AI-Driven Decision-Making for Water Resources Planning and Hazard Mitigation Using Automated Multi Agents

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Abstract

This project simulates the Multi-Hazard Tournament (MHT) framework, a decision support system designed for the U.S. Army Corps of Engineers, using AI agents to enhance decision-making processes for flood mitigation and water resource management. The objective of the framework is to develop optimal strategies for protecting water resources, habitats, and communities within a defined budget. The simulation integrates AutoGen for managing multi-agent interactions and DarkIdol-Llama-3.1-8B, an advanced language model, to facilitate complex, long-context discussions. AI agents are configured with distinct roles and engage in structured dialogues to collaboratively evaluate and refine mitigation strategies. The study demonstrates the potential of AI-driven simulations to replicate real-world collaborative environments, improving stakeholder engagement and enhancing the efficiency of hazard mitigation planning. The findings highlight the effectiveness of AI agents in multi-stakeholder decision-making processes, offering valuable insights for disaster risk reduction and showcasing the benefits of integrating advanced technologies in planning. This work contributes significantly to fostering more resilient, well-prepared communities through innovative approaches to decision-making.

Keywords: Water Resources Planning, Hazard Mitigation, AI-Driven Agents, Multi-Agent System, Decision-Making, Budget Optimization.

1. Introduction

Water resource planning and hazard mitigation are vital for sustainable water management, aimed at addressing hydrological risks like floods, droughts, and water pollution. These hazards pose significant socio-economic and environmental threats, making comprehensive planning essential. While traditional hydrological models have provided mathematically optimal solutions, they often overlook social and public dimensions crucial for long-term success and acceptance (Chang et al., 2023; Kamyab et al., 2023; D'Alpaos & Bottacin, 2021; Daniell et al., 2023).

Recent advancements in artificial intelligence (AI) have revolutionized water resource management by enabling the processing of large datasets and simulating complex systems in flood prediction and management through remote sensing (Pennings, 2024; Motta et al., 2021; Hammam et al., 2020). AI-driven tools such as AutoGen (Wu et al., 2023), GPT-4o-mini (OpenAI, 2024), and DarkIdol-Llama-3.1-8B (QuantFactory, 2024) are being incorporated into decision-making frameworks (Vald et al., 2024; Samuel et al., 2024; Martin & White, 2024; Kadiyala et al., 2024), offering more adaptive and responsive strategies. This integration helps decision-makers balance hydrological challenges with community needs and social concerns while contributing to a more holistic disaster mitigation strategy encompassing environmental risks like wildfires, flooding (Alabbad et al., 2024; Algarni, 2023) and droughts (Ghaffarian et al., 2023; Elshaikh-Hayaty et al., 2024; Salimi et al., 2024).

Social hydrology emphasizes the integration of community input into decision-making processes, exemplified by the Multi-Hazard Tournament (MHT) framework. This framework bridges the gap between technically sound and socially acceptable solutions by simulating community involvement in hazard mitigation decisions (Saravi et al., 2019; Yousefi et al., 2020; Konar et al., 2019). Technology facilitates knowledge dissemination and engagement in disaster mitigation efforts (Sermet & Demir, 2018; Le & Nguyen, 2022), as demonstrated by AI applications in professional contexts like the US Fundamentals of Engineering exam (Pursnani et al., 2023; Sajja et al., 2024a).

This study introduces an AI-driven MHT framework that leverages advanced models to simulate decision-making processes in water resource planning and hazard mitigation (Salimi et al., 2024; Vekaria & Sinha, 2024; Sharma et al., 2024). The framework uses AutoGen to manage multi-agent interactions, with each AI agent representing a community stakeholder with unique attributes and priorities. Large-scale models enable structured discussions, evaluations, and negotiations (Sajja et al., 2023a; Bowes et al., 2021a), while exploring how AI-driven serious gaming can improve hazard mitigation planning (Teague et al., 2022; Chang et al., 2023). The research evaluates the framework's capacity to increase stakeholder awareness, understanding, and collaboration in water resource management, demonstrating how these technologies can facilitate teamwork and address challenges in educational and problem-solving contexts (Sajja et al., 2023b, 2024b, 2024c; Farzana et al., 2024).

By integrating advanced AI technologies with socio-hydrology, this study provides a robust framework for understanding and addressing the complex interplay between technical solutions and public preferences in water resource management. The dual focus on public preferences and community response simulation offers valuable insights into social dynamics influencing flood mitigation strategies, which can guide policymakers and planners in designing more effective and socially acceptable water management strategies (Farhaoui & El Allaoui, 2024; Project Performance International, 2024; Qin et al., 2024; Bowes et al., 2021b; Piemontese et al., 2024).

2. Methodology

This study employs the MHT framework to explore and analyze decision-making processes in water resource management and hazard mitigation. By leveraging advanced AI technologies, the framework simulates complex, real-world scenarios involving multiple stakeholders with diverse backgrounds and preferences. The methodology integrates both technical and social dimensions into a comprehensive decision-making process.

2.1. Scope and Purpose

The MHT framework addresses limitations in traditional hydrological models by incorporating social and public dimensions crucial for successful implementation of mitigation strategies (Kamyab et al., 2023). While these traditional models provide mathematically optimal solutions, they often overlook community preferences and social dynamics that significantly impact strategy adoption and effectiveness.

The framework expands water resources management by integrating AI-driven technologies to simulate realistic decision-making scenarios that reflect both technical requirements and community preferences. This comprehensive approach balances flood damage reduction, water quality improvement, habitat protection, and community recreational needs while incorporating diverse stakeholder viewpoints (Elshaikh-Hayaty et al., 2024; Project Performance International, 2024).

Through AI-driven agents representing various stakeholders, the framework facilitates structured dialogues to evaluate mitigation strategies, capturing the complex interplay of technical, social, and economic factors (Teague et al., 2022; Salimi et al., 2024). By simulating decision-making processes across diverse community configurations, the study examines how demographic and socio-economic factors shape public preferences and influence the effectiveness of hydrological actions (Saravi et al., 2019; Yousefi et al., 2020). This approach aligns with social hydrology principles, emphasizing public participation in water resource management (Chang et al., 2023) while fostering community resilience and sustainable environmental planning (Ray, 2023).

2.2. System Architecture

The MHT framework employs a sophisticated system architecture integrating multiple AI technologies to simulate decision-making processes in water resource management and hazard mitigation. The architecture combines advanced natural language processing models with a multi-agent system to create a dynamic, interactive environment for stakeholder collaboration and strategy development.

The framework leverages a multi-agent system where autonomous agents represent diverse community stakeholders, each configured with unique attributes such as age, occupation, and personality. AutoGen manages these structured interactions, ensuring orderly and meaningful dialogues between agents. DarkIdol-Llama-3.1-8B enhances these conversations by supporting extended dialogues and maintaining context over long discussions, enabling complex multi-round negotiations. This flexibility allows for various community configurations, providing insights into how different mitigation strategies may unfold across different contexts.

2.2.1. AI Technologies and LLM

The study utilizes several AI technologies and large language models including natural language processing (NLP), Autogen, Open AI GPT-4o, and DarkIdol-Llama-3.1-8B for development and implementation of AI agents to the decision support framework.

Autogen and OpenAI's GPT-4o mini: AutoGen serves as the backbone for orchestrating multi-agent interactions within the MHT framework, providing the structure necessary for agents to engage in realistic, collaborative dialogues. Each agent, configured with distinct attributes such as age, occupation, and personality, represents a community stakeholder, thus reflecting the diversity typically found in real-world communities (Martelo et al., 2024). AutoGen's flexibility enables these agents to participate in both hierarchical and parallel conversations, simulating the complexity of real-world decision-making, where multiple issues are often deliberated concurrently (Teague et al., 2022). The platform also supports "conversation programming," which integrates natural language processing with computational logic, allowing agents to engage in structured negotiations and reconcile competing priorities (Elshaikh-Hayaty, Mabrouki, & Mohamed, 2024).

Enhancing this capability, OpenAI's GPT-4o-mini provides the NLP functionality necessary for generating coherent, contextually relevant responses during multi-agent interactions. While GPT-4o-mini is a more compact version of OpenAI's full-scale model, it retains the essential features needed for simulating detailed and realistic conversations. By interpreting complex language inputs and balancing multiple decision factors, GPT-4o-mini enables agents to adapt their dialogue according to their pre-defined characteristics—such as age, cultural background, and problem-solving styles—thereby increasing the realism of the simulation (Du et al., 2021). The integration between AutoGen and GPT-4o-mini ensures real-time interaction, allowing agents to dynamically adjust their strategies and responses as the conversation progresses, which mirrors the fluid nature of decision-making in real communities (Salimi et al., 2024). These tools provide a comprehensive framework that simulates both the technical and social dimensions of flood mitigation strategies, offering a realistic and data-driven platform for community-level decision-making (Chang et al., 2023).

DarkIdol-Llama-3.1-8B: DarkIdol-Llama-3.1-8B plays a critical role in handling long-context interactions within the MHT framework, ensuring that conversations maintain coherence over multiple rounds of discussion. Developed by QuantFactory, this large-scale language model is optimized for extended dialogues, with the ability to manage up to 35,000 tokens in its context window (QuantFactory, 2023). This extended capacity allows agents to refer to earlier decisions and inputs, ensuring that conversations remain consistent and contextually informed as they evolve. DarkIdol's uncensored instruction-based fine-tuning further enhances its capability to engage in detailed, unrestricted dialogues, allowing for comprehensive and realistic discussions during flood mitigation planning (Elshaikh-Hayaty et al., 2024).

