Rivers run and people may meander. Water body-oriented land use decisions in the Neuwied Basin during the Late Upper Palaeolithic and Late Palaeolithic

Fluss im Lauf und Lauf am Fluss. Wasser-orientierte Landnutzungsentscheidungen im Neuwieder Becken während des späten Jungpaläolithikums und Spätpaläolithikums

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Abstract - Rivers are often seen to have played an important role for Palaeolithic hunter-gatherers as landmarks and resource location. While the former view regards rivers as passive guidelines or obstacles, the latter reduces them to their economic value. Both views, therefore, look at generic properties, equally valid for all streams and their sections and partly overlook the interaction between humans and specific rivers within the landscape. In this article, we contribute to the discussion by looking explicitly at an historically contingent and specific case of interaction between humans and a particular section of an individual river, i.e., the Rhine in the Neuwied Basin. Using an agent-based model, we aim at identifying differences in water-oriented land use decisions between the Late Upper and Late Palaeolithic occupations of the region. We observe a clear shift from a dominant focal role of the Rhine during the former to a less important spatial entity during the latter period and conclude that these differences are as much an expression of a changed perception of the Rhine as they are a result of environmental change and the transition from a pioneering to a stationary settlement phase and that indeed both aspects are inextricably intertwined.

***Zusammenfassung -** Flüssen wird häufig eine wichtige Rolle als Orientierungspunkt und Ressourcenquelle für wildbeuterische Gruppen des Paläolithikums zugesprochen. Während erstere Betrachtungsweise in Flüssen eine passive Funktion als Orientierungshilfe oder Hindernis sieht, reduziert letztere Perspektive die Flüsse auf ihren ökonomischen Wert. Beide Perspektiven sind dementsprechend auf generische Eigenschaften fokussiert, die als gleichwertig gültig für alle Flüsse und Flussabschnitte gelten und möglicherweise nicht die spezifische Interaktion zwischen Menschen und einem Fluss berücksichtigen. In diesem Artikel tragen wir zu der Diskussion bei, indem wir uns explizit mit einem historisch kontingenten und spezifischen Fall von Interaktion zwischen Menschen und einem klar umrissenen Flussabschnitt befassen: dem Rhein im Neuwieder Becken. Wir nutzen ein agentenbasiertes Modell, um Unterschiede in wasserbezogenen Landnutzungsentscheidungen zwischen spät-jungpaläolithischen und spätpaläolithischen Besiedelungen in der Region zu identifizieren. Zu beobachten ist ein deutlicher Wechsel von einer dominanten Schlüsselrolle des Rheins während des späten Jungpaläolithikums zu einer weniger bedeutsamen räumlichen Komponente während des Spätpaläolithikums. Wir folgern, dass diese Unterschiede genauso Ausdruck einer veränderten Wahrnehmung des Rheins als auch eine Konsequenz klimatischer Veränderung und einem Wechsel von einer initialen zu einer stationären Besiedlungsphase sind und beide Aspekte untrennbar verflochten sind.*

Keywords - **Agent-Based Model, Palaeoenvironment, Mobile Societies, Socio-Ecological System, Entanglement, Upper/Late Palaeolithic**
Agentenbasiertes Modell, Paläoumwelt, mobile Gesellschaften, Sozio-Ökonomisches System, Entanglement, Jung-/Spätpaläolithikum

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Introduction

Rivers and their tributary networks function as guides and landmarks to a variety of species. From birds using them as movement corridors to aid their migratory behaviour (Meyer et al. 2007: 94) to fish affected by the specific properties of a river (Crook & Robertson 1999: 941), streams have had vital meaning to the mobility of a plethora of species. To humans, rivers seemingly did and still do fulfil similar function. Their influence is not only limited to mobility, but they provide means of transferring knowledge along and across their shores (Classen 2018: 466), adding a highly complex social component to the relationship between humans and their surrounding nature.

For Palaeolithic hunter-gatherers, streams likely served as guidelines during expansions into formerly uninhabited areas (Richter 2018: 199 & 203), and it is rivers in particular that seem to have structured the movement of Late Upper Palaeolithic hunter-gatherers on a larger spatial scale. With glaciers in retreat, they seem to have followed roughly along river networks (Maier 2015: 85).

Recently, the meaning and function of rivers for the Late Upper and Late Palaeolithic inhabitants of Europe has received notable attention. Hussain and Floss (2015) provide a theoretical background and discuss the long-term relation between humans and rivers in the Late Palaeolithic with a focus on southern France and northern Iberia. Hölzchen et al. (2021) instead focus on individual agents within a landscape regarding larger water bodies, such as the Strait of Gibraltar. This approach explicitly looks at expanding populations, thus modelling a path from A to B. An agent-based model addressing the relation between rivers and a population in a stationary (non-expanding) phase and its corresponding behaviour, however, has yet to be developed.

To contribute to the current discussion about the role of water bodies for Palaeolithic societies, this study looks at two clusters of 13 Late Upper Palaeolithic (LUP) and 26 Late Palaeolithic (LP) sites – roughly dated between 16-14 ka calBP (GS-2a and GI-1e) and 14-12 ka calBP (GI-1c to GS-1; Rasmussen et al. 2014), respectively – east and west of the Rhine river in the wider region of the Neuwied Basin and the surrounding Rhenish Slate Mountains (Fig. 1).

In our model, the LUP site cluster represents a dynamic period of the resettlement of the region after the Last Glacial Maximum (Maier 2015) and subsequent population turnover (Posth et al. 2023). The LP, in contrast, represents a rather stationary phase of a stable population in the landscape (Fig. 2). The fact that both periods are represented in the same region provides testing ground for a model attempting to analyse decision-making parameters of two distinct hunter-gatherer communities, regarding the Rhine river at a particular location. Instead of aiming at generalisation or the transition from one system to the other, we thus focus on the historically contingent settings of what we regard as two socio-ecological systems in a steady state. The method, however, is applicable to other rivers and periods. Using an agent-based model, we will address the following two main questions:

Are there differences in Rhine-oriented land use decisions in the Neuwied Basin between the LUP and LP? And in this case, can these differences be explained by either ecological or socio-cognitive factors?

Material and methods

The use of agent-based models in Archaeology has gained momentum in recent years (Cegielski & Rogers 2016: 283). Particularly the close incorporation of human agency within its surrounding conditions bears potential for testing hypotheses concerning mutual influences between humans and nature (Crooks et al. 2019: 64; Widlok et al. 2012: 260). Further, integrating agent-based modelling into the theoretical framework of socio-ecological systems creates fertile ground for illuminating both the complexity of a system's components and the systemic intertwinement of both social and ecological aspects (Levin et al. 2013: 118).

It is important to stress that agent based spatial decision making as a research subject does not inherently require a profound and emic understanding of those decisions (Codling et al. 2008: 814). In this case, the acknowledgement of the inevitability of decision making in a spatial context alone may suffice modelling through carefully applying correlated random walks as a tool originally borrowed from biological science (Codling et al 2008: 813). Using the correlated random walk allows for the modelling of a land use practice without blindly assuming explanations behind these decisions. Genuine reasoning behind spatial decisions will thus remain to be discussed (see section 'Discussion').

Material

The investigated area spans from the foothills of the Eifel uplands and the Lower Rhine Basin in the North to the Hunsrück and Taunus uplands in the South. In the centre lies the Neuwied Basin, an approximately 20 km long and 10 km wide lowland with an average altitude of about 150 m and a rich Palaeolithic research history.

The dominant water body in this region is the Rhine river. Tributaries relevant for this study are – from south to north - the Lahn, Saynbach, Wied and Sieg on the eastern bank, and the Moselle, Nette Brohl and Ahr on the western bank. Additionally, Elzbach, Kyll and Rur are sourced within the Eifel uplands with LP sites in close proximity. The former two drain into the Moselle whilst the Rur drains northwest into the Meuse River (Fig. 1).

