BB′ from east to west (Fig. 8). The location of CFB-2 also matches the steep hydraulic gradient observed in Figure S2 of the ESM. CFB-2 extends from the transition zone from the east to the west to Six Mile Canyon. Similarly, CFB-3 was delineated through cross-sections CC′ and DD′, as well as the topographic structure of the Lower Umatilla Basin GWMA extending from the region close to the Umatilla and Columbia River confluence point to the Juniper Canyon near Boardman. The faults disrupting the alluvium have been delineated in cross-sections AA′, FF′ and EE′, whereas GG′ (Fig. 8) shows the effect of the front-facing step depositing sand and gravels on either side of the fold and low permeable fine-grain successions on the tabletop of the hydraulic jump (Fig. 8g). The tabletop with a relatively flat surface allows a less turbulent flow, facilitating fine-grain deposition. Therefore, low permeability hydrologic barriers were identified as the fault located between Hermiston and Cold Spring Reservoir, the north–south-oriented fold parallel to Umatilla River, the east–west fold parallel to the Columbia River, CFB-2, and CFB-3, all terminating at Six Mile Canyon to effectively compartmentalize groundwater flow in the Lower Umatilla Basin GWMA. The compartments and the corresponding boundaries are detailed in Table 2.

The uncertainty in the spatial locations of the boundaries of CFB-2 and CFB-3 is due to the quality of the data archived in the well-log database. In these six compartments, there are several hydrologic features present—including the Umatilla River, Butter Creek, Cold Spring Canyon River, Juniper and Six Mile Canyons—and wetlands in compartment-5 have a significant impact on the conceptualization of the groundwater flow regulating the baseflow, recharge, and discharge of the groundwater in different compartments. Furthermore, the results obtained from constructing the cross section were scrutinized by comparing with the topography of the Lower Umatilla Basin GWMA. It was observed that the CFBs have a visible presence on the vertically exaggerated DEM (Fig. 10). The cut sections with finer spatial scale, presented in Fig. 10, depict the surface impressions of the CFBs with

Table 2 Groundwater compartments, description of boundaries, groundwater flow properties, and presumed hydrologic properties for a future groundwater numerical model based on the conceptual model 2

Compartments	Boundaries	Model hydraulic property
Compartment 1 (COM-1)	North: Wallula and Umatilla Lake	General head
	East: Lower Umatilla Basin GWMA east boundary	Specified flux
	South: Hermiston fault and CFB-2	No flow
	West: Hermiston fold	No flow
Compartment 2 (COM-2)	North: Hermiston fault and CFB-2	No flow
	East: Lower Umatilla Basin GWMA east boundary	Specified flux
	South: Lower Umatilla Basin GWMA south boundary	Specified flux
	West: Hermiston fold and leaky suspected boundary	No flow and head-dependent/specified flux
Compartment 3 (COM-3)	North: CFB-2	No flow
	East: Hermiston fold (suspected to be leaky)	No flow and head-dependent/specified flux
	South: Lower Umatilla Basin GWMA south boundary	Specified flux
	West: Six Mile Canyon	General head
Compartment 4 (COM-4)[a]	North: Lake Umatilla	General head
	East: Six Mile Canyon	General head
	South: Lower Umatilla Basin GWMA south boundary	Specified flux
	West: Lower Umatilla Basin GWMA west boundary	Specified flux
Compartment 5 (COM-5)	North: Lake Umatilla, Juniper Canyon, and CFB-3	General head and no flow
	East: Hermiston fold	No flow
	South: CFB-2	No flow
	West: Six Mile Canyon	General head
Compartment 6 (COM-6)	North: Lake Umatilla	General head
	East: Hermiston fold	No flow
	South: CFB-3	No flow
	West: Juniper Canyon	General head

