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Research article

Identifying the optimal type and locations of natural water retention measures using spatial modeling and cost-benefit analysis

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ABSTRACT

Water management has shifted from solely technical and engineering approaches towards nature-based solutions (NBS), like natural water retention measures (NWRM), offering benefits beyond hydrology, such as improved well-being and biodiversity conservation. Determining the best type and location of these measures is challenging due to diverse options with varying benefits and effects depending on measure type and location characteristics. While most studies regarding the optimal allocation and implementation of NBS focus on the urban environment, this study presents a methodology for decision-makers focusing on inter-urban regions with limited data on NWRM implementation. Through hydrological modeling and cost-benefit analysis (CBA), we identify Pareto optimal NWRM sites and types, considering water quantity and quality alongside economic, environmental, and social objectives. We defined optimal locations that seek the most significant reduction of runoff, sediment, and pollutants, whilst optimal NWRM types are defined to seek the most cost-effective measures based on hydrological, ecological, and social criteria. Using the Open Non-point Source Pollution and Erosion Comparison Tool (OpenNSPECT), we simulated increased infiltration in different inter-urban areas and identified the optimal placement. The criteria for selecting suitable NWRM types for the identified areas are derived from the EU Directorate General for the Environment (DG-ENV) NWRM database. The results show different effective areas for reducing runoff, sediment, and pollutants. While one NWRM (natural bank stabilization) was identified as most beneficial for reducing sediment, several measures were selected for runoff reduction. Interestingly, measures with high potential for pollutant reduction seem to offer limited social and biodiversity benefits, suggesting conflicting objectives and highlighting the importance of accounting for multiple criteria. By employing simplified models and qualitative benefit assessments, this paper presents a practical decision-making approach to facilitate NWRM implementation in data-scarce areas.

1. Introduction

Urban and regional water management is related to many important environmental issues with several associated ecological and social challenges (Zhang and Chui, 2018). Conventional runoff management treats stormwater as a nuisance that needs to be quickly removed to avoid flooding and sanitation risks. However, stormwater can be a valuable resource that needs to be considered in urban development.

The past few decades have seen the rise of population, urbanization, and water demand. These factors, combined with the increased risk of storm damage due to climate change and growing public awareness of environmental issues, have led to a change in the attitude toward stormwater (Goulden et al., 2018). Traditional runoff management methods, referred to as "gray" infrastructure (e.g., waste-water treatment plants and water storage facilities), are sometimes insufficient to address these challenges, and a more holistic catchment-based approach combining gray and green solutions is needed (Collentine and Futter, 2018; Pitt, 2008). Newer management approaches use various solutions (e.g., wetlands, pervious pavement, and green roofs) to increase infiltration, evapotranspiration, and water detention/retention (Hunt et al., 2009). Sustainable water management has many different terms that are occasionally overlapping and sometimes complementary but not identical. For example, green infrastructure (GI), nature-based solutions (NBS), best management practices (BMP), and sustainable drainage

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systems. The advantage of GI measures is that they can be implemented in both urban and rural areas and offer multiple benefits and ecosystem services, like biodiversity preservation and recreational opportunities (Collentine and Futter, 2018).

Natural water retention measures (NWRM) are a type of green infrastructure that could be beneficial in the context of runoff management (Collentine and Futter, 2018). These are multi-functional measures for water resource management that utilize the natural properties of water bodies to restore the local ecosystem and enhance the water retention capacity (Strosser et al., 2015). NWRM can reduce flood risk and improve water quality through increased soil infiltration, evapotranspiration, water storage, and slowing the runoff overland flow by increasing surface roughness. NWRM includes many different measures that offer a variety of benefits. For example, *riparian buffers* can support biodiversity and provide an aesthetic contribution while reducing both nutrient flow and the likelihood of downstream flood conditions (Collentine and Futter, 2018). These measures are usually placed in upland areas and can include a single solution or a set of solutions to maximize the retention and removal of pollutants (Jefferson et al., 2017).

Much of the research regarding NBS and NWRM focuses on local on-site solutions in urban environments (Gimenez-Maranges et al., 2020). However, increased urbanization and the resulting flood risk affect rural watersheds significantly, where damage occurs to agriculture and local ecosystems (Ristianti et al., 2022). Furthermore, implementing NWRM measures that are suited for rural and agricultural areas in the basin can detain rain at the source and help mitigate flood risk in downstream urban areas. Additionally, implementing these measures in rural areas can reduce their costs since it avoids the cost of interfering with the urban infrastructure and environment (Collentine and Futter, 2018). It is crucial to select appropriate measures based on the area characteristics, land use, scale, hydrological issues, and pollutants (McFarland et al., 2019). Accurate evaluation of the specific spatial allocation is vital since the effects of these practices are, in most cases, synergistic and will vary according to their spatial configuration.

Decision Support Systems (DSS) are tools and systems, usually computerized, to assist decision-making in semi-structured and unstructured problems (Mysiak et al., 2005). DSS can be knowledge-based, GIS-based, use mathematical models, or rely on more complex decision support strategies (Le Page et al., 2020). Hydrologic modeling is often used to simulate hydrological processes to help with stormwater management decisions (Gallo et al., 2020). Hydrological models simplify hydrological processes by using mathematical equations describing the relationship between climate, land uses, topography, soils, and various hydrological processes such as runoff generation. They help predict the dynamic water balance of watersheds by considering spatio-temporal characteristics (Puttaswamigowda, 2016).

Cost-benefit analysis (CBA) is another important tool when decision-making involves weighing the costs and benefits of different alternatives. Using NWRM has many benefits; some, like additional water supply, are easily quantifiable, while others are intangible and more difficult to quantify. For example, the benefits of green space and certain ecosystem services include the provison of runoff mitigation, carbon sequestration, urban temperature reduction, and more. Accounting for these processes could enhance the cost-effectiveness of sustainable watershed management projects. (Gunawardena et al., 2020). CBA compares the costs and benefits of different alternatives and is based on the rational that the decisions should be made to increase individual welfare. It quantifies, usually in monetary terms, and compares the advantages and disadvantages of different options, even in cases when costs and benefits lack clear economic estimation. Though CBA plays an important role in decision-making, it does not dictate the outcome; instead, it offers rational benchmarks for decision-making (Strosser et al., 2015).

In this research, we aim to identify areas for intervention by simulating water retention measures in different areas and assessing the resulting effect to find the most effective locations. We then identify the most beneficial NWRM by comparing costs and potential benefits (hydrological, ecological, and social) based on qualitative assessments. We used the hydrological modeling tool, the Open-Source version of the Non-point Source Pollution and Erosion Comparison Tool (OpenNSPECT),[1] to simulate implementing NWRM in different areas of the Tavor drainage basin in Israel. We utilized the efficiency of OpenNSPECT to compare land use scenarios as part of a runoff management strategy. We used the tool to systematically identify the optimal placement of NWRM by conducting a sensitivity analysis on the case study of the Tavor basin. We simulated adding a water retention measure in different basin areas and assessed the resulting reduction in runoff, sediments, and pollutants to find the most effective locations to implement NWRM. Upon identifying the NWRM location, the appropriate NWRM type was sought by examining the potential benefits of different measures against their costs.