In the study area, a total of 19 occupations at 13 sites are reported for the LUP of (Kretschmer 2016)

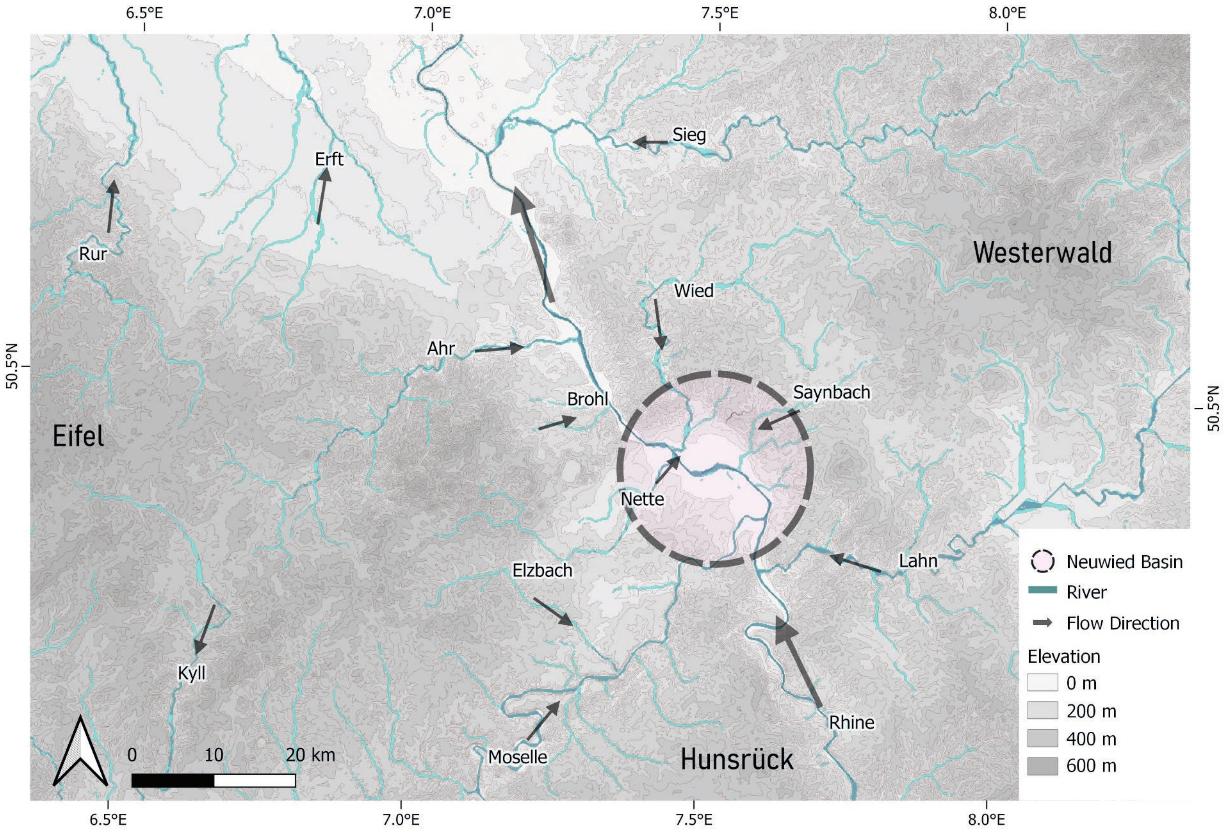

Fig. 1. The Middle Rhine Valley, with rivers and flow directions marked on the map, showing the three low mountain ranges of Eifel, Westerwald and Hunsrück surrounding the Neuwied Basin. DEM: Copernicus EU-DEM v1.1; EPSG: 3035.

Abb. 1. *Das Mittelrheintal, hier gezeigt mit Flüssen und Flussrichtungen. Zu sehen sind auch die drei Mittelgebirge Eifel, Westerwald und Hunsrück, die das Neuwieder Becken umgeben. DEM: Copernicus EU-DEM v1.1; EPSG: 3035.*

and 30 occupations at 26 sites for the LP (Schmidt & Zimmermann 2020). For the analysis, each occupation event is considered individually (Fig. 2; SI-A Tab. 1) as we argue that different layers indicate occupation frequency. We have decided against the implementation of further characteristics, such as extent or type to reduce complexity of the model.

Methods

The use of simulation within the field of Archaeology and, more specific, the implementation of Agent-Based Models (ABM) was ignited in the 1970s with reaction-diffusion models such as the "Wave of Advance Model for the Spread of Agriculture in Europe" (Ammerman/Cavalli-Sforza 1979: 275). Reaction-Diffusion models have gained in popularity since and found their way into a number of publications (for a detailed history of simulation in archaeology see Lake 2014). Agent-based approaches focussing on interactions between humans and their environment, however, came much later. In 1995, McGlade (1995: 113) noted that there had been a shift towards "human ecodynamics" within the research field of agent-based modelling in Archaeology. Lake (2014: 273) adds that this shift is accompanied by a heavy focus onto Geographical Information Systems (GIS) and often builds upon multiple models and simulation on different scales. It is primarily this context from which models concerning water body-based decisions emerged (e.g. Kohler et al. 2007). Hölzchen et al. (2021) have recently programmed the latest palaeolithic centred around the interplay of humans and hydrology.

For the present study, an agent-based approach using the open-source software NetLogo (Wilensky 1999) was chosen to simulate the behaviour-oriented relation of agents to their natural surroundings. The model follows the concept of socio-ecological systems in which a system containing non-linear feedback allows for a number of steady or stable states (Levin et al. 2013: 119; Widlok et al. 2012: 260). Instead of focussing on the factors influencing the transition between stages, the objective of this study is the identification of external and internal parameters relating to river-oriented land use decisions that are necessary to sustain the observed structure, and thus, steadiness, of the two site clusters; that is, both their internal density as well as their extent to the outside. To this end, we perform three statistical tests to understand the influence of the modelled water level, the initial position of sites, and the internal behavioural parameters of agents in our model necessary to keep the two observed systems in a steady state. This is done on the basis of exported "time-occupied" raster data. "Time-occupied" is a patch variable used to count

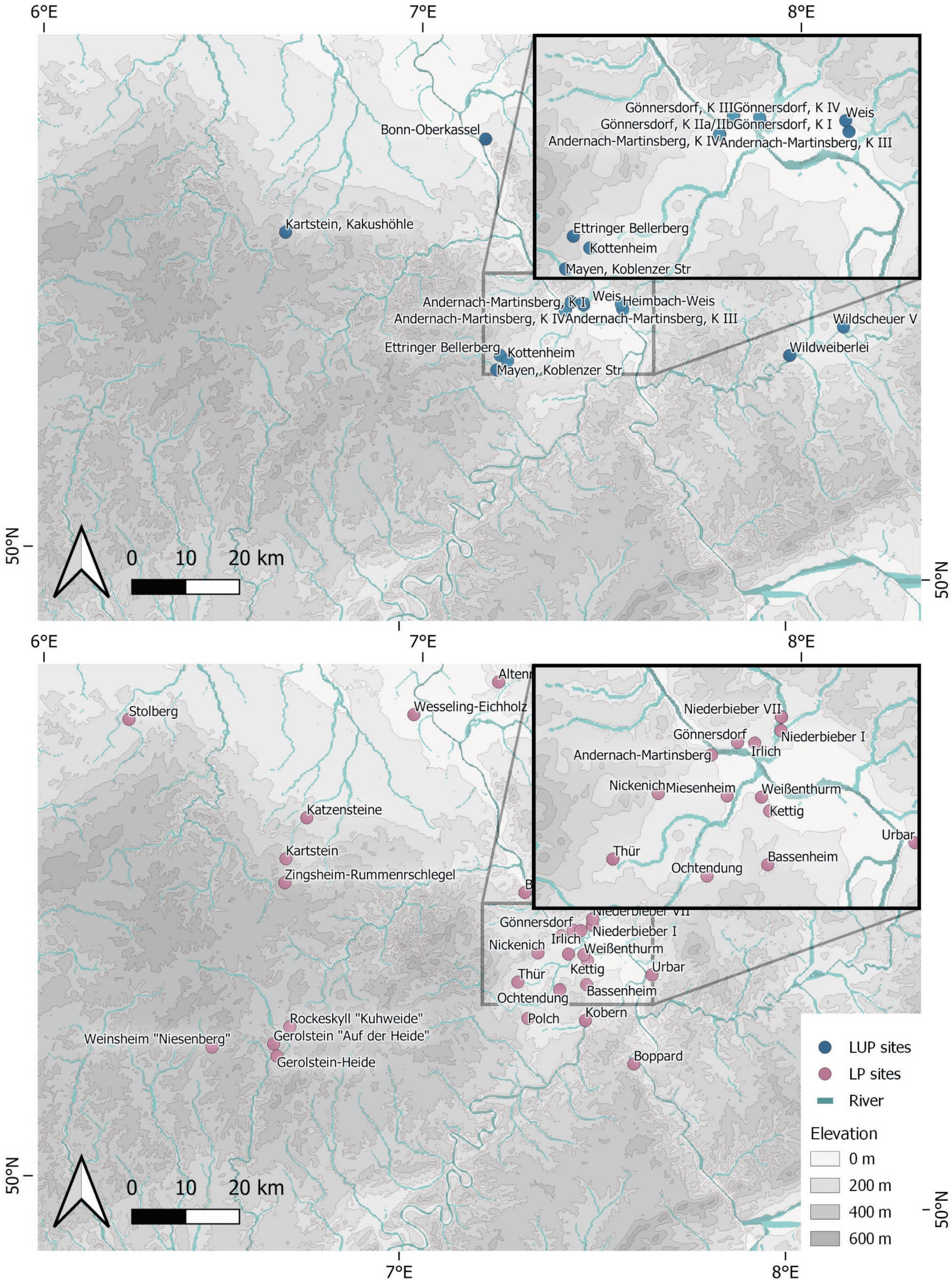

Fig. 2. Working Area with Late Upper Palaeolithic and Late Palaeolithic sites. Database: Kretschmer (2016), Schmidt/Zimmermann (2020). DEM: Copernicus EU-DEM v1.1; EPSG: 3035.