[a]Low data availability

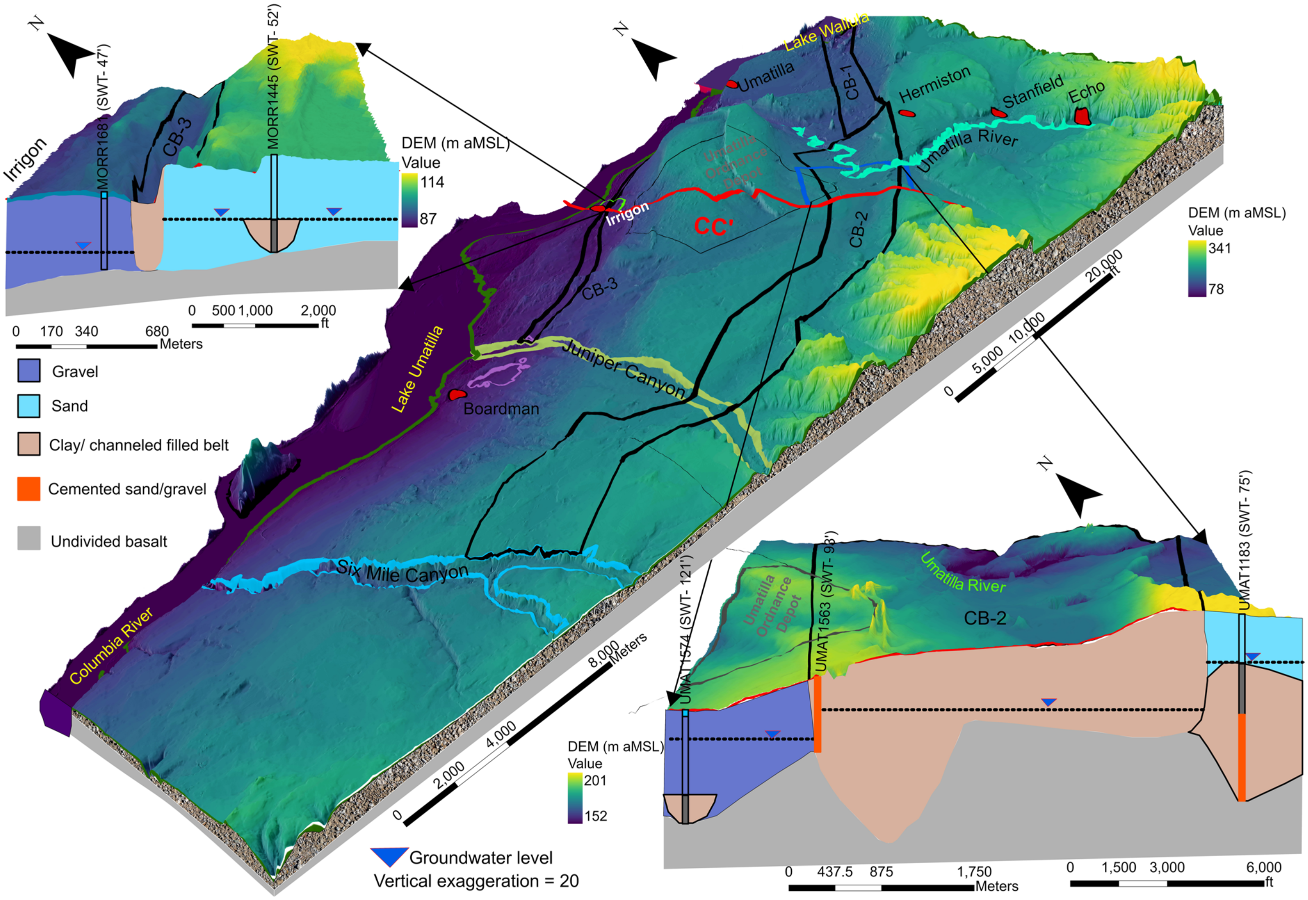

Fig. 10 Three-dimensional structure of the Lower Umatilla Basin GWMA highlighting major hydrogeological features. Detailed sections from CFB-2 (bottom right) and CFB-3 (top left) show the surface topography of the channeled filled belts along with the different successions observed in the CC′ cross-section drawing. The detailed sections show the CFBs acting as hydrologic barriers responsible for the observed GWL gradients across the CFBs. The groundwater level shown is the static water levels (ft) obtained from the well reports. The elevation range of the ground surface elevation is overlain with hillshade

clear outlines as well as the well logs in these CFBs with low permeability deposits. Hence, the results presented in Fig. 9 confirm the potential presence of CFBs beyond the riverbanks, which are considered to be barriers to groundwater flow.

The impact of the CFBs on the GWL in the GWMA was evaluated by redrawing the contour map using conceptual model 2 with a contour interval of 15.24 m (50 ft) and comparing it with the potentiometric surface map of Grondin et al. (1995) by using the same contour interval. Grondin et al. (1995) presented the GWL variability and flow directions in the Lower Umatilla Basin GWMA using this potentiometric surface. While many wells in the well-log database are completed in the underlying basalt aquifer, the replotting of the GWL contour only considered wells in the alluvial aquifer. It was observed that the 473 wells monitored for GWL in the alluvial aquifer are only clustered in the central and eastern parts of the Lower Umatilla Basin GWMA (Fig. 11).

The feasibility of the contour interval adopted from Grondin et al. (1995) used in conceptual model 2 was critically assessed by analyzing the GWL statistics of individual alluvial wells spanning from 1952 to 2023. The mean and standard deviations of the GWL for the individual wells were calculated (Fig. 11) to observe the distribution of the GWL data. It was observed that out of 473 wells, only eight wells have a standard deviation value greater than 7.6 m (25 ft). Additionally, the maximum standard deviation was 12.7 m (41.7 ft), which is significantly lower than the considered contour interval. A spatial correlation was observed between the clustering of the mean and standard deviation classes of GWLs and the delineated compartments (as depicted in Fig. 11). For instance, 65.9–92.3 m mean GWL in compartment-6, 118.7–145.1 m in compartment-1, 145.7–171.5 m in compartment-5, and 171.5–197.9 m in compartment-2. Furthermore, the spatial autocorrelation test through Moran's Index of 0.94 (+ve) and $p < 0.01$ validated the clustering of the GWL by rejecting the null hypothesis that the GWL is