There are still some obstacles and knowledge gaps to implementing NWRM as part of catchment-based runoff management. Though there are many studies about the individual effectiveness of NWRM, few studies examine how to implement them as part of a watershed-scale management plan. Several online database repositories, such as The International BMP Database, have been compiled to assist researchers and practitioners in improving the design and selection of BMP[2] (Clary et al., 2020). To support NWRM implementation, the EU Directorate General for the Environment (DG-ENV) commissioned a project to develop a NWRM database, cataloging NWRM case studies and their hydrological, biophysical, and socio-economic impacts[3] (Collentine and Futter, 2018). We selected several NWRM and used the database to give each measure an ordinal scale assessment (low, medium, or high) of its potential benefits. We used a series of Pareto graphs to examine costs against social and biodiversity benefits and the potential for hydrological benefits to find the most beneficial measure.

This research proposes a practical methodology for DSS to help decision-makers with sustainable runoff management using natural measures for water retention and considering various hydrological, ecological, social, and economic objectives. Unlike most studies that focus on urban areas and rely heavily on extensive observational data and stakeholder input, our method targets inter-urban regions. It is particularly suited for areas with limited observational data and information on NWRM implementation. This approach addresses two key questions: (1) Where are the most effective locations for NWRM placement? (2) What are the most beneficial measures for these identified locations? The focus on data-scarce rural watersheds, combined with the use of a simple hydrological model for land use scenario comparison and an existing NWRM database, offers a practical solution for effective watershed management in areas with limited data.

2. Literature review

NWRM are increasingly recognized as effective tools for sustainable water management, offering a range of environmental, social, and economic benefits. A comprehensive study by the Joint Research Centre of the European Commission evaluated the hydrological impacts of NWRM across Europe. This study employed extensive modeling to assess various scenarios by integrating climate, land use, and hydrological models on a pan-European scale. The results demonstrated that NWRM

[1] ***OpenNSPECT*** is a software tool developed by staff at the Coastal Services Center of the US National Oceanic and Atmospheric Administration (NOAA) and freely available from https://coast.noaa.gov/digitalcoast/tools/qnspect.html.

[2] Information about the International BMP DataBase is available at https://bmpdatabase.org.

[3] Information about the NWRM case studies is available at http://www.nwrm.eu.

can significantly enhance low flows and mitigate flood peaks, with some scenarios showing up to a 20% change in discharge. The study also underscored the importance of incorporating NWRM into comprehensive water management strategies to maximize their effectiveness and ensure holistic benefits (Burek et al., 2012). To further support NWRM implementation, the DG-ENV provided a comprehensive practical guide on the selection, design, and implementation of NWRM. This guide highlights the various benefits of NWRM, including flood risk reduction, enhanced biodiversity, and the creation of recreational spaces. It presents a structured approach to implementing NWRM and offers guidance on navigating the internet-based NWRM knowledge base at http://www.nwrm.eu (Strosser et al., 2015).

Several studies have explored the effectiveness of NWRM implementation. Collentine and Futter (2018) examined how NWRM can complement traditional gray infrastructure in managing catchment-scale flood risks. They highlighted the importance of addressing financial responsibility and discussed potential payment mechanisms to compensate landowners for implementing NWRM. The authors conclude that the widespread adoption of NWRM is hindered by knowledge gaps, institutional barriers, and the lack of empirical studies that demonstrate their effectiveness. Baldan et al. (2021) examined the effectiveness of NWRM in addressing fine bed material deposits in river catchments. The study integrates hydrological modeling, hydraulic modeling, and Random Forest ensemble models to assess the impacts of NWRM on the Aist catchment in Austria. Results show that vegetated filter strips increase the natural condition of the river network by 5%, sediment retention ponds reduce clogged reaches by 8%, and hydromorphological improvements decrease material deposits by 10% during mean flow. The study also emphasizes the importance of a multi-scale assessment to fully understand the benefits and trade-offs of NWRM.

Various modeling tools can simulate hydrological processes. These may be used to quantify the effects of stormwater management practices (Zhang and Chui, 2018). Most DSS for sustainable runoff management use simulation hydrological models paired with optimization algorithms to evaluate the effects of potential measures (so-called simulation-optimization framework). However, this approach requires running many iterations of the simulation-optimization problem and can be very time-consuming. Effective management of sustainable runoff requires the involvement of diverse stakeholders from different fields. Thus, DSS are commonly employed to foster structured discussions among stakeholders regarding proposed solutions. Slow and inefficient simulation systems can impede real-time interaction with the decision support system, hindering collaborative efforts. As such, solution efficiency is important for implementing practical DSS.

Another popular method for identifying areas to implement nature-based solutions is multi-criteria decision analysis (MCDA). MCDA is a decision-making method that balances the advantages and limitations of using various options to select the optimal alternatives that achieve a predefined goal (Kumar et al., 2021). Ruangpan et al. (2021) used MCDA to select NBS measures addressing different flood hazard types for different scales (urban, basin, and coastal) based on the qualitative preference of stakeholders and the potential benefits of NBS. They suggested that there is a need to develop a spatial allocation method to identify potential locations for implementing the selected measures. Pacetti et al. (2022) used spatial multi-criteria analysis (SMCA) to identify pluvial flood “hot spots” in Florence, Italy, based on local hydrological conditions and social vulnerability and selected appropriate NBS measures. Asare et al. (2024) used SMCA to identify target areas to implement urban flood-related NBS measures in a low-income urban area. They identified appropriate measures based on their design features and functionality.

Some studies have also addressed NBS implementation in non-urban areas. Pittman et al. (2022) used SMCA to rank planning units in the coastal seascapes of Abu Dhabi Emirate and the Northern Emirates for NBS implementation based on their potential for climate change mitigation, biodiversity, and socio-economic benefits. Higuera et al. (2023) used MCDA to select an appropriate NBS for climate adaptation and disaster risk reduction in the rural area of the Southern High Andes of Peru. Nonetheless, they did not consider social benefits beyond climate change adaptation. Their spatial analysis to identify possible intervention areas was based on aggregating local conditions (socio-economic conditions, ecosystem characteristics, and future climate change trends).

Various models and tools have been developed over the years with various abilities. One type of hydrological model that is particularly suitable for placement decisions regarding NBS is physically based distributed and semi-distributed models, which explicitly represent spatial variability in watershed characteristics and climatic parameters. They can incorporate topographic features, vegetation, soil properties, and climate data, providing a more detailed representation of hydrological processes (Puttaswamigowda, 2016). Several hydrological models have been applied to the issue of sustainable runoff management. The Storm Water Management Model (SWMM) has been used to find the optimal size and location of BMP to mitigate the urbanization effect on water quality (Saadatpour et al., 2020). Uniyal et al. (2020) used the Soil and Water Assessment Tool (SWAT) to propose effective BMP for erosion-prone areas in the Baitarani catchment, India. They evaluated the efficacy of eight agricultural and structural BMP, finding that combined BMP are more effective than individual ones and that structural BMP were particularly effective. Agarwal et al. (2024) assessed NBS effectiveness in reducing peak discharge rates in the Banas River catchment, India, using the HEC-HMS modeling system. Results showed the potential of NBS to mitigate surface runoff, peak flows, and flood volumes.