Abb. 2.*Arbeitsgebiet mit spät-jungpaläolithischen und spätpaläolithischen Fundstellen. Datenbank: Kretschmer (2016), Schmidt/Zimmermann (2020). DEM: Copernicus EU-DEM v1.1; EPSG: 3035.*

the number of times each cell has been visited by an agent. Thus, "time-occupied" raster data gives information about the density of agents' movements during a model run. Further, visual assessment is conducted on exported visual data in order to understand the difference of initial agent parameters needed to sustain the initial distribution of sites from the two datasets of either LUP or LP. The analysis individually addresses both datasets to identify comparable and distinctive differences. Divergent climatic conditions during both phases have been considered from the very beginning, starting with the hydrological analysis that forms the backbone of the model.

The simulation is supposed to portray abstracted group behaviour, rather than individuals, since we assume site location reflects collective decision making rather than that of single people. Thus, sites are seen as reflecting a group of people acting in a coherent and group-orientated manner (Romanowska 2021: 91). Additionally, while time as a factor does play a role in the analysis, it is solely used to keep a balance between land- and water-movement and provide a measure for the duration of actions and change. Therefore, no two sites are necessarily strictly contemporaneous within the model, and the separation into two distinct periods is a tool to analyse the coherence of decision-making between different groups of agents.

GIS-analysis

In order to compute the course of the Palaeolithic river, the Digital Elevation Models (DEM) of the Copernicus LandSat DEM 1.1 (EEA 2016) was chosen as the base for the flow accumulation (for details see SI-A).

A comparison of the hydrographic analysis of the Neuwied Basin with a map displaying various terraces relevant to the past hydrography of the Rhine river (Bosinski 2008: 293) shows a good agreement (Fig. 3). First, the general course of the Rhine river is similar in both visualisations. Second, the river similarly branches out in the centre of the basin, corresponding to the flat topography of the area. When reaching the Andernachian Gate, the river narrows into the Rhenish Slate Mountains. As a major difference, the map from Bosinski (2008: 293) shows individual branches in the flood plain, adding a seasonal and temporal dimension to the map that is beyond the resolution of our approach. The overall similarity of both visualisations supports the use of the topography-based hydrological analysis in an ABM.

To attain a usable raster for the ABM, the flow accumulation had to be reclassified into three distinct classes representing a low, a medium and a strong current induced by varying climatic conditions such as glacier melt of the Alps, periods of higher precipitation, dry winters etc. (Bosinski 2008: 294). The three bins representing water values have had their boundaries set at 2,000, 20,000 and 2,000,000 accumulated cells (SI-A Fig. 2).

Additionally, a flow direction layer indicating the direction of flow into one of the bordering eight cells, a slope layer and a layer containing the detailed course of the Rhine have been computed and subsequently imported into Netlogo (SI-A).

Setup of the agent-based model

The model was computed using the GIS-extension to NetLogo (SI-A). The model's environment was set up with a modulable "water-level" and corresponding flow velocity ("current-speed"). The former had settings covering a "high", a "medium" and a "low" "water-level" responding to the flow accumulation raster. A "current-speed" slider was given a range of values from 0 to 12 km/h corresponding to the overall flow velocity on the whole layer. The default "current-speed" was set to 3 km/h. However, "current-speed" has a neglectable impact on the model as it affects very few actions on a small scale and a constant value for all water-bodies was set in order to reduce complexity of the model.

The agents' decision-making processes were approached by choosing a range of parameters affecting a non-seeded correlated random walk (Codling et al. 2008: 813). A correlated random walk is a movement type where every prior step affects the next: the probability to head towards the prior direction of heading is highest, with a normally distributed probability to head elsewhere. A commonly used standard deviation for a correlated random walk is 45° (Romanowska 2021: 115). The parameters affecting the correlated random walks' standard deviations (thus the agents' heading) in this model are "decision-randomness", "rhine-directedness", "pioneering-along-rivers" and "water-sensitivity". Each tick, every agent would move forward a distance affected by the slope in the direction of heading and a tick represents an approximate time of 15 minutes. During each tick, an agent can do one of three actions: "undirected-walk", "directed-walk" and "water-crossing" (Fig. 4). "Undirected-walk" is a correlated random walk with a standard deviation of 45° The standard deviation is changeable by using the "decision-randomness" slider, ranging from 22.5° to 225°.

The "directed-walk" is, in turn, more complex. A "directed-walk" is initiated when the agent is located within 300 patches (30 km) of the Rhine, which is set as the agent's perception radius to allow a focus on hunter-gatherers in the Neuwied Basin, and a randomly generated number between 0 and 1 is lower than the setting of "rhine-directedness". Thus, when the "rhine-directedness" slider is set to 0.75, the agent will initiate a "directed-walk" in ¾ of cases, and first change the agent's direction of heading to face the next patch that is "rhine = true".

The "directed-walk" then initiates a correlated random walk that is now affected by two factors: the agents' distance to the Rhine and the setting of

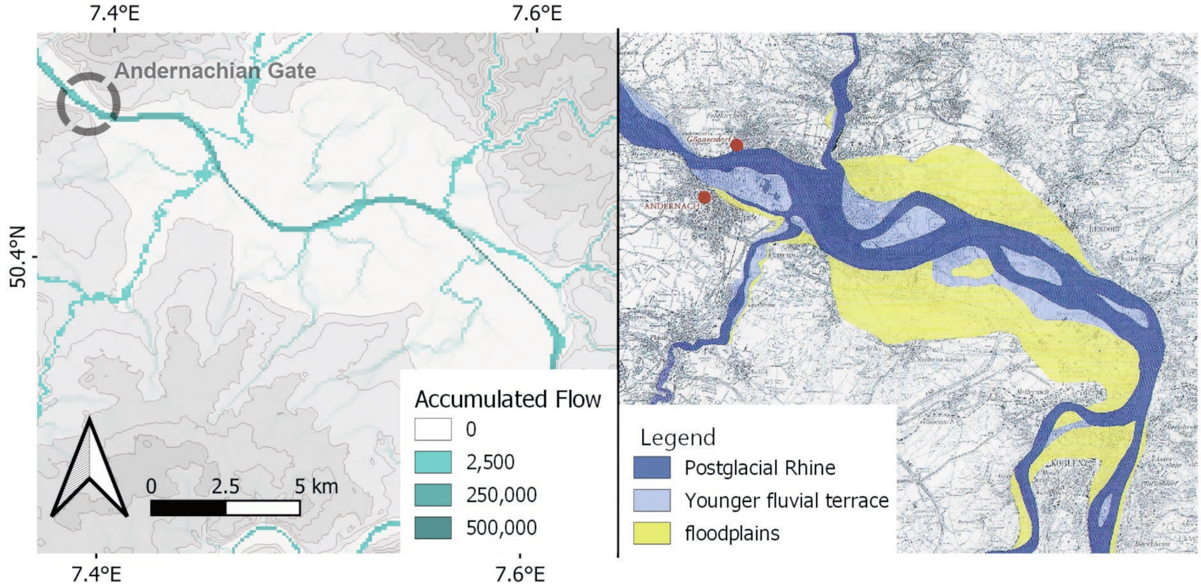

Fig. 3. Comparison of the hydrological analysis in QGIS and the map by Bosinski (2008: 293). Note that the view is slightly obscured by the use of another projection system on the right. Left: DEM: Copernicus EU-DEM v1.1; EPSG: 3035.