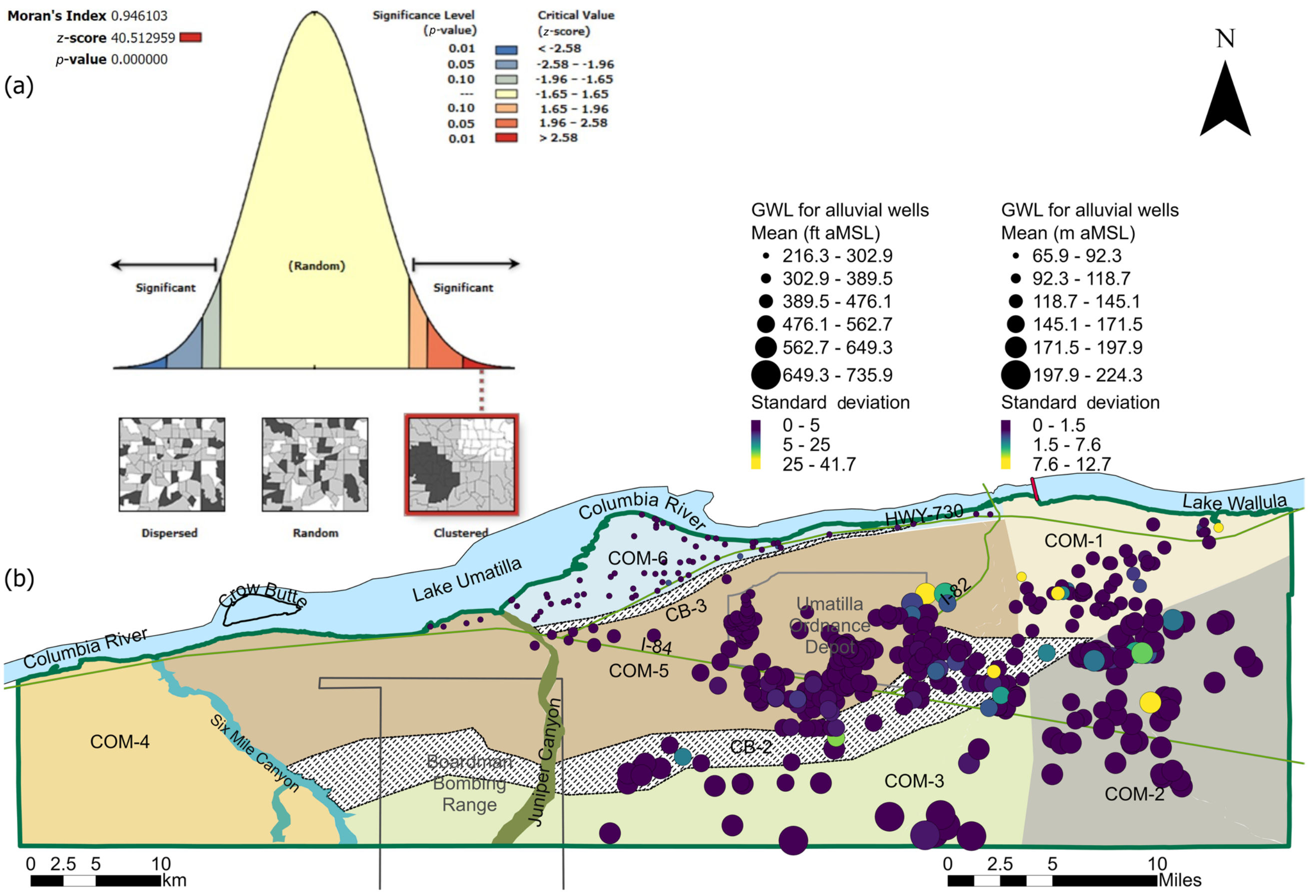

Fig. 11 **a** Summary of spatiotemporal statistics on alluvial GWLs in the Lower Umatilla Basin GWMA, **b** The distribution of GWL means (bubbles) and standard deviation (color codes) for individual wells between 1952 and 2023. The spatial autocorrelation test through Moran's Index of 0.94 (+ve) and *p*-value of 0.00 validated the clustering of the GWL by rejecting the null hypothesis that the GWL is randomly distributed

randomly distributed. These results indicate that the compartmentalized groundwater system in the Lower Umatilla Basin GWMA is regulating the GWL distribution in the GWMA. Further, these findings encourage a more targeted stochastic model investigation through clustering analysis, supported by the silhouette index evaluation, to refine cluster boundaries and enhance the understanding of compartment associations with groundwater variability. The rationale for using the silhouette index lies in its ability to quantify the quality of clustering, ensuring more precise delineation of compartments (Rousseeuw 1987). Additionally, the observed groundwater variability and compartmental associations prompt future research to assess hydrogeological controls over groundwater fluctuations. Techniques such as joint entropy (Singh 1997), principal component analysis (PCA) (Abdi and Williams 2010), empirical orthogonal functions (EOF) (Lorenz 1956), wavelet analysis (Torrence and Compo 1998), and geographically weighted regression (GWR) (McMillen 2004) will be employed to isolate the dominant controls on groundwater level fluctuations and their spatial variability. These methods were selected for their proven ability to detect patterns in hydrological data, assess variability, and identify spatial dependencies. Integrating these techniques with additional data can solidify the compartmentalization concept by disentangling the distinct physical and anthropogenic processes responsible for groundwater variability within individual compartments.