Another key feature of DarkIdol is its computational efficiency, particularly its ability to leverage GPU power through torch.cuda, making it ideal for the large-scale simulations used in the MHT framework. This ensures that even with the model's extensive context window and detailed language processing capabilities, it can run smoothly and effectively during resource-intensive simulations (Salimi et al., 2024). By integrating DarkIdol-Llama-3.1-8B with AutoGen and GPT-4o-mini, the MHT framework benefits from its ability to sustain complex, multi-round discussions. This integration allows the simulation to address both short-term and long-term planning, providing deeper insights into how various flood mitigation strategies might unfold over time. DarkIdol's capacity to manage extended, meaningful interactions adds depth to the decision-making process, ensuring that the social and technical implications of water resource management decisions are thoroughly explored and well-understood (Chang et al., 2023).

2.2.2. Multi Agent Configuration

The framework configures 1,000 agents with diverse attributes reflecting real-world communities (Gent, 2024). These attributes shape each agent's decision-making approach and communication style, enabling the simulation to capture a wide array of perspectives. The configuration encompasses demographic information, personality traits, communication preferences, and other characteristics as detailed in Table 1.

Table 1. Role attributes and their options for AI Agents

Attribute	**Options**
Age	18 - 80
Gender	nondisclosed, female, genderqueer, male
Occupation	Student, Retired, Engineer, Unemployed, Teacher, Doctor, Artist, Scientist
Personality Traits	Extroverted, Traditional, Open to Experience, Pessimistic, Innovative, Introverted
Communication Style	Empathetic, Informal, Mixed, Humorous, Direct, Formal
Interests and Hobbies	Video Games, Painting, Soccer, Reading, Cooking, Traveling, Sports
Educational Background	High School, Graduate Degree, Self-taught, Bachelor
Cultural Background	Middle Eastern, Western, Eastern, Latin American, African
Language Proficiency	English, Spanish, Mandarin, English, English and Spanish, French, Spanish, Mandarin
Technology Savviness	Intermediate, Novice, Expert

Communication Medium	Voice, Mixed, Video, Text
Lifestyle	Sedentary, Active
Values and Beliefs	Christianity, Environmentalism, Traditional, Humanism, Islam, Atheism
Relationship Status	Widowed, Divorced, In a relationship, Single, Married
Economic Status	Low income, High income, Middle income
Health and Wellness	Health-conscious, Average health, Healthy
Time Availability	Sporadic, Full-time, Part-time
Problem-solving Approach	Practical, Creative, Collaborative, Analytical

2.3. System Workflow

The system workflow establishes a structured approach to simulating decision-making processes in water resources planning and hazard mitigation, encompassing initialization, execution, and outcome documentation stages. The simulation begins with an initial message providing agents with comprehensive context about the discussion's objectives. This includes the focus on flood mitigation strategies, primary goals for optimizing resource allocation and protecting water resources, and the available budget of $15 million. The system extracts and compiles essential data from academic papers, project reports, and legal documents using PyMuPDF (fitz) (Artifex Software Inc., 2024) python library, creating a structured knowledge base for agent reference during simulations.

Agent Interactions and Decision Process Agents interact under the guidance of a user proxy agent who facilitates discussions and ensures alignment with exercise objectives. The interaction process involves collaborative deliberation on various flood mitigation strategies, considering factors such as cost-effectiveness, long-term sustainability, and public acceptability. Agents engage in structured negotiations, sharing expertise and working toward consensus while representing their assigned stakeholder perspectives. The system meticulously documents all decisions, including selected mitigation options, budget allocations, and the reasoning behind choices. This comprehensive documentation captures both majority decisions and dissenting opinions, providing valuable data for post-simulation analysis.

2.4. Decision Support Framework Setup

The framework simulates community decision-making with multiple teams composed of diverse stakeholder agents (Sermet et al., 2020). Each team must allocate a fixed budget of $15 million across local or watershed-wide mitigation options to maximize benefits in flood damage reduction, water quality improvement, habitat protection, and community recreational enhancements. Decisions must be transparently documented, including justifications for strategy selection and fund allocation.

2.4.1. Mitigation Options

The decision support framework provides several mitigation alternatives under various categories including capital improvement projects, stormwater management policies, flood protection ordinances and recreational investments.

Capital Improvement Projects: These projects involve substantial infrastructure investments aimed at controlling and managing water flow to reduce flood risks. Examples include the construction of flood control reservoirs, levees, stormwater detention basins, and channel modifications. These projects typically have high upfront costs but offer significant long-term benefits in terms of flood damage reduction and water management.

Stormwater Management Policies: These policies focus on the implementation of traditional as well as green infrastructure and other sustainable practices to manage stormwater runoff. Options include the installation of permeable pavements, rain gardens, bioswales, and other low-impact development techniques. These measures are generally more cost-effective than large-scale infrastructure projects and provide benefits such as improved water quality, reduced urban heat islands, and enhanced groundwater recharge.

Flood Protection Ordinances: These ordinances involve regulatory measures that require new developments and existing structures to incorporate flood protection features. Examples include elevated buildings, flood barriers, and zoning regulations that restrict construction in flood-prone areas. These ordinances help reduce the vulnerability of properties to flood damage and promote long-term resilience in the community.

Recreational Investments: These investments aim to enhance community well-being by developing recreational spaces in flood-prone areas, including recreational sport facilities. Options include the creation of parks, trails, sports facilities, playgrounds, and picnic areas. While these investments do not directly reduce flood risks, they provide significant social and economic benefits by improving the quality of life for residents, promoting outdoor activities, and increasing public support for flood mitigation efforts. The associated costs and benefits are carefully considered to maximize the overall value to the community.

By incorporating these diverse mitigation options and adhering to the structured framework rules, the framework provides a robust platform for simulating the decision-making processes using an integrated water resources management approach (Biswas, 2004). This comprehensive approach allows stakeholders to explore the complexities and trade-offs of different strategies, fostering a deeper understanding of the local factors that influence effective and socially acceptable water management solutions. Through this interactive and data-driven simulation, the MHT framework aims to contribute to more resilient and sustainable communities by promoting informed and collaborative decision-making.

2.5. Experimental Design

The experimental design using AI simulates community stakeholder decision-making through three primary phases, as illustrated in Figure 1. The flowchart demonstrates systematic progression from initialization through execution to analysis, highlighting the interconnections between different system components. Initial setup involves configuring agents with diverse attributes using GPT-4o-mini and DarkIdol-Llama-3.1-8B, supplemented by a comprehensive data extraction process that builds the knowledge base from technical guidelines, historical flood events, and legal frameworks. As shown in Figure 1, this initialization phase establishes the foundation for agent interactions and decision-making processes.

The simulation execution phase, depicted in the central portion of Figure 1, leverages both AutoGen's GroupChat and GroupChatManager classes for orchestrating multi-agent interactions, while DarkIdol-Llama-3.1-8B ensures contextual relevance across multiple discussion rounds. The system executes two rounds of collaborative debate (max_round=2), allowing agents to refine their strategies while maintaining structured discussion flow. Data collection, represented in the final stage of Figure 1, occurs continuously throughout simulation, recording agent decisions, budget allocations, and justifications. This information is compiled into a CSV file for subsequent analysis of decision-making patterns and strategy effectiveness. The increased context length provided by DarkIdol-Llama-3.1-8B enables comprehensive analysis of how agents handle complex, multi-round discussions, contributing to deeper insights into community-driven decision-making for disaster risk reduction and environmental planning.

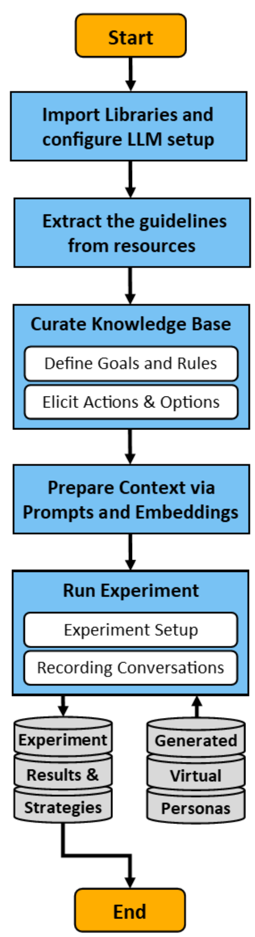

Figure 1. Experimental setup flowchart for AI-based decision simulation

3. Results

The results section presents findings from the MHT framework simulations, examining decision-making processes of diverse community stakeholders through case studies and simulation outcomes. The analysis focuses on strategy selection, budget allocation patterns, and the influence of demographic factors on decision-making.

3.1. Case Studies

The MHT framework simulations evaluated how teams allocated a $15,000,000 budget across various mitigation options. These options included capital improvement projects, infiltration policies, freeboard policies, buyouts, and recreational investments, with the goal of maximizing benefits in flood damage reduction, water quality improvement, habitat protection, and community recreational enhancement.

3.1.1. Insights from Specific Case Studies

Analysis revealed distinct patterns in strategy selection based on demographic and professional characteristics:

Age-Based Preferences: The 19-30 age group prioritized immediate infrastructure improvements and capital improvement projects, focusing on transformative actions with immediate benefits. In contrast, participants aged 61-75 favored long-term, conservative strategies such as buyouts and freeboard policies, emphasizing sustainability and cautious resource management.