Abb. 3. *Vergleich der hydrologischen Analyse mittels QGIS und der Kartierung von Bosinski (2008: 293). Eine leichte perspektivische Verzerrung ist auf die Verwendung verschiedener Kartenprojektionen zurückzuführen. Links: DEM: Copernicus EU-DEM v1.1; EPSG: 3035.*

"pioneering-along-rhine". The further away the agent is from the Rhine, the lower the standard deviation will be. As it is approaching the river-banks, the walk will be less straight forward as it is assumed that agents that are directed towards the river do not seek to spend their time directly within the current but rather roam in close proximity to the river and along its banks. "Pioneering-along-rhine" amplifies or weakens this effect on the standard deviation by values of above or below 0.5, hence it either multiplies or divides the deviation:

∑= 90 * (1 *"distance–to–river" / 300) * ("pioneering–along–rhine" * 2).

After establishing a direction of heading, the agent moves its "effective-walking-distance". The "effective-walking-distance" is calculated each tick from the sum of (("patch-slope")/100 * 0.99) of all patches that are in the agent's current heading range ("optimal–walking–speed"*2.5), subtracted from the number of patches in his range. Multiplying the slope values by 0.99 was done in order to avoid agents getting stuck on patches with succeedingly high slope values (Hölzchen et al. 2019: 5). Whenever an agent has to pass a patch with "water = true" within its current heading range, the agent stops at that very patch. Whilst this is potentially

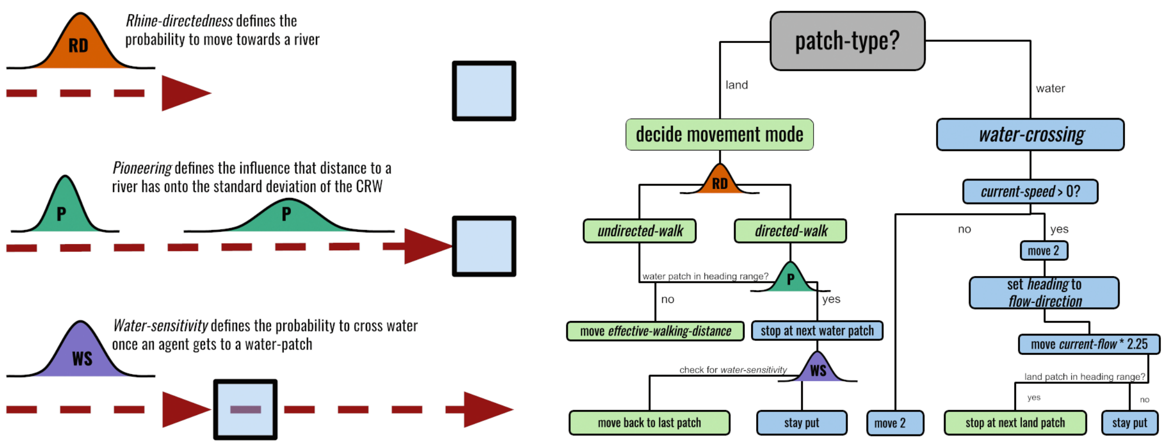

Fig. 4. *Flow chart showing the behavioural chain of each agent at each tick, including parameters affecting the correlated random walk (CRW).*
Abb. 4. *Die Flow Chart bildet die Verhaltenskette ab, die jeder Agent an jedem Tick vollzieht, und zeigt Parameter, die den correlated random walk (CRW) beeinflussen.*

strongly restricting an agent's movement depending on both "water-sensitivity" and "water-level", these two parameters can be used to precisely adjust agent behaviour to match specific land-use patterns observed in the Neuwied Basin.

In case the agent lands on a patch with "water = true", a check on "water-sensitivity" is ran to define the course of the agent's following actions: when the randomly generated number between 0 and 1 surpasses its "water-sensitivity", the agent stays put. In case the number is lower than its current "water-sensitivity" value, the agent turns around and moves to the last patch with "water = false" it has been on.

The last action that an agent can take up is "water-crossing". "Water-crossing" may be initiated whenever an agent is located on a patch with "water = true" at the beginning of a tick, that is, when the "water-sensitivity" check has surpassed the value set in the parameters of the agents' setup. The agent moves forward by two patches into the direction it was heading before following a correlated random walk with the deviation being 45°. Whenever the value of "current-speed" on the patch the agent just moved to is higher than 0, the agent turns towards the direction that is implied by the underlying "flow-direction" raster and moves forward by the speed that is set by "current-speed". If there is a patch with "water = false" in the range given by ("current–speed" * 2.5), the agent will stop at that patch and initiate either "directed-walk" or "undirected-walk" when the next tick starts.

At the end of each tick, every agent will add +1 to the "time-occupied" value of the patch the agent is located on.

The NetLogo-integrated tool BehaviorSpace was used to set up a series of experiments running the model with different parameter settings. During these experiments, we had to assess an appropriate duration per model run and have decided to run each model for 100 ticks, in order to keep the computational requirements at an appropriate measure. First, the model was run 240 times testing a "high" and "low" "water-level" for both LUP sites and LP sites, iterating through the parameter settings while testing every possible parameter combination 15 times. The experiment ran all possible combinations for these settings:

Water-level: "high" and "low"
Period: "Late Upper Palaeolithic" and "Late Palaeolithic"
Rhine-directedness: 0.25 and 0.75
Pioneering-along-rhine: 0.25 and 0.75
Water-sensitivity: 0.35 and 0.75
Decision-randomness: 0.2
Optimal-walking-speed: 5 km/h
Current-speed: 3 km/h

A second experiment aimed at a comparison of initial locations of sites was set up using two sets of 32 points. Each of these sets has points distributed around the geographical centre of either all LUP sites or all LP sites. The points are in an equal distance to each other that corresponds to the median distance of all LUP or LP sites, one of which is 448 m, the other being 4,390 m (Fig. 5) The two sets of points were tested against each other to establish whether different initial positions result in any significant difference. Following parameters have each been tested 15 times in all possible combinations, resulting in an overall of 240 model runs:

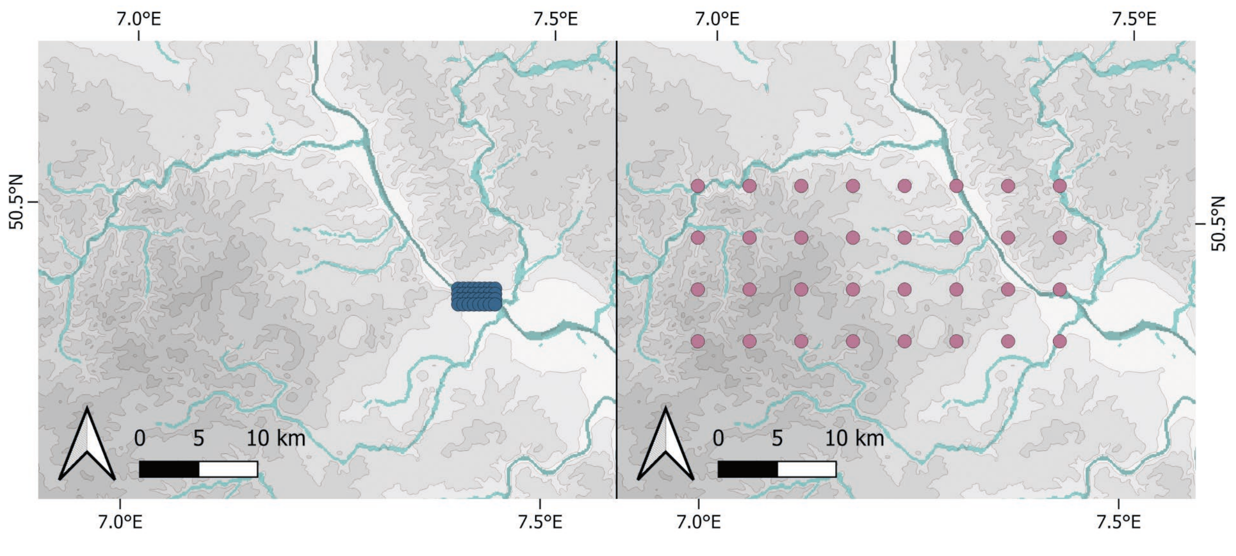

Fig. 5. Two sample point patterns used to test differences of results due to variance in initial site position and density. The left map shows sample points in a distance of 448 m to each other, the right map shows sample points in a distance of 4,390 m to each other. DEM: Copernicus EU-DEM v1.1; EPSG: 3035.