Although there were around 19 recorder wells (wells with pressure transducer) that collect high temporal resolution data in the studied GWMA, in order to conduct the spatial analysis with better areal coverage and obtain the overall range of GWL fluctuation to decide the contour interval, this study focused on GWL data collected in the form of the GWIS Sheet from the OWRD's GWIS online database. Therefore, the evaluation of the GWL well hydrographs with over 70 data points (Fig. 12) revealed the maximum GWL fluctuation to be approximately 10 m (~30 ft). Hence, the selected contour interval appears well suited to capture the GWL variability and the uncertainty associated with the GWL measurement.

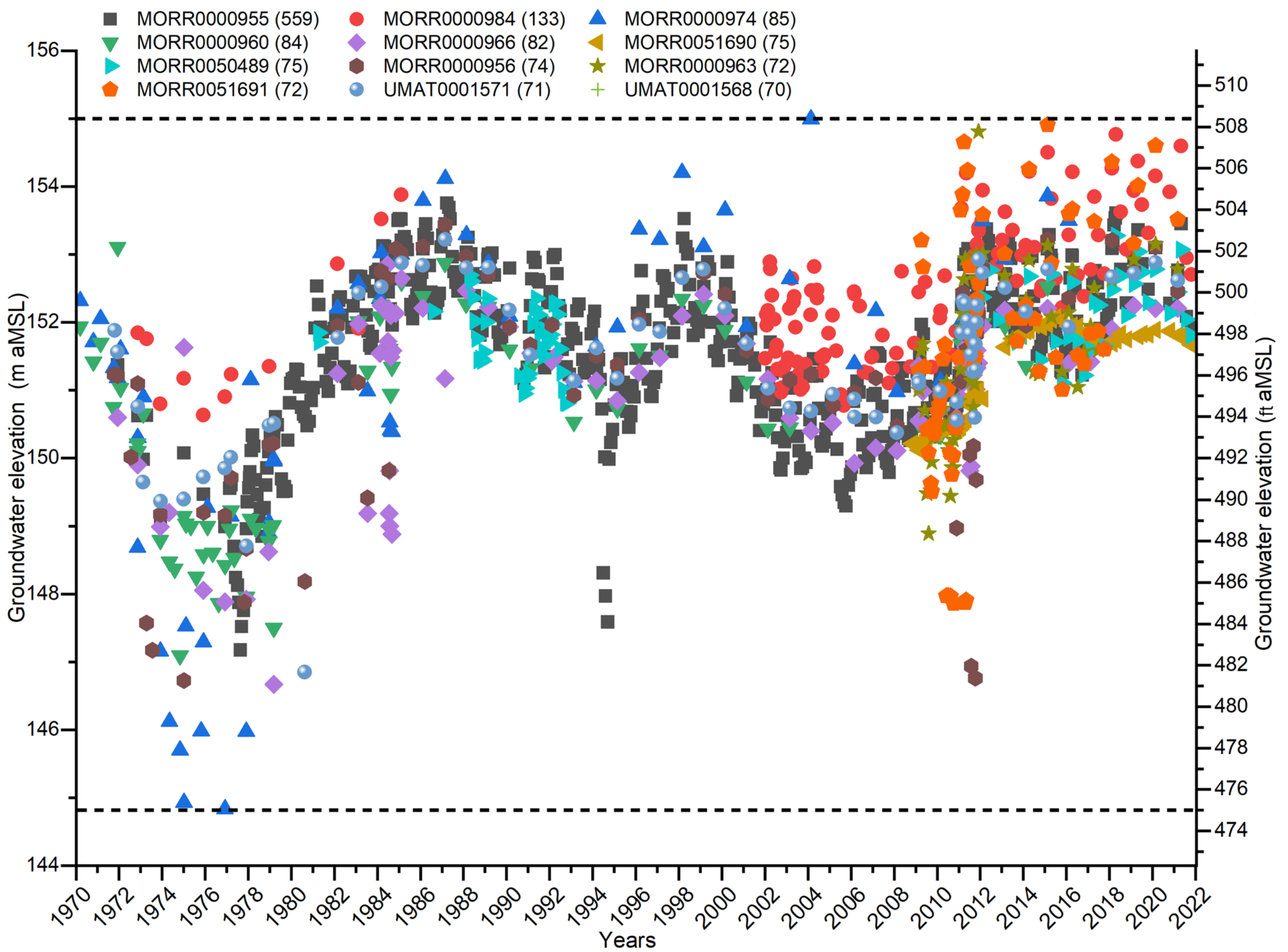

Fig. 12 Hydrograph depicting the GWL of alluvial aquifers in the Lower Umatilla Basin GWMA, alongside the maximum possible range of the GWL fluctuation in wells with at least 70 measurements recorded over the last 70 years

Given the limited number of measurements available from the 473 alluvial wells within Lower Umatilla Basin GWMA on daily, monthly, seasonal, or even yearly scales (as depicted in Fig. 3), the most recent observations from these wells were used for water level contour mapping. The challenges posed by the sparse spatial distribution of the wells were addressed by adopting a coarser contour interval which matched the 1995 study; as outlined in section 'Materials and methodology', manual contouring was employed using ArcGIS Pro, given the limitations of automated contouring tools, especially when dealing with the irregular orientation of the low permeability hydrologic barriers and the limited geographic distribution of the observation wells within the Lower Umatilla Basin GWMA. Figure 13 shows the 25-ft contour lines derived from the 473 wells (Fig. 11), further substantiating the serviceably impermeable barriers identified in this research.