In this research we have utilized the hydrological modeling tool OpenNSPECT, which is designed to compare water quantity and quality differences between baseline landscapes and managed or disturbed landscapes (Figueroa-Sanchez et al., 2015). For example, OpenNSPECT has been used to understand changes in future runoff due to development and climate change (Tunnell et al., 2015). However, despite its ability to simulate runoff, its primary use has been comparing differences in water quality rather than flood mitigation. Therefore, it has been used to simulate changes in pollutant loads due to land use modification (Butler et al., 2011; Tulloch et al., 2016; Viswanathan and Karim, 2015) and to determine the contribution of non-point source pollution loads (El-nakib & Alameddine, 2020; Morrison and Kolden, 2015). Nevertheless, there is still a lack of comprehensive tools capable of assessing multiple benefits, particularly the performance and cost-effectiveness of NBS for mitigating the risks of different hydro-meteorological extreme events such as floods (Kumar et al., 2021).

CBA has often been used to assess the pros and cons of potential actions and policies (Liu et al., 2016). Using NBS has many benefits. Some (like additional water supply) are easily quantifiable, while others are intangible and more difficult to quantify. For example, the benefits of having public access to green space and the ecosystem services that green space can provide (runoff mitigation, carbon sequestration, urban temperature reduction, and more) are difficult to quantify. Accounting for these aspects can enhance the cost-effectiveness of sustainable water management projects. However, quantifying the intangible benefits of NBS remains an underdeveloped research area (Gunawardena et al., 2020). Liu et al. (2016) calculated the costs and benefits of different GI on stormwater reduction. They used CBA to compare different GI scenarios in a typical community in Beijing. They found that despite higher construction and maintenance costs, the potential benefits of water replacement could outweigh the costs. Fan and Matsumoto (2019) used a simplified hydrological model to estimate flood risk reduction as a result of integrated urban water management practices (referred to as ‘sponge cities’) and tried to precisely calculate costs and potential benefits based on previous studies to conduct a CBA from private and social perspectives. They found that a sponge city project is more effective from a social perspective. Biasin et al. (2023) analyzed the contribution

of NBS in improving resiliency to urban heat islands and floods. They examined different scenarios of NBS mixes and found that flood risk mitigation NBS (especially forested green areas and retention ponds) had the most impact.

Despite numerous DSS developed for water management, there is still a growing demand for more sophisticated DSS tailored to address the intricacies of water resource management effectively (Mysiak et al., 2005). Furthermore, most DSS focus on hydrological water quantity and quality issues while devoting little attention to ecological and social aspects (Ferrans et al., 2022). Additionally, some hydrological models require a large amount of data and can have a lengthy calibration process. Simpler models requiring minimal data and using the empirical or statistical relationship between variables (e.g., between pollution concentrations, land use, runoff, and rainfall) can offer a generalized understanding of pollutant loads and runoff amounts (Yuan et al., 2020).

3. Methodology

3.1. Case study

We applied the methodology presented here to the rural areas of the Tavor basin. Fig. 1 shows the location of the Tavor basin, in the northeast part of Israel (Fig. 1A), and the land uses in the basin and the Tavor river floodplain (Fig. 1B). For many years, streams in Israel have been neglected and polluted, themselves used for sewage transport and their water for agriculture (Tal and Katz, 2012). In recent years, with the transition towards desalinated water for drinking and treated water for irrigation, the attitude towards streams has also changed, with several projects aimed at stream restoration and water quality improvment (Goulden et al., 2018). The Tavor basin represents an area with mixed land uses (Fig. 1B) and various hydrological, ecological, and social issues that could benefit from NWRM implementation.

Urban expansion into rural areas (urban sprawl) in the northern part of the Tavor basin and over agricultural land has led to more impermeable surfaces, resulting in more frequent and egregious flood events. The Tavor Stream upland (marked in red in Fig. 1B) is the most flood-prone area in the basin due to increased runoff from the urban expansion in the upland areas (SJDA, 2021). Increased agriculture activity and soil erodibility has resulted in increased sediment and non-point source (NPS) pollution. The different communities living within the case study area suffer from limited access to open spaces and a lack of integration due to significant social, ethnic, and economic disparities, which also involve differences in culture, language, and religion (SJDA, 2020). The basin has many natural open areas, which are important for the well-being of the population and the preservation of the local ecosystem (SJDA, 2018). Finally, in Israel, the local authorities and water and sewage corporations manage stormwater within urban areas, while the local drainage authority manages stormwater beyond municipal boundaries. This separation (and sometimes lack of coordination) between water management headed by local authorities (responsible for aggregations of smaller settlements and villages) and municipal corporations managing drainage, water supply, and sewage infrastructure in towns, hinders an integrated watershed-scale stormwater management plan (Goulden et al., 2018). The Tavor basin falls under the jurisdiction of South Jordan Drainage Authority (SJDA), which also provided data and input for this research.

3.2. Applying OpenNSPECT to identify optimal locations

To identify the most effective areas for NWRM implementation, we used the hydrological model OpenNSPECT, a plugin for the GIS package MapWindow (Eslinger et al., 2012). The software estimates runoff volumes, sediment yield, and pollutant loads or concentrations. As such, it identifies areas susceptible to soil erosion and estimates the impact of land-use changes on water quality, respectively (Yuan et al., 2020). It can also compare outputs and calculate the absolute change and the percent change between two land-use scenarios, enabling easy comparison of outputs (Figueroa-Sanchez et al., 2015).

OpenNSPECT provides several advantages: it is open, freely available for download, simple to use, requires minimal data, and can be used to