Abb. 5. *Zwei schematische Punkt-Verteilungen werden genutzt, um Ergebnisunterschiede aufgrund von Varianz in anfänglicher Fundstellenposition und -dichte zu testen. Die linke Karte zeigt Punkte im Abstand von 448 m zueinander, die rechte Karte zeigt Punkte im Abstand von 4.390 m zueinander. DEM: Copernicus EU-DEM v1.1; EPSG: 3035.*

Water-level: “high”
Period: “Sample Points 3 km” and “Sample Points 6 km”
Rhine-directedness: 0.25 and 0.75
Pioneering-along-rhine: 0.25 and 0.75
Water-sensitivity: 0.35 and 0.75
Decision-randomness: 0.2
Optimal-walking-speed: 5 km/h
Current-speed: 3 km/h

A third experiment was conducted to allow for statistical analysis of the decision parameters’ influence. The settings of this third experiment in BehaviorSpace were as follows, again iterating 15 times through all combinations, amounting an overall of 240 runs:

Water-level: “high”
Period: “Late Upper Palaeolithic” and “Late Palaeolithic”
Rhine-directedness: 0.25 and 0.75
Pioneering-along-rhine: 0.25 and 0.75
Water-sensitivity: 0.25 and 0.75
Decision-randomness: 0.2
Optimal-walking-speed: 5 km/h
Current-speed: 3 km/h

Statistical analysis

Metrics about the individual model runs were recorded using BehaviorSpace in NetLogo. Specifically, the value that we have used for the statistical analysis is the number of cells at the end of each model run that had a “time-occupied” value higher than 0. This value is implicitly representative of all cells that have been visited more than once, as the overall number of “time-occupied” stamps has been the same for every run. Thus, the lower the value, the denser the outcome of the model run has been. The higher the value, the more scattered the run was, as less cells have been visited more than just once.

This indicator for land use of each model run was then prepared to undergo a number of Kolmogorov-Smirnov tests to establish significances regarding a set of questions. The Kolmogorov-Smirnov test assesses differences between two distributions by comparing their cumulative distribution with the null hypothesis being that the two compared distributions are statistically similar.

For the purpose of conducting the statistical analysis, an R-Project was set up and the tables collected from the reports in BehaviorSpace were imported into the environment of R (R Core Team 2021). The R-integrated “ks.test” function was used in order to calculate p-values for the selected data.

First, we tested whether different water conditions result in a significant difference of land use density. 2 times 240 model runs with equally changing parameter settings were tested, with one set of runs with a “water-level” being “high” and one set of runs being run with a “water-level” set to “low”.

Additionally, we have compared whether the overall difference of start positions already makes for a different degree of density in land use patterns. To this end, results of both sample point layers that have been run with equally changing parameter settings were tested against each other in order to evaluate the statistical importance of the initial distribution of agents.

Lastly, we tested the agents’ decision-making parameter settings against each other. The “rhine-directedness”, “pioneering-along-rhine” and the “water-sensitivity” parameters were run 120 times, each with one set being set to a value of 0.25 and the second set being set to a value of 0.75. This last Kolmogorov-Smirnov test aimed at establishing whether the movement decisions make for a significant difference in land use density and pattern.

Results

Throughout the following section, both the statistical analysis of densities under varying parameter settings and the visual representation of the patterns by each run will be presented. In order to evaluate parameter importance, the results of the statistical tests are going to be presented first, followed by an evaluation of a number of model runs with commented outcome. Whilst the first part of the results will be of quantified nature, the second part is limited to visual comparison and understanding. Given that each model run will produce a spatially divergent distribution of “time-occupied” values, a statistical analysis of the spatial distribution regardless of density but instead focussed on the north-east distribution of “time-occupied” values proves difficult and would require more extensive research. The main difficulty is the intended randomness of the model that may lead to very different spatial outcomes using the same parameter settings.

Statistical results

The first experiment testing 240 model runs with a “water-level” setting of “high” against 240 model runs with a “water-level” setting of “low” did return a significant p-value of 0.0000. It may be concluded that within the model, the “water-level” settings and the subsequent obstructions they cause to the agents’ movement cause a significant difference in the overall density of the distribution of the agents’ “time-occupied” values.

Following the test of the 240 runs with two sets of 32 evenly spaced points with a distance of 448 m and 4,390 m, it can also be concluded that changing the initial starting points of agents within the Neuwied Basin causes a significant difference between the final two densities of the model (p-value of 0.0000).

The final three statistical tests explore whether the parameter settings of the agents’ decisions are resulting in a statistically significant difference of the density of “time-occupied” values and hence the agents’ paths.

First, the two sets of each 120 model runs with "rhine-directedness" values of 0.25 and 0.75 were tested against each other, returning a significant result (p-value = 0.0004). We may thus conclude that the parameter settings of "rhine-directedness" significantly affect the outcome of the model.

Secondly, the two sets of each 120 model runs of "pioneering-along-rhine" 0.25 and 0.75 have been tested against each other, also returning a significant test result (p-value = 0.0000). Thus, we can also consider the parameter of "pioneering-along-rhine" to be significant for the model's outcome.

A third test was done on the two sets of each 120 model runs corresponding to a "water-sensitivity" setting of 0.25 and 0.75. This test may be of particular interest regarding the results of the first test comparing the "water-level" settings of "high" and "low". The test returned a significant result with a p-value of 0.0000.

Following the statistical analysis of the "time-occupied" values produced by an overall of 960 model runs, each doing 100 steps including approximately 2.5 million individual agents' decisions, we conclude that it is neither the environmental settings nor the initial distribution of sites alone that shape the final results of the model. Ultimately, both the internal and external parameters of the model cause significant differences in the densities of the agents' paths. This happens in an interdependent manner, where parameters such as "water-level" interact with parameters such as "water-significance", and jointly shape the final outcome of the model. An initial series of experiments with lower sample size has returned no significant results for the tests of "water-level" and initial position, whereas the decision parameters have all tested significant (for results, see SI-A).

Visual results

In this section, a selection of model runs will be evaluated and commented regarding their sustainment of the original site distribution of the relevant periods. It is beyond the scope of this study to discuss all available results. Instead, a representative selection will be used for comparison, focussing on three parameter settings for each period (for detailed visual results and all ASCII-files, see SI-D). The visual analysis is concerned with agents' paths through the landscape of the Neuwied Basin, following the assumption that they are leaving sites behind along their routes. In order to keep conditions stable for the sake of replicability, we choose to continuously apply a "high" "water-level" for this visual assessment, and thus maximally account for obstructions imposed by water bodies in the area.

This section is aimed to establish parameters relevant to both LUP and LP that sustain the density (referring to continuous revisits of certain patches) and extent (referring to the two-dimensional use of space) of agents in the Neuwied Basin. Both density and extent are thus interrelated in the model, as a larger extent of the agents' distribution in the Neuwied Basin will, in most cases, correlate with a lower density. A particular difference between the two original datasets is that the LP appears to be more scattered and shows a lower site reuse redundancy. Combinedly using density and extent allows for a sound understanding of the most striking differences between the varying model runs.

We expect "rhine-directedness" to particularly affect density along the Rhine, with a higher "rhine-directedness" resulting in an overall higher density and smaller extent. Secondly, "pioneering-along-rhine" is thought to affect the density of the pattern in a way that a high "pioneering"-value results in a lower density along the Rhine, since decreasing distance to the Rhine increases the probability to turn away from the river. Lasty, "water-sensitivity" can be expected to most significantly affect how agents are crossing water bodies and will thus have a very notable impact onto the cluster shifting its concentration elsewhere, dependent on initial locations in regard to the presence of water in the area.

Looking at visual data produced by 282 additional model runs it becomes clear that for the LUP site cluster, the model is required to have a relatively high setting of "rhine-directedness" to maintain the cluster's approximate extent in the Neuwied Basin (Fig. 6). Whilst a "rhine-directedness" of 0.5 already keeps agents within a distance of about 15–20 km of the Rhine river, the original cluster is characterised by an even closer density within the Neuwied Basin with three occupations located closely to the edges of the Eifel uplands. There is no presence of sites within the centre of the Basin on the west bank of the Rhine. In order to simulate a comparable distribution, the high "rhine-directedness" has to be combined with a similarly high "pioneering-along-rhine" setting, causing a certain degree of scattering combined with a close confinement of agents within the extent of the original site cluster. Regarding the value of "water-sensitivity", the results are more ambiguous, possibly due to the high degree of randomness that already affects the results. However, a low value of "water-sensitivity" raises the likelihood of the whole cluster shifting eastwards. This is because fewer agents turn around when they reach water and are thus less prone to continue to roam the slopes on the northern fringe of the Neuwied Basin.

Hence, the visual assessment shows that for the purpose of containing agents within the original site cluster of the LUP, the values of "rhine-directedness" and "pioneering-along-rhine" need to be set to a high level.