The difference in the GWLs in the different compartments and the CFBs with low permeability is visualized in Fig. 13. The contours also indicate the permeability of CFB-1 due to sand and gravel deposits moving across CFB-1. Again, the leaky boundaries of the compartments were also encapsulated by the contour lines in the GWMA boundary region and the leaky suspected boundary between compartments 2 and 3. The contour map shows the GWL mounds (possibly associated with land application of water from irrigation and wastewater disposal) and some cones of depressions (possibly associated with pumping from irrigation and municipal wells) in different compartments near the serviceably impermeable barriers, justifying the effectiveness of the barriers on groundwater movement in the regions. The distribution of contour lines depicts losing and gaining streams and canyons in different areas of the Lower Umatilla Basin GWMA.

The potentiometric lines also present the overall groundwater flow direction in the different compartments—e.g., the flow of groundwater in compartment-1 towards the northeast direction and discharging to Lake Wallula, where the Umatilla River acts as a hydraulic sink for the baseflow from compartment-2, streambed recharge and baseflow associated with Butter Creek, westward flow of groundwater in

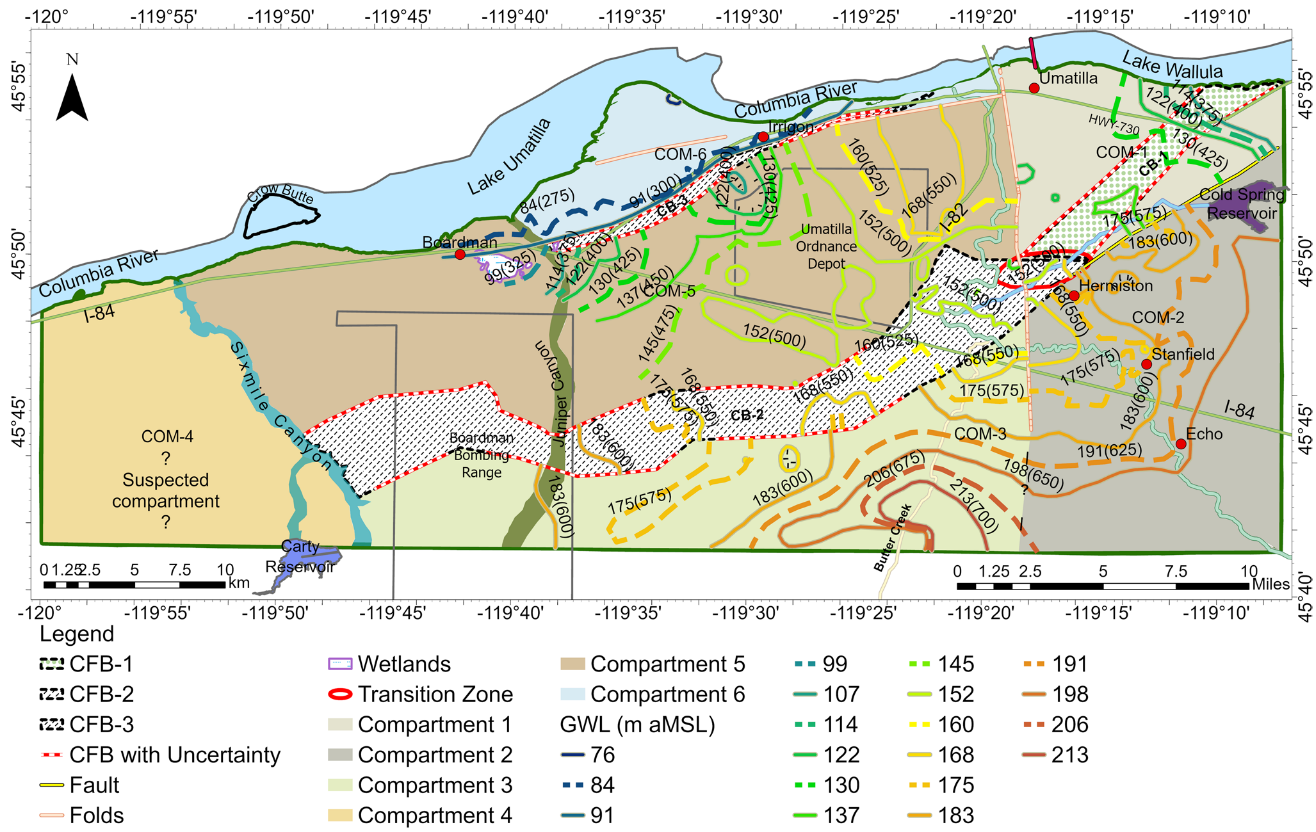

Fig. 13 Potentiometric surface map of the alluvial aquifer system featuring 50-ft contour lines, with intermediate 25-ft contour lines shown as dashed lines, overlaid on the compartments, and CFBs in conceptual model 2. The contour lines were drawn using GWL data from alluvial wells exclusively. As illustrated in Fig. 10, no alluvial wells are present or monitored by OWRD west of Juniper Canyon