Professional Background Influence: Technical professionals, particularly engineers, showed strong preference for capital-intensive projects, prioritizing robust structural benefits. Those in policy or community-oriented roles favored investments directly enhancing social well-being, such as recreational area development.

Communication and Personal Factors: Participants with collaborative communication styles and community-focused interests typically advocated for balanced strategies combining infrastructure improvements with recreational investments, demonstrating a holistic approach to community resilience.

3.1.2. Key Findings from the Simulations

The simulation results highlighted several critical factors influencing water resource management decisions:

Demographic Impacts: Age emerged as a primary determinant in budget allocation, with younger participants favoring immediate infrastructure investments while older participants preferred conservative spending strategies focused on long-term sustainability.

Professional Expertise: Occupation significantly influenced strategy selection. Technical experts consistently prioritized capital-intensive projects, while those from policy-making or community service backgrounds emphasized social well-being enhancements.

Social Dynamics: Communication styles and personal interests shaped by decision-making beyond technical considerations. The simulations revealed that interpersonal dynamics and personal values played crucial roles in strategy development and implementation.

Additional factors such as relationship status, language proficiency, and cultural background, while secondary to age and occupation, contributed to the complexity of budget allocation decisions. These findings emphasize the importance of flexible, inclusive decision-making frameworks that can integrate diverse perspectives for optimal outcomes.

3.2. Simulation Outcomes

The analysis of the simulation outcomes provides a comprehensive understanding of the decision-making processes and the effectiveness of various strategies employed by different teams. The metrics for evaluating the effectiveness of the strategies include budget allocation, option selection, and the impact of various features on these decisions. The following charts illustrate these metrics and their interpretations.

3.2.1. Significant Parameters for Budget Spent

The MHT framework, supported by AI, reveals how different demographic factors influence budget allocation in flood mitigation. Age emerged as the most significant factor, with older participants (61-75 and 76+) adopting a conservative approach, reserving more funds for future contingencies. This indicates a preference for long-term sustainability. In contrast, younger participants (19-30) spent heavily on immediate infrastructure improvements, reflecting a proactive mindset and a higher risk tolerance, focusing on current needs over future uncertainties.

Occupation also plays a key role in shaping budget decisions. Participants with technical backgrounds, such as engineers, allocated more funds to capital-intensive projects, emphasizing long-term structural benefits. Meanwhile, participants in policy-making or community-oriented roles prioritized regulatory measures and social investments, such as recreational areas and public health initiatives. These differences reflect the contrasting priorities of technical versus community-focused participants.

Communication style and personal interests further influence spending behavior. Collaborative participants with a strong interest in community-centered investments advocated for balanced spending on both recreational add-ons and infrastructure, indicating that personal values and social engagement shaped their decision-making processes. Socio-demographic factors, including language proficiency, relationship status, and cultural background, added complexity to budget decisions. For example, participants with higher language proficiency negotiated budgets more effectively, while those with diverse cultural backgrounds prioritized different strategies based on their perceptions of risk and resilience.

Overall, the analysis highlights the multi-faceted nature of budget allocation decisions in flood mitigation. Understanding how age, occupation, communication style, and socio-demographic factors interact helps optimize resource allocation and balance the technical and social needs of communities. AI-driven models like GPT-4o-mini and DarkIdol provide deeper insights into these decision-making processes, as shown in Figure 2.

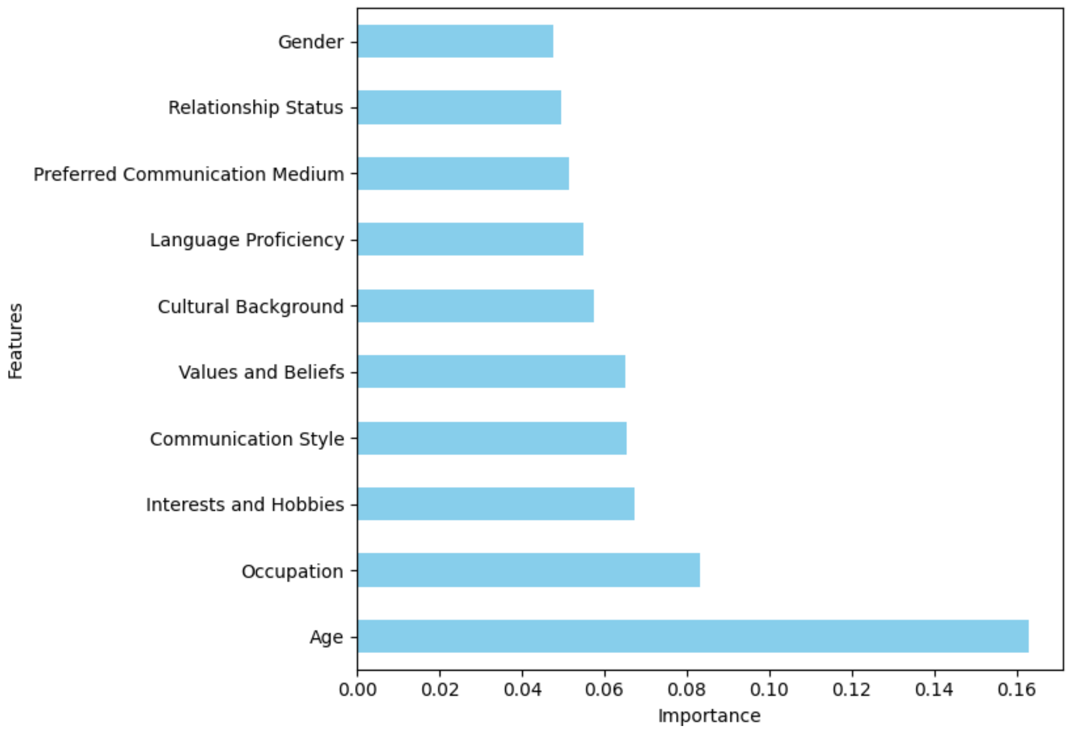

Figure 2. Significant parameters and their importance for budget spent

3.2.2. Significant Parameters for Options Chosen

Age also strongly influenced the options selected in the simulations. Younger participants (19-30) favored immediate, tangible outcomes such as infiltration policies and capital improvement projects, focusing on visible infrastructure enhancements. Conversely, older participants (61+) leaned towards long-term strategies like freeboard policies, reflecting a risk-averse approach that prioritizes future flexibility and resilience. As shown in Figure 3, age emerged as the most significant factor in determining the options chosen.

Occupation further impacted strategy selection. Engineers and technical professionals opted for infrastructure-heavy solutions like channel modifications and capital projects, while those in policy-making roles emphasized social and community-based options, such as recreational developments and buyouts. This divide underscores the influence of professional background on what participants perceive as effective mitigation. Values and beliefs also shaped decisions, with environmentally focused participants supporting strategies that enhance environmental quality or social cohesion, such as infiltration policies and recreational investments. This demonstrates how personal ethics and priorities influence mitigation choices.

Communication style and personal interests influenced holistic decision-making. Participants who favored collaboration selected a balanced mix of infrastructure and social investments, reflecting their preference for teamwork and consensus-building. Similarly, participants with outdoor or environmental interests were more likely to support recreational area development. Other socio-demographic factors like cultural background, gender, and language proficiency also played a role, albeit to a lesser extent. For example, participants with specific cultural views on risk tended to prefer strategies aligned with their cultural understanding of resilience. Figure 3 illustrates these diverse preferences.

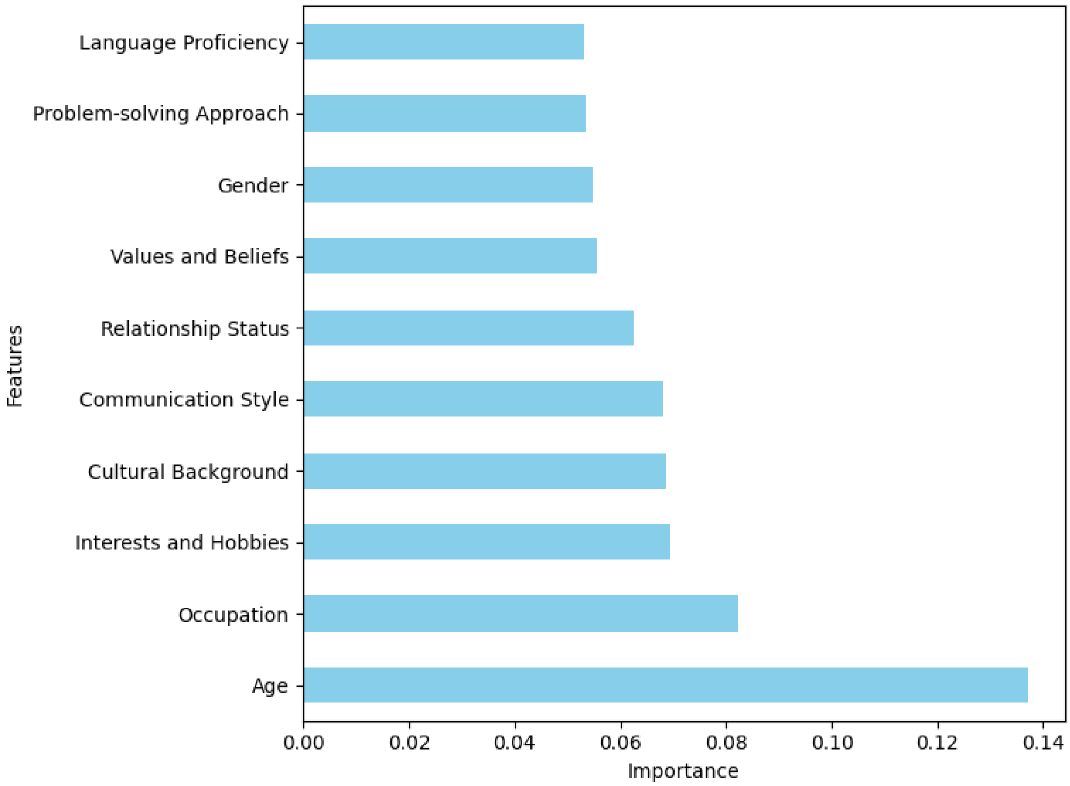

Figure 3. Significant parameters and their importance for selected options

3.2.3. Attribute Correlation Heatmap

The correlation matrix heatmap in Figure 4 illustrates the relationships between various features that influence decision-making within the MHT framework. One key observation is the strong negative correlation (-1.00) between budget spent and budget remaining, as expected—when one increases, the other decreases. Additionally, the positive correlation (0.29) between options chosen and budget spent shows that as participants allocate more budget, they also tend to implement more strategies, indicating a direct relationship between resource allocation and decision complexity.

