

Roll the Dice: Where Does a Water Molecule Go, and How Long Does It Stay?

Investigation question: If you follow one water molecule through a chance-based model of the water cycle, where does it spend most of its time, which processes move it, and how well does the model match Earth's real reservoirs?

Collaborative systems modeling

Groups of 3

1 session

Setup 8 · Activity 42 · Cleanup 5 min

MS-ESS2-4 · assesses

Scientific purpose

Students walk a water molecule through eight stations (ocean, atmosphere, snowpack, river, lake, soil, plant, groundwater) using dice rules that encode which moves are likely from each place. Every roll is recorded with its process and driver, groups pool their tallies, and the class computes how long the model keeps water in each reservoir. Students then compare the model's ranking to approximate real residence times, find where the model is faithful and where it is crude, and propose a rule change for a real scenario such as a warm winter or heavy groundwater pumping.

Why this helps students with this chapter

A diagram of the water cycle shows every pathway at once and gives no sense of likelihood or time. The dice turn pathways into probabilities: from the ocean, four rolls out of six keep you there; from the atmosphere, every roll sends you down. After fifteen moves students have felt that the ocean and groundwater are sticky, that the air is a brief stop, that the river is a corridor, and that no two routes are alike. Pooling the class's tallies produces numbers they can compare to real residence times, which makes the model something to test rather than something to memorize.

Standards connections

MS-ESS2-4 (assesses, developing, using and revising a model of water cycling with multiple pathways driven by sunlight and gravity): Students use the model to generate route data, explain each move as Sun-driven, gravity-driven or cooling, draw their route as a network, evaluate the model against real reservoirs and modify its rules; the route record, class analysis and proposed revision are evidence toward this PE. It is a California Grade 6 expectation that this seventh-grade textbook revisits.

Roles (rotate each session)

- **Traveler:** Rolls the die at each station, reads the number aloud, and carries the group's token (or bead string) to the next station.
- **Recorder:** Writes each move in the journey log: station, roll, where the molecule went or that it stayed, the process named on the station sign, and the driver.
- **Process checker:** Reads the rule for the roll from the station sign, confirms the process and whether it is Sun-driven, gravity-driven or caused by cooling, and keeps the group's tally sheet.

Materials

Item	Quantity	Per	Note
Station signs printed from the station rules table (one per reservoir, large type)	8	class	
Six-sided dice	8 (one per station) plus 2 spares	class	
Recording sheet	1	student	
Class tally chart on the board or a large sheet, with a row per station and columns for total rolls, stays, departures and average stay	1	class	
Colored pony beads, one color per station, in cups at each station, and a pipe cleaner per group (optional)	about 40 beads per station and 1 pipe cleaner	class	The bead string becomes a physical record of the route; the journey log carries the same information if beads are not available.
Timer or clock visible to the room	1	class	

Estimated cost: 0 to 15 per class (an estimate; Estimate. Printing the signs is free; a pack of 10 dice costs about 5 dollars; pony beads and pipe cleaners add about 8 to 10 dollars and are optional and reusable.)

Safety

- Students move between stations; keep aisles clear, walk, and leave bags under desks.
- Pony beads are a choking hazard for small children; keep them in cups, pick up any that drop, and do not use them in rooms shared with younger students.
- No other hazards; no chemicals, heat or sharp tools are used.

Teacher preparation and setup

1. Print the eight station signs from the station rules table in large type and post them around the room with space to stand at each; put one die (and the optional bead cup) at each.
2. Assign starting stations so that groups begin spread out, not all in the ocean: for eight groups, one per station; for fewer groups, skip the plant and soil as starting points.
3. Draw the class tally chart on the board with the eight stations as rows and the columns total rolls, stays, departures and average stay.
4. Decide the number of moves (15 is the default; 12 if time is short) and the round length (about 30 seconds) so that all groups roll together on your signal.
5. Print or project the approximate real residence-time table from the recording sheet for the comparison step.
6. If you plan the rule-change round, prepare blank station cards so groups can write a modified rule for one station.

Investigation design

Independent variable	The station the molecule is at, with its fixed set of dice rules (in the rule-change round: the one rule the group modifies)
Dependent variable	Where the molecule goes next and how many consecutive rolls it stays, pooled into total rolls, stays and average stay per station
Controlled	The same rule table at every station for every group; The same number of moves (15) for every group; One roll per move; the roll decides, not the group; Starting stations spread evenly so no reservoir is overloaded at the start
Trials	Each group's 15-move journey is one trial; the class pools 6 to 10 journeys (90 to 150 rolls) so that the average stay at each station is estimated from many rolls.
Comparison	The model's average-stay ranking is compared to the approximate real residence times, and the rule-change round compares class data before and after a modified rule.