compartment-3, west and north-westward flow of groundwater in compartment-5 discharging to Juniper Canyon, and the wetlands located near Boardman. The 91 m (300 ft) contour near Boardman beyond the CFB-3 and Juniper Canyon shows a northward flow of groundwater towards the reservoirs along the Columbia River. However, further investigation is needed to understand the uncertainty associated with the flow direction, as the GWLs reported in the well-log database near Boardman underlie the Lake Umatilla surface water level, indicating a lack of direct hydraulic communication between the alluvial aquifer system and the reservoirs along the Columbia River (Fig. 8b; BB′ cross-section). Conclusively, the six compartments delineated in this study and the illustration of important features of the Lower Umatilla Basin GWMA are presented in Fig. 14.

The forensic evidence and the analogous channel structures presently submerged under the Umatilla Lake, as depicted in Fig. 15, underscore the importance of looking back before embarking on future studies and policies. The hydrologic barriers and the groundwater compartments tentatively delineated in this study through an analysis of 30 years of new hydrogeologic data provide a new paradigm of groundwater flow dynamics in the Lower Umatilla Basin GWMA and provide a foundation for revisiting the hydrogeology of other GWMAs in Oregon since their original designations. Likewise, the tacit assumption that alluvium deposited along large river systems has relatively isotropic and homogeneous hydraulic properties (Grondin et al. 1995) requires finer-scale conceptualization to efficiently monitor, model, and sustainably manage these complex aquifer systems of global importance.

Conclusion and future implications

This study reevaluated the alluvial formation in the Lower Umatilla Basin GWMA using a forensic hydrological framework by collecting and analyzing historical datasets. Often, reanalysis necessitates revisiting fundamental principles, such as redrawing hydrogeologic cross sections through the lens of multiple working hypotheses. The results revealed a significant possibility: the alluvial deposits in the Lower Umatilla Basin GWMA do not constitute a thoroughly connected singular aquifer system but are segmented into six potential highly permeable and distinct compartments (COM 1–6), or hydrological zones, that are hydraulically connected