Yet, after changing the dataset from the LUP to the LP and, therefore, the starting points of agents, the agents still create a pattern strikingly similar to the LUP dataset used before: with "rhine-directedness", "pioneering-along-rhine" and "water-sensitivity" set to high values, it is the banks of the Rhine

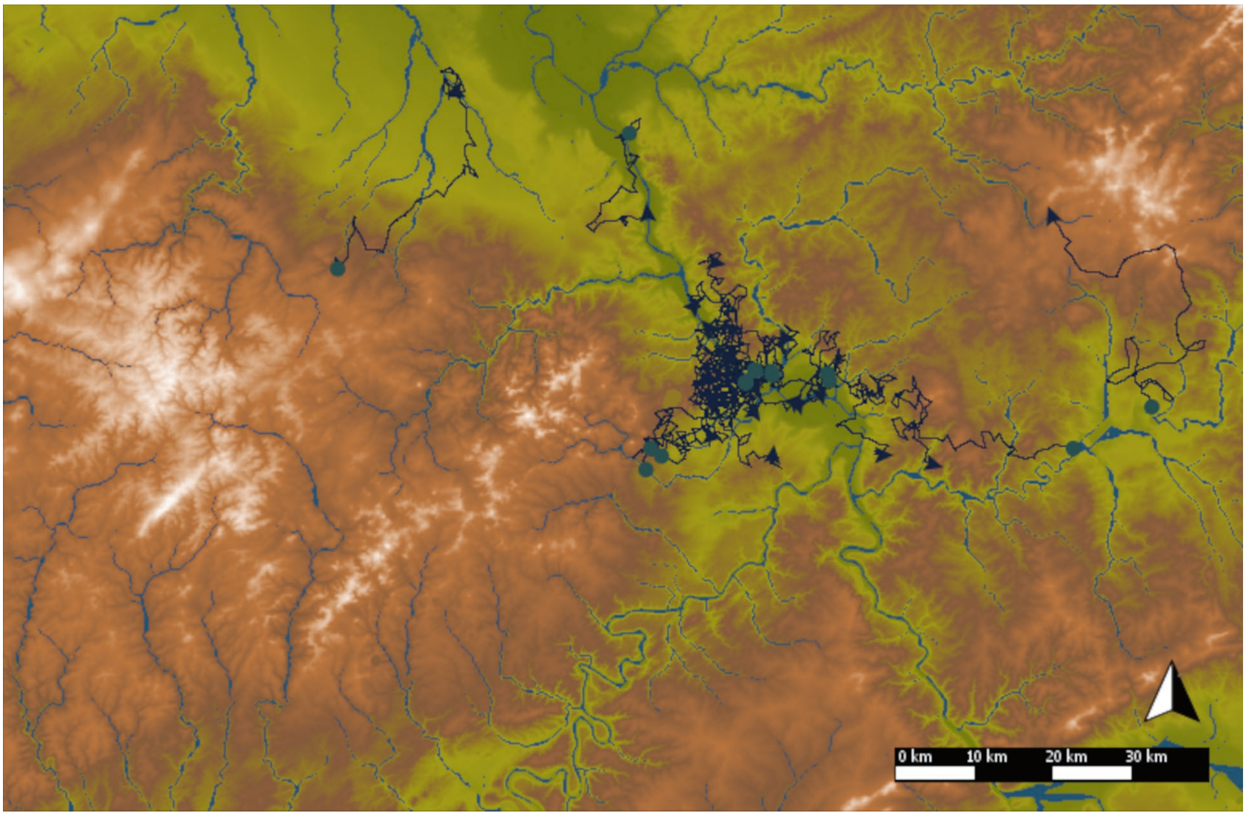

Fig. 6. Agent-Based Model Run 2021-12-07_03-09-54. The model is set to "rhine-directedness" = 0.75, "pioneering" = 0.75 and "water-sensitivity" = 0.25. The shown run resembles the original clustering of the Late Upper Palaeolithic site pattern in the Neuwied Basin. Database: Kretschmer (2016), Schmidt/Zimmermann (2020). DEM: Copernicus EU-DEM v1.1. EPSG: 3035.

Abb. 6. *Agentenbasiertes Modell, Durchlauf 2021-12-07_03-09-54. Das Modell ist eingestellt auf „rhine-directedness" = 0.75, „pioneering" = 0.75 und „water-sensitivity" = 0.25. Der abgebildete Durchlauf ähnelt dem originalen Cluster der spät-jungpaläolithischen Fundstellenverteilung im Neuwieder Becken. Datenbank: Kretschmer (2016), Schmidt/Zimmermann (2020). DEM: Copernicus EU-DEM v1.1. EPSG: 3035.*

in its very close proximity that are most densely used. Again, a high "pioneering-along-rhine" value raises the likelihood of the northern slopes of the Basin being used more regularly as they are located closely to the river, while higher slope values also provide a natural obstacle and thus interfere with the movement of the agents.

In order to contain the agents' paths within the initial boundaries of the LP site cluster, the agents need to act based on other decision parameter settings than the agents of the LUP (Fig. 7). First, it is the "rhine-directedness" that needs to be toned down. Within the 282 model runs used for the visual analysis, none of the runs with a "rhine-directedness" higher than 0.25 allow to sustain the degree of scattering observable for the LP. With a high "rhine-directedness", agents would turn towards the Rhine and distort the scattered state that we attempted to sustain. That means, in turn, that within the model, far less decisions are taken with the river being an attracting landmark.

Looking at the value of "pioneering-along-rhine", a value similarly high to the one used for suitable LUP parameter settings may be used. The high degree of scattering of the LP site cluster results from dispersed agents' paths that roam the surrounding landscape in a less river-directed and potentially more local way. In this case and combined with the low value of "rhine-directedness", a high "pioneering-along-river" value does just that: dispersing agents' paths within the soft spatial boundaries set by "rhine-directedness".

But it is again the "water-sensitivity" that may be regarded as more ambiguous and would require further evaluation: Whilst a low "water-sensitivity" value raises the chances of agents staying on the side of the Rhine that they have started from, it also substantially influences the degree to which the cluster will extend to the east. In this case, we chose a "water-sensitivity" of 0.75 with the "water-level" set to "high" to maintain the most accurate resemblance to the original cluster of LP sites in the Neuwied Basin. Nonetheless, as the parameter of "water-sensitivity" is so closely intertwined with the setting of the "water-level" (defining the very number of patches at which actions corresponding to "water-sensitivity" may be called), the close relationship of the two will have to be examined more thoroughly.

Discussion

Model implications

Naturally, the more patches with "water = true" are present in the model (hence, the higher the