Interestingly, a moderate correlation (0.44) between educational background and cultural background suggests that individuals with similar educational levels tend to share cultural similarities, which may influence their decision-making preferences. On the other hand, weak correlations, such as the one between language proficiency and technology savviness (-0.10), indicate that higher language skills don't necessarily align with higher technical skills, highlighting the diversity in participant backgrounds. This heatmap provides valuable insights into how these variables interact, informing future planning and flood mitigation efforts by offering a more nuanced understanding of the factors driving decision-making.

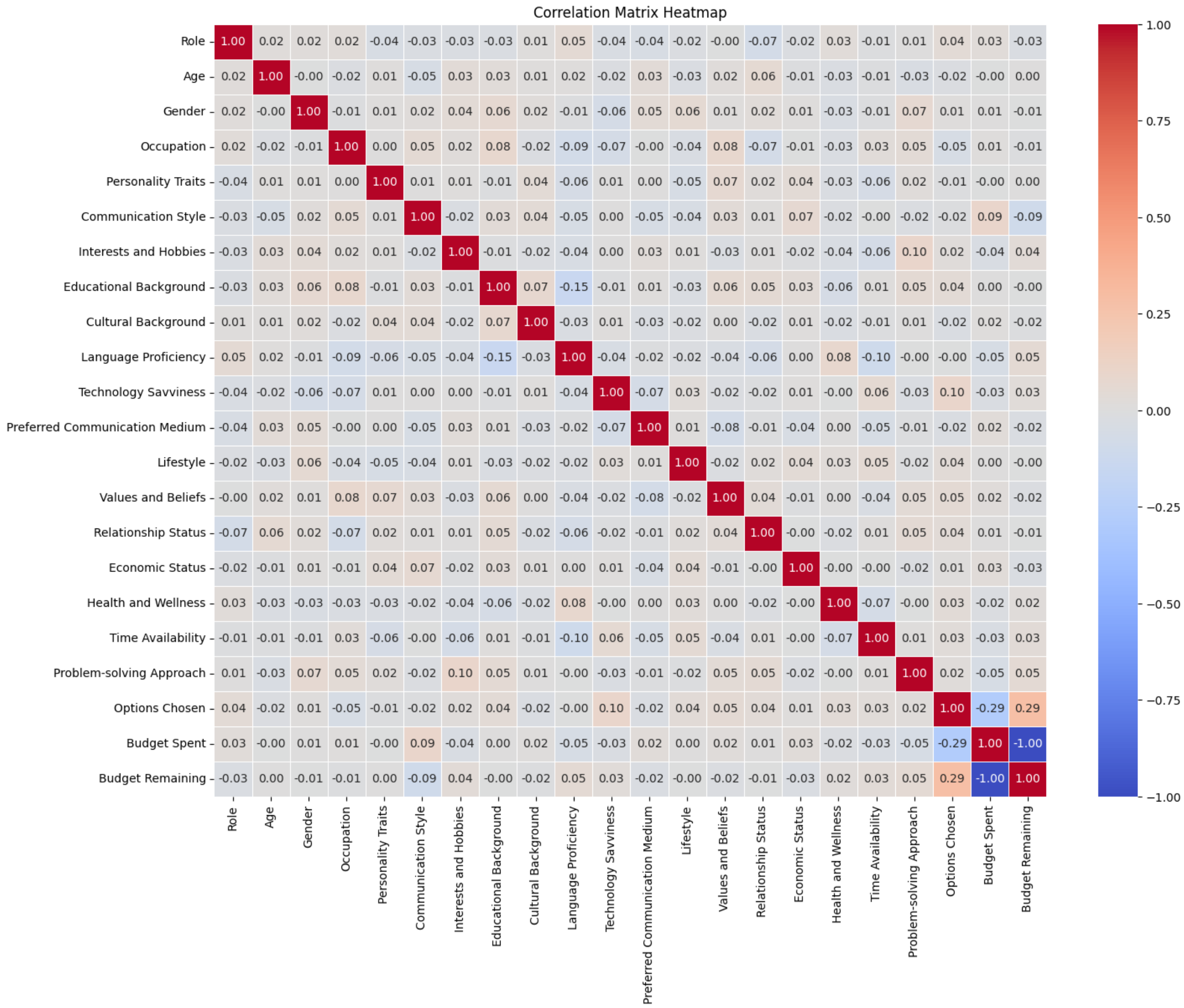

Figure 4. Correlation Matrix Heatmap of the relationships between various features

3.2.4. Category Counts by Age Group

The histograms depicted in Figures 5 and 6 reveal the varied flood mitigation preferences among different age groups, as simulated in the DarkIdol-Llama-3.1-8B and GPT-4o-mini models, respectively. Across both models, participants aged 19-30 showed a strong preference for Buyouts and Recreational Area Development, reflecting their focus on immediate relief and community enhancement.

The 31-45 age group exhibited similar interests to the younger cohort, but with an increased emphasis on Freeboard Policy, suggesting a desire to balance immediate needs with future precautions. Those in the 46-60 age group also emphasized Buyouts and Recreational Area Development, indicating widespread support for these measures. Participants aged 61 and above tended to prioritize long-term strategies such as the Freeboard Policy, although Buyouts remained a popular choice across all age groups. This distribution of preferences suggests that while younger participants are inclined toward immediate actions, older groups favor more cautious, long-term approaches.

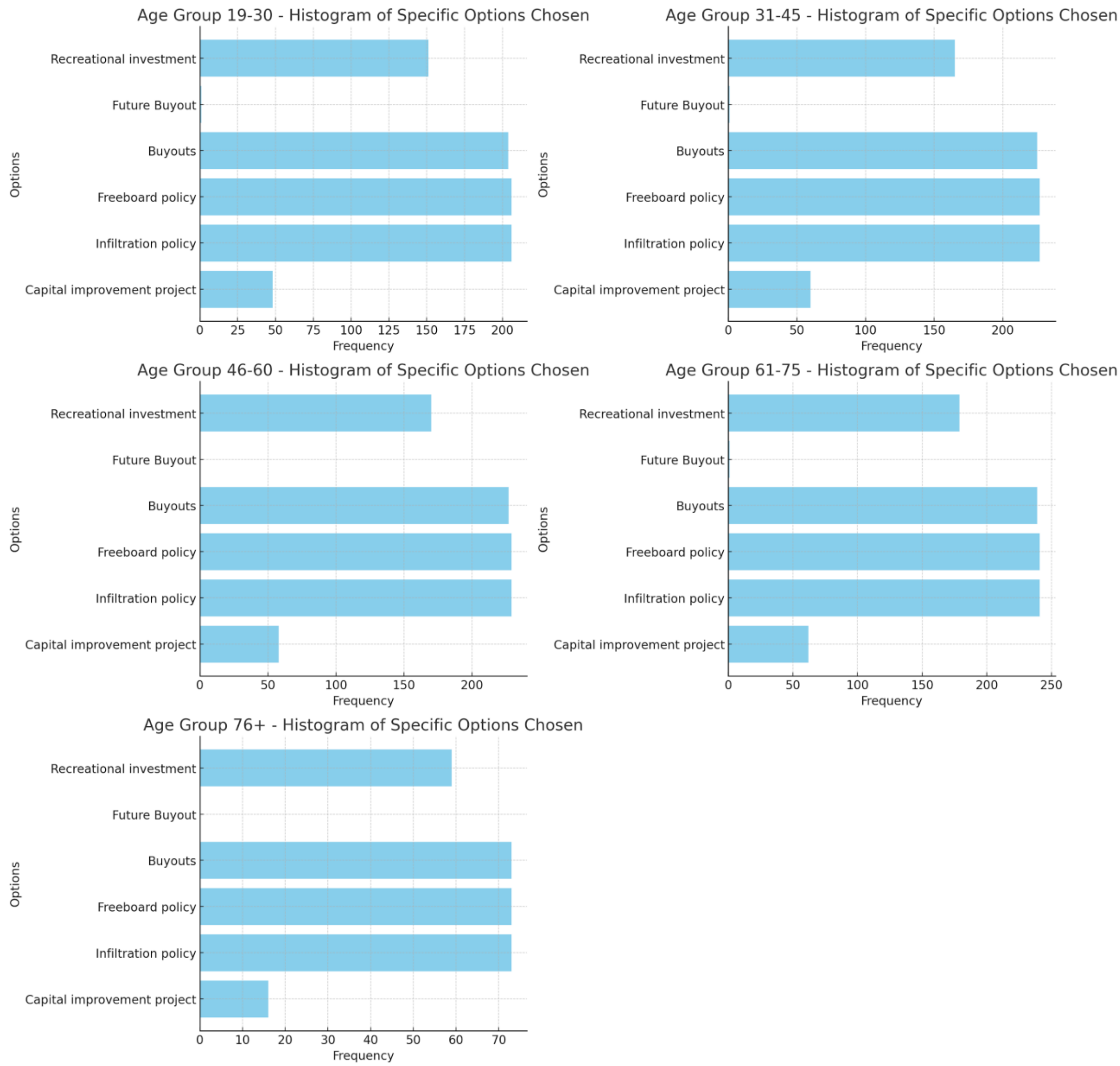

Figure 5. Histogram of age-based comparison of flood mitigation option preferences in DarkIdol-Llama-3.1-8B model.