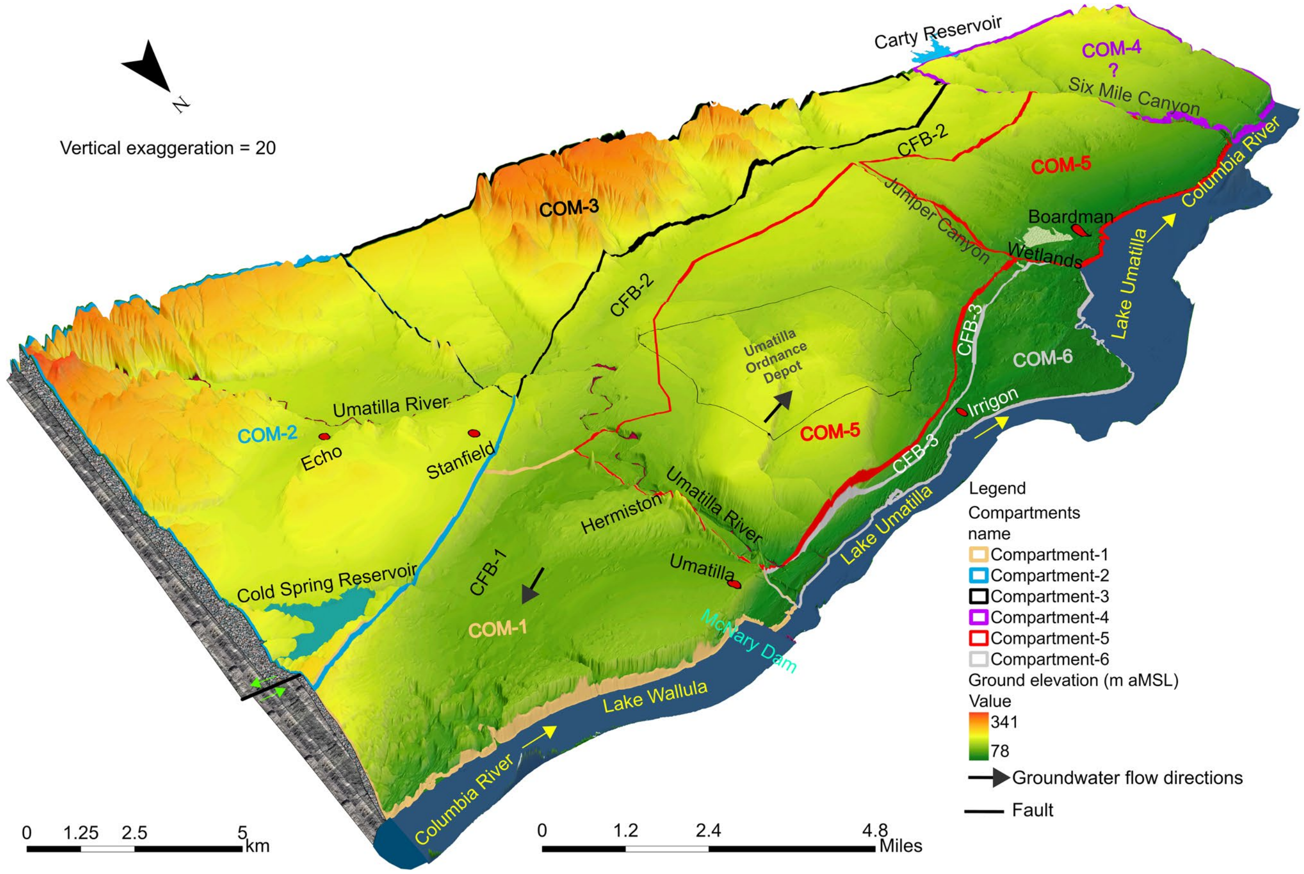

Fig. 14 Three-dimensional representation of the spatial extent of the six identified compartments, along with the key hydrogeological features of the Lower Umatilla Basin GWMA. Juniper Canyon is shown here for illustration. Note that the Six Mile Canyon marks the western boundary of compartment 5

or disconnected. These compartments are due to the presence of CFBs, folds, faults, and modifications in the hydrologic system from surface-water resource management like dams and diversions.

Additionally, more detailed analysis with higher accuracy and finer resolution datasets may be required to confirm the number of compartments delineated and better define the CFB boundaries. The CFBs with low permeability fine-grained deposits create serviceably impermeable barriers between the river bank and the main aquifer and compartmentalize the entire floodplain. Structural geology, including folds and faults with surface impressions, disrupts the alluvial deposits, forming serviceably impermeable barriers within the formations. Furthermore, folds with front-facing steps regulate sedimentation during flood events, creating further serviceably impermeable barriers for groundwater interaction across the folds. The steep hydraulic gradient in GWL and the clustering of mean GWLs provide additional insights into compartmentalization.

The updated contour lines, based on the new conceptual model 2 of the Lower Umatilla Basin GWMA, suggest a more complex groundwater flow pattern than previously proposed by conceptual model 1. Although conceptual model 1 indicated a primarily northward groundwater flow discharging into the Columbia River, the recent findings present diverse flow directions, with certain compartments interfacing with the Columbia River at specific points within the Lower Umatilla Basin GWMA.

The historic analysis of nitrate trends in the Lower Umatilla Basin GWMA indicates that concentrations have remained relatively static or increased in specific locations over the past 30 years, despite the implementation of best management practices. This persistence highlights the limitations of current policies, which often focus on immediate measures, such as fertilizer management, without addressing the long-term nature of nitrate contamination. The data gaps present in this study, associated with irregular monitoring frequencies, and the lack of detailed aquifer hydrogeology further complicate accurate nitrate mass balance modeling. To address these challenges, a comprehensive understanding of the basin's hydrogeological framework is critical. This includes identifying data gaps, implementing a new