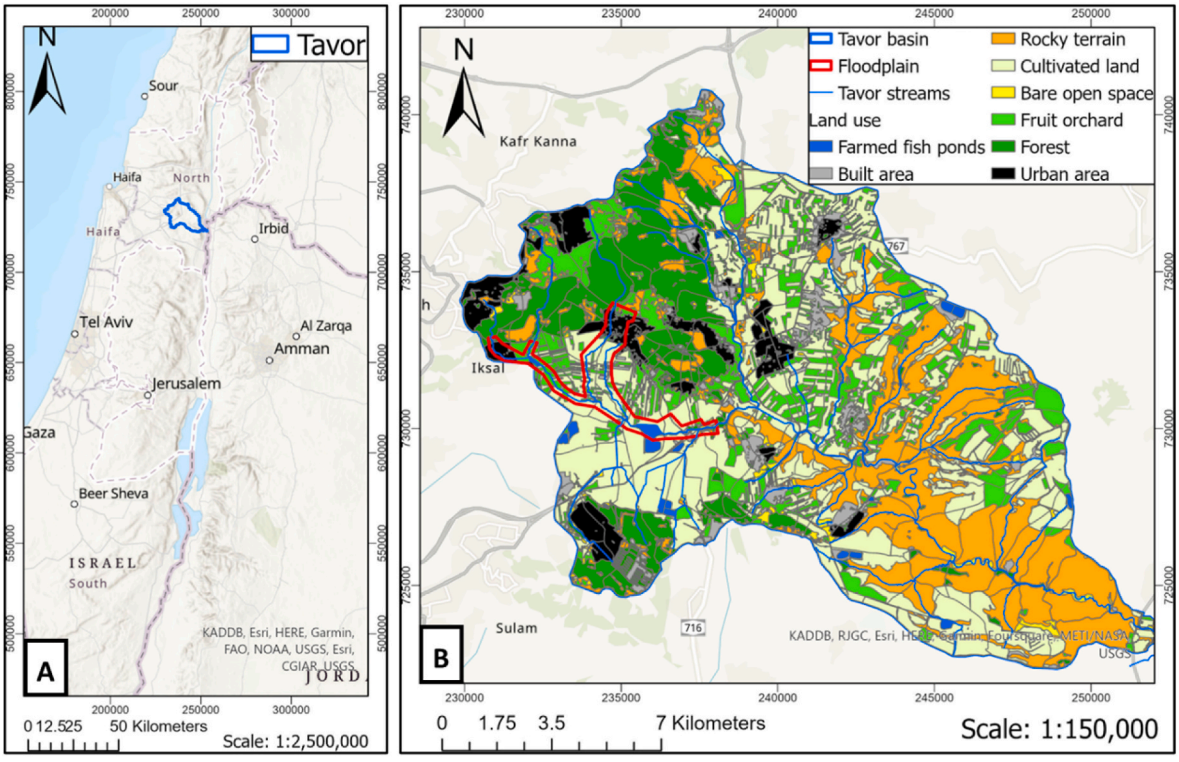

Fig. 1. The Tavor basin (A) the Tavor basin floodplain and land uses (B).

model any watershed, given that the relevant data is available. Most importantly, it allows for a quick comparison between different land-use scenarios. However, the simplicity of OpenNSPECT also comes with some limitations. The tool only simulates evapotranspiration, infiltration, and overland flow while omitting stormwater diversion structures or systems to redirect or manage the flow, landslide, and groundwater flow processes. The model is not time-dependent and does not simulate sediment redeposition or nutrient uptake. Therefore, the water quality values produced probably overestimated what would be measured in the field.

OpenNSPECT is a lumped model that was developed for mainly comparing the impacts of changing land use between a baseline scenario and proposed development scenarios. According to the developers of OpenNSPECT (Figueroa-Sanchez et al., 2015), in comparative analysis, one might rely on general parameters of the model without specific calibration against in situ observations. The assumption is that although the precise quantities could be inaccurate, the relative change between scenarios resulting from changes in land use should be reasonably accurate (Figueroa-Sanchez et al., 2015). This assumption was adopted by other researchers when the task at hand involved comparative analysis of scenarios (e.g., Butler et al., 2011; El-nakib & Alameddine, 2020; Morrison and Kolden, 2015; Viswanathan and Karim, 2015). The comparative nature of OpenNSPECT is especially useful in case there is little (as in the case of the Tavor basin) or no observation data in the study area.

OpenNSPECT can be used with any watershed, provided the required data is obtained. The accuracy of the results depends on data layers and input-output coefficients that are also dependent on the local data and conditions (Eslinger et al., 2012). The application runs a relatively simple hydrologic model requiring minimal data and can provide quick screening tools for watersheds using a generalized understanding of relevant hydrologic processes (Yuan et al., 2020). OpenNSPECT depends on local data when possible. In this study, we used local data, mostly supplied by the local drainage authority as input for the Tavor basin (e.g., land use, soil type, and elevation data). Our methodology for identifying optimal placement is based on comparing runoff, sediment, and pollutant concentrations before and after implementing a water retention measure. Particularly, we primarily focus on assessing the relative differences in runoff, sediment, and pollutants between different land use scenarios rather than directly comparing absolute values. This approach allows us to mitigate the impact of potential overestimation by the model despite the lack of a traditional hydrologic calibration process against in situ observations (Figueroa-Sanchez et al., 2015).

OpenNSPECT calculates runoff using the Soil Conservation Service (SCS) (NRCS, 1986), which determines soil infiltration capacity and water retention factor for cover types to calculate runoff.

$$Q = \frac{\left(P - 0.2 \bullet \frac{1000}{CN}\right)^2}{\left[\left(P - 0.2 \bullet \frac{1000}{CN}\right) + \frac{1000}{CN}\right]} \quad (1)$$

where Q is the runoff, P is the rainfall (both measured in inches), and CN is a runoff curve number representing the overall permeability varying from 0 for a 100% infiltration to 100 for 0% infiltration.

OpenNSPECT estimates the mean concentration of pollutants in runoff based on land cover type by applying specific contribution coefficients for each pollutant in each land cover (NOAA, 2012b). We used nitrogen (N) with the coefficient supplied by the tool as a representative indicator of NPS pollution. To compute sediment amounts, identify erosion sources, and estimate total sediment yield, OpenNSPECT uses the Revised Universal Soil Loss Equation (RUSLE), a widely used mathematical model, to calculate soil erosion (NOAA, 2012a). OpenNSPECT calculates the average annual soil loss based on rainfall erosivity, soil erodibility, slope steepness, and length. It can calculate the annual average amounts or average amounts per rainfall event.

The accuracy of OpenNSPECT results depends on using local data when possible (NOAA, 2012b). To that end, we constructed a baseline model for the Tavor basin in OpenNSPECT using land use, soil type, and elevation data supplied by the SJDA. The soil erodibility factor (K-factor) was adapted from Aviad et al. (2010), and the hydrological soil groups are from the Global Hydrologic Soil Groups database (Ross et al., 2018). We calculated mean annual precipitation using monthly precipitation data for 2010–2020 from five monitoring stations in the area, collected from the Israeli Meteorological Service website (Israeli Meteorological Service, 2018). Finally, OpenNSPECT requires a rainfall erosivity factor (R-factor) to quantify the effects of raindrop impacts and the associated rate of rain runoff (NOAA, 2012b). R-factor data was taken from the Global Rainfall Erosivity Database of the European Soil Data Center (Panagos et al., 2017). We used this baseline scenario to compute accumulated runoff, sediment, and N concentration before applying any management scenarios.

In the next phase, we generated results from multiple scenarios to identify the most effective areas for implementing NWRM in the rural regions of the basin. We divided the basin into 1 km^2 land parcels and excluded the urban areas using Geographic Information Systems (GIS). This spatial analysis provided a clear framework for scenario modeling. We then applied an enumeration procedure in which we ran the model multiple times using the hydrological modeling tool OpenNSPECT. Each time, we altered the land use of a different parcel into a wetland to simulate increased infiltration, essentially conducting a sensitivity analysis of the basin to NWRM implementation. In a sensitivity analysis, varying one parameter while all other conditions remain fixed can help rank the systems' sensitivity to change (Lenhart et al., 2002). We used this strategy to assess the impact of changing land use (i.e., change to a NWRM) on the hydrological processes in the basin.

Each scenario involved changing only one parcel to gauge the effect that increased infiltration at that specific location on the floodplain. We examined the impact of these changes on the most flood-prone area of the basin by using the Compare Outputs tool in OpenNSPECT by comparing each scenario to the baseline scenario. This comparison allowed us to assess accumulated runoff, accumulated sediment, and N concentration in the floodplain before and after the change to each land parcel.