Student procedure

1. Before moving, write your prediction in q1: at which station will your molecule spend the most rolls, and which processes will move it most often? Give a reason.
2. Go to your assigned starting station. Record it as move 0 in the journey log and, if using beads, thread one bead of that station's color.
3. On the teacher's signal, the Traveler rolls the die once. The Process checker reads the rule for that number on the station sign and says the process and the driver aloud. The Recorder writes the move: station, roll, 'stayed' or the new station, the process, and the driver (Sun, gravity, cooling, or 'held' for a stay).
4. If the rule says move, walk to the new station and thread a bead of its color; if it says stay, thread another bead of the same color and wait for the next signal. Keep going for 15 moves.
5. After the last move, complete the group tally: for each station, count how many rolls you made there and how many of those were stays. Count the processes by driver.
6. Add your group's numbers to the class tally chart. When all groups are in, compute for each station: departures = total rolls minus stays, and average stay = total rolls $\div$ departures (if a station has zero departures, write 'no departures').
7. Draw your route as a network on the recording sheet: a circle for each station you visited, an arrow for each move, labeled with the process, with loops for stays.
8. Compare the class's average-stay ranking to the approximate real residence-time table, and answer the analysis questions individually.
9. If time allows, each group proposes one rule change for one station that models a real scenario (a warm winter with rain instead of snow, a drought, heavy pumping of groundwater, a paved city) and predicts how the class data would change. Play 8 more moves with the changed rule at that station and check the prediction.

Expected observations

- With 90 or more pooled rolls, average stays come out near 3 for Ocean and Groundwater, near 2 for Snowpack and Lake, near 1.2 for River, Soil and Plant, and exactly 1 for Atmosphere; small classes will see noisier values.
- The Ocean collects the most total rolls because it is sticky and many moves lead back to it; the Atmosphere comes second (visited often, one roll each time) and Groundwater third. The Plant and Soil stations get the fewest rolls, and each visit is brief.
- Almost no two groups have the same route; many routes include a stretch that goes up and down between land and air without touching the ocean (for example lake to atmosphere to river), and a few molecules spend nearly all their moves in the ocean or groundwater.
- Students who start in the Atmosphere are moved immediately, which surprises them and anchors the idea that water's stay in the air is short.

Likely difficulties

- Recorders write the destination but not the process; the Process checker must say both aloud before anyone moves. Checking the log for blank process cells is the first thing to do at the end.
- Groups rush ahead between signals, so moves get out of step and tallies are uneven. Use a visible timer and roll only on the signal.
- Students confuse 'moves that began with cooling' with 'moves driven by cooling'; the model never has cooling move water on its own, which is itself a discussion point.
- Average stay is undefined when a station has no departures (possible for Groundwater in a small class). Write 'no departures' and discuss what that implies.
- The ocean's roll 1-4 'stay' can frustrate a group; point out that this boredom is the point of the model.

Structured debrief

1. Fill the class tally together and compute the average stays aloud. Expected pattern: Ocean and Groundwater near 3 rolls, Snowpack and Lake near 2, River, Soil and Plant a little above 1, Atmosphere exactly 1 (it has no stay rule). Ask what rule makes a station sticky and what rule makes it a corridor.
2. Put the real residence-time table beside the class ranking. The ends agree (ocean and groundwater longest, atmosphere shortest) and the middle is compressed. Make the key modeling point: a roll is not a fixed length of time. One roll in the ocean stands for centuries; one roll in the air stands for days. The model gets the order roughly right and the scale completely wrong, which is a limitation students should be able to state.
3. Tally the drivers for the whole class. Gravity usually leads (every exit from the atmosphere and groundwater, most exits from the river and lake, plus infiltration and runoff from the soil), the Sun is second (every evaporation, transpiration, melting and sublimation move), and cooling appears only as the first half of each atmosphere exit. Ask why condensation never appears as a move by itself in this model (the model lumps condensation and precipitation into one step; a more detailed model would add a Cloud station).
4. Hear two or three proposed rule changes and their predictions. A warm-winter rule (atmosphere roll 5 sends water to River instead of Snowpack) empties the snowpack station and shortens the delay

between winter storms and river flow, which is the California water-supply story from the presentation. A pumping rule (groundwater roll 4 sends water to Soil via a well) shortens the groundwater stay and is the Lesson 19 bridge.