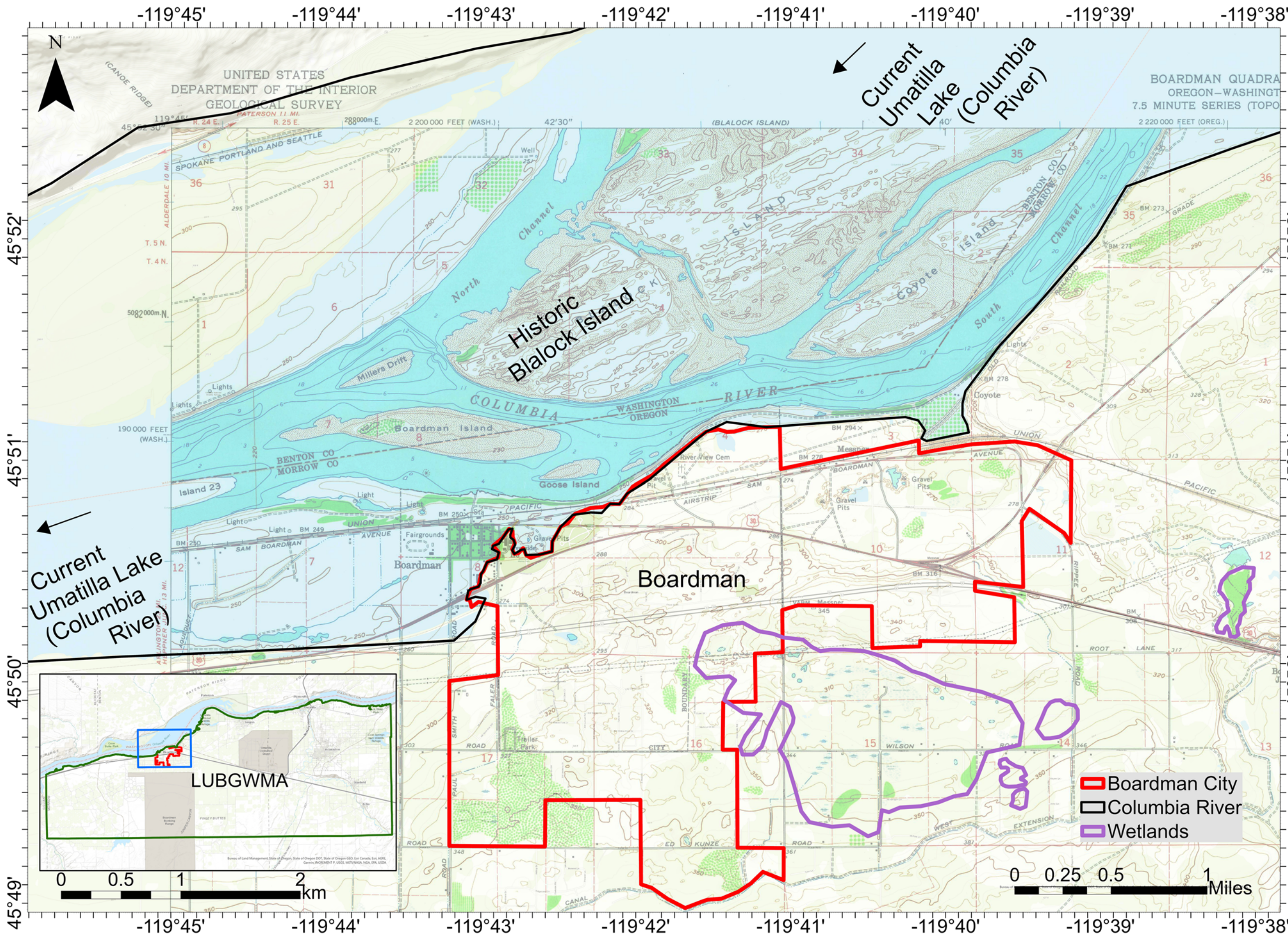

Fig. 15 Forensic hydrologic evidence indicating the presence of channeled filled belts in the Lower Umatilla Basin GWMA. Boardman's 1962 topographic map, obtained from the United States Geological Survey, is overlayed on the current extent of Lake Umatilla, showing Blalock Island. The geographic distribution of the submerged CFBs mimics the paleochannel belts discussed herein

monitoring network, and integrating nitrate data into a basin-scale numerical model.

Future research should focus on expanding the existing well-monitoring network and conducting geophysical investigations (test drilling, borehole, and surface geophysics) providing stratigraphic information in areas with previously limited data or no data. Establishing long-term benchmark monitoring sites will provide the essential historical context for nitrate pollution assessment and management. This additional information gathered through controlled and scientific field campaigns will substantially lower the uncertainty introduced by the driller's logs and sparsely monitored data. In conjunction with data collection efforts, the study area would benefit from the input of sedimentary geologists with expertise in subsurface interpretations and continental sedimentology. The collective efforts of sedimentary geologists and authors with hydrogeology expertise could enhance the understanding of the alluvial successions and consequent permeability architecture, enabling multiscale analysis using currently available and additional systematic data. Additionally, developing and validating large-scale numerical models that incorporate the revised hydrogeological framework, including detailed aquifer hydrogeology and compartmentalization, is crucial. These models can simulate nitrate mass balance and predict future trends under various management scenarios, thereby informing groundwater management policies tailored to the local hydrogeological setting. This dual approach of addressing immediate and long-term challenges of nitrate contamination will enhance the effectiveness of groundwater management strategies. Furthermore, stochastic data-driven analysis of both the GWL and nitrate concentration, and finding a correlation of the same with a GWMA's hydrogeologic makeup, might provide sufficient evidence for the compartmentalization revealed in this study. However, the data gaps identified in this study suggest that rigorous data collection is required to successfully execute these future endeavors.

In conclusion, this study significantly advances the understanding of the Lower Umatilla Basin GWMA's groundwater system by revealing the potential presence of the complex compartmentalization that impacts groundwater flow and quality. The novel forensic hydrology framework and new conceptual model provide a foundation for more effective groundwater management. Future research should focus on refining these findings with higher-resolution data and validating the models to ensure sustainable groundwater use and pollution mitigation.

This novel framework offers a blueprint for understanding the hydrogeology of alluvial deposits worldwide, paving the way for more informed decision-making in water resource management. By integrating forensic hydrology with robust datasets, conceptual "surprises" can help understand previously elusive groundwater challenges, fostering better comprehension of subsurface groundwater fate and transport dynamics. The insights from this research can also aid in shaping policy guidelines, ensuring sustainable and equitable water distribution, and fostering collaboration among stakeholders, ultimately contributing to the global goal of water security.

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Author contribution statement Suraj Jena: Investigation, Methodology, Software, Formal analysis, Validation, Data curation, Writing – original draft, Visualization. Todd Jarvis: Conceptualization, Software, Resources, Writing –review & editing, Supervision, Project administration. Salini Sasidharan: Conceptualization, Software, Resources, Writing –review and editing, Supervision, Collaborator Engagement and Communication, Community Outreach, Data Coordination, Project administration.

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Data availability Actual data documenting the sedimentary and groundwater level heterogeneity of the aquifer is available in the repository accessible at https://doi.org/https://doi.org/10.7267/5h73q5328

Competing interest

The authors declare that they have no competing interests.

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