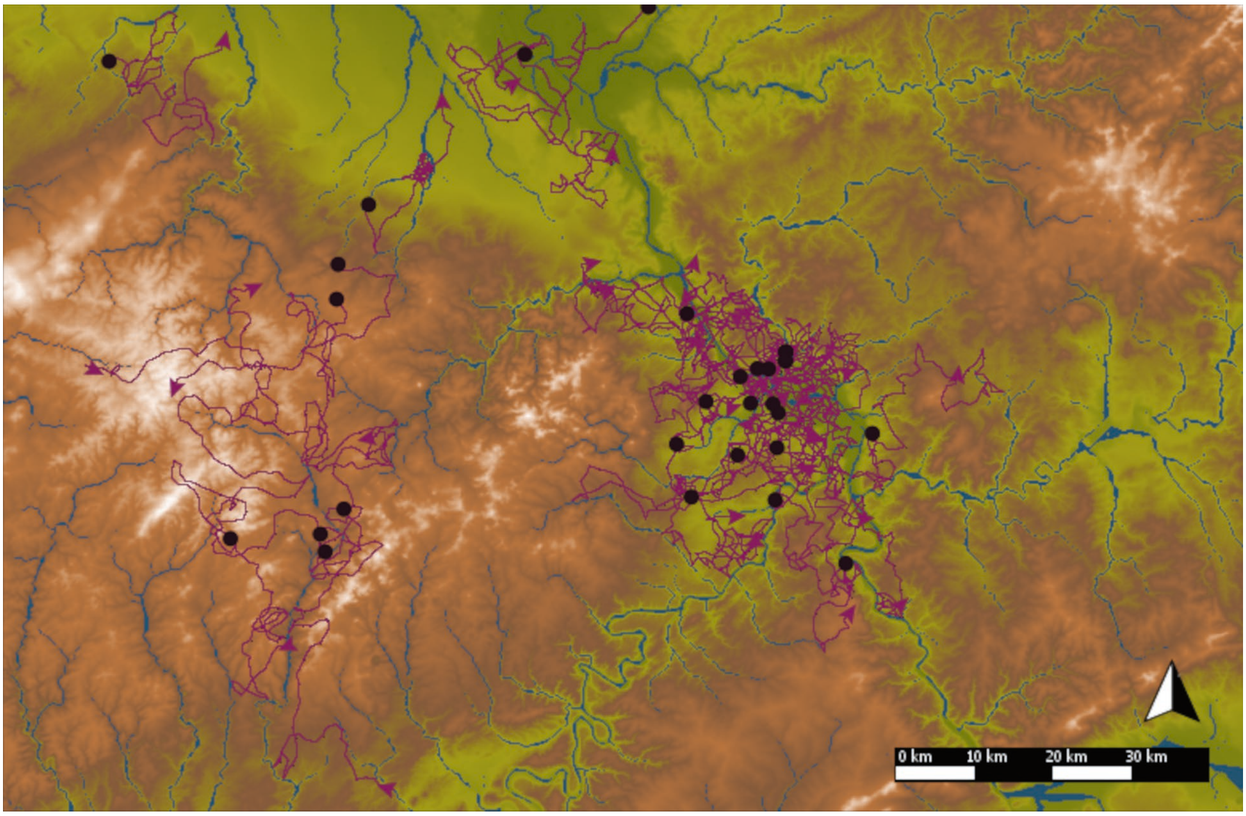

Fig. 7. Agent-Based Model Run 2021-12-07_18-54-44. The model is set to "rhine-directedness" = 0.25, "pioneering" = 0.75 and "water-sensitivity" = 0.75. The shown run resembles the original clustering of the Late Palaeolithic site pattern. Database: Kretschmer (2016), Schmidt/Zimmermann (2020). DEM: Copernicus EU-DEM v1.1. EPSG: 3035.

Abb. 7. *Agentenbasiertes Modell, Durchlauf 2021-12-07_18-12-07. Das Modell ist eingestellt auf „rhine-directedness" = 0.25, „pioneering" = 0.75 und „water-sensitivity" = 0.75. Der abgebildete Durchlauf ähnelt dem originalen Cluster der spätpaläolithischen Fundstellenverteilung. Datenbank: Kretschmer (2016), Schmidt/Zimmermann (2020). DEM: Copernicus EU-DEM v1.1. EPSG: 3035.*

"water-level"), the more river interactions are going to take place. Each river interaction will either lead to a directed crossing of the river, or a downstream movement of the agent due to flow mechanics that may sweep the agent onto the same shore it has just moved from, or a turnaround to the direction the agent has come from ("aborted-river-interaction"). Consequently, the more water patches, the more frequently will the movement of the agent be inflicted.

As mentioned above, this is closely related to the setting of "water-sensitivity", defining the probability threshold at which the agent decides to cross the water. Infliction of movement is thus influenced in a twofold and possibly even contradictory manner with a high "water-sensitivity" value counterbalancing a "water-level" set to "high". Accordingly, a contrast of LUP and LP will only be established when adhering to the idea of different water levels within the two phases – the LUP being characterised by a cold and relatively dry climate and the LP with its oscillating colder and warmer phases as well as higher precipitation (Bosinski 2008: 220). During the LUP, the Rhine is, as most other rivers during that time, understood to be a braided system. During the Late Glacial, the Rhine went through a transitional stage, before turning into a single channel meandering system, possibly in the Preboreal. However, there is growing evidence that this transition from a braided to meandering Rhine is not solely dependent on climatic conditions, but also on geological setting of the Upper Rhine Graben and wider catchment of the Rhine (Erkens et al. 2009: 491). The LUP would have possibly seen the Rhine being more shallow, especially in areas with a high potential for braiding (e.g. the Neuwied Basin), whilst the LP would bring stronger currents and deeper water levels, accelerated by the melt of Alpine glaciers (Mills 2023: 3; Busschers et al. 2007: 3242). In order to attain more profound results on the influence of climate factors on water levels and its dynamic and complex interplay with human decisions and possibly animal behaviour, further analysis would be paramount (see 'Conclusion').

Ecological and social reasons for Rhine-directed behaviour

However, this discussion shall not only concern the reasons for the specific model mechanics. In the following section, we will explore potential ecological and social reasons behind the observed change in Rhine-orientation between LUP and LP hunter-gatherers. The two perspectives – ecological, on one hand, and social, on the other – may have, throughout research history, to some extent been regarded as oppositional or even conflictive (e.g. Schiffer 1981). Research emphasising ecological determinants is widespread in the field of Palaeolithic research (e.g. Lisá 2013: 71; Maier et al. 2016; Shao et al. 2021). Whilst we confidently accept the natural environment as a frame in which humans will have acted according to complex behavioural rules, constraints, or maxims, we argue that it is the integration of both social and environmental factors that will lead towards a genuine ecology of the Palaeolithic – that is, a more thorough understanding encompassing a wider array of interconnected natural and social factors and their mutual relations (cf. Widlok et al. 2012: 260).

In a seminal paper, Binford (1980: 21) states that the availability of resources in a region may have a strong impact on the mobility patterns of a group. More specifically, if resources are scarce or unevenly distributed, a group may show a less dispersed patterns of movement and camp locations as well as continuous reuse of locations. Binford distinguishes between 'residential mobility', characterised by a tendency to reuse sites and a low spatial variability, and 'logistical mobility', the latter creating less dense spatial records and showing a lower site use redundancy (Binford 1980: 9). However, both modes can coexist within the same group depending on season and region (Binford 1980: 12).

LUP hunter-gatherers in Central Europe mainly relied on terrestrial ungulates for their subsistence, in particular horse and reindeer (Maier 2015: 16). This is also reflected in the faunal remains of Gönnersdorf (Bosinski 2008: 305) and Andernach (Holzkämper 2006: 44) in the Neuwied Basin. Aquatic resources also played a role, but due to the size and often poor preservation of fish remains, their importance and contribution to the diet is currently unclear (Torke 1981). However, the incorporation of fish and other aquatic resources in the diet seems to have an important impact on the land use patterns of forager groups (Weniger 1982; Kelly 1995; Greaves 2006). Thus, the presence of aquatic resources in the area that are easy to exploit may create an unequal distribution of overall resources and may have, following the arguments of Binford (1980: 21), well been a factor in the strong directedness towards the river during the LUP.

A general chronological trend in this regard seems to be a shift from a dominance of salmonids during the LUP to cyprinids, pike, chub, and bass in the LP, as part of an overall increase in the use of fish (Torke 1981; Cleyet-Merle 1990; Clottes 1987; Le Gall 1992; Kretschmer 2015). This is in line with a general warming trend also affecting the river systems. With the appearance of the beaver in the region, water abundance in the Neuwied Basin probably increased further (Busschers et al. 2007: 3220; Bosinski 2008: 371).

Migrating behaviour is a particular trait of salmonids (Hayden et al. 1987). While it is generally held that anadromous salmon retreats to freshwater river section in spring or early summer to spawn (Street 1998: 50), salmonids in colder biomes, such as northern Scandinavia withdraw to shallow and calm sections of a river in colder months and rest relatively immobile until it eventually gets warmer (Huusko et al. 2013: 182). Such sections might have been present in the Neuwied Basin. Seasonal sedentary salmonids, if known to hunter-gatherers, could have likely been an easy target.

In order to assess natural factors playing into land use decisions and potential change of social perception of space, it is paramount to gain information on seasonality. Unfortunately, seasonal information is only available for very few sites in the region. The LUP occupations at Andernach and Gönnersdorf seem to have mainly been occupied during cold seasons (Bosinski 2008: 282; Poplin 1976: 102; Street 1998: 50), while the LP sites, with faunal remains of primarily elk, deer, aurochs, and beaver (Bosinski 2008: 372), do not indicate a specific seasonality in hunting events. The available information thus broadly indicates a seasonal use during the colder period for the LUP (Kretschmer 2015: 116), while LP groups may have roamed the area all year.

In line with the general pattern, fish remains have been found in LUP-associated Magdalenian layers at the site of Andernach, mainly consisting of salmonids (Street 1998: 50), while in the LP, there is a diversification with pike, chub, and bass gaining importance (Bosinski 2008: 373). Thus, while salmonids might still have retreated to the shallow waters of the Neuwied Basin in the winter months, their exploitation was seemingly less important to hunter-gatherers in the area. In contrast, fish with a more localised mobility pattern spread across more widely distributed fluvial system may have a homogenising effect on the availability of resources and thus may have supported more dispersed mobility patterns relying on similar fishing techniques throughout the year. Indeed, when compared to the LUP, LP hunter-gatherer land use in the Neuwied Basin may be described as leaning towards 'logistical mobility' with a lower site redundancy and a less dense site pattern (Binford 1980: 8).