Recording sheet: what students fill in

Lab 3 recording sheet: Roll the dice through the water cycle

The station rules below are also posted on the station signs. The die decides every move; your job is to record it accurately, name the process and its driver, and then analyze the class's pooled data.

Station rules (roll a six-sided die)

Station	Rolls 1-2	Rolls 3-4	Roll 5	Roll 6
Ocean	Stay: carried by currents	Stay: carried by currents	Evaporation to Atmosphere (Sun)	Evaporation to Atmosphere (Sun)
Atmosphere	Condensation, then rain to Ocean (cooling, then gravity)	Rain to River (roll 3) or to Soil (roll 4) (cooling, then gravity)	Snow to Snowpack (cooling, then gravity)	Rain to Lake (cooling, then gravity)
Snowpack and glacier	Stay: frozen in place	Stay (roll 3) or melting to River (roll 4) (Sun, then gravity)	Melting, then infiltration to Soil (Sun, then gravity)	Sublimation to Atmosphere (Sun)
River	Stay (roll 1) or flow to Ocean (roll 2) (gravity)	Flow to Ocean (roll 3) or to Lake (roll 4) (gravity)	Evaporation to Atmosphere (Sun)	Seep through the riverbed to Groundwater (gravity)
Lake	Stay: held in the lake	Stay (roll 3) or outflow to River (roll 4) (gravity)	Evaporation to Atmosphere (Sun)	Seep to Groundwater (gravity)
Soil	Stay (roll 1) or evaporation to Atmosphere (roll 2) (Sun)	Root uptake to Plant (Sun, via transpiration pull)	Infiltration to Groundwater (gravity)	Runoff to River (gravity)
Plant	Stay (roll 1) or transpiration to Atmosphere (roll 2) (Sun)	Transpiration to Atmosphere (Sun)	Transpiration to Atmosphere (Sun)	Transpiration to Atmosphere (Sun)
Groundwater	Stay: creeping through pores	Stay: creeping through pores	Spring flow to River (gravity)	Seep out under the sea to Ocean (gravity)

1. Prediction: at which station will your molecule spend the most rolls, and which driver (Sun, gravity or cooling) will move it most often? Explain using the rules.

Answer: Most students will predict the Ocean or Groundwater for the most rolls, because four of six rolls keep water there, and gravity as the most common driver, because every exit from the atmosphere and the groundwater, and most exits from the river and lake, are moved by gravity. Any prediction earns credit if it is reasoned from the rules.

Why: The prediction forces students to read the rule table before playing; the stay rules make the answer visible to a careful reader.

- Names a station and a driver
- Justifies both from the rule table

Journey log

Move	Station	Roll	Stayed, or moved to	Process	Driver (Sun / gravity / cooling / held)
0 (start)					
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					
12					
13					
14					
15					

Group tally

Station	Rolls we made here	Of those, stays	Moves driven by the Sun	Moves driven by gravity	Moves that began with cooling
Ocean					
Atmosphere					
Snowpack and glacier					
River					
Lake					
Soil					
Plant					
Groundwater					

Class tally (copy from the board)

Station	Total rolls (all groups)	Stays	Departures (rolls minus stays)	Average stay (rolls ÷ departures)	Rank (1 = longest stay)
Ocean					
Atmosphere					
Snowpack and glacier					
River					
Lake					
Soil					
Plant					
Groundwater					

Approximate real residence times (rough estimates; sources differ)

Reservoir	Typical time water stays
Ocean	thousands of years
Groundwater	years to thousands of years
Glaciers and ice sheets	decades to many thousands of years
Lakes	years to centuries
Seasonal snowpack	months
Soil moisture	weeks to months
Rivers	weeks to months
Plants	days
Atmosphere	about 9 days

-  Draw your route as a network: a circle for each station you visited, one arrow per move labeled with its process, and a loop on a circle for each stay. Mark Sun-driven arrows with a small sun and gravity-driven arrows with a down arrow.

Answer: A network with a circle for each visited station, one arrow per move labeled with the process (evaporation, rain, infiltration, transpiration, and so on), loops for stays, a small sun on Sun-driven arrows and a down arrow on gravity-driven arrows. Atmosphere exits should be marked as cooling-then-gravity.

Why: This is the student's water cycle model drawn from their own data; it should match the journey log move for move.

- Every move in the log appears as an arrow with a process label
- Stays shown as loops
- Drivers marked on the arrows

2. After 15 moves: how many different stations did you visit, where was your longest stay and how long was it, and did your prediction in q1 hold? Explain.