3.2.5. Category Counts by Gender Group

The histograms in Figures 7 and 8 display gender-specific preferences for flood mitigation strategies, as simulated in the DarkIdol-Llama-3.1-8B and GPT-4o-mini models, respectively. The Non-Disclosed and Genderqueer groups show a strong preference for immediate infrastructure investments such as Buyouts and Current Traditional CIP Costs, along with Recreation Area Development.

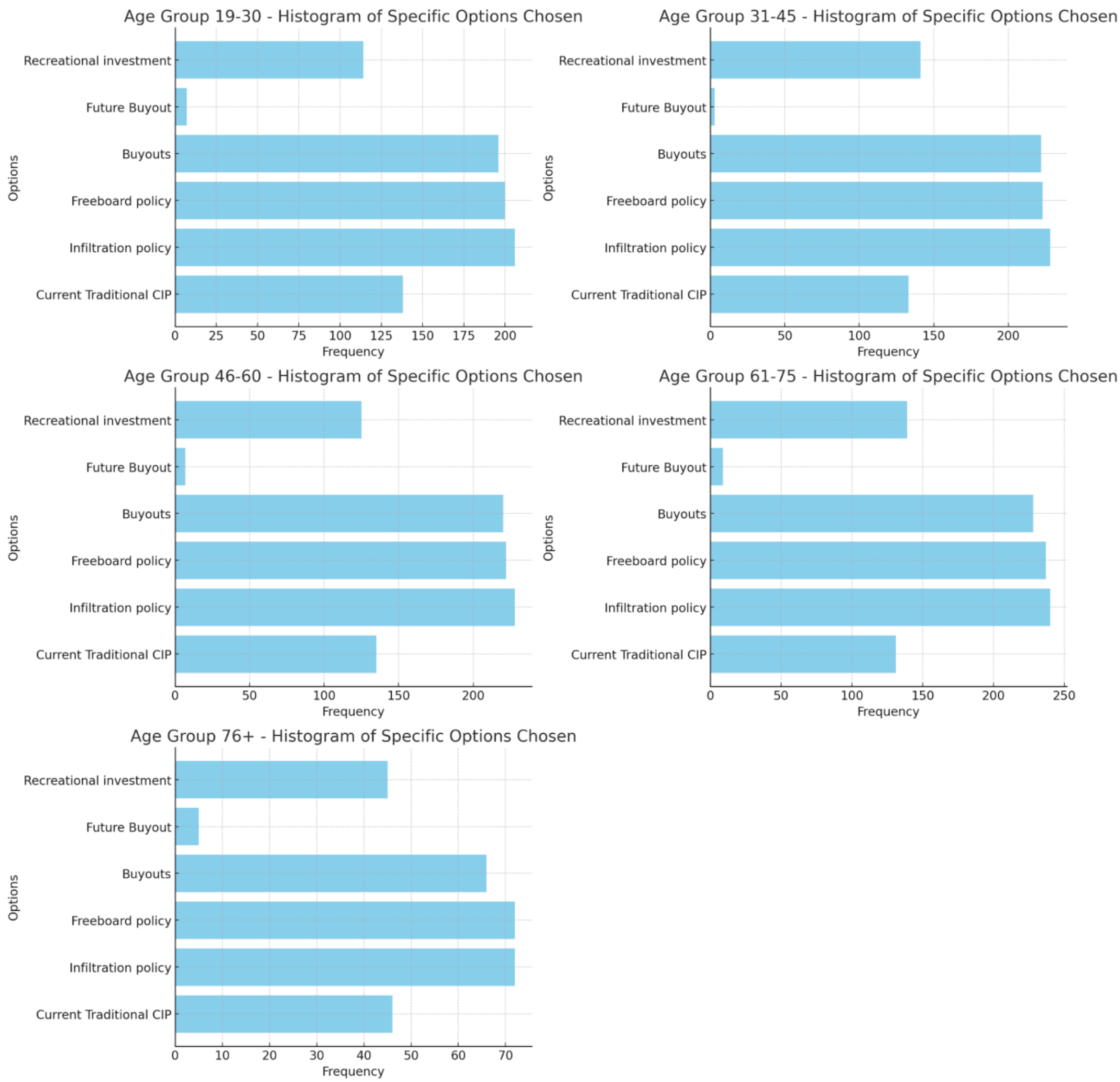

Figure 6. Histogram of age-based comparison of flood mitigation option preferences in GPT-4o-mini model.

Similarly, the Female group exhibits a preference for Buyouts and Recreational Investments, with a focus on reducing current flood risks and enhancing community spaces. In contrast, the Male group demonstrates mirrored preferences, also choosing Buyouts and Current Traditional CIP Costs, but placing less emphasis on future-oriented strategies like Freeboard Policy. These gender-specific patterns indicate consistent priorities across all groups, with a shared emphasis on immediate actions and community enhancements.

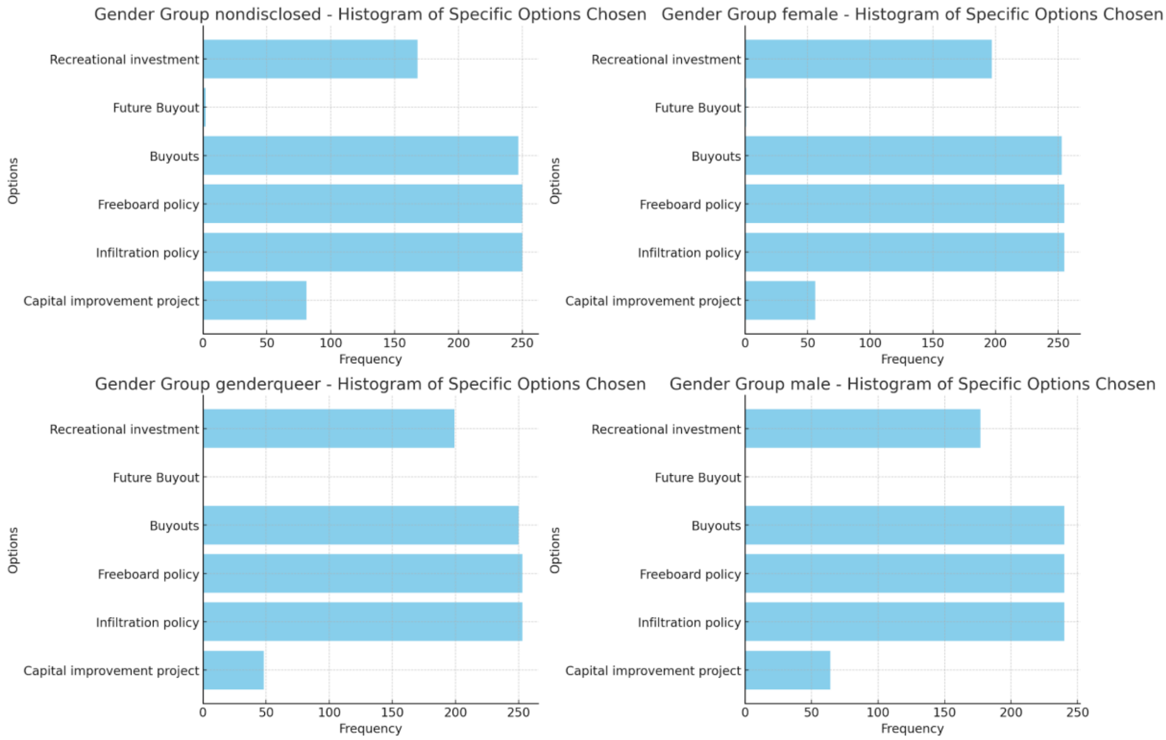

Figure 7. Histogram of gender-based comparison of flood mitigation option preferences in DarkIdol-Llama-3.1-8B model.