We used the resulting reduction in runoff, sediment, and N concentration in each scenario to build a Pareto frontier for identifying non-dominated solutions (i.e., Pareto optimal solutions) of the wetland locations based on these three objectives. That is, from that total number of land parcels, we identify a subset that contains Pareto optimal locations (i.e., achieve the best outcome for one objective, for given values of the other two objectives). This subset of locations is considered for implementing NWRM. Fig. 2 illustrates the stages comprising the methodology employed in this research and described above.

3.3. Cost-benefit analysis to identify optimal types of NWRM

To identify the optimal measure or set of measures to implement, we examined the potential benefits of various NWRM against their costs. The measures were selected from the previously mentioned NWRM database constructed by the DG-ENV. The DG-ENV promotes NBS in various fields, including water management, to restore and maintain healthy ecological water systems. The directorate website dedicated to NWRM has information on various NBS and their potential benefits based on a collection of case studies. Conducting a CBA of NBS requires extensive knowledge from experts and monitoring of existing NBS (Kumar et al., 2021). Using the NWRM database allows for the evaluation of NWRM based on multidimensional performance indicators without the need to collect observations from existing NBS. The measures we examined were selected from different runoff management projects in Israel, including those implemented in the Tzipori River basin restoration. These solutions were further identified in the NWRM database as belonging to non-urban sectors (agriculture, forest and

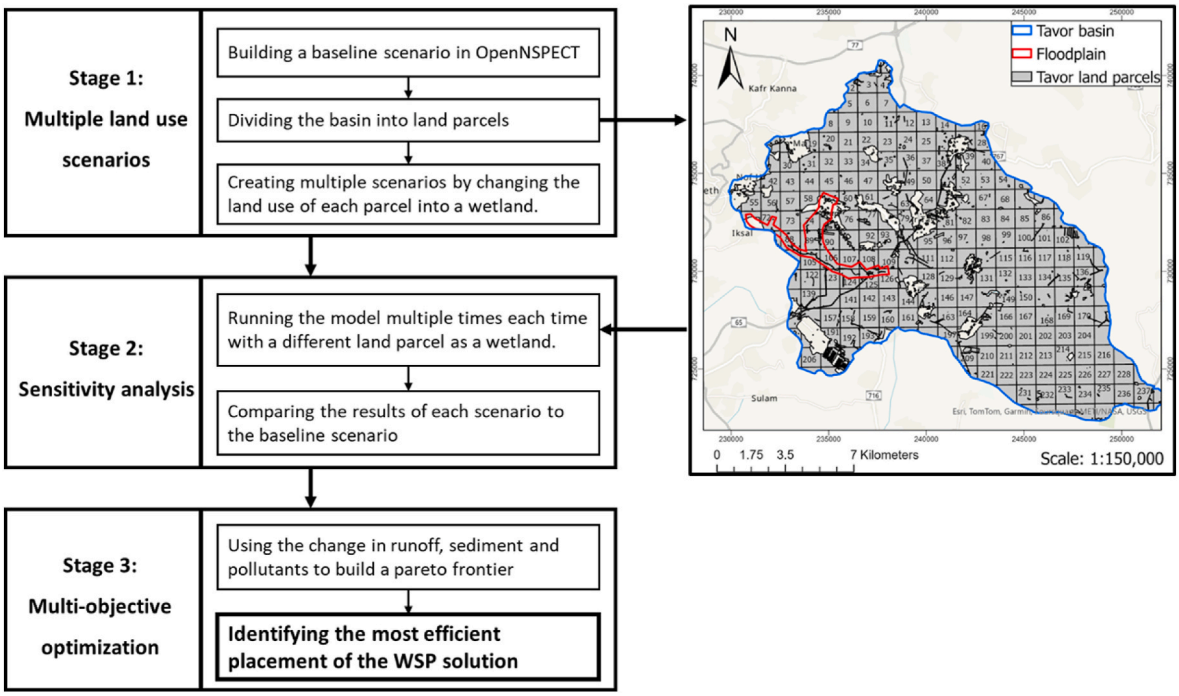

Fig. 2. Illustration of the *OpenNSPECT* methodology and basin division.

hydro-morphology). The selected potential NWRM are terracing (TR), re-meandering (RM), natural bank stabilization (NS), floodplain restoration (FR), basins and ponds (BP), flow-control structures (FS), targeted planting (TP), stream bed re-naturalization (SR), sediment-capture ponds (SP), and buffer strips (BS).

We derived the benefits for each measure from the NWRM database, where each solution received an ordinal scale assessment (low, medium, or high) of its potential to promote various benefits. We selected several hydrological, social, and ecological benefits and divided them into categories: a) store/reduce runoff, b) sediment control, c) flood risk reduction, d) pollutant reduction, e) social benefits, and f) biodiversity. We used the ordinal scale assessments from the database for each benefit (1-low, 2-medium, 3-high) to calculate the average score for each category (Appendix A provides a complete listing of the benefits, their

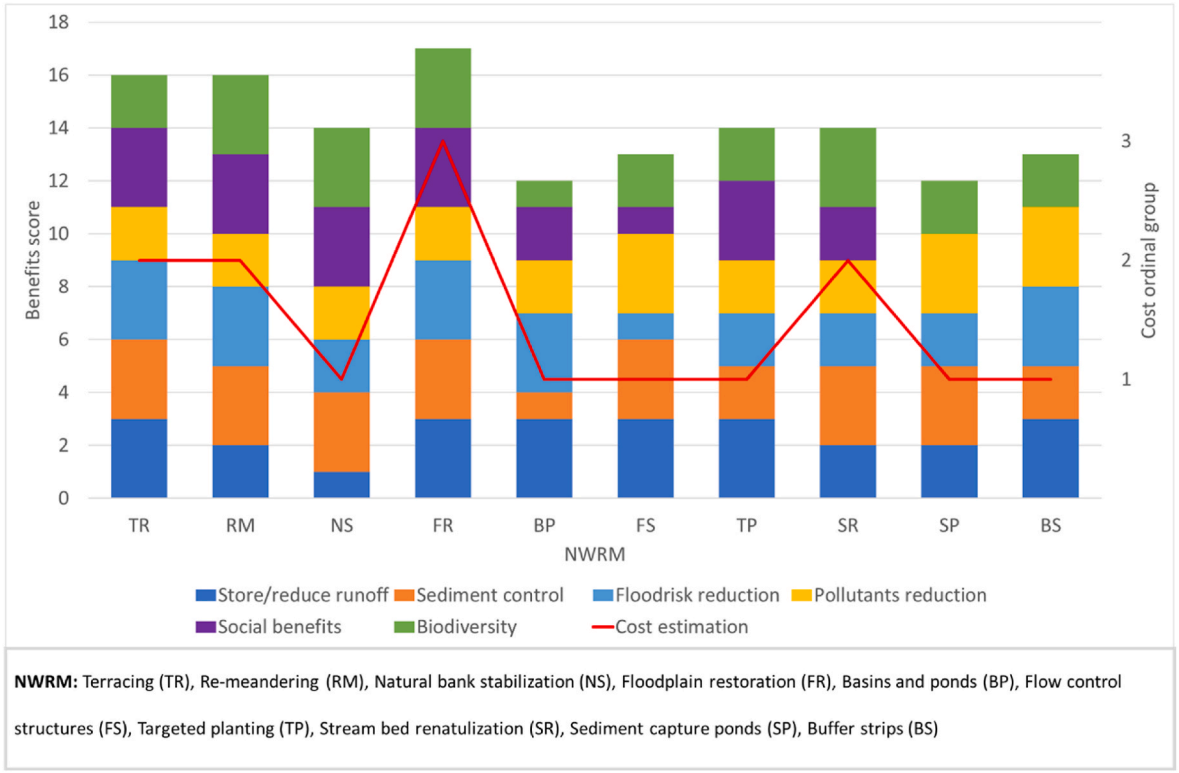

Fig. 3. Benefits and costs for NWRM.

ordinal scale assessments, our categories, and their average scores). Fig. 3 shows stacked bar charts of the benefits of each NWRM in each category. Each bar is the accumulation of the potential benefits of each measure we examined. For each measure, the potential benefits are stacked on top of one another, where the height of each segment represents the proportion of that potential benefit within the total for each bar. This visualization method enables easy comparison of both the total sum of potential benefits and the composition of benefits for each measure.