The question arises to what extent the change in natural parameters and land use coincided with change of social perception of space and, ultimately, hunting strategies aimed at the river. At a socio-cognitive level, the relation of humans and their aquatic environment has been discussed using the concept of entanglement (Hussain & Floss 2015). Entanglement as a concept was introduced to archaeology by Ian Hodder and is strongly influenced by the work of philosopher Bruno Latour, in particular his Actor-Network Theory (Latour 2005: 16). However, while Latour avoids a clear taxonomic distinction between humans and nature (Harman 2014: 41), Hodder, in turn, maintains the dichotomy of either humans and things (Hodder 2012: 88) and defines the sum of the relations of humans and things as entanglement. Whether agency is a property that is either exclusively innate to humans, as it is commonly understood following Hodders arguments, or an emergent property of interaction regardless of human or non-human actants has been debated in recent years (e.g. Malafouris 2008; Johannsen 2012). Be that as it may – seeing a river as a persona defined by a set of ascribed characteristics underlines that behavior in a landscape is not just ecologically forced but negotiated (Hussain & Floss 2015). In this view, it is the interplay between factors such as the properties of flow and degree of meandering, quality and availability of aquatic and terrestrial resources, availability of raw material, but also narratives and world views, that creates the focality of a river, a non-human element of a system that continuously interacts with other elements (Hussain & Floss 2015: 1166).

Seeing rivers as elements of a system where agency is an emergent property of the interaction (Malafouris 2008) turns their physical role into a biosocial one. This view does not solely rely on the spatial aspect of the term vector (e.g. Hussain & Floss 2015; Maier 2015), but also stresses their function as an acting carrier of knowledge. With humans travelling along rivers, these rivers are not only guidelines for the transport of physical objects, but also become vectors of constantly changing and negotiated knowledge conjoining natural and social space.

Knowledge is closely related to familiarity. Assessing the familiarity of a group to its given surroundings may thus help to understand land use decisions. Site location and raw material procurement patterns can give valuable information complementing those from seasonality. LP groups have obtained raw material from an approximate radius of about 100 km, relying on exogenous flint from the Meuse watershed and Baltic flint from the north (Fig. 8). Additionally, Tertiary chalcedony from Bonn-Muffendorf (about 40 km to the north) and locally available Tertiary quartzite as well as lydite pebbles carried along the Rhine river have also been used (Baales/Street 1996: 293). LUP groups have obtained raw material from a seemingly similar range, but some raw material also came from outcrops further south, such as the Main catchment or the Markgräfler Land (Floss 1994). This points to more extensive networks in which rivers – and the Rhine in particular – may have played a crucial role (Maier 2015).

Regarding site location, LUP occupations are often positioned at salient points in the landscape, such as the Andernachian Gate, and are re-used multiple

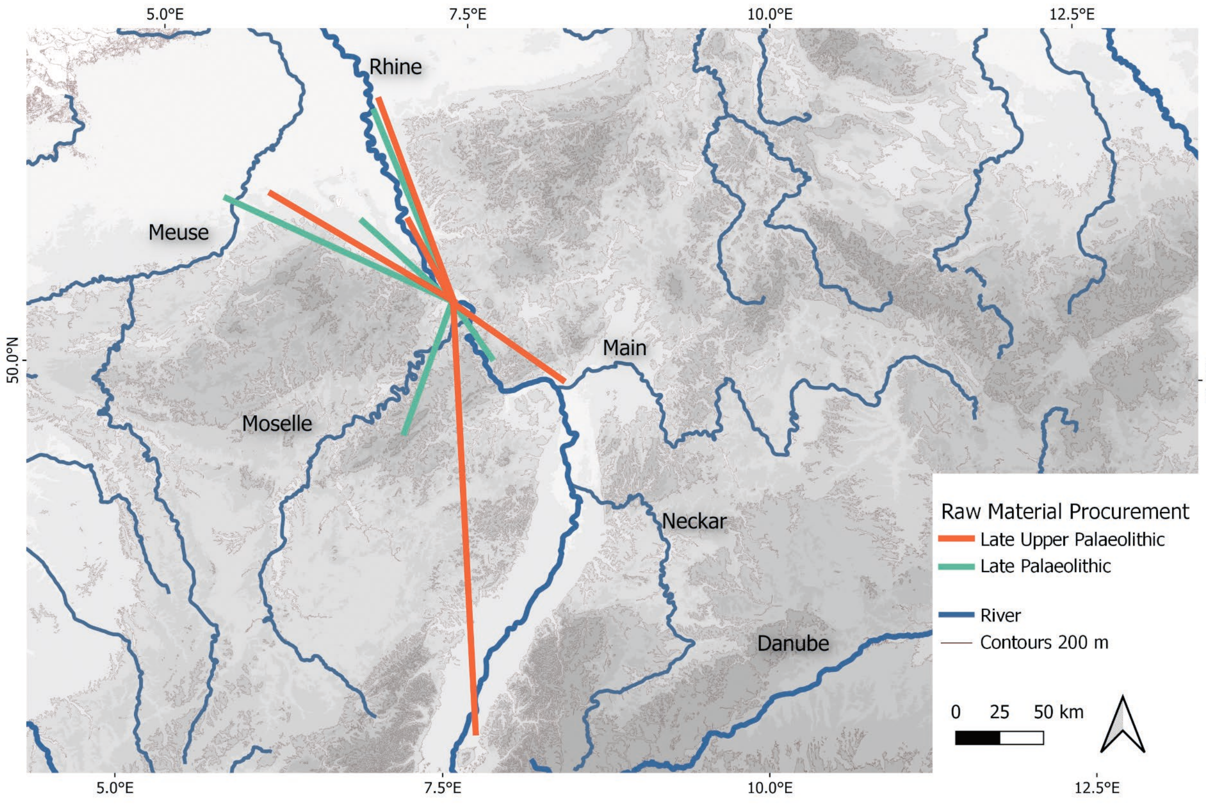

Fig. 8. Map showing raw material catchments of Late Upper Palaeolithic and Late Palaeolithic sites in the Neuwied Basin. From: Baales/Street (1996: 293); Kretschmer (2015: 87); Maier (2015: 95). Rivers: EEA (2009). DEM: Copernicus EU-DEM v1.1. EPSG: 3035.

Abb. 8. *Die Karte bildet Rohmaterial-Einzugsgebiete von spät-jungpaläolithischen und spätpaläolithischen Fundstellen im Neuwieder Becken ab. Aus: Baales/Street (1996: 293); Kretschmer (2015: 87); Maier (2015: 95). Rivers: EEA (2009). DEM: Copernicus EU-DEM v1.1. EPSG: 3035.*

times (see above). LP groups, in contrast, have left a far more dispersed site pattern in the Basin, with a reduced focus on the Rhine river and a usual single use of sites. Together, these observations point towards a perception of the area as a known, yet not intimately familiar place for LUP groups. This is congruent with the fact that this period corresponds to the resettlement phase of Central Europe after the Late Glacial Maximum during which larger rivers might have exhibited a stronger potential to act as a dominant feature (Maier 2015; Mills 2022:3). The LP occupation, in contrast, corresponds to a period of established settlement patterns with more regional orientation and intimate knowledge of the landscape. Here, smaller rivers might have gained importance structuring the landscape in a potentially more planar and less spatially linear manner.

Conclusion

In light of the results of the agent-based model, we conclude that water-oriented land use decisions in the Neuwied Basin were clearly different during the LUP and LP with the former showing a strong propensity towards decisions directly oriented at the Rhine. Visual inspections and statistical tests suggest that these patterns are susceptible to changes in water levels and initial positions of agents, but are ultimately reliant on behavioural parameters. The tests further indicate that natural and social parameters are partially interconnected. Given the shift from a predominantly seasonal use of salient topographic points in the Neuwied Basin during the colder period of the LUP towards a more regionally oriented year-round presence during the LP and a change in the exploitation of aquatic resources, we cautiously argue that the social perception of space will have to have changed as well.

While the Rhine exerted a particularly strong focality during the LUP, its importance as dominant landscape feature is clearly reduced during the LP in favour of the surrounding slopes and tributaries. The use and thus probably perception of the area has changed towards a higher level of familiarity. It is thus the interaction with and therefore probably perception of the Rhine that has changed from a dominant object/agent/persona during the resettlement phase of LUP to a less important entity during the LP, with a year-round use of the area. This change cannot be reduced to environmental or ecological change alone but encompasses aspects of landscape cognition and eventually choice. River-oriented land use decisions echo such choices both in regard to movements along and across rivers and the exploitation of aquatic resources. To pursue the aspect of human-river interaction further, a combination of several agent-based models integrating a sub-system of natural entities acting as non-human agents into negotiation with human agents may bring the field to new shores.

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