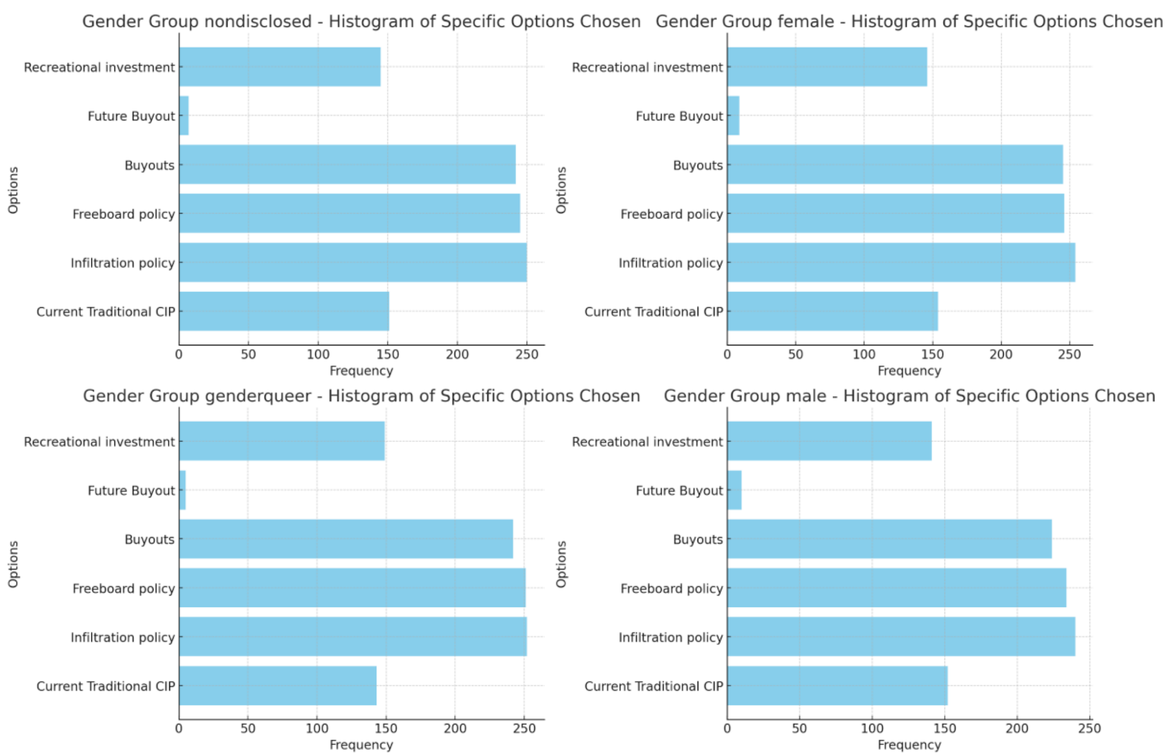

Figure 8. Histogram of gender-based comparison of flood mitigation option preferences in GPT-4o-mini model.

3.2.6. Interpretation of Recreation Investments Results

The histograms in Figures 9 and 10 illustrate the recreational add-ons selected by the DarkIdol-Llama-3.1-8B and GPT-4o-mini models during flood mitigation planning. The GPT-4o-mini model prioritizes smaller, versatile community spaces, such as volleyball courts and open areas, suggesting a strategy aimed at maximizing immediate community engagement with limited resources.

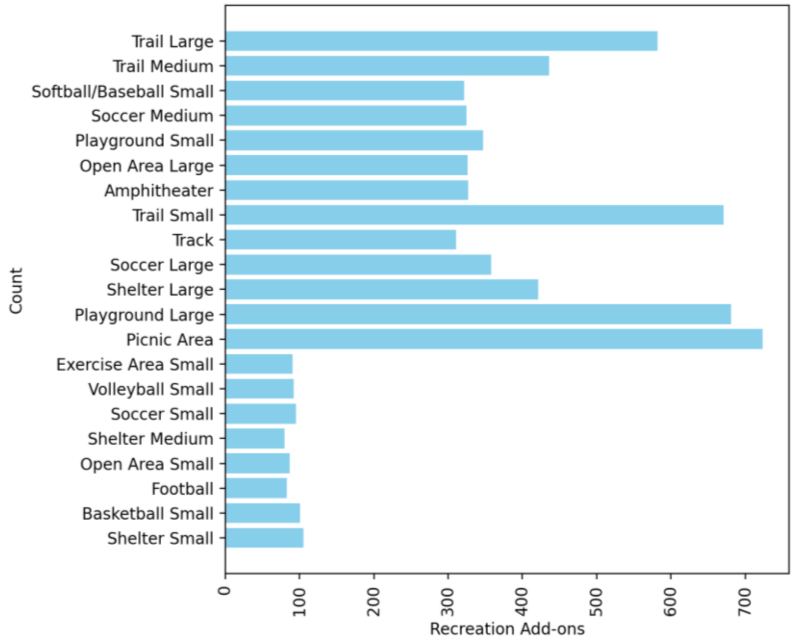

Figure 9. Histogram of recreational options chosen in DarkIdol-Llama-3.1-8B model.

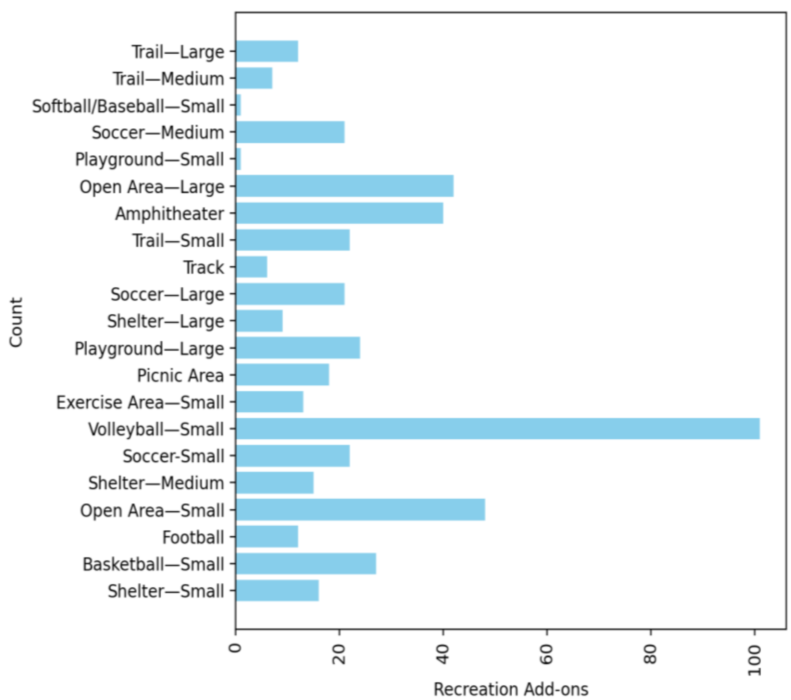

Figure 10. Histogram of recreational options chosen in GPT-4o-mini model.

In contrast, the DarkIdol-Llama-3.1-8B model displays a greater preference for larger, infrastructure-heavy facilities like trails, playgrounds, and shelters, indicating a focus on long-term investment. This approach targets the development of durable, multi-functional spaces that serve both recreational and environmental objectives. The differences between the models underscore a balance between short-term community engagement and long-term infrastructure investment, providing complementary insights into recreational priorities across the planning strategies.

4. Discussions

The discussion section interprets the findings from the MHT framework simulations, focusing on the strengths and limitations of the approach and its broader implications for water resource management and hazard mitigation. By leveraging AI-driven tools, the framework provides a comprehensive analysis of the factors influencing decision-making processes. This section explores key insights from the study, highlights the strengths and limitations of the MHT framework, and provides recommendations for improving the approach and its real-world applications.

4.1. Study Insights

The MHT framework, enhanced by AI-driven tools, has provided useful insights into decision-making processes for water resource management and hazard mitigation, capturing diverse scenarios and a range of demographic perspectives. However, contrary to expectations, there were minimal differences in the options chosen across age groups. Most participants selected similar strategies with only small variances, primarily in preferences for recreational investments. Specifically, DarkIdol-Llama-3.1-8B demonstrated a unique emphasis on recreational investments, aligning with community-centric goals and quality-of-life improvements in flood resilience.

This limited variance across demographics may reflect the challenges current LLMs face in making sophisticated, multi-step connections between persona attributes and situation-specific behaviors. While the models simulate basic preferences, they struggle to fully capture complex, persona-driven behaviors in extended, multi-stage decision processes. Additionally, with a substantial budget and few available options, agents tend toward larger selections to maximize spending, rather than conserving resources. Thus, the real differentiation in decision-making emerges in the types of options chosen rather than the overall amount spent, underscoring the need for more nuanced decision models.

4.1.1. Strengths of the Approach

The MHT framework's primary strength is its ability to simulate a broad range of decision-making scenarios, accounting for diverse individual characteristics. The integration of AI tools enables advanced language processing and strategic modeling, offering insight into how age, occupation, and values influence flood mitigation choices. For instance, the recreation investment analysis revealed slight distinctions, with younger participants and certain groups, like the genderqueer and non-disclosed, favoring small-scale recreational investments. DarkIdol-Llama-3.1-8B, on the other hand, showed preferences for larger, community-enhancing recreational projects, highlighting varied perspectives on long-term investments. Another strength is the MHT framework's collaborative environment, where agents representing different community stakeholders engage in structured discussions. This interaction fosters more inclusive and balanced flood mitigation strategies, ensuring that diverse viewpoints are incorporated.

4.1.2. Limitations of the Approach

Despite its strengths, the framework has limitations. A key issue is the reliance on static agent characteristics, which restricts flexibility. While models like DarkIdol-Llama-3.1-8B and GPT-4o-mini aid in nuanced decision-making, they cannot fully capture dynamic human decision-making, which evolves with emotional responses, social pressures, and real-time updates. The framework’s rigid structure thus limits its ability to mirror complex, adaptive decision environments accurately. Additionally, the framework’s assumptions and predefined agent roles may introduce bias, particularly in scenarios requiring spontaneous adaptation to evolving contexts. This lack of flexibility in agent roles constrains the model's realism, as human decisions are often context-driven and highly adaptive.