To maintain the same relative value scale to the benefits, we ranked the costs into three ordinal groups: 1-low, 2-medium, and 3-high. This division is based on costs found in Artita et al. (2013), costs from the economic section of the planning and management plan for the Tzipori River basin, and the type of NWRM. Local measures that can be applied in specific locations to specific issues were placed in the low category, and measures that span over a larger area and require more extensive projects were placed in the medium and high categories. Fig. 3 shows an estimate of the cost of each measure by overlaying the cost line (marked in red) on the stacked bars to compare the relative cost of each measure. We defined optimal measures as those that are most beneficial, meaning those with the highest benefits potential at the lowest cost. For instance, consider two measures, TR and RM, have the same total benefits sum of 16 and medium costs (ordinal group 2) but different scores for their potential benefits. TR has high potential to reduce runoff, sediment, and flood risk along with high potential for social benefits, but only medium potential for pollutant reduction and biodiversity. RM, while having the same total benefits sum and cost as TR, has a lower potential for runoff reduction and higher potential for biodiversity benefits. Each planner and stakeholder may prioritize different measure based on their specific interests and objectives.

The heterogeneity of stakeholder interests adds another layer of complexity to the decision-making process. In response, our analysis examined the costs against the social and biodiversity benefits, as well as their potential contributions to mitigating runoff, sediment, and pollutants in a series of Pareto graphs to evaluate and analyze the trade-offs in the NWRM selection process.

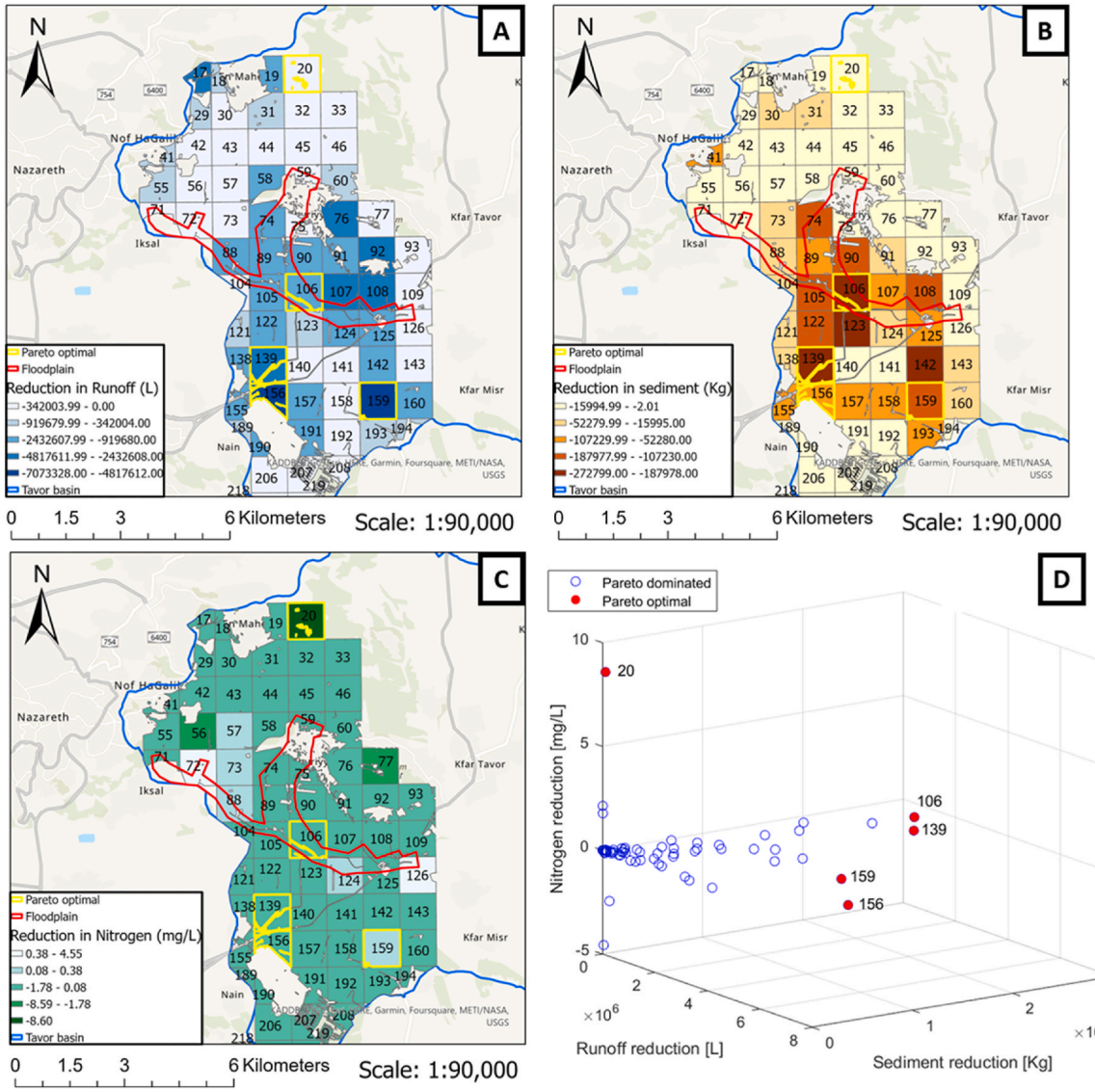

Fig. 4. OpenNSPECT simulation results-runoff reduction (Pareto-optimal areas in yellow) (A), sediment reduction (B), Nitrogen concentration reduction (C), and Pareto frontier (numbers correspond to land parcels) (D). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

4. Results and discussion

4.1. Identifying the optimal locations

We defined optimal location as the land parcels where increased infiltration resulted in Pareto optimal solutions, achieving the most significant reduction in runoff amounts, sediment amounts, and pollutant concentration in the Tavor stream floodplain. In Fig. 4A–C, the results of OpenNSPECT simulations illustrate the effectiveness of increased infiltration in each land parcel on the Tavor floodplain (marked in Fig. 4A–C in red). Darker shades indicate that increased infiltration in this land parcel resulted in a more substantial reduction in runoff (Fig. 4 A), sediment (Fig. 4 B), and N concentration (Fig. 4 C).