Answer: Varies. A typical answer: visited 4 to 6 different stations; longest stay 3 to 5 rolls in the Ocean, Groundwater, Lake or Snowpack; the prediction held if the molecule reached a sticky station and did not hold if the dice kept it in corridors. The explanation should refer to the stay rules and to chance.

Why: The point is that the route is produced by rules plus chance, so a prediction about likely behavior can be right in general and wrong for one molecule.

- Reports the count of stations and the longest stay with its station
- Evaluates the prediction with reference to the rules and chance

Analysis questions: answer key

3. Using the class tally, calculate the average stay for the Ocean and for the Atmosphere (average stay = total rolls ÷ departures). Show the numbers. Then explain, using the station rules, why these two values are so different.

Answer: Worked example from a class with 60 Ocean rolls of which 41 were stays: departures = $60 - 41 = 19$; average stay = $60 \div 19 = 3.2$ rolls. Atmosphere with 48 rolls and 0 stays: departures = 48; average stay = $48 \div 48 = 1.0$ roll. The Ocean's rules keep water there on four of six rolls, so most rolls are stays and departures are rare; the Atmosphere has no stay rule, so every roll is a departure and the average stay is exactly one roll.

Why: Check that departures are rolls minus stays and that the division is rolls over departures. The expected values are about 3 for the Ocean (the exact long-run value is $6 \div 2 = 3$) and exactly 1 for the Atmosphere.

Also acceptable: Accept any correct computation from the class's actual numbers; values of 2.5 to 3.5 for the Ocean are typical in a real class.

4. Compare the class's average-stay ranking with the approximate real residence-time table. Name two reservoirs where the model's ranking agrees with reality and one where it does not, and explain what a single roll stands for in each case.

Answer: Agreement: the Ocean and Groundwater have the longest stays in both the model and reality, and the Atmosphere has the shortest in both. Disagreement examples: the model gives Snowpack and Lake the same stay, while real lakes hold water for years to centuries and seasonal snow for months; or the model gives the River and the Plant about the same stay while real rivers hold water longer than plants; or glaciers, which can hold water for thousands of years, are lumped with seasonal snow. A roll stands for a different length of time at each station: thousands of years per roll in the ocean, days per roll in the air, so the model preserves the order but not the scale.

Why: Full credit requires two agreements, one disagreement and the explicit statement that a roll is not a fixed amount of time.

- Two correct agreements with the real table
- One correct disagreement
- Explains that one roll represents different amounts of time in different reservoirs

5. From your group tally, which driver moved your molecule most often: the Sun, gravity or cooling? Explain why every move out of the Atmosphere counts as 'cooling, then gravity' and why no move out of the Ocean counts as gravity.

Answer: Most groups find gravity moved them most often, with the Sun second and cooling only as the first part of atmosphere exits. Every move out of the Atmosphere starts with vapor cooling and condensing into droplets or ice crystals (cooling), and the drops or snow then fall under gravity; the model combines the two steps into one move. No move out of the Ocean is gravity because the ocean is already at the lowest point; the only way out is upward, as vapor, which needs energy from the Sun.

Why: This is the energy-accounting idea applied to the model's rules: cooling makes clouds, gravity makes them fall, and the Sun is the only way up.

- Reports the group's most common driver from the tally
- Explains the atmosphere exits as cooling then gravity
- Explains that leaving the ocean requires energy in, not gravity

6. Find a stretch of your route that never touched the Ocean, or one that went up and down between the ground and the air more than once. Describe it, name the processes, and explain why Earth's real water cycle allows that route.

Answer: Example: Soil, root uptake to Plant, transpiration to Atmosphere, rain to Soil, evaporation to Atmosphere, rain to Lake. The route never touched the ocean and went up and down twice. The real cycle allows it because evaporation and transpiration can happen wherever liquid water meets enough energy from sunlight, rain can fall on land as easily as on the sea, and nothing requires a molecule to reach the ocean before rising again; the lesson's own point that the cycle has no starting point and no fixed order is exactly this.

Why: The question targets the single-loop misconception. Credit any real stretch of the student's log with correct process names and a reason grounded in where evaporation and precipitation can occur.

Also acceptable: If the student's route did touch the ocean every time (rare), accept a route they construct from the rules with the same explanation.

- Quotes a real stretch of the route with processes named
- Explains why the real cycle permits skipping the ocean or repeating the air

7. Propose one rule change for one station that models a real change: a warm winter with rain instead of snow, a long drought, heavy pumping of groundwater for irrigation, or a city paving over its soil. Write the new rule, say which real process it represents, and predict how the class's average stay at two stations would change.