Another challenge is the requirement for extensive data and computational power. The high computational demands for running models like DarkIdol-Llama-3.1-8B can make the framework less accessible to small communities or organizations with limited resources. The implementation of these models involves substantial data processing capabilities, which may pose a barrier to adoption in regions with constrained technological infrastructure. Developing more lightweight or optimized versions of these models could help mitigate this issue and improve accessibility.

4.1.3. Insights and Recommendations

The simulations emphasize the importance of inclusive decision-making that accounts for diverse community preferences. Using both DarkIdol-Llama-3.1-8B and GPT-4o-mini, the results demonstrate the need to balance immediate flood protection with long-term structural improvements. Future iterations of the MHT framework would benefit from dynamic agent configurations that adapt to new information and evolving circumstances, better reflecting real-world decision-making. Incorporating broader behavioral models and real-world community input could reduce potential biases while simplifying the interface and providing educational resources would make the framework more accessible to smaller communities and non-experts.

4.2. Study Implications

The insights from the MHT framework underscore valuable applications for real-world water resources planning and hazard mitigation. Through a thorough analysis of how demographic and socio-economic factors influence decision-making, the framework enables strategies that are both technically robust and representative of community needs. Policymakers can leverage the MHT's data-driven insights for developing flood mitigation strategies that balance short-term actions with long-term goals, directly support policy development, resource allocation, and stakeholder engagement. This contributes to outcomes such as improved flood damage reduction, water quality, community resilience, and recreational benefits.

4.2.1. Impact on Water Resources and Hazard Mitigation

The MHT framework's ability to simulate diverse decision-making scenarios—incorporating DarkIdol-Llama-3.1-8B for complex, long-term strategies and GPT-4o-mini for immediate actions—reveals significant real-world applications. For instance, age and gender groups were observed to prioritize a range of options, from buyouts to longer-term infrastructure investments like freeboard policies. These findings illustrate the value of inclusive flood mitigation strategies that reflect a broad spectrum of community preferences.

Moreover, the MHT framework's insights can help policymakers design flood protection strategies that integrate immediate actions, such as buyouts, with resilient infrastructure investments. The data-driven approach also emphasizes the need to engage diverse stakeholders, as their perspectives contribute to more balanced and widely supported flood mitigation efforts. This approach enables policymakers to pinpoint the most impactful measures, making resource allocation more efficient and maximizing community benefits.

4.2.2. Recommendations for Policymakers and Practitioners

To fully realize the potential of the MHT framework, policymakers and practitioners should prioritize inclusive, participatory decision-making processes. The simulation results demonstrate that incorporating diverse community perspectives leads to more representative and sustainable strategies. Using AI tools allows decision-makers to capture the nuanced preferences of stakeholders, aligning strategies with both short-term and long-term community objectives.

Policymakers should also emphasize collaborative planning, involving technical experts, community leaders, and residents. This approach ensures that all relevant viewpoints contribute to the development of comprehensive mitigation strategies. Additionally, improving the framework's accessibility and usability through user-friendly interfaces and training resources can extend its benefits to smaller organizations and communities with limited resources.

4.3. Future Work

Future development should focus on enhancing the adaptability and usability of the MHT framework to better mirror real-world decision-making. Although current models offer substantial potential, additional improvements are needed to incorporate adaptive behavioral models that evolve with real-time data and shifting circumstances. A promising area for further research includes integrating dynamic agent characteristics that adjust in response to new information and stakeholder input, allowing simulations to better reflect the fluid nature of decision-making.

Expanding the MHT framework to analyze scenarios related to climate change, urbanization, and population growth would provide deeper insights into how emerging challenges may influence decision-making. Exploring behavioral models that account for psychological and emotional influences could enhance the realism of the simulations, offering a fuller picture of how communities respond to flood mitigation strategies over time. Longitudinal studies could also track decision impacts, adding depth to the MHT's predictive capability.

Additionally, improving the framework's accessibility and scalability will be essential. Interactive dashboards, visualization tools, and user-friendly interfaces can help non-experts more easily interpret results. Incorporating real-time environmental data, community feedback, and social media analytics can increase simulation accuracy and relevance, making the framework even more effective for tailored decision-making.

Extending the MHT framework as an interactive, web-based simulation tool could significantly benefit the hydrology and water management fields. Such an environment would allow real-time simulation of different goals and decision-making tasks, enabling users to instantly observe how various community segments might behave or support specific options under given scenarios. This interactive component would be invaluable for both public education and expert analysis, providing a visual and data-rich platform for exploring the social dynamics of decision-making.

5. Conclusion

This study utilized the Multi-Hazard Tournament framework to simulate decision-making processes in water resource management and hazard mitigation, exploring how factors like age, gender, and occupation influence flood mitigation strategies and resource allocation. By simulating diverse scenarios with AI agents representing various community stakeholders, the study provided insights into demographic influences on decision-making. Two advanced AI models—DarkIdol-Llama-3.1-8B and GPT-4o-mini—supported a nuanced analysis, revealing the priorities of different demographic groups.

Notably, the study found minimal differences in selected options across age groups, with most participants choosing similar strategies. However, DarkIdol-Llama-3.1-8B notably emphasized recreational investments, highlighting a focus on community-centered enhancements alongside flood resilience. The results showed that present large language models (LLMs) are limited in making sophisticated, multi-step connections between an agent's persona and its behavior in specific situations. The large budget in the simulation led to high option selection rates, as most roles aimed to utilize their allotted funds, resulting in only slight differences in decision-making across demographics. The true variety was observed in the specific options chosen, influenced by the variety of available choices.

This study illustrates the transformative potential of AI in enhancing decision-making frameworks for water resource planning and hazard mitigation. By fostering collaborative decision-making among AI agents configured as diverse community stakeholders, the MHT framework enabled a more comprehensive understanding of community needs and promoted strategies that gain broad-based support, ultimately enhancing resilience.

The integration of AI-driven agents into water resource management has promising implications for real-world applications. Modeling diverse stakeholder perspectives helps policymakers develop strategies that are inclusive, adaptable, and effective. AI tools also enable the rapid processing of extensive datasets, making it possible to evaluate complex, evolving scenarios in real-time. This adaptability is particularly valuable for addressing dynamic challenges like climate change, urbanization, and population growth, where flexible, responsive planning is critical.

Practically, AI-driven simulations can guide urban planning, infrastructure development, and disaster risk reduction by providing data-driven insights tailored to specific community requirements. Policymakers and practitioners can use these tools to assess the immediate and long-term effects of interventions, ensuring that strategies are not only technically sound but also socially responsive. In conclusion, integrating AI into decision-making frameworks like the MHT offers critical insights for creating sustainable, resilient, and inclusive water resource management strategies. As AI technology advances, its role in policy development and resource management will become increasingly crucial in equipping communities to face future environmental challenges and uncertainties.

Declaration of Generative AI and AI-Assisted Technologies

During the preparation of this manuscript, the authors used ChatGPT, based on the GPT-4 model, to improve the flow of the text, correct grammatical errors, and enhance the clarity of the writing. The language model was not used to generate content, citations, or verify facts. After using this tool, the authors thoroughly reviewed and edited the content to ensure accuracy, validity, and originality, and take full responsibility for the final version of the manuscript.

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Credit Author Statement

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References

Alabbad, Y., Mount, J., Campbell, A. M., & Demir, I. (2024). A web-based decision support framework for optimizing road network accessibility and emergency facility allocation during flooding. Urban Informatics, 3(1), 10.

Algarni, M. (2023). Deploying Artificial Intelligence for Optimized Flood Forecasting and Mitigation. 1-6. doi: 10.1109/aiccsa59173.2023.10479337

Artifex Software Inc. (2024). *PyMuPDF 1.24.12 documentation*. https://pymupdf.readthedocs.io/en/latest/

Biswas, A. K. (2004). Integrated water resources management: a reassessment: a water forum contribution. Water International, 29(2), 248-256.

Bowes, B. D., Tavakoli, A., Wang, C., Heydarian, A., Behl, M., Beling, P. A., & Goodall, J. L. (2021a). Flood mitigation in coastal urban catchments using real-time stormwater infrastructure control and reinforcement learning. Journal of Hydroinformatics, 23(3):529-547.

Bowes, B. D., Wang, C., Ercan, M. B., Culver, T. B., Beling, P. A., & Goodall, J. L. (2021b). Reinforcement learning-based real-time control of coastal urban stormwater systems to mitigate flooding and improve water quality. Environmental science, 8(10):2065-2086.

Chang, F.-J., Chang, L.-C., & Chen, J.-F. (2023). Artificial intelligence techniques in hydrology and water resources management. *Water*, 15(10), 1846. https://doi.org/10.3390/w15101846

Daniell, J., Schaefer, A., Claassen, J., Ward, P., de Ruiter, M., Khazai, B., Mysiak, J., Stuparu, D., & Girard, T. (2023). The development of multi-hazard risk scenarios for use in sector specific analyses in Europe and beyond. EGU General Assembly 2023, Vienna, Austria, 24-28 Apr 2023, EGU23-5959. https://doi.org/10.5194/egusphere-egu23-5959

D'Alpaos, C., & Bottacin, G. (2021). Social Choices and Public Decision-Making in Mitigation of Hydrogeological Risk. 289-300.