We used these reduction results to construct the 3D Pareto frontier depicted in Fig. 4D. The Pareto frontier identifies the most efficient placement considering the three objectives. At these points, one cannot improve one objective without worsening the other two objectives. Namely, all the blue points are dominated points (i.e., not Pareto optimal) since for each blue point, a red point dominates it by improving at least one objective without worsening the other two objectives. As such, the red points are non-dominated Pareto optimal points. Ideally, we consider the most efficient land parcels to be those that bring the most significant reduction of runoff, sediment, or nitrogen. However, unlike single-objective optimization, when using multi-objective optimization, one cannot obtain the maximum performance for the three conflicting objectives simultaneously. Instead, in multi-objective optimization, we aim to select the best trade-off (i.e., along the Pareto frontier) among the competing objectives (Kurek and Ostfeld, 2013).

The optimization results depicted in Fig. 4D, illustrate that the most effective land parcels for NWRM interventions vary depending on the specific objective. In our model, parcel 106 is identified as the most efficient for reducing sediment, parcel 156 for reducing runoff, and parcel 20 for reducing nitrogen concentration. Parcels 139 and 159 represent trade-offs, where improving the efficiency of one objective (runoff or sediment) leads to a decrease in the efficiency of the other. In total, five Pareto optimal solutions were identified (marked in yellow in Fig. 4A–C), each offering its own balance between the competing objectives. The selection of a land parcel for NWRM intervention is a decision influenced by the priorities and interests of planners and stakeholders, depending on whether the primary concern is runoff, sediment, or pollutant concentration. For instance, parcel 156 would be optimal for stakeholders primarily concerned with runoff reduction, while parcel 106 would be the best choice for sediment control. Alternatively, an integrated approach targeting all three issues may be

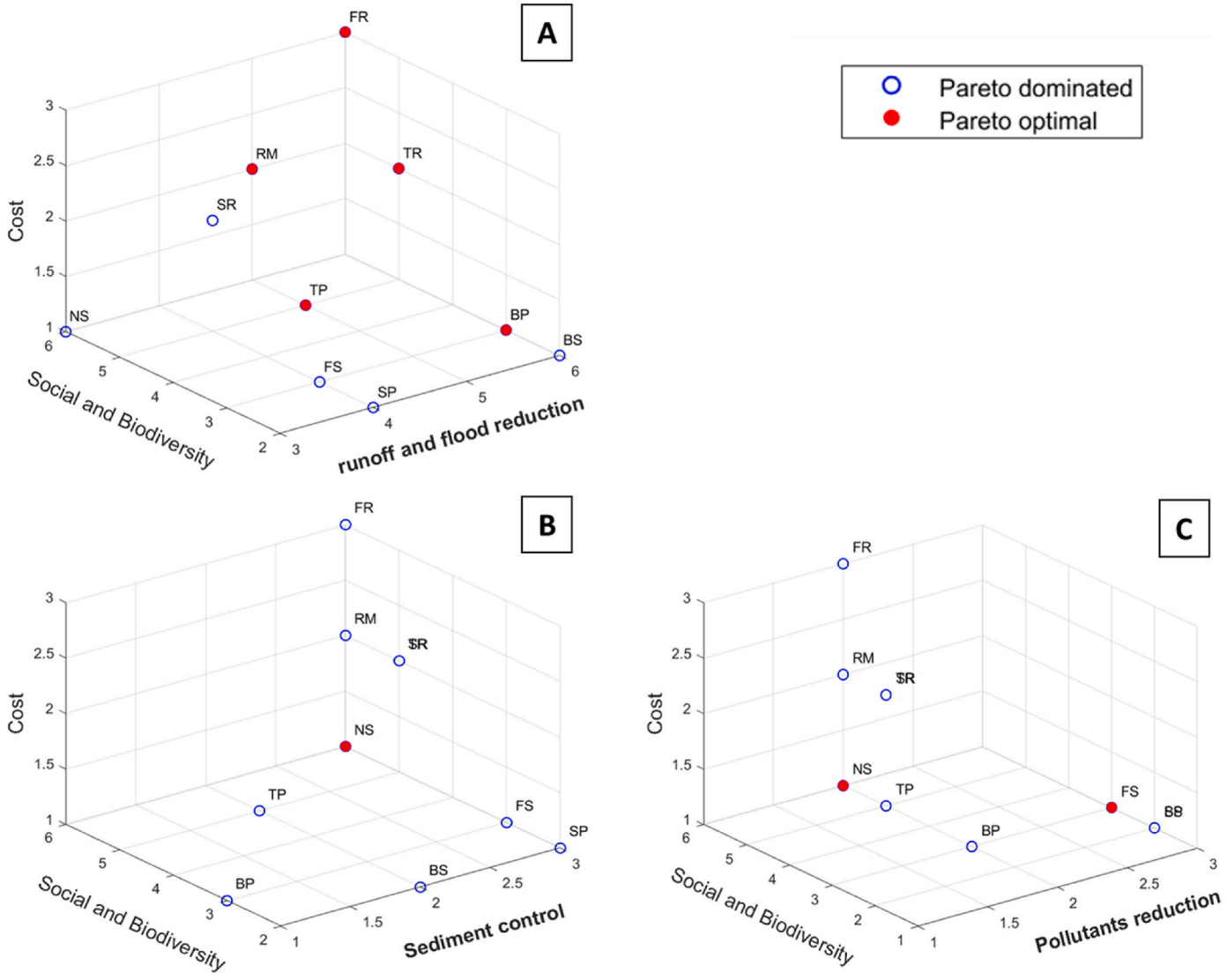

Fig. 5. Pareto results for optimal NWRM solutions considering cost, social and biodiversity benefits and runoff and flood reduction (A), sediment control (B), and pollutant reduction (C).

preferred. In that case, it is important to select NWRM that align with the primary objective each land parcel affects. The following section addresses the issue of NWRM selection in more detail, considering these spatial distribution insights.

4.2. Identifying optimal types of NWRM

We defined optimal NWRM as the most cost-effective measures, meaning those with the highest potential benefits relative to their costs. Our CBA approach involved a detailed comparison of the costs and benefits of each NWRM using a series of Pareto graphs to systematically compare costs and benefits across multiple dimensions. Fig. 5 depicts the Pareto results comparing the costs and benefits of each NWRM. In this analysis, we match suitable measures to the areas we have identified in the previous section while also accommodating economic, ecological, and social aspects. To that end, the axes of cost (vertical axis) and social and environmental benefits (horizontal axis) remain constant, while the third axis (depth axis) varied to represent different hydrological benefits: runoff reduction (Fig. 5A), sediment reduction (Fig. 5b) and pollutant reduction (Fig. 5c). This process enabled us to identify measures that offered the best trade-offs between costs and benefits, providing a nuanced understanding of their relative effectiveness and cost-efficiency. This approach allows decision-makers to select NWRM that align best with their specific objectives and constraints.

In the areas most effective in reducing runoff (parcels 156 and 159) we identified five Pareto optimal solutions (marked in red): FR, RM, TR, BP, and TP (Fig. 5A). As previously discussed, a solution is considered Pareto optimal if no other solution can improve one criterion without worsening at least one other criterion. In this context, Pareto optimal solutions are those where no single benefit can be improved without sacrificing another. For example, BP dominates Flow-control Structures (FS) because, while both have low costs and the same potential for social and biodiversity benefits, BP offers a higher potential for runoff and flood risk reduction. This means BP is a better overall choice, as it enhances one key benefit without compromising others, which is the essence of Pareto optimality. This analysis enables decision-makers to understand the trade-offs involved and select the most suitable NWRM for specific objectives.