Answer: Example (warm winter): change the Atmosphere's roll 5 from 'snow to Snowpack' to 'rain to River'. It represents precipitation falling as rain instead of snow when winters are warmer. Prediction: the Snowpack station gets almost no arrivals, so its total rolls drop and its average stay cannot be measured; the River gets more arrivals, and water reaches the Ocean sooner, so the ocean's share of rolls rises and the delay the snowpack provided disappears. Example (pumping): change Groundwater's roll 4 to 'pumped by a well to Soil for irrigation'; the Groundwater average stay falls from about 3 to about 2 rolls and Soil and Plant get more visits. Example (paving): change Soil's roll 5 from infiltration to runoff; Groundwater gets fewer arrivals and River more.

Why: Full credit needs a specific rule, the real process it represents, and a prediction for two named stations that follows from the rule.

- States a precise new rule for one station
- Names the real process or change it models
- Predicts the effect on two stations in a way consistent with the rule

8. List three things about the real water cycle that this dice model cannot show, and for one of them explain how you would change the model to include it.

Answer: Cannot show: how much water is in each reservoir (the ocean holds most of it); how long a roll really lasts; clouds and fog as separate places; condensation as a step of its own; animals and people using water; wind carrying vapor from the sea over the land; sublimation and deposition from most stations; changes of state inside a station such as a frozen lake. Example fix: add a Cloud station between the Atmosphere and the ground, with a roll that sends water back up as evaporated rain and rolls that drop it as rain or snow, so condensation becomes its own move driven by cooling. Any three limitations with one workable fix earn credit.

Why: Naming limitations and improving the model are the SEP 'developing and using models' in its revising form.

- Three real limitations of the dice model
- One concrete rule or station change that addresses one of them

Individual evidence of learning

Each student submits their own journey log, group and class tallies, route network drawing, and answers to q1 through q8. The route drawing with labeled processes and drivers, together with q4 and q7, is the primary evidence for developing, using and revising a water cycle model; q3 is the evidence for the data analysis.

Assessment criteria

Criterion	Proficient looks like
Accurate model use	Journey log complete for all 15 moves with the correct process and driver for every roll, and tallies that add up.
Model as a network	Route drawing shows stations as nodes, every move as a labeled arrow, stays as loops, and drivers marked; the student explains in q6 why a route that skips the ocean is realistic.
Data analysis and comparison	Computes average stays correctly and compares the model's ranking with real residence times, stating where it matches and that a roll stands for different lengths of time at different stations.
Model revision	Proposes a rule change tied to a real process, predicts its effect on specific stations, and names limitations of the dice model.

Accessibility adaptations

- Provide a journey log with the station names as a word bank and the eight drivers pre-printed as circle-one options so recording is a matter of circling rather than writing.
- Allow students with limited mobility to stay seated with a die while a partner moves the bead string, or run the whole model at the desks with the eight signs as cards.
- Give the class tally as a partially completed table and a calculator for q3; accept a verbal explanation for q4 and q7 recorded by the teacher.
- Print station signs with large type and a color band per station that matches the bead color; add icons (sun, down arrow, snowflake) for the three drivers.
- Provide a bilingual word list for the eight stations and the nine processes.

Low-cost alternative

No beads: the journey log is the record. No dice: use a spinner printed from a hexagon, or number slips drawn from a cup and returned. With very few students, each student carries a token and the class pools 4 or 5 journeys of 25 moves each.

Model limitations

A roll is not a unit of time, so the model can show the order of residence times but not their scale; the ocean's three-roll average stands for thousands of years and the atmosphere's one roll for about a week. The rules lump condensation and precipitation into one move and leave out clouds, fog, animals, human use, desalination, wind and the amount of water involved, and the probabilities are chosen to make the order come out sensibly, not measured from Earth. The model treats one molecule at a time, so it cannot show that the ocean holds most of the water or that a drought changes how much water is at a station. This activity has

not been physically run by the authors; the expected average stays are computed from the rule probabilities and will be noisier in a real class.

Teacher notes

Check q3 against the actual class tally, not the worked example. The exact long-run average stays from the rules are Ocean 3, Groundwater 3, Snowpack 2, Lake 2, River 1.2, Soil 1.2, Plant 1.2, Atmosphere 1; a class of 100 rolls will scatter around these. In q5, 'cooling' never appears as a stand-alone driver in this model, which is a limitation worth naming aloud rather than a student error. Keep the class tally; the rule-change predictions in q7 make a good warm-up for Lesson 19.