Du, N., Huang, Y., Dai, A. M., Tong, S., Lepikhin, D., Xu, Y., Krikun, M., Zhou, Y., Yu, A. W., Firat, O., Zoph, B., Fedus, L., Bosma, M., Zhou, Z., Wang, T., Wang, Y. E., Webster, K., Pellat, M., Robinson, K., ... Cui, C. (2021). GLaM: Efficient scaling of language models with mixture-of-experts. ArXiv Preprint arXiv: 2112.06905

Elshaikh-Hayaty, A. E., Mabrouki, J., & Mohamed, A. A. O. (2024). The future of water management: Leveraging AI for effective decision support. In Advancements in Climate and Smart Environment Technology (Chapter 15). IGI Global. https://doi.org/10.4018/979-8-3693-3807-0.ch015

Farhaoui, Y., & El Allaoui, A. (2024). Sustainability in the Internet of Things: Insights, scope, and AI-driven optimized water management with big data integration.

Farzana, S. Z., Paudyal, D. R., Chadalavada, S., & Alam, J. (2024). Decision Support Framework for Water Quality Management in Reservoirs Integrating Artificial Intelligence and Statistical Approaches. Water, 16(20):2944-2944.

Gent, E. (2024, October 11). AI agents could collaborate on far grander scales than humans, study says. Singularity Hub. Retrieved from https://singularityhub.com/2024/10/11/ai-agents-could-collaborate-on-far-grander-scales-than-humans-study-says/

Ghaffarian, S., Taghikhah, F. R., & Maier, H. R. (2023). Explainable artificial intelligence in disaster risk management: Achievements and prospective futures. *International Journal of Disaster Risk Reduction*, 104123. https://doi.org/10.1016/j.ijdrr.2023.104123

Hammam, R., Santoso, E. W., Tejakusuma, I. G., & Prawiradisastra, F. (2020). Advancing Flood Disaster Mitigation in Indonesia Using Machine Learning Methods. doi: 10.1109/ICISS50791.2020.9307561

Kadiyala, L. A., Mermer, O., Samuel, D. J., Sermet, Y., & Demir, I. (2024). The Implementation of Multimodal Large Language Models for Hydrological Applications: A Comparative Study of GPT-4 Vision, Gemini, LLaVa, and Multimodal-GPT. Hydrology, 11(9), 148.

Kamyab, H., Khademi, T., Chelliapan, S., Saberi Kamarposhti, M., Rezania, S., Yusuf, M., Farajnezhad, M., Abbas, M., Jeon, B. H., & Ahn, Y. (2023). The latest innovative avenues for the utilization of artificial intelligence and big data analytics in water resource management. *Results in Engineering*, 101566. https://doi.org/10.1016/j.rineng.2023.101566

Konar, M., Garcia, M., Sanderson, M. R., Yu, D. J., & Sivapalan, M. (2019). Expanding the Scope and Foundation of Sociohydrology as the Science of Coupled Human-Water Systems. Water Resources Research, 55(2):874-887.

Le, V. T. T., & Nguyen, T. B. (2022). Application of socio-hydrological approach to study water-related hazards in Can Tho City. Can Tho University Journal of Science, 14(3):8-16.

Martin, N., & White, J. T. (2024). Water Resources' AI–ML Data Uncertainty Risk and Mitigation Using Data Assimilation. Water, 16(19):2758-2758.

Martelo, R., & Wang, R.-Q. (2024). Towards democratized flood risk management: An advanced AI assistant enabled by GPT-4 for enhanced interpretability and public engagement. ArXiv Preprint arXiv:2403.03188.

Motta, M., de Castro Neto, M., & Sarmento, P. (2021). A mixed approach for urban flood prediction using machine learning and GIS. *International Journal of Disaster Risk Reduction*, 102154. https://doi.org/10.1016/j.ijdrr.2021.102154

Omar, P. J., Gupta, P., & Wang, Q. (2023). Exploring the rise of AI-based smart water management systems. AQUA - Water Infrastructure, Ecosystems and Society, 72(11), iii–iv.

OpenAI. (2024). GPT-4o-mini. Retrieved from https://openai.com

Pennings, A. J. (2024, June 24). AI and remote sensing for monitoring landslides and flooding. https://apennings.com/space-systems/ai-and-remote-sensing-for-monitoring-landslides-and-flooding/

Piemontese, L., De Angeli, S., Castelli, G., Villani, L., Boni, G., & Bresci, E. (2024). Framing co-production in socio-hydrological modelling for drought impact assessment and mitigation. European Geosciences Union General Assembly 2024 (EGU24), Vienna, Austria, 14-19 April, 2024. https://doi.org/10.5194/egusphere-egu24-9744

Project Performance International. (2024, September 19). AI for instant flood detection. *PPI International*. https://www.ppi-int.com/industry-news/featured-news/ai-for-instant-flood-detection/

Pursnani, V., Sermet, Y., Kurt, M., & Demir, I. (2023). Performance of ChatGPT on the US fundamentals of engineering exam: Comprehensive assessment of proficiency and potential implications for professional environmental engineering practice. Journal of Engineering Education, 2666920X.

Qin, H., Liang, Q., Chen, H., & Silva, D. (2024). A Coupled Human and Natural Systems (CHANS) framework integrated with reinforcement learning for urban flood mitigation. Journal of hydrology, 643:131918-131918.

QuantFactory. (2024). DarkIdol-Llama-3.1-8B-Instruct-1.2-Uncensored-GGUF. Retrieved from https://huggingface.co/QuantFactory/DarkIdol-Llama-3.1-8B-Instruct-1.2-Uncensored-GGUF

Ray, P. P. (2023, June 15). Leveraging deep learning and language models in revolutionizing water resource management, research, and policy making: A case for ChatGPT. *American Chemical Society*.

Sajja, R., Sermet, Y., & Demir, I. (2024a). End-to-end deployment of the educational AI hub for personalized learning and engagement: A case study on environmental science education. EarthArXiv.

Sajja, R., Ramirez, C. E., Li, Z., Demiray, B. Z., Sermet, Y., & Demir, I. (2024b). Integrating Generative AI in Hackathons: Opportunities, Challenges, and Educational Implications. Big Data and Cognitive Computing, 8(12), 188.

Sajja, R., Sermet, Y., Cikmaz, M., Cwiertny, D., & Demir, I. (2024c). Artificial intelligence-enabled intelligent assistant for personalized and adaptive learning in higher education. *Information*, *15*(10), 596.

Sajja, R., Sermet, Y., Cwiertny, D., & Demir, I. (2023a). Platform-independent and curriculum-oriented intelligent assistant for higher education. International Journal of Educational Technology in Higher Education, 20(1), 1-18.

Sajja, R., Sermet, Y., Cwiertny, D., & Demir, I. (2023b). Integrating AI and learning analytics for data-driven pedagogical decisions and personalized interventions in education. ArXiv Preprint arXiv:2312.09548.

Salimi, A., Ghobrial, T., & Bonakdari, H. (2024). A comprehensive review of AI-based methods used for forecasting ice jam floods occurrence, severity, timing, and location. *Cold Regions Science and Technology*, 104305. https://doi.org/10.1016/j.coldregions.2024.104305

Samuel, D. J., Sermet, M. Y., Mount, J., Vald, G., Cwiertny, D., & Demir, I. (2024). Application of Large Language Models in Developing Conversational Agents for Water Quality Education, Communication and Operations. EarthArxiv, 7056. https://doi.org/10.31223/X5XT4K

Saravi, S., Kalawsky, R., Joannou, D., Rivas Casado, M., Fu, G., & Meng, F. (2019). Use of artificial intelligence to improve resilience and preparedness against adverse flood events. *Water*, 11(5), 973.

Sermet, Y., & Demir, I. (2018). An intelligent system on knowledge generation and communication about flooding. Environmental Modelling & Software, 108, 51-60.

Sermet, Y., Demir, I., & Muste, M. (2020). A serious gaming framework for decision support on hydrological hazards. Science of The Total Environment, 728, 138895.

Sharma, S., Baisla, P., Rajput, H., & Tanwar, R. K. (2024). AI and Water Resource Management. 75-85.

Teague, A., Sermet, Y., Demir, I., & Muste, M. (2022). A collaborative serious game for water resources planning and hazard mitigation. Water, 14(6), 912.

Vald, G. M., Sermet, M. Y., Mount, J., Shrestha, S., Samuel, D. J., Cwiertny, D., & Demir, I. (2024). Integrating Conversational AI Agents for Enhanced Water Quality Analytics: Development of a Novel Data Expert System. EarthArxiv, 7202. https://doi.org/10.31223/X51997

Vekaria, D., & Sinha, S. (2024). aiWATERS: An artificial intelligence framework for the water sector. *AI in Civil Engineering*, 3(1). https://doi.org/10.1007/s43503-024-00025-7

Wu, Q., Bansal, G., Zhang, J., Wu, Y., Li, B., Zhu, E., Jiang, L., Zhang, X., Zhang, S., Liu, J., Awadallah, A., White, R. W., Burger, D., & Wang, C. (2023). AutoGen: Enabling next-gen LLM applications via multi-agent conversation. Microsoft Research.

Yousefi, S., Pourghasemi, H. R., Emami, S. N., Pouyan, S., Eskandari, S., & Tiefenbacher, J. P. (2020). A machine learning framework for multi-hazards modeling and mapping in a mountainous area. *Scientific Reports*, 10, Article 12144. https://doi.org/10.1038/s41598-020-68912-2