Upon uncovering the Pareto optimal solutions, decision-makers need to discern the solution that aligns best with their subjective preferences and interests. This demands a nuanced consideration of their attitudes towards each option. Engaging local stakeholders, including landowners and community members, is vital for gaining insights into historical land management practices and ensuring social acceptability. Understanding the economic and institutional context, such as available funding and institutional support, can facilitate the implementation and maintenance of NWRM.

For example, in Fig. 5A TP and BP have the lowest cost. Therefore, decision-makers interested in minimum cost must decide between a solution with a higher potential for biodiversity and social benefits (TP) or a solution with a higher potential for runoff and flood reduction (BP). Nonetheless, one might argue that TP is a better compromise solution since, compared to BP, it increases the benefits' score by two at the price of reducing the score of runoff reduction by 1. Decision-makers with a higher budget may prefer the solution RM or TR, which offers a higher potential for biodiversity and social benefits (RM) or a higher potential for runoff and flood reduction (TR) than TP. Finally, decision-makers with a high budget who want maximum benefits will choose FR.

Interestingly, for areas that are more effective in sediment reduction (parcels 106 and 139), we found a unique Pareto optimal solution (Fig. 5b). Namely, natural bank stabilization (NS) has the highest potential for sediment control, biodiversity, and social benefits at the lowest cost.

As for the most effective areas for pollutant reduction (parcel 20), we again found more than one Pareto optimal measure (NS and FS), as shown in Fig. 5c. Decision-makers need to decide on a compromise solution between NS and FS or consider implementing both measures together, as they can complement each other. One perspective is that NS is a preferable compromise, offering a moderate pollutants reduction score of 2 with a top social and biodiversity score of 6, while FS scores lower (only 3 in both metrics). NS was also identified as optimal for sediment control, making it a versatile option. On the other hand, FS scores higher than NS with pollutant reduction. A decision-maker who prioritizes pollutant reduction might prefer FS, even if it means sacrificing some social and biodiversity benefits. These results could suggest that pollutant reduction and social and biodiversity benefits might be conflicting objectives. Assessing local biodiversity and ecosystem services can further guide the selection of measures. If an area is particularly important for ecosystem services, a measure with higher potential for biodiversity benefits, like NS, would be preferable. This predicament highlights the importance of considering the ecological and social benefits of NWRM when deciding on an appropriate measure to implement. Balancing these conflicting objectives is crucial for achieving an outcome that addresses hydrological issues of water quantity and quality that also aligns with broader environmental and societal goals.

5. Summary and conclusions

Most of the research on optimal NBS placement has focused on urban environments and urban-type NBS, with limited attention to rural areas. However, rural areas also suffer from flood damage, and implementing NBS can offer ecological and social benefits in both rural and urban settings. Many existing NBS decision-making methodologies require extensive data and expert input, making it challenging to develop strategies for NBS implementation in areas with little monitoring and knowledge about the impact of NBS.

In this study, we presented a methodology to identify the optimal type and placement of NWRM in inter-urban regions with limited observational data and information on NWRM. We used the hydrological modeling tool OpenNSPECT to systematically simulate a water retention measure in different locations and identify the most effective areas for NWRM implementation. We then conducted CBA of different NWRM suited for non-urban areas, considering hydrological, ecological, and social issues to determine the most beneficial measures to implement.

The results show that the most effective areas for reducing runoff differ from those focused on reducing sediment and pollutants. For runoff reduction, five Pareto optimal solutions were identified in the most effective areas (parcels 156 and 159), with Basins and Ponds (BP) and Targeted Planting (TP) offering the highest potential benefits for the lowest cost. For sediment reduction (parcels 106 and 139), Natural Bank Stabilization (NS) emerged as the unique Pareto optimal solution, providing the highest potential for sediment control, biodiversity, and social benefits at the lowest cost. For pollutant reduction, measures with the highest potential for pollutant reduction had a lower potential for social and biodiversity benefits and vice versa. These findings suggest that pollutant reduction and social and biodiversity benefits may be conflicting objectives. The choice of measures depends on the decision-maker's interests and objectives. Our study highlights that considering multiple objectives, particularly social and ecological ones, provides a more comprehensive view of the benefits of NWRM for runoff management. The significant influence of potential biodiversity and social benefits on the results underscores the importance of integrating these factors into decision-making processes.

The methodology we present has several limitations that offer opportunities for future research. Our simulations in OpenNSPECT focused on only one aspect of NWRM hydrological effects (i.e., increased infiltration). However, NWRM can influence a range of hydrological processes, including water detention, groundwater recharge, evapotranspiration, and water filtration. Future studies should aim to incorporate these additional hydrological processes to provide a more comprehensive understanding of the impact of NWRM implementation.

Additionally, our selection of optimal NWRM was based on social benefits, ecological benefits, and hydrological benefits, with costs considered only in terms of the initial cost of the measures. However, future studies should incorporate a broader range of economic objectives. These could include a reduction of flood damage costs, savings in drainage infrastructure costs, and increased property values due to enhanced green spaces. Finally, our method of identifying the optimal location is separate from identifying optimal NWRM. Integrating hydrological models with the ecological and social impacts of NBS in one holistic tool is one of the main challenges of runoff management (Kumar et al., 2021). Future research should aim to combine both parts into a single optimization problem by simulating different types of measures with quantitative assessments of the social and ecological benefits of NWRM.

Despite its limitations, our research contributes to the field of watershed management in several key ways. We demonstrate a novel way to use OpenNSPECT, traditionally focused on non-point source pollution and water quality, by adapting it for runoff management. We believe that OpenNSPECT could prove to be an effective tool for optimal placement of water retention measures due to its ability to quickly compare different land use scenarios. This comparative nature makes it particularly useful in areas with limited observational data for calibration. Our research also provides a practical method that utilizes the DG-ENV NWRM database to select the most beneficial measures through qualitative estimations of their potential benefits. By leveraging existing resources, this approach facilitates informed decision-making about NWRM implementation, especially in data-scarce rural watersheds that have been largely overlooked in the literature.

In conclusion, the methodology presented here uses simple and readily available tools and information. It does not require specialized expertise in modeling and optimization, making it accessible to a wide range of practitioners. It is applicable to all watersheds, particularly rural ones, where observation data sources are limited. We believe these methods could significantly benefit planners and stakeholders by facilitating the examination of different NWRM scenarios, developing optimal runoff management strategies, reducing flood risk, and better utilizing the potential benefits of runoff. This methodology can support policymakers in integrating NWRM into regional and national water management policies. By addressing hydrological, ecological, social and economic objectives, our methodology promotes a more comprehensive approach to watershed management, thus making a significant contribution to the field.

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CRediT authorship contribution statement

Merav Tal-maon: Writing – original draft, Methodology, Formal analysis, Conceptualization. **Michelle E. Portman:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Dani Broitman:** Writing – review & editing, Supervision, Project administration, Funding acquisition. **Mashor Housh:** Writing – review & editing, Supervision, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2024.122